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USAAVLABS TECHNICAL REPORT 69-13

REVIEW AND PRELIMINARY EVALUATION OF LIFTING HORIZONTAL-AXIS ROTATING-WING AERONAUTICAL SYSTEMS (HARWAS)

By

W. F. Foshag

G. D. Boshler

March 1969

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
Fort Eustis, Virginia 23604

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This report, which is essentially a literature search, summarizes the horizontal axis lifting device technology from its inception to the present. The work was undertaken to permit evaluation, in the light of current mission requirements, material, and propulsion technology, of various mechanisms proposed over the years.

Frequently, in the solution of immediate problems, techniques are inadvertently reinvented at considerable expenditure of time and money. If this report can prevent such duplication of effort or repetition of prior mistakes, it will have served its purpose.

It is published to permit dissemination of information which might otherwise be unavailable and for the stimulation of ideas.

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REVIEW AND PRELIMINARY EVALUATION OF LIFTING HORIZONTAL-AXIS ROTATING-WING AERONAUTICAL SYSTEMS (HARWAS)

By

W. F. Foshag
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Prepared by

Aerophysics Company
Washington, D. C.

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

SUMMARY

The results of a Review and Preliminary Evaluation of Lifting Horizontal-Axis Rotating-Wing Aeronautical Systems (HARWAS) are presented.

Among the purely aeronautical applications, near-horizontal axis as well as horizontal axis devices are considered. The former cover the radial-lift propeller or "self-propelling" wing; the latter cover Magnus effect and related systems; cyclogiro systems and horizontal-axis propeller systems with cyclic pitch. A limited investigation of non-aeronautical applications of HARWAS is also made, which covers wing-rotor type windmills, cyclogiro windmill turbines, Magnus effect ship propulsion and cycloidal ship propulsion.

Approximately 1200 references are listed. A series of cross-index tables is also included to provide a quick means for the reader to determine the content and availability of the references.

An analysis of the various lift systems pertinent to the HARWAS field is made with a view to potential air vehicle applications. Over 20 original aeronautical applications are identified and evaluated in the light of recent advances in power plants, transmissions and lightweight structural techniques. This analysis points out the extraordinary variety of HARWAS and identifies promising new aeronautical systems, especially wing rotor aerial delivery devices, the rotating airfoil flap STOL airplane, and the cyclogiro VTOL or STOL airplane.

A preliminary performance and design study of two promising HARWAS concepts is also reported. The two concepts are the STOL logistics aircraft using a rotating airfoil flap and the amplified high-pitch cyclogiro for application to the composite aircraft mission.

FOREWORD

This report is the final report prepared by the Aerophysics Company in the performance of Contract DAAJ02-67-C-0048 (Task 1F 162204A14231) for the U. S. Army Aviation Materiel Laboratories (USAAVLABS). It describes a comprehensive review and evaluation of all known horizontal-axis rotating-wing aeronautical systems (HARWAS).

The research program was performed during the period from March 1967 to September 1968. Technical monitoring of the project for USAAVLABS was by W. E. Sickles.

The report is presented in three parts corresponding to the three phases of the program.

The first part discusses the bibliographical search; the bibliography itself is shown in Appendixes I and II. The second part presents an analysis of the material discovered during the search. The third part shows the results of the preliminary performance and design study of two promising concepts which were identified in the second part: the rotating flap STOL aircraft and the V/STOL cyclogiro transport.

In the conclusion, the various aeronautical systems that were identified are classified in the order of potential interest.

The authors would like to acknowledge the considerable assistance that they have received during the compilation of this report from the Stack and Reader Division, Library of Congress, and the staff of the National Air Museum. Special thanks are generally extended to all of those interested persons who acknowledged the general inquiry letter. This form letter, which was given wide distribution, was a useful tool in unearthing background information which would not necessarily have been found in the literature search. Further thanks are due F. Eastman, H. Focke, H. Platt, and I. Laskowitz for their detailed contributions to the report background.

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INTRODUCTION

In the growth of aircraft technology, lifting devices that rotate around a horizontal axis have been proposed and studied on many occasions, only to be discarded in favor of fixed-wing aircraft or of the helicopter rotor. It is the intention of this study to make a preliminary review and classification of all such devices and to evaluate them in the light of current structural and aerodynamic technology against requirements for higher performance rotating wing and composite aircraft. As far as is known, such a review has never been done before.

The project is divided into three phases:

Phase I - Bibliographical Search
Phase II - Analysis
Phase III - Preliminary Performance and Design of Two Promising Concepts

The report is also divided into three parts corresponding to the three phases. The references and the cross-index tables are presented as appendixes.

The investigation uncovered a larger amount of material than was anticipated. It was not possible, therefore, to go into as much detail for each topic as would be desirable. No attempt was made to use a consistent and completely defined set of symbols.

Because of the exceptionally large number of picture credits, these are listed separately in the Foreword.

All devices discussed in this report are referred to as: Lifting Horizontal-Axis Rotating-Wing Aeronautical Systems (HARWAS).

HARWAS BIBLIOGRAPHY

Scope of the Search and Survey

The bibliography search consisted of a detailed review of periodicals, journals, reports, newspapers, films, patents, and books, as well as interviews with technical researchers in the field of horizontal-axis rotating-wing aircraft systems. It has resulted in the bibliographical collection presented here. The broad and general nature of this collection is reflected by the inclusion of material not directly of an aeronautical nature. It is obvious that this additional material strongly complements the aeronautical background of the other references. For example, the theoretical treatment of the cycloidal propeller and its mechanical arrangement is of direct application to similar aeronautical problems. Another example of this double utility is the case of the wing rotor systems where the enhancement of horizontal-axis windmill performance indicates a means of also improving the wing rotor as an aircraft lifting system. Other examples of the complementary usefulness of these allied technical areas may be sensed by an examination of the cross-index tables.

The search began by looking up the citations in a number of accumulated references. This process was repeated several times, with the number of references involved growing to several hundred. It rapidly became obvious that a more efficient type of search would be necessary if the search was to be continued. This technique of looking up the citations in each reference generally went backward in time in the same problem area.

The content of the material varies from the complicated theoretical to the fascinating antique. In a review of this order, it is felt to be pertinent to include some of the more noteworthy older works. In the general spectrum of aeronautical development, the present knowledge on HARWAS might be considered at that evolutionary level the fixed-wing aircraft was at, say, in 1910. One point that this review may reveal to engineers and innovators of "advanced" aeronautical systems--in the words of Mademoiselle Bertin, milliner to Marie Antoinette--is that:

"There is nothing new except what is forgotten."

Naturally, other existing broad-area bibliographical collections were carefully examined. These would be generally:

Technical Abstract Bulletin (TAB/DDC) Indexes and Abstracts

Government-Wide Index to Federal Research and Development Reports (GWI/CFSTI)

Scientific and Technical Aerospace Reports (STAR/NASA)

International Aerospace Abstracts (IAS/AIAA)

The collection of the Defense Documentation Center was examined by means of various bibliographical requests and machine searches.

Secondary and specific bibliographies (for example, References 46B and 47B) were examined for further background. Nearly all of the books, periodical serial publications, and pre-1950 report material was examined directly in the stacks of the Library of Congress. This search has been generally through the engineering technology area and specifically, in the very extensive aeronautics collection.

Besides search by the means of cross-checking other author references, a very effective means of uncovering fresh references, lost material, and obscure publications was the mass search by hand, piece by piece, through pertinent journals and publications. Although such a task could not be completed altogether, the time spent was rewarded with many sources of unusual interest.

The earlier material published before 1920 may be of limited technical value, especially the innumerable patents. Some of this background information is, however, cited in those instances where the descriptions or disclosures show a definite understanding of the problem at hand, an awareness of the aerodynamic forces at play, and the description of realistic structures and workable mechanisms. Often, some of the earlier material is included which demonstrates an intriguing mechanical solution or mechanism which might suggest an evolution of ideas toward a more modern solution.

The patent literature is a special case of the technical background and is all too often neglected in surveys such as this. Admittedly, the patent description is essentially a technico-legal document and nearly always avoids or purposely overlooks the use of formulas and those mathematics so essential to the enquiring engineer. Nonetheless, if one learns the style of reading out the technical essence of a patent description, the results are often useful. This is particularly so to the design engineer.

Some general comments on the patent material are in order here to help toward a better understanding of, and a guide to, their technical usefulness:

1. One of the main purposes of the patent search was to intercept, classify, and retrieve any of the earlier material that demonstrated any applicable realistic technical worth. With this review of thousands of aeronautical patents, it became very difficult, with the very few moments which could be spent scanning an individual patent, to make a positive technical assessment of the value of an inventor's idea or device. One had to be able to literally, at a glance, accept or reject the patent on the spot.

2. One must have a general knowledge of the inventor's intent with his patent and must not be misled by the patent's drawing presentation (often no more than a technical cartoon) or the technico-legal language of the body of the patent proper. The often exaggerated proportions of the material pictured in patent description drawings must always be considered as a means of calling attention to certain novel portions or functions of the patent. There was always the temptation to dismiss a perfectly sound technical invention because of its odd presentation in the drawing. Literal engineering or shop drawings hardly ever make acceptable (to the examiner, for example) patent presentations.

3. Most often the inventor's intent was described in the preamble of the description or occasionally in the central explanation of detailed functioning. The patent claims were seldom of direct technical interest. Often a series of patent descriptions and patented devices would appear to be repetitive in their invention. This was often quite exasperating when one was attempting to make quick "go/no-go" decisions whether to accept or to reject a particular patent. A closer examination of the description in this case would nearly always reveal subtle and often very clever improvements over prior patent art.

4. One is often at a loss as to how to handle patent material of the 19th and early 20th centuries (up to about 1910), especially in matters of the cyclogiro or paddle wheel concepts. There was such a bulk of it! This search indicated that the horizontal-axis paddle wheel system is probably the most frequently used concept for aeronautical propulsion and sustenance--possibly even by number, in excess of the screw or propeller system. A moment's reflection shows why this is true. If one reconsiders the background of naval propulsion of this time--the stern and side wheelers--it was only natural to extend this thinking to yet unproven aircraft systems. Today, this material may be considered to be only a technical curiosity. Although the basic mechanical arrangements are often sound, the aerodynamic performance, with a very few outstanding exceptions (to be described), would appear to be about nil. A total review of this material would have been of benefit only to a patent examiner where a search of all prior art is required as standard patent procedure.

5. There is no question that a patent search of this magnitude was the perfect complement to the search of technical publications, periodicals, and reports. A researcher would often not disclose in an open journal that which he would (since he then has protection) in a patent. The patent, therefore, often supports the other technical publications. A patent, on the other hand, is

a very prejudiced document and is useful only for a qualitative understanding of the function of a particular device.

The search of the patent literature at this level can be shown to be a very useful tool. It demonstrates the abundance and availability of ideas, most of which are in the public domain. One of the continual temptations of the practicing engineer is to reinvent old ideas and, with enough incentive, to expand upon them. One feature that is unmistakably shown in a review such as this is the repeated occurrence of discovery and rediscovery of identical ideas by investigators who are completely unaware of the former results of identical or similar ideas, theories, or tests. It is in this case that a review such as this can serve as a strong tool to prevent such duplication and can serve, in its stead, as a means of cross-fertilizing older ideas to produce new advancing ideas. All in all, the review may well furnish that heuristic background from which come the technological breakthroughs and state-of-the-art advances.

The patents collected herein, although fairly complete, should not be regarded as a substitute for a final or professional patent search.

Another source of background information was sought from direct interviews with some of the authors or inventors. Initial contact with these interested persons was made through the use of a general inquiry form letter which was mailed widely to persons and institutions throughout the world. Response to this letter was moderately favorable, as it revealed unpublished material and otherwise obscure references. Some findings from the personal interviews resulting from this letter have been incorporated in the previous background discussion.

As an aid to the reader, several similar bibliographies have been included which cover adjacent fields of interest and application. The cited AGARD VTOL/STOL Bibliographies (Reference 6A and its supplements) may be used for comparative systems evaluation. The extensive FitzPatrick bibliography (Reference 15F) on natural flight covers the older references on unsteady aerodynamic problems as possibly encountered in most instances with horizontal-axis rotating-wing aircraft systems, as well as most citations on insect flight aerodynamics. This latter area is of interest to the problem of the cyclogiro.

At the writing of this report, most of the nearly 1200 listings have been verified with the exception of those specifically "not searched" in the index table. The actual reference, a copy thereof, or a microfilm version has been actually examined.

It is pertinent to mention at this point that the bibliographies appearing at the end of reports and articles contain too high a percentage of errors. This makes the locating of references extremely difficult. Often the error is repeated through a series of publications, which indicates either that the bibliographies are copied from other reports or that very little proofreading or checking of bibliographies is done by authors.

The reader will make note of the fact that no classified reports are listed in the bibliography.

Presentation of Results

Each reference citation is assigned a number to establish its order and to identify it in the cross-index tables. The references are generally listed in alphabetical order according to the author's last name. In very many instances, especially in the periodical literature, articles of interest have been presented without the credit of a specific author. More likely than not, this material will discuss a particular project or the work of a specific inventor or engineer. This material is thus entered into the body of the bibliography under the inventor's name, placed in parentheses, and arranged in an approximate alphabetical manner. Many reports were found which did not specify a particular author, and these too have been entered alphabetically by corporate issuing agency name or title.

Some of the references, especially those of a report nature, could be cited as published from more than one publication source. Thus, for example, a thesis may appear as a laboratory report, a journal article, or a meeting preprint. In such instances of multiple publication, the most readily available retrieval source is cited, and the alternate sources are briefly noted.

In the instance of the translation of foreign material into English text, the English reference source is given as the primary citation, with the original foreign language reference noted.

Patents are cited in alphabetical order by the inventor's last name. Inventors will often patent the same invention in one or more countries. In cases where this has happened, the United States or British English language patent is considered to be the primary citation, and the alternate foreign patents are noted.

The slant mark used with some British numbers is preceded by the last two numbers of the official A.D. (anno Domini) date. Until about 1913, British patent numbers were repeated annually. In general, six-digit numbers on British patents do not need the A.D. date for complete identification. Several of the cited British patents are not to be found in the collection of patent specifications and drawings but only in the British patent abstracts. These omitted patents were never formally issued. In some instances, foreign patents are issued in the name of a firm, and this name is used because the inventor remains anonymous.

Explanation and Key to the Index Tables

A series of cross-index tables is included to provide a skeleton form of reference abstracts and to provide a quick means to determine the content and availability of references. With these tables it becomes possible to search out a combination of subject or interests to a number of specific sources. By scanning the appropriate columns of descriptors, the scope of a particular reference may be quickly determined.

For the fullest understanding and use of the cross-index tables, the following key to some of the descriptors will serve to broadly explain their coverage:

1. Cyclogiro or Cycloidal Propulsion. This category includes and broadly covers aeronautical or marine lift and propulsion devices in which a multibladed feathering rotor system is rotated about a specific axis. In aircraft, this axis is usually horizontal; in marine applications, vertical. This group may also include devices which also extract energy from a moving fluid medium (mills or pumps).

2. Wing Rotor. This category includes winged systems in which a fixed-geometry foil or blade rotates about an axis to produce thrust and, in the case of mills, torque. Thrust or lift is produced on these vaned devices by Magnus effect. Most of these devices autorotate in an air stream, and power may be extracted from the axis shaft. Lift may be enhanced in the wing rotor system by driving the system above its natural autorotating condition by an exterior power source. The wing rotor must be impressed in a moving current to produce thrust or resultant forces.

3. Magnus Cylinder. This group includes a cylindrical rotor device operating much like the wing rotor to produce thrust or lift by Magnus effect. Unlike the wing rotor, it must be rotated by power, and, as a cylinder, it cannot absorb power in itself from a moving current. Like the wing rotor, it also must be impressed in a moving current to produce lift or thrust.

4. Cross-Flow Fan. This group includes a multibladed fan or pump device not too unlike certain cyclogiro systems but with a fixed geometry. Like the cyclogiro system, the cross-flow fan will produce static thrust when its shaft is power driven. As there is a large general description of this fan system in the engineering literature, the reader is referred to References 3E and 4E for a review in this area. The cross-flow fan, or tangential blower as it is sometimes called, may have a rotor with blades shaped somewhat like those of a forward curved centrifugal fan impeller. Unlike the common squirrel-cage fan rotor, both ends of the rotor or impeller are sealed, and the rotor is fitted into a casing or shroud in which the air enters at the periphery on one side, passes through the rotor, and leaves on the peripheral face at the other side. References included here describe this fan as applied to V/STOL aircraft only.

5. Other. This group includes various other systems which have been suggested, tested, or built in which a winged

or rotor system rotates about a horizontal axis. Among these, for example, is the Thrust Wing (German), Helicoplane (French), or Radial-Lift Concept (Curtiss-Wright), in which an especially designed VTOL propeller blade and feathering mechanism may be arranged to directly furnish a substantial vertical component of lift while the propeller axis of rotation is nearly horizontal. Also, miscellaneous devices of interest are loosely classified in this category.

6. Theoretical Exposition. This category includes references in which an analysis is presented toward the understanding of a phenomenon or toward the answer to a specific problem. The text may be merely a hypothetical discussion or may be supported by detailed mathematical and graphical formulations. For a more comprehensive means of determining the content and method of approach of the fully theoretical references, it is suggested that the reader first review related summaries in the interpretative review and cross-index tables those items called out in: 12 - Review.

7. Performance. This group includes a qualitative and/or quantitative discussion of performance, range, etc., especially that of the complete system.

8. Stability. This group includes a qualitative and/or quantitative discussion of stability of a complete flight system and its criteria.

9. Control and Maneuverability. This category discusses in a qualitative and/or quantitative manner, controllability, control means, and mechanisms. Maneuverability is discussed primarily with reference to marine systems.

11. Phenomenon Demonstration. Discussion and demonstration of basic HARWAS fundamental flight mechanics such as in the deflection of spinning missiles in flight, the autorotation of free-falling cards and shapes, the curved flight of baseballs, the tumbling of aircraft, and the like are discussed under this heading.

12. Review. A category in which the reference covers an interpretative, comprehensive background review and evaluation.

13. Comment of Interest. A usually brief statement or clipping often accompanied by a photograph or drawing describing a matter of some technical importance. Usually the content of the statement does not warrant the full attention of a report or article, yet it is not altogether trivial for its background.

14. Aircraft Sustentation. This category pertains to an aeronautical system which is concerned primarily with the production of lift.

15. Aircraft Propulsion. This category pertains to an aeronautical system which is concerned primarily with the production of thrust.

When both items 14 and 15 are checked, the system may usually be considered to be that of a fully controllable cyclogiro device.

16. Marine Propulsion. This category pertains to a nautical system concerned solely as a thrust-producing device. Below the waterline, this may be a cycloidal propeller; above, it may be a sailing Magnus or wing rotor.

17. Complete Aircraft. The system as applied to a complete flying article as opposed to a test component will be discussed under this heading.

18. Complete Ship. This group discusses the complete marine system, including problems of hull hydrodynamics, interference, and overall performance.

19. Rotating Flap or Slat. This category pertains to an autorotating or powered wing rotor or Magnus cylinder used in conjunction with a fixed aircraft to enhance lift circulation and/or to energize the boundary layer. Such systems are to be considered as auxiliary to the main lifting wing. They may be located at or near the trailing edge (flap), in or near the leading edge (slat), or above or below the main wing surface. They may, at times, be retracted or faired into the structure of the fixed wing.

20. Convertible Rotor to Wing. These are systems in which the rotor (wing rotor or cyclogiro) may be stopped and/or started in flight are discussed under this heading. The blade of the stopped rotor is then considered to be a fixed lifting wing of the converted aircraft.

21. Rotor-Rotor. This is a system peculiar to the wing rotor or Magnus cylinder in which the horizontally rotating rotor system is corotated about a vertical axis or shaft. In essence, the rotor then may be considered to be a replacement for fixed blades (say, for example, in the case of thrust propeller). This group may also apply to decelerators, windmills, etc.

22. Device Other Than Aircraft or Marine System. As indicated by the following key letters, HARWAS may be applied to the following devices:

B - Bomblet
C - Control Device
D - Decelerator
F - Fluid Motor or Meter
K - Kite
W - Windmill

23. Feathering Pitch System. Refer to Figure 92 for key. This category classifies cyclogiro feathering systems by blade motion relative to rotor axis of rotation.

24. Rotor Systems per Installation. A rotor system is considered to be that independent collection of cyclogiro rotor blades or wing rotor vanes that, together, function as a singular lifting or thrusting system. Thus, the arrangement for Figure 64 is considered to have one rotor, that of Figure 68 is considered to have two, and that of Figure 59 is considered to have four rotor systems.

25. Number of Blades per Rotor. Rotor systems may have one or more blades as numbered in index. M stands for multiple, more than eight. Savonius wing rotor systems are considered to have two blades per rotor.

26. Blade or Rotor Profile. This category discusses profile or cross section of rotors, a prominent parameter in wing rotor studies. Subindexed in the following manner, they are:

A - Conventional
C - Cylinder
D - Driving or Auxiliary Vanes System
E - Ellipse
F - Flat Plate
G - Regular Geometric Shape
I - Irregular Geometric Figure
L - Lenticular
P - Powered, Driven by External Source
R - Rectangular, May Have Rounded Edges
S - Semicircular Halves, Savonius
X - Cruciform, Three or Four Points

27. Tip Path Other Than Circular. In cycloidal propulsion rotors, the blades usually sweep out the surface of

a cylinder, but, in some (mainly aeronautical) arrangements, they may describe a cone or other irregular truncated developments (in an attempt to simulate insect wing motions).

28. Auxiliary to Fixed Wing. Rotor systems are used to increase lift or drag. They may stop, start, convert, retract, or otherwise supplement aircraft control or performance.

30. Flight or Drop Test. The test in which horizontal-axis rotating-wing aircraft systems are flight-tested or dropped in wind tunnels (both horizontal or vertical), from aircraft, balloons, or towers is discussed under this heading.

58. Presentation.

B - Book
P - Patent Description
R - Report
S - Serial Publication
T - Thesis

59. Classified. References under this broad classification may be considered to have limited distribution to one degree or another. They may be generally considered to be Secret, Confidential, Restricted, Limited, Controlled Access, or not available for foreign circulation. This material is to be found in a supplementary report.

60. Company Proprietary. Material which is limited in its distribution and availability, in that it is usually generated for a particular organization for in-house knowledge or business falls under this heading. These references may consist of proposals, laboratory reports, etc.

61. Not Generally Available. This category refers to references which are not available to the general public at the time of this writing for a variety of reasons. Also see Index Items Nos. 59 and 60.

64. Not Searched. This category is cited where the references were not examined by the authors because of their immediate unavailability and the lack of time required to search for them. The reader may therefore only know of their existence, sense the content from the title, and hope to have better access to sources.

Status and Retrieval of References

Nearly all of the books, journals, serial publications, newspapers, general publications, and reports issued before 1950 are to be found in the collection of the Library of Congress, Washington, D. C. This material is readily available for examination at that library. A limited amount of this material (that is, that material which is not specifically copyrighted) may be copied by the photoduplication service of that library. Much of this material may also be obtained outside of Washington, D. C., on a library loan basis.

An alternate source for some of this earlier material, and for much of it that has been published since then, is the Technical Information Service, American Institute of Aeronautics and Astronautics (AIAA).

Those German World War II aeronautical publications that formerly were part of the Defense Documentation Center collection are to be found in the microfilm collection of the National Air Museum, Washington, D. C. Those German documents with Department of Commerce Publication Board (PB) numbers may also be purchased through the regular Clearinghouse for Federal Scientific and Technical Information (CFSTI).

Those individuals or organizations within the Government or working on Government contracts, if presenting the proper field of interest register and other requirements, can obtain most of the Government-sponsored reports issued since 1950 from the Defense Documentation Center (DDC). All of the NACA/NASA reports, memorandums, notes, etc., are available, in a similar manner, from the NASA Scientific and Technical Information Facility.

Domestic and foreign patents may be directly examined in the search rooms of the U. S. Patent Office, Washington, D. C. Domestic patents may be purchased by mail, for cash ($ .50) or special coupons, from the U. S. Patent Office, Washington, D. C. Only the patent number is required to identify the order. Foreign patents are also kept in the Patent Office library in bound volumes by number or classification. Zerox copies may be made for $ .50 per page only at the main Patent Office. Domestic patents may be examined in one of the 22 patent copy libraries around the country. In order to examine patent material outside Washington, D. C., refer to: "How to Obtain Information From U. S. Patents", U. S. Department of Commerce, Patent Office, Washington, D. C. (for sale by the U.S. G.P.O., Washington, D. C., $.20). Foreign patents may best be obtained by writing directly to the foreign patent office in question. The current addresses of these offices and their patent costs are described in the front portion of each issue of <u>Chemical Abstracts</u>.

ANALYSIS

I. HORIZONTAL-AXIS LIFTING DEVICES

A. MAGNUS EFFECT AND RELATED SYSTEMS

1. Wing Rotor (Rotating Airfoil) Decelerators

a. Introduction

Some aerodynamic properties of autorotating or forcibly rotated cylinders and airfoils were investigated even prior to the beginning of aviation. It was Maxwell who wrote the earliest (1853) known paper on the subject (Reference 41M). That entirely nonmathematical paper tried to explain the curious behavior of an oblong card which, left to fall freely in the air, started immediately to rotate about its longitudinal axis while deviating from the vertical in the horizontal direction perpendicular to the axis of rotation. Steady "terminal" conditions are soon reached, in which speed, rate of rotation, and path angle are all constant. This simple experiment revealed at once two important properties of an "aerofoil of large aspect ratio": (1) ability to autorotate; (2) ability, when rotating in an airstream, to create an asymmetrical pressure distribution, resulting in a force normal to both axis of rotation and mainstream velocity. About the same time, the famous "Magnus effect" on rotating circular cylinders was discovered, but it was not until the Kutta-Joukowski theory of aerodynamic lift appeared some 50 years later that a more general understanding of the "lift through circulation" principle became possible.

Very little has been done to exploit the use of airfoils rotating about a horizontal and transverse axis for generating lift in aircraft. The basic reason is that a rotating airfoil as the main lifting surface of an aircraft can generate high lift, but this is accompanied by a correspondingly high drag, so that it will have a lower lift-to-drag ratio than the corresponding fixed-wing configuration. The configuration is not competitive for standard aircraft applications.

Such rotating wings have been proposed in recent years for other aeronautical uses, particularly as "aerodynamic decelerators", for the air-to-ground precision delivery of cargo payloads. Such applications will be discussed in detail later in this section. The main features of the aerodynamics of rotating airfoils will first be reviewed. Aerophysics Company suggested in 1964 that devices embodying the use of single airfoils rotating about a horizontal and transverse axis be called "wing rotors". This name will be used extensively in the discussion that follows.

b. Pictorial Review

Magnus' original experimental apparatus, by means of which he established the existence of a side thrust on a rotating cylinder in an airstream, is shown in Figure 1 (Reference 13M). Thus, in Figure 2A, a stream of air is continuously discharged from the radial blower F as long as the crank-wheel E is kept in rotation. This air impinges upon the rotating cylinder and the deflection of the airstream will be indicated by the weather-vaning of the pivoted surfaces a and b. In Figure 2B, the radial blower discharges air onto the heavy brass cylinder mounted between bearings a and b. This Magnus cylinder is set into prolonged rotation by means of the small pulley e and a quickly pulled and unwinding starter string. The Magnus effect on the system will now cause the spinning cylinder, along with its supporting beam y - z, to slowly rotate in a horizontal plane about the vertical axis c - w. The lower board B - A, which also carries the blower F, is so arranged with the vertical pivot, that it will tend to rotate and lag behind the moving Magnus cylinder, thus demonstrating the continuous side or Magnus force produced by the rotating cylinder.

The original autorotating wing rotor device with a useful payload, found in nature, the locust tree seed pod (Robinia pseudoacacia), is shown in Figure 1.

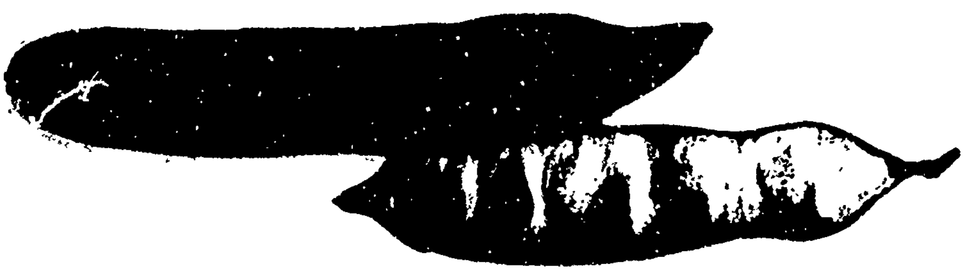


Figure 1. The Original Autorotating Wing Rotor Device With Useful Payload Found in Nature: The Common Locust Tree (Robinia pseudoacacia) Seed Pod.

The first measurements and primitive theory on wing rotors were made by Ahlborn in 1897; his apparatus and typical trajectories are shown in Figure 3.

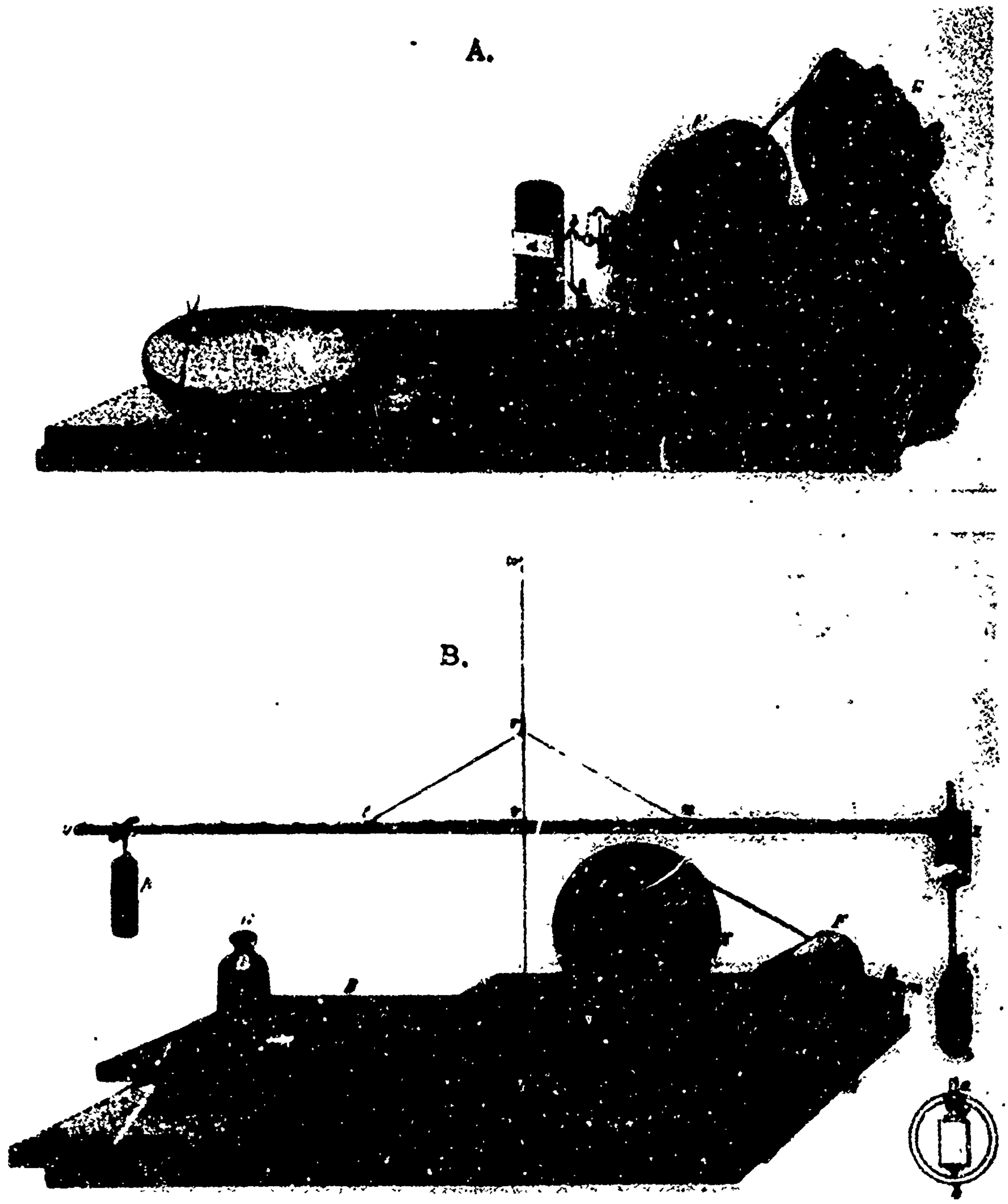


Figure 2. The Original Experimental Arrangement by Magnus in Determining the Side Thrust on a Rotating Cylinder in an Airstream.

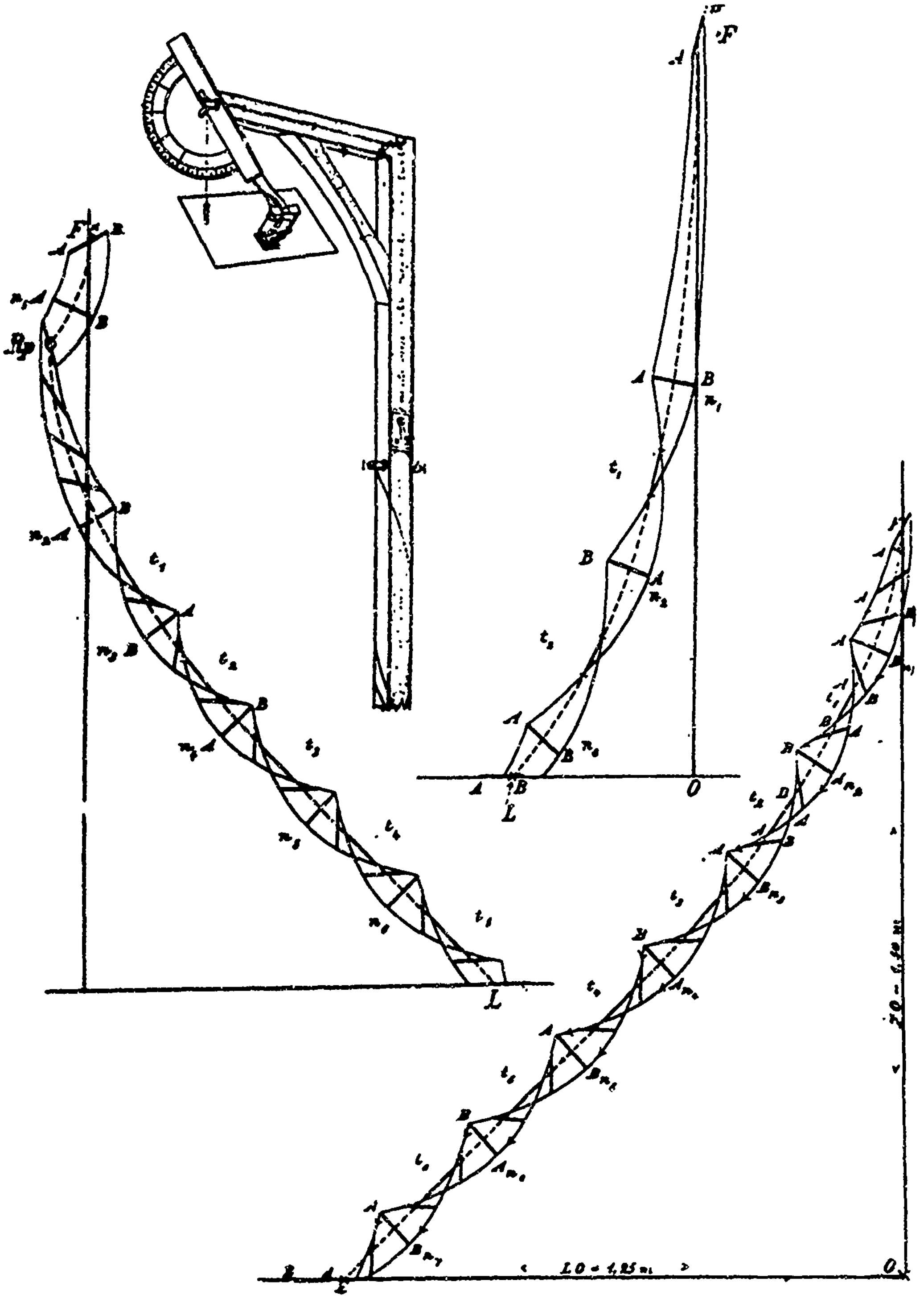


Figure 3. First Wing Rotor Performance Measurement and Theory by Ahlborn in 1897 (Ref. 9A). Autorotating Metal Plate Released From Tower as Shown.

Koppen's wing rotor glider (1903), of which models were built, is shown in Figure 4.

Another early wing rotor system, devised by Ames, is shown in Figures 5 and 6.

Several airplanes using Magnus cylinder lift for their main sustentation have been proposed at various times. Two such odd configurations are shown in Figures 7 and 8.

Wing rotors have often been used as toy kites.

A serious attempt was made in the thirties in France by Chappedelaine to develop an airplane with a main wing rotating about a horizontal axis. The "Aérogyre", shown in Figure 9, was built and flown. However, it crashed, and the project was abandoned. Performance of the aircraft is shown in the performance curves of Figures 15 and 16 (References 16C through 26C).

This project, though unsuccessful, is worth more than a passing mention, because the aircraft was basically sound. The reason that Chappedelaine used a rotating wing was that he knew he could obtain a higher lift out of a rotating wing, either autorotating or self-powered, than out of the same wing operating as a fixed wing. He intended to use this feature for takeoff and landing only, and to lock the wing for cruise flight. The "Aérogyre" type aircraft thus would have been a short takeoff and landing (STOL) airplane with the high cruise efficiency of the fixed-wing airplane and the additional safety of the autorotational landing.

Modern versions of the "Aérogyre" type aircraft have been proposed in the United States (Foshag, 1947; see Figure 11) and, very recently, in Germany (Horstenke, one of whose models is shown in Figure 12).

As a result of work done in Germany at the end of World War II, recent interest has been expressed in using rotating airfoils, not as main lift units but as auxiliary high-lift devices on aircraft wings. Crabtree, in 1957, reviewed the state of the art (Reference 52C). Following work done by Alvarez-Calderon since that time (References 18A through 24A), NASA/Ames is currently testing a rotating cylinder flap on a COIN-type aircraft (Reference 31A). Noncylindrical rotating devices can also be considered; two such configurations are shown in Figure 10.

Most research and development work currently performed in the United States on Magnus rotors and wing rotors is related to the dynamics and aerodynamics of bomblets. This

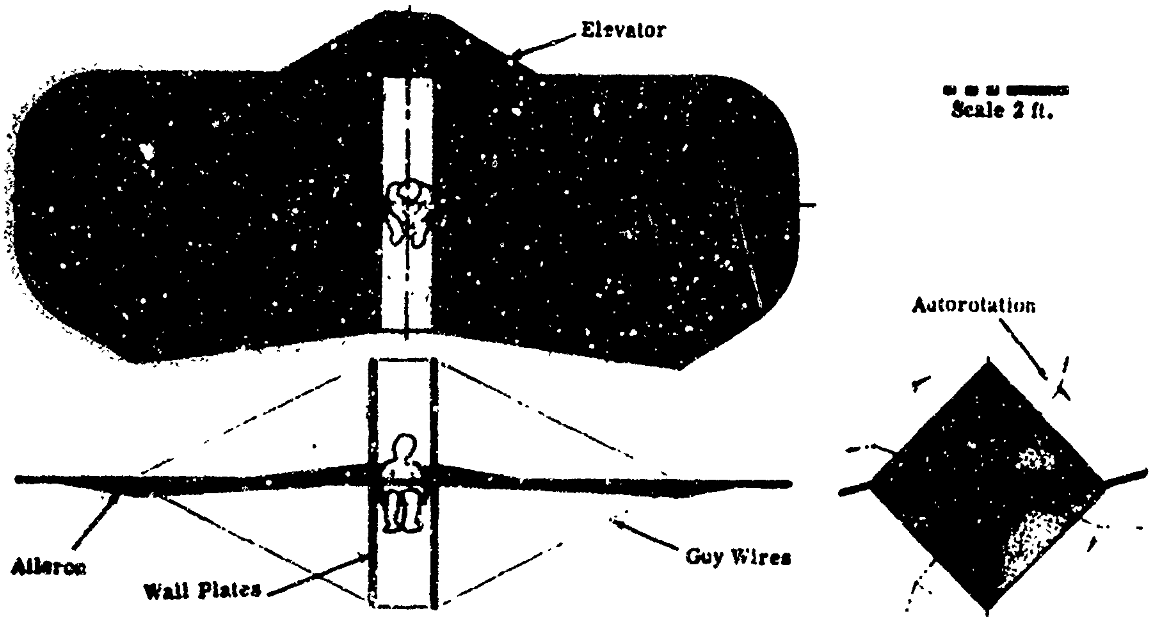


Figure 4. Early (1903) Wing Rotor Glider Project Demonstrated by Koppen as Model (Ref. 52M).

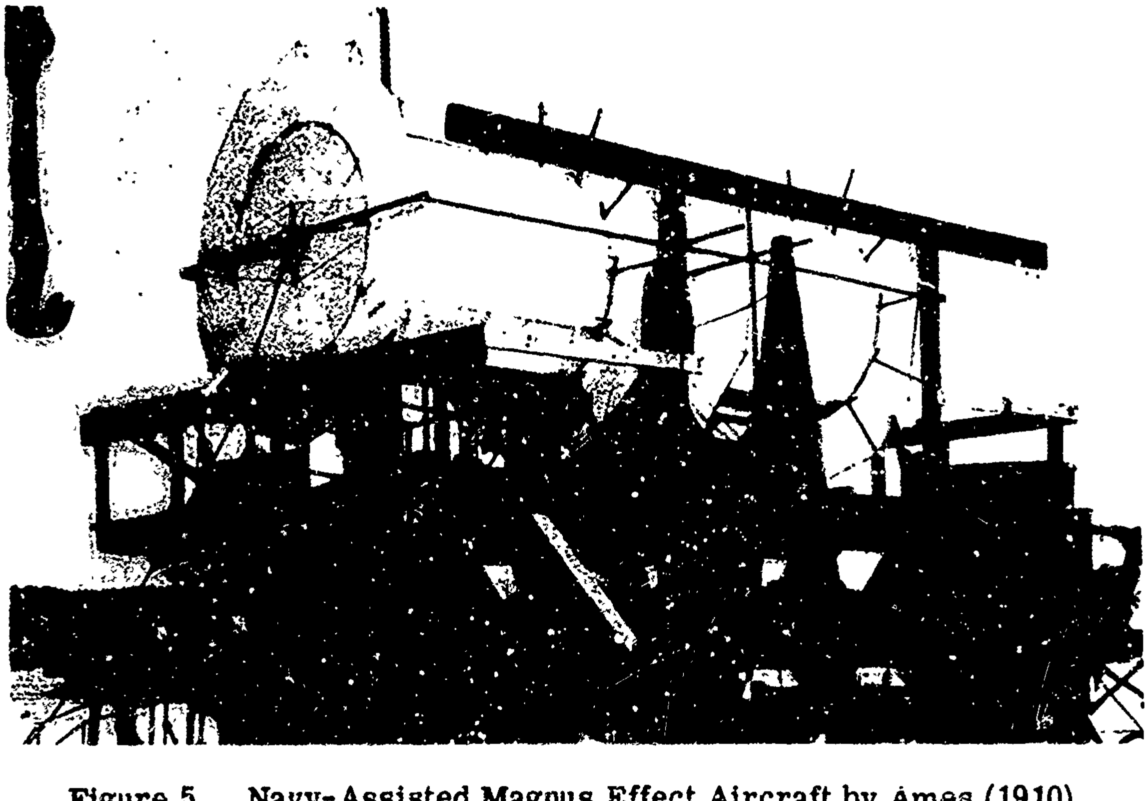


Figure 5. Navy-Assisted Magnus Effect Aircraft by Ames (1910) Mounted Atop Fast Steam Launch (Ref. 26A).

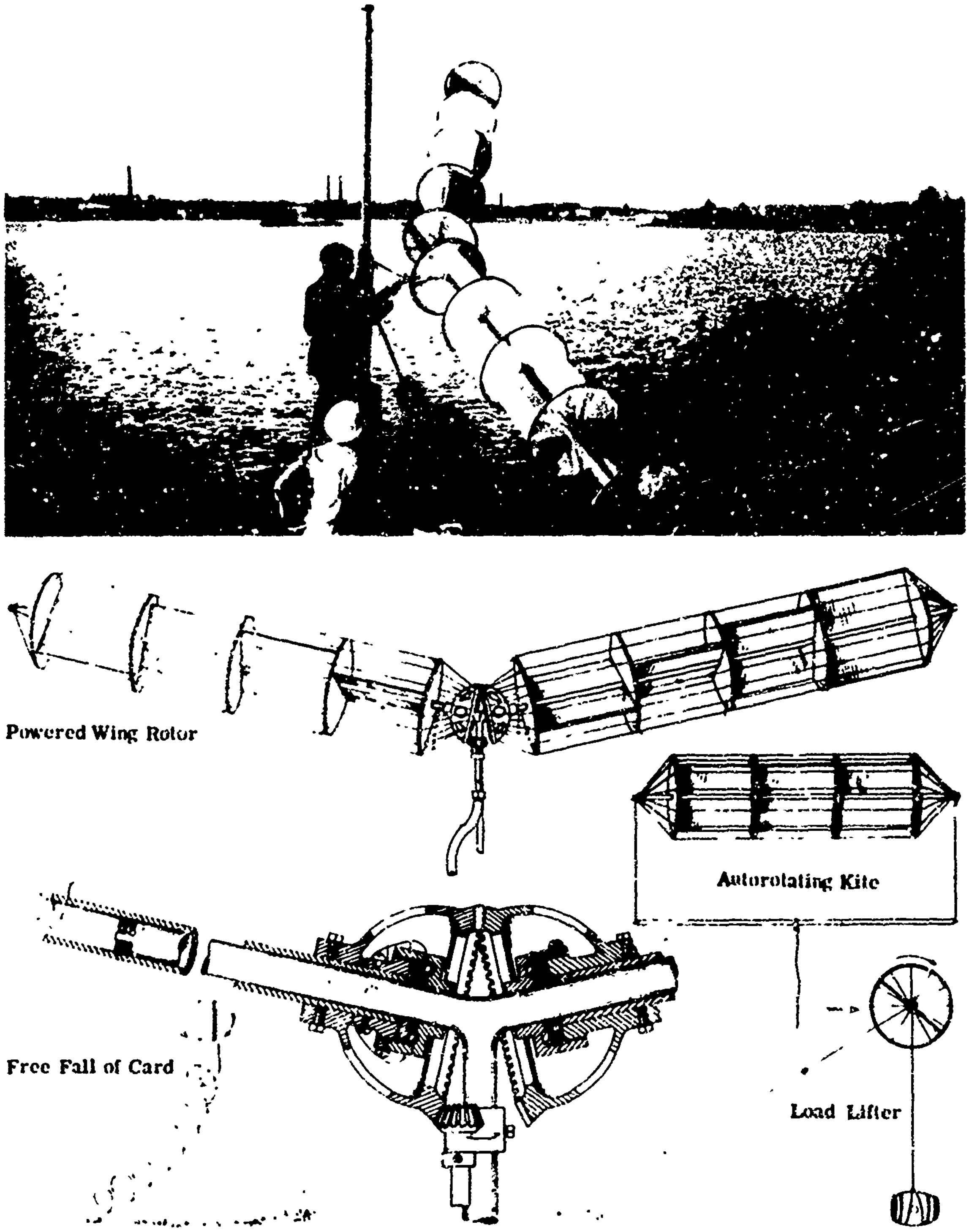


Figure 6. Further Autorotating and Powered Wing Rotor Systems by Ames (Ref. 25A).

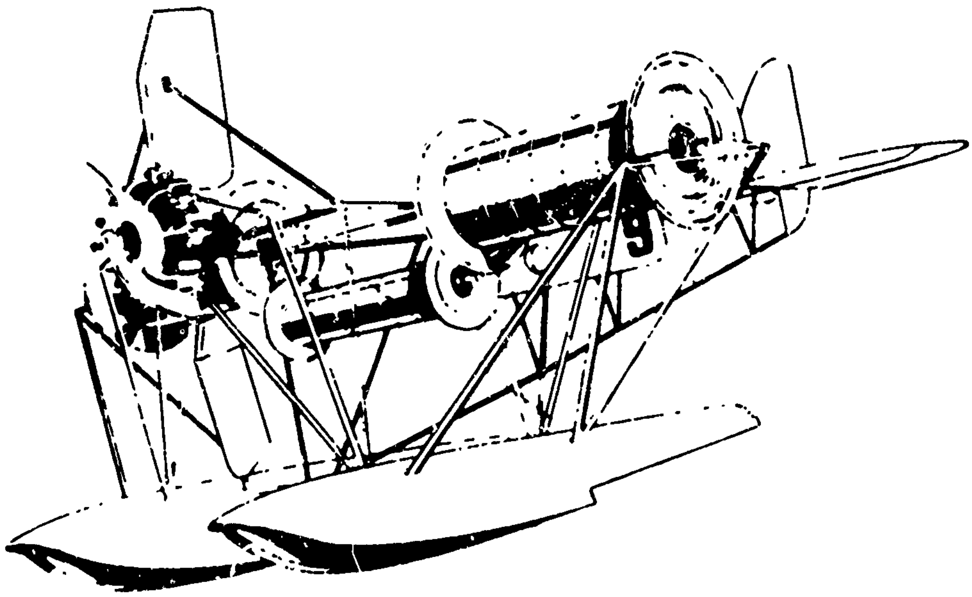


Figure 7. Zaparka Magnus Rotor Aircraft. Possibly Flown Full Size Briefly in 1930 (Refs. 2Z Through 12Z).

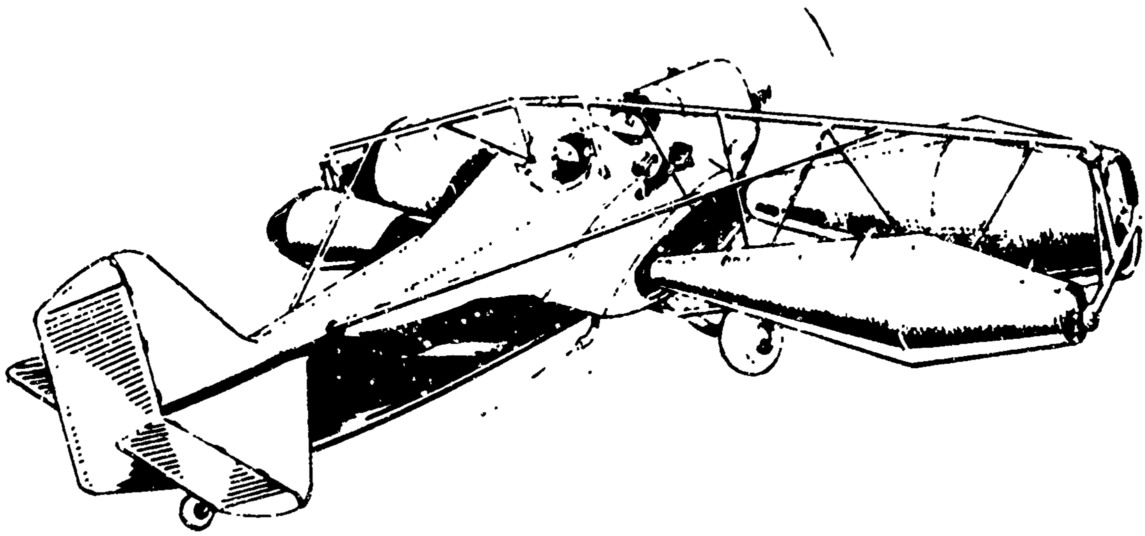


Figure 8. Guest and Popper Full-Size Magnus Rotor Aircraft. Main Engine 85 HP. Serrated and "Pocketed" Rotor Surface to Enhance Circulation (Refs. 53G Through 58G).

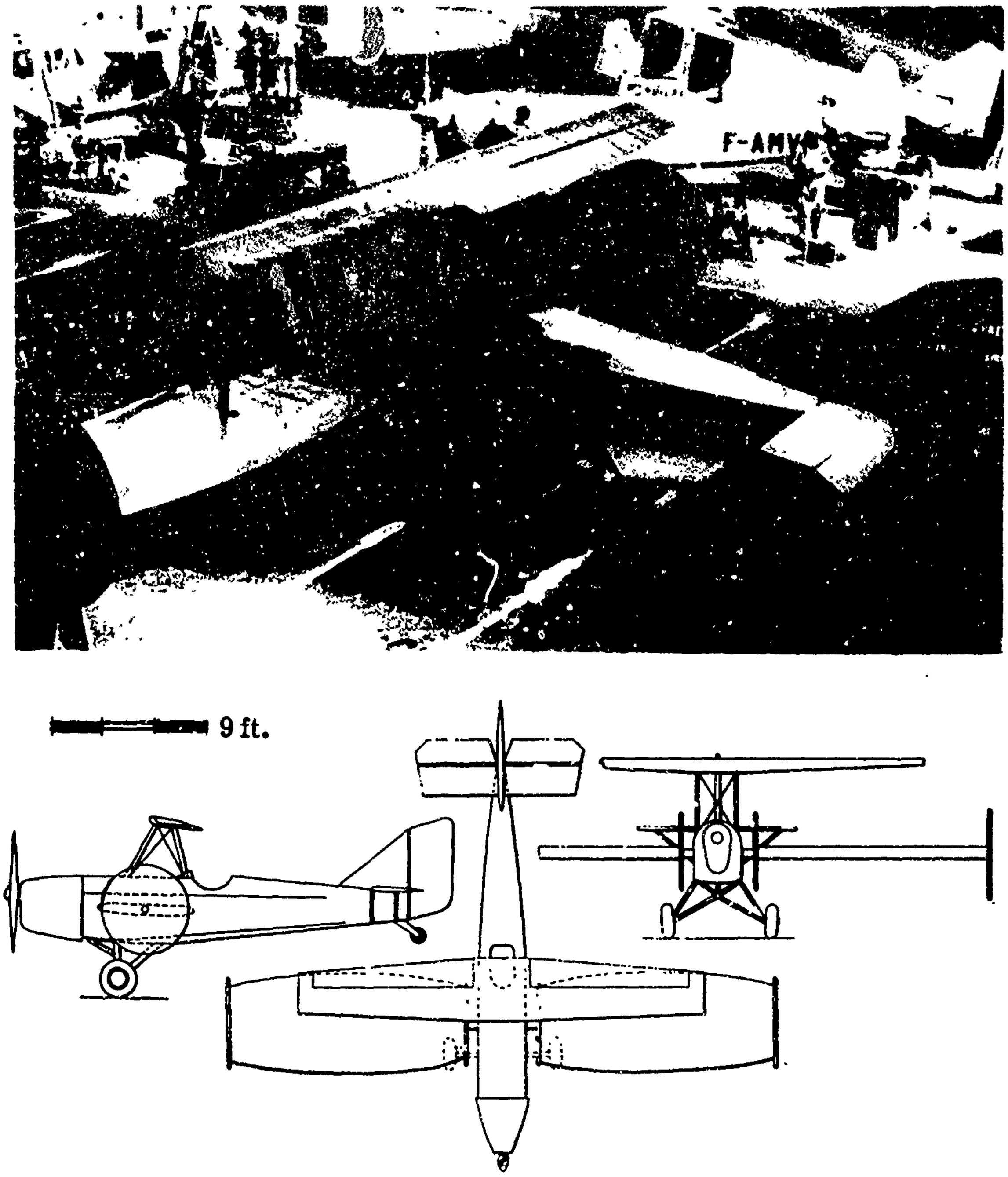


Figure 9. The Chappedelaine-Desgrandechamps-Caud[illegible]on "Aérogyre" Being Rigged and Shown in Th[illegible] Views. Several Flights in 1934. Lower Wings Rotate and Lock for STOL Conversion. (Refs. 16C through 26C).

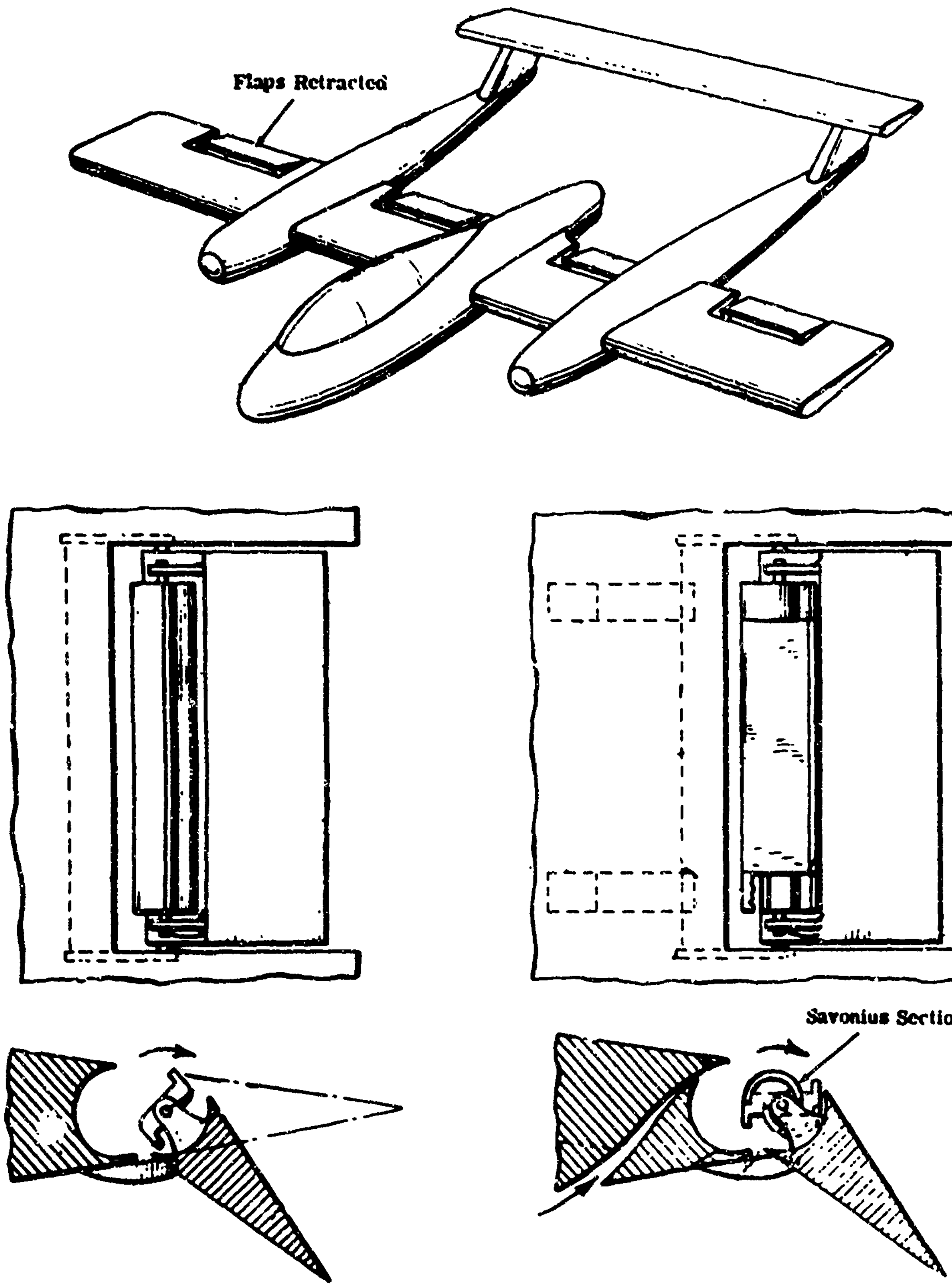


Figure 10. Recent (1966) Adaptation of Autorotating Wing Rotors to Trailing-Edge Flap Systems To Turn the Flow Over Flap. (From Brunk, Refs. 84B and 86B.)

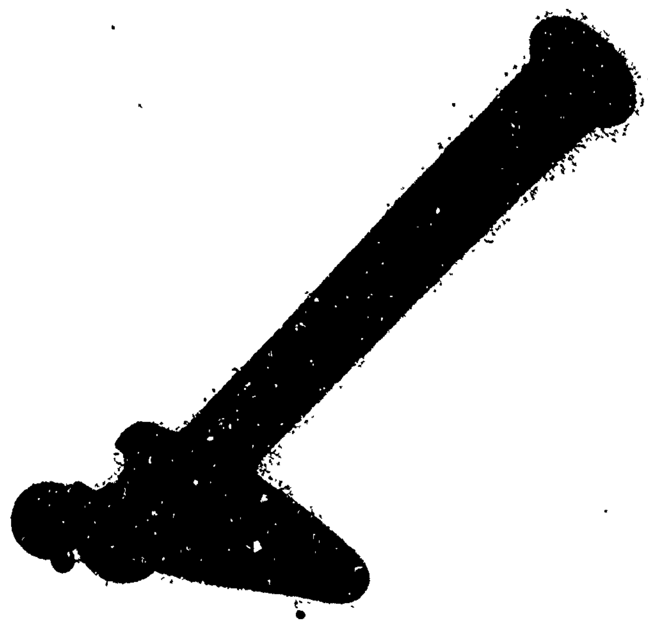


Figure 11. Eight-Foot Wing Rotor Sailplane (1947) Demonstrating Good Flight Performance and Stability About All Axes. (Ref. 65F).

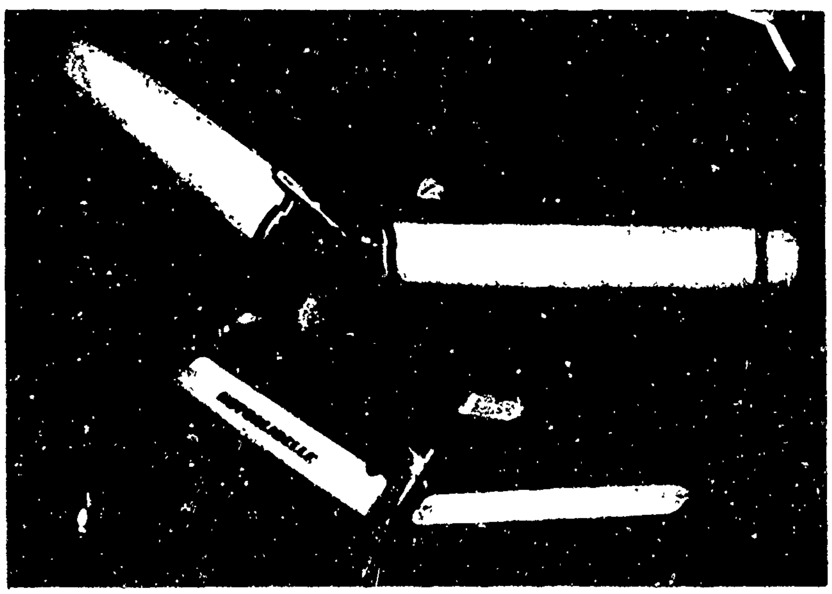


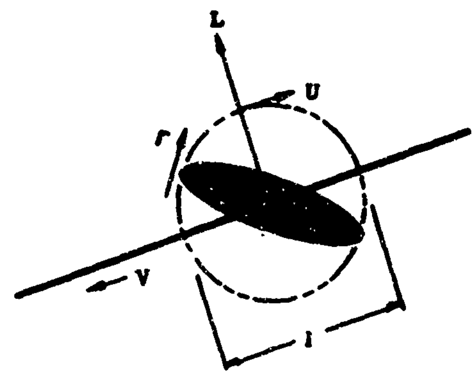
Figure 12. Successful Powered Wing Rotor Model by Horstenke (Refs. 52H Through 59H). The Larger Model Is Controlled by Radio Command.

work is concentrated at the Edgewood and Detrick facilities, as far as the Army is concerned, and at the Air Force Armament Laboratory, Eglin Air Force Base, as far as the Air Force is concerned. This work is mostly of a classified nature and will not be discussed further here. It is summarized in the Proceedings of the Conference on Dynamics and Aerodynamics of Bomblets, which took place at Eglin Air Force Base, Florida, September 26-28, 1967.

c. Aerodynamics and Dynamics of Wing Rotors

A conventional airfoil or wing placed in an airstream will not usually autorotate if its center of pressure and its chordwise center of gravity approximately coincide. One can, however, create a strong pitching moment and cause autorotation of any airfoil by moving its center of gravity backward, sufficiently far from the center of pressure. Similarly, a flat plate, a modified rectangular shape, or a cylinder with driving vanes will autorotate; the Magnus smooth cylinder is about the only one that will not. Actually, there are considerable differences between the wing rotor and the Magnus cylinder. The circular cylinder enforces circulation through viscosity alone and must be driven to overcome the resisting frictional torque; the circulatory motion of the air exhibits a complete axial symmetry and, thus, in steady conditions, should not differ much from an idealized "linear vortex", so that the usual formula $L = \rho V \Gamma$ (L is the lift, ρ the density, V the translational velocity, and Γ the circulation) should apply, at least approximately. In the case of a wing rotor, the velocity field is more or less unsteady and much more complicated, involving some significant radial out-and-in flow. In the presence of a mainstream, the mean aerodynamic torque will be positive (driving) at low rotational speeds and negative (resisting) at higher rates of rotation, so that the airfoil without an external drive will autorotate at some intermediate rate. A significant lift appears in such conditions, but it may be increased several times if the airfoil is driven by external power so as to acquire much higher rotational speeds than the autorotational one. At such speeds, the velocity field outside the cylindrical volume swept by the airfoil becomes more steady and may approach the form of a linear vortex field.

The theory of fluid motion associated with a rotating airfoil presents enormous difficulties. No successful analytical attempt has been made thus far to determine the aerodynamic characteristics of the rotating airfoil. An extremely crude estimate of lift for the two-dimensional case has been suggested, based on the concept of an idealized linear vortex whose circulation is assumed to be r-ωu.



where l is the airfoil chord and U is the peripheral velocity. The lift per unit span is thus:

$$L = \rho V \Gamma = \pi \rho \, lUV$$

whence,

$$C_L = \frac{2\Gamma}{V} = 2\pi \frac{U}{V}$$

This formula leads to large values of C_L. The maximum theoretical value of the lift coefficient, for the cylinder, would correspond to the situation in which the two stagnation streamlines, obtained by superimposing the potential flow about a cylinder to the flow with circular streamlines to obtain a flow with circulation, coincide. This happens when U/V = 2.

Hence,

$$C_{Lmax} = 4\pi = 12.56$$

A compilation of the state of the art of the aerodynamics of Magnus cylinders and wing rotors is shown in Figures 13 through 18. To avoid burdening the figures, three tables were prepared.

Table I lists the references pertinent to the performance of powered Magnus cylinders and the physical characteristics of each model. Performance is plotted, in Figures 13 and 14, in the form of C_{Lmax} versus U/V and C_{Lmax} versus C_D. C_D is the drag coefficient.

Table II correspondingly lists the same information for powered noncircular rotors. It is used in conjunction with Figures 15 and 16.

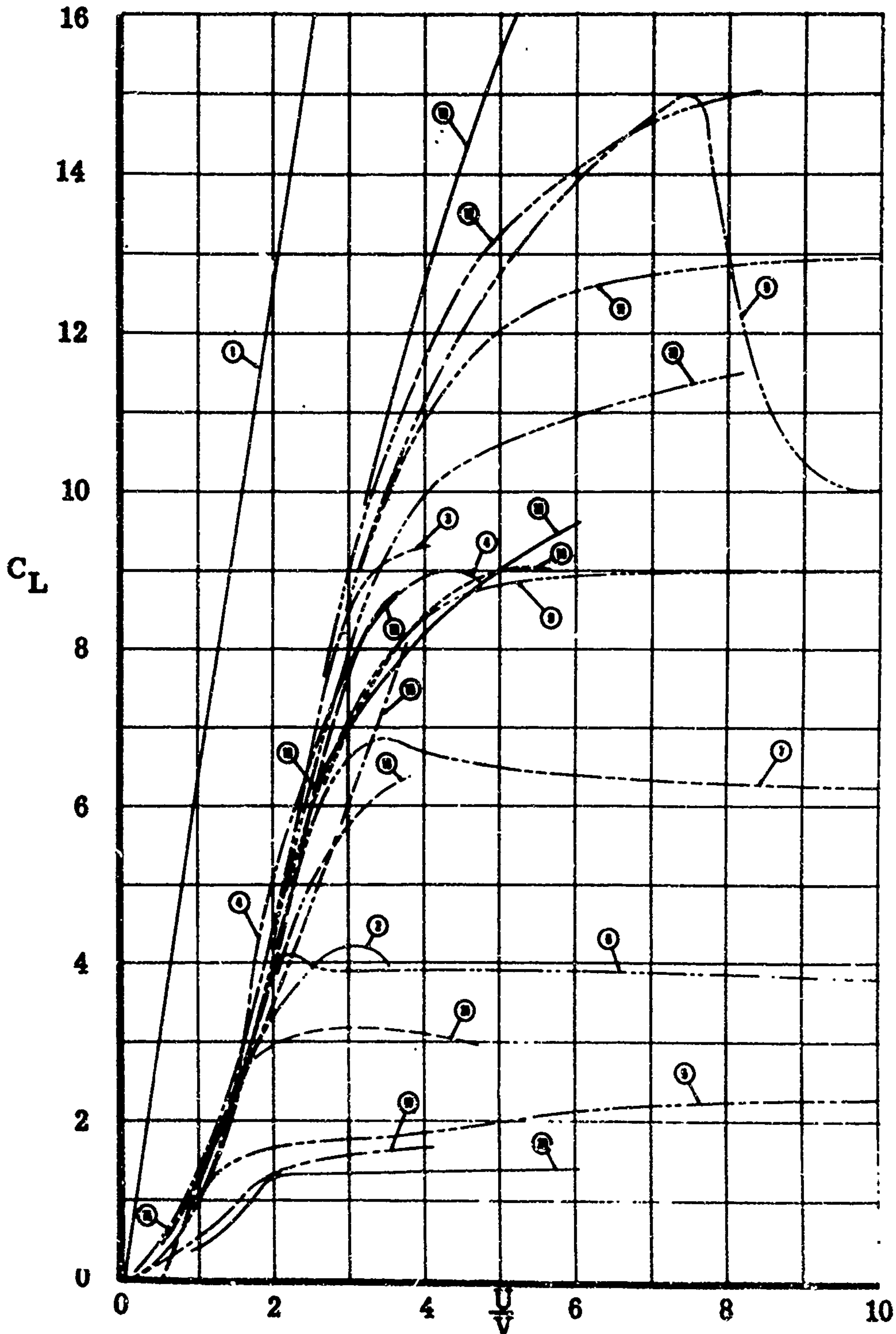


Figure 13. Aerodynamic Performance of a Collection of Powered Cylindrical Magnus Rotors at Several Aspect Ratios, With and Without Tip Plates. See Table I for Identification of Indicated Magnus Rotor Points.

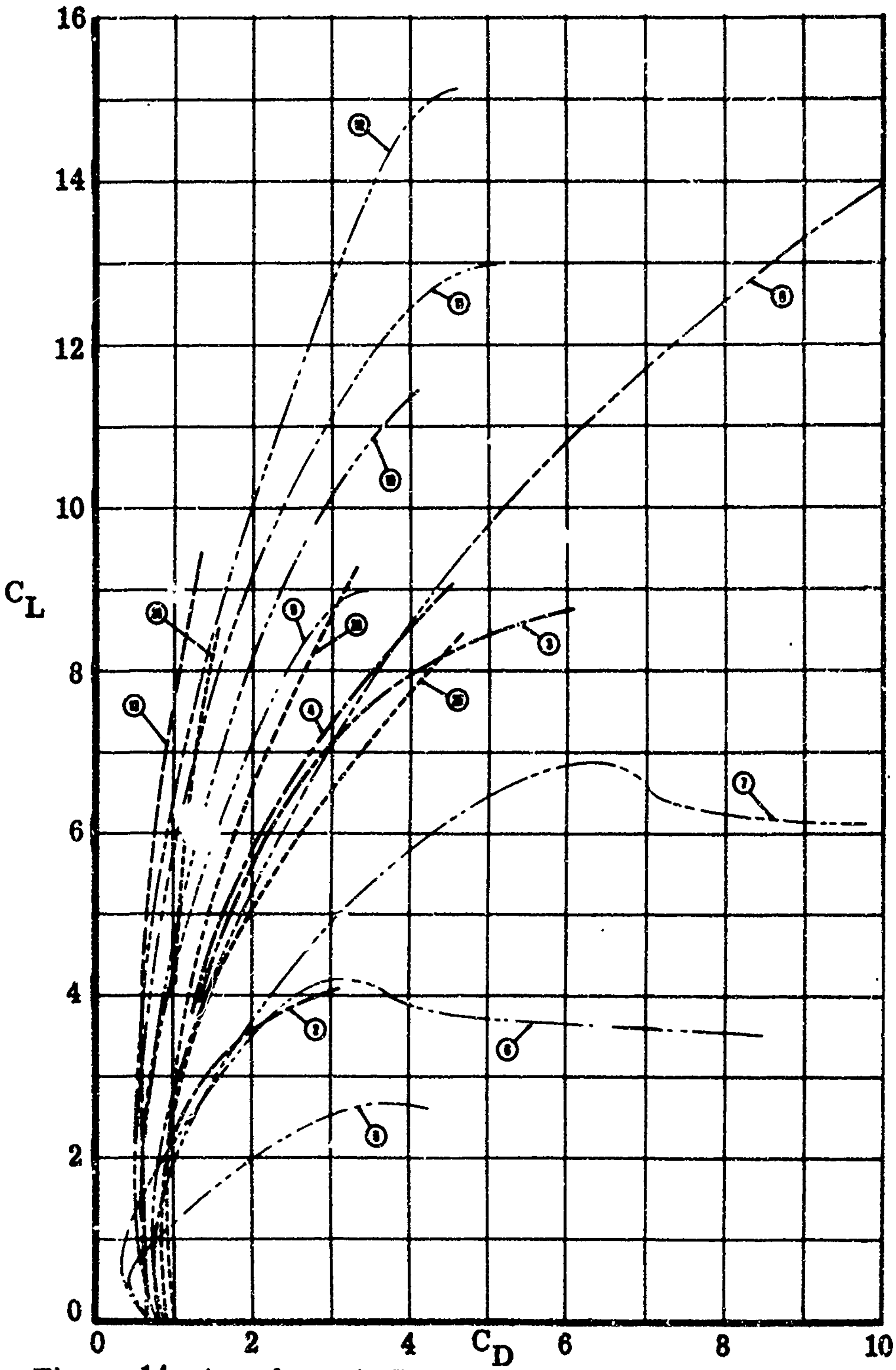


Figure 14. Aerodynamic Performance of a Collection of Powered Cylindrical Magnus Rotors at Several Aspect Ratios, With and Without Tip Plates. See Table I for Identification of Indicated Magnus Rotor Points.

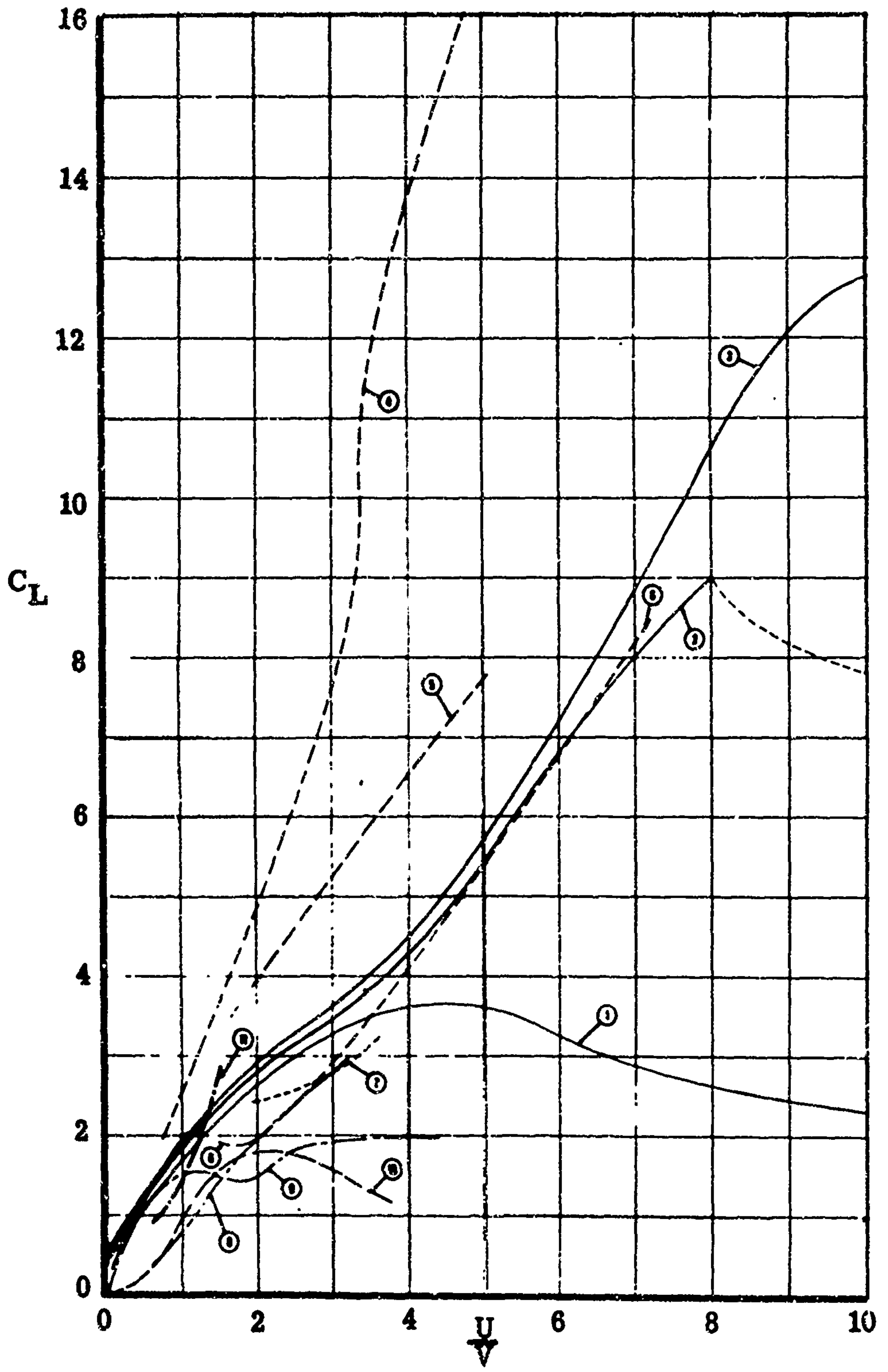


Figure 15. Aerodynamic Performance of a Collection of Noncircular Powered Rotor Shapes With Various Tip Plates, Aspect Ratios, and Profiles. See Table II for Identification of Curves.

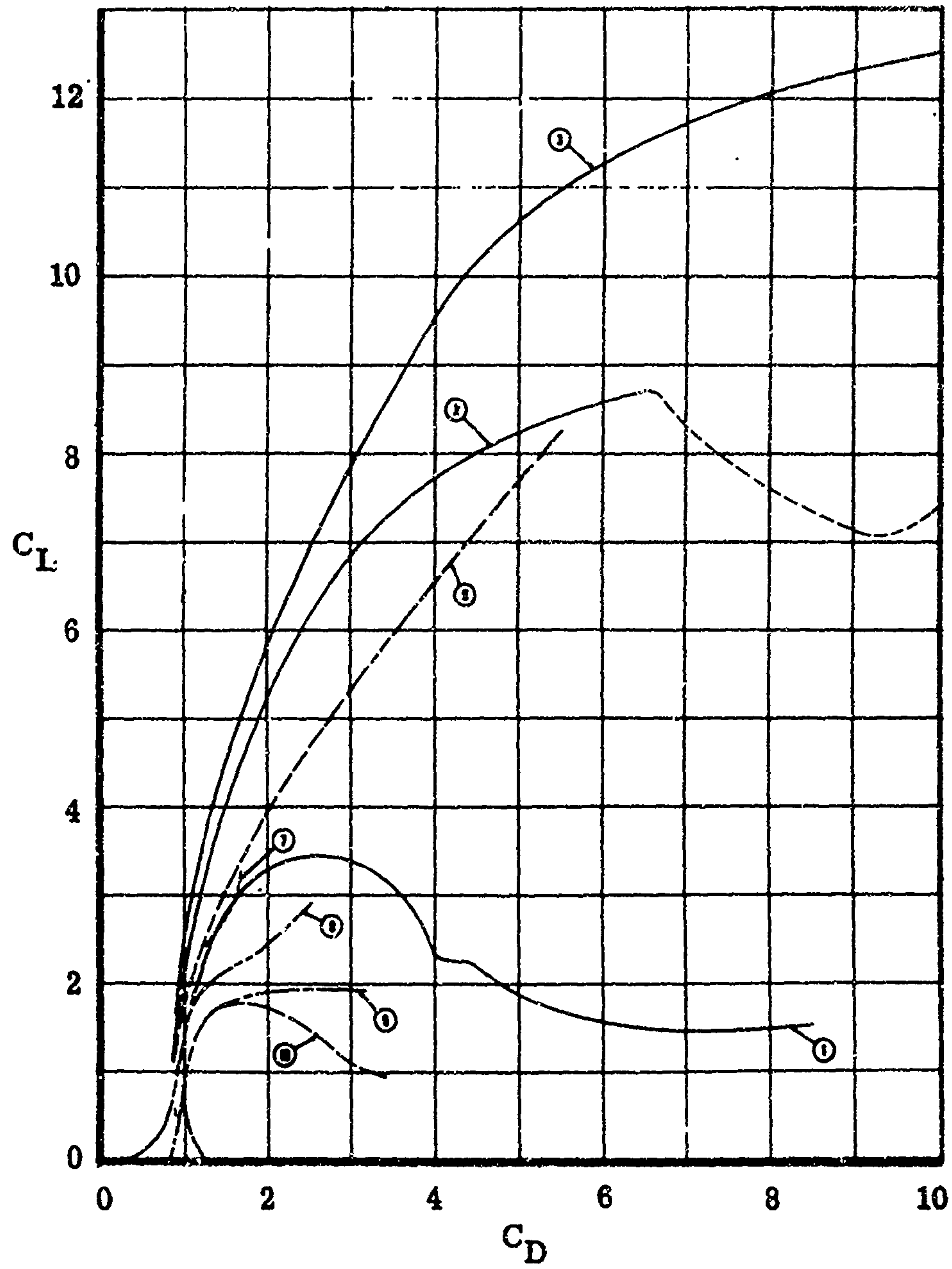


Figure 16. Aerodynamic Performance of a Collection of Non-circular Powered Magnus Rotor Shapes, With and Without Tip Plates, at Several Aspect Ratios and With Various Profiles. See Table II for Identification of Indicated Rotor Points (C_L vs. C_D).

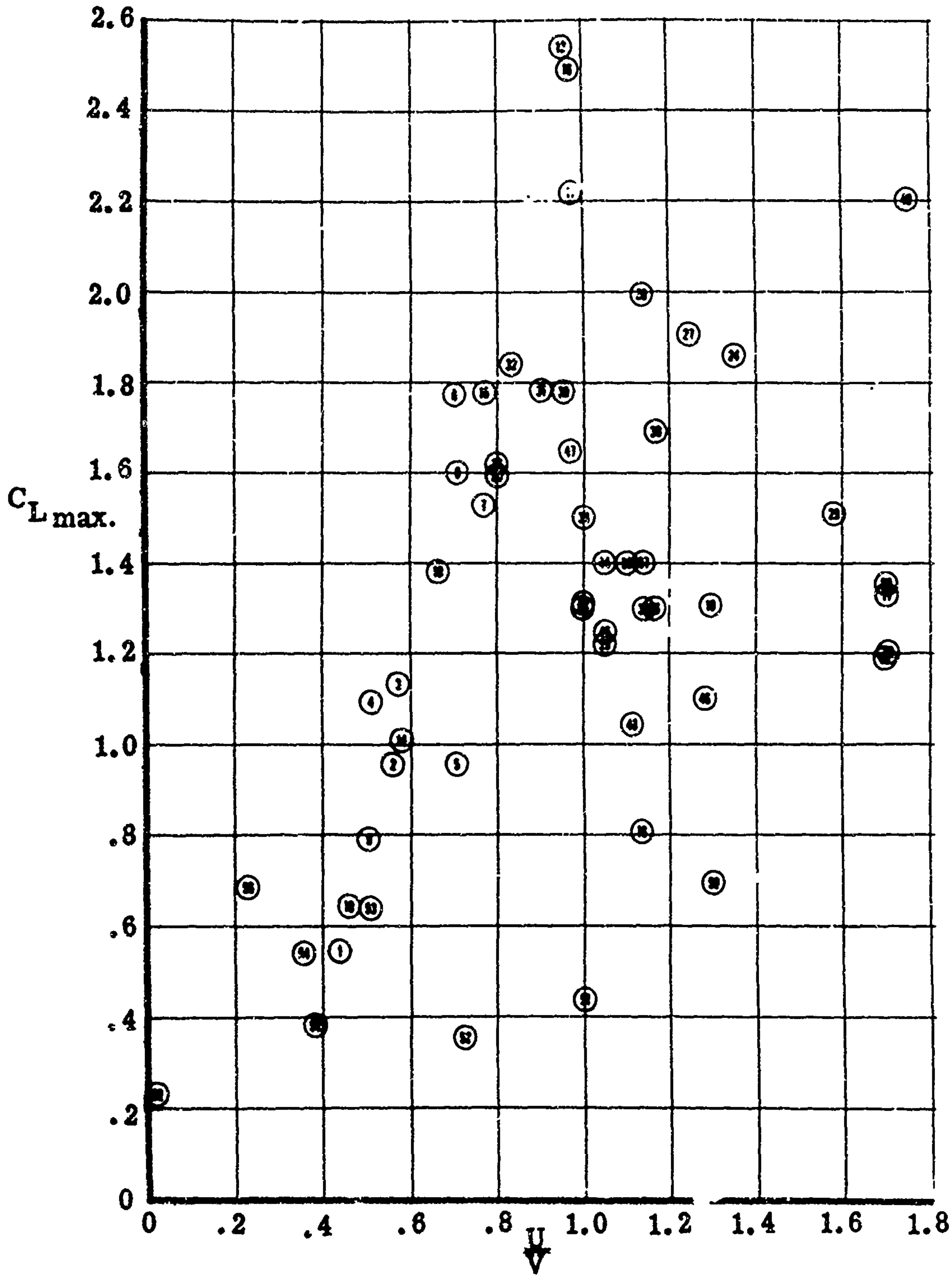


Figure 17. Aerodynamic Performance of a Collection of Autorotating Wing Rotors With and Without Tip Plates, at Several Aspect Ratios and With Various Profiles. See Table III for Identification of the Indicated Wing Rotor Points.

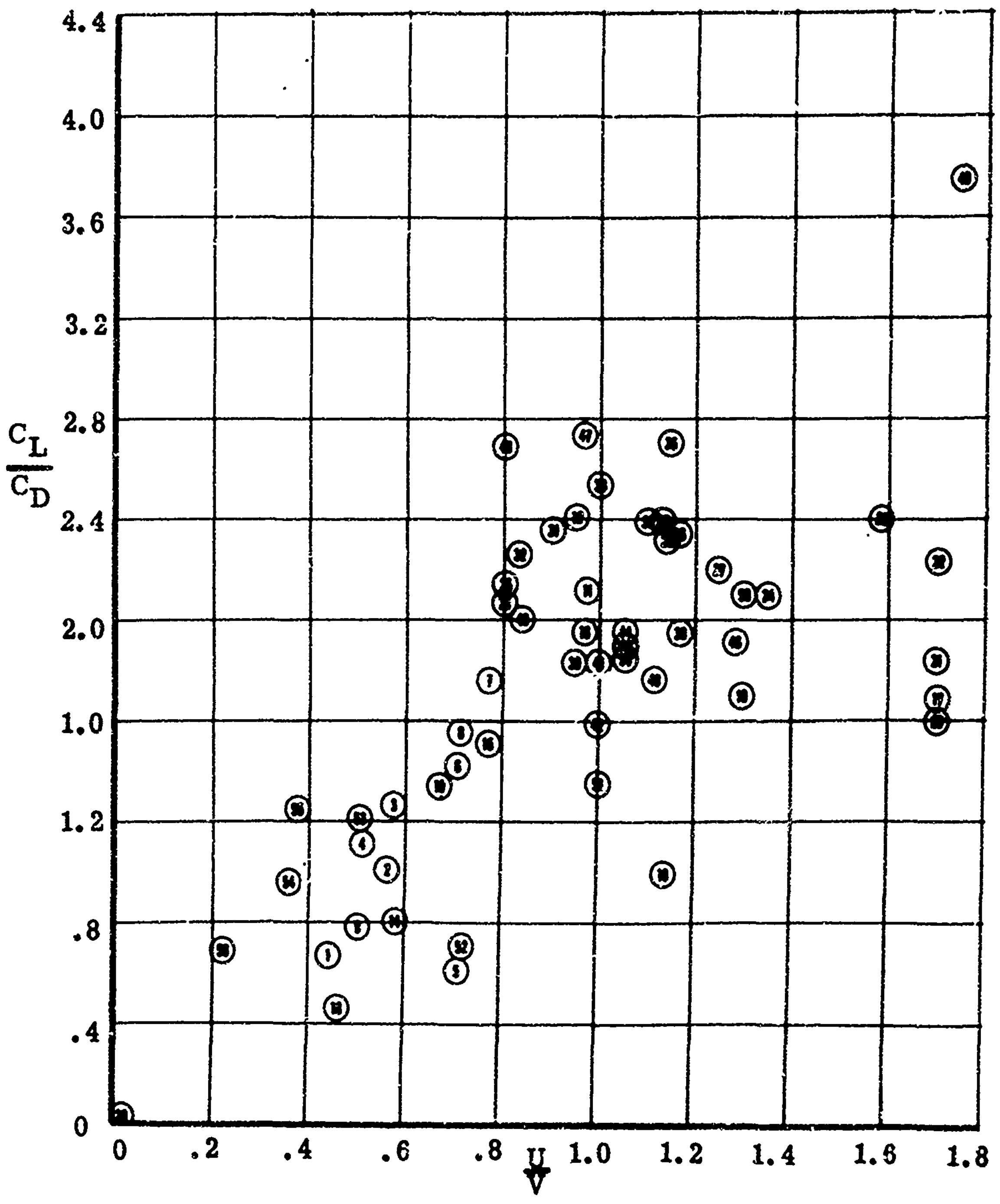


Figure 18. Aerodynamic Performance of a Collection of Autorotating Wing Rotors With and Without Tip Plates, at Several Aspect Ratios and With Various Profiles. See Table III for Identification of the Indicated Wing Rotor Points.

TABLE I. KEY TO FIGURES 13 and 14. POWERED MAGNUS CYLINDER ROTOR TESTS - PERFORMANCE

Curve Bubble No.	INVESTIGATOR	Reference Number	AR Aspect Ratio	h/c Tip Plate Ratio	t/c Thickness Ratio	REMARKS
1	Ideal Fluid		∞		Circular	
2	Ackeret	4A-43P	4.7	1		Test for Rotor Ship
3	Flettner	4A-43P	4.7	1.72		Test for Rotor Ship
4	Goettingen	4A-43P	4.7	2.00		Test for Rotor Ship
5	Busemann	83B	1.7	1		
6	Goettingen		1.7	1.5		
7			1.7	2		
8			1.7	3		
9			12	1		
10			12	1.5		
11			12	2		
12	Busemann	83B	12	3		
13	Thom	24T	12.5 / 26	3		
14		19T	8	1		
15		23T	5.7			Rough"Sanded" Surface
16		23T	5.7			Smooth Surface
17	Thom	19T	4.4			Ends Fair into Hemi-Ellipsoids
18	Reid - NACA	12R	13.3			Across Tunnel Wall
19	Swanson	143S	∞	1		
20	Swanson	143S	2	1		
21	Schwartzenberg	143S	4.5			
22	Mattoli	38M				Plain Cylinder
23	Mattoli	38M				Cylinder with Fixed Coaxial Shield
24	Mattoli	38M			Circular	Cylinder with Fixed Coaxial Shield

TABLE II. KEY TO FIGURES 15 and 16. POWERED NONCIRCULAR ROTOR TESTS - PERFORMANCE

Curve Bubble No.	INVESTIGATOR	Reference Number	AR Aspect Ratio	h/c Tip Plate Ratio	t/c Thickness Ratio	REMARKS
1	Kuechemann	52C-52K	5	0	.167	
2	Kuechemann	52C-52K	5	(1)	.167	Elliptical Tip Plate - 1/1.83
3	Kuechemann	52C-52K	5	2.5	.167	
4	Holst	48H	5.3	2.5		Tested in Water
5	Holst	48H	5.3	0		Tested in Water
6	Holst	48H	3	1.5		Tested in Water
7	Chappedelaine	21C	6	≈ 1	.100	Convertible to Fixed Airfoil-3X
8	Riabouchinsky	19R	(8)	0		Flat Plate Rotating About L. E.
9	Riabouchinsky	19R	4	0		Flat Plate Rotating About Mid-Chord
10	Riabouchinsky	19R	4	0		Cruciform
11	Reid-NACA	12R	13.3			Cruciform Across Tunnel Wall

TABLE III. KEY TO FIGURES 17 and 18. AUTOROTATING WING ROTOR PERFORMANCE

Curve Bubble No.	INVESTIGATOR	Reference Number	AR Aspect Ratio	h/c Tip Plate Ratio	t/c Thickness Ratio	REMARKS
1	Joukovski	23J	1.5	0	-	Flat Plate
2		23J	3.0		-	
3		23J	6.0		-	
4	Joukovski	23J	12		-	
5	Dupleich	35D	2		.01	
6			4		.01	
7			5		.01	
8			6		.01	Flat Plate
9			1.5		.134	Rectangular Prism in Water
10			3		.134	
11			6		.134	
12			8.57		.134	
13			1.42		.333	
14			2.85		.333	
15			5.71		.333	
16	Dupleich	35D	8.57		.333	Rectangular Prism in Water
17	Bach	3B	2	0	-	Rotor Profile II
18				1.18	-	IIIa
19					-	IIIb
20					-	IV
21					-	V
22					-	VI
23					-	VIa
24					-	VIb
25					-	VIc
26	Bach	3B	2	1.18	-	Rotor Profile VId
27	Chappedelaine	21C	6	1	.125	Shallow "S" Profile-1X
28	Chappedelaine	21C	6	1	.100	Symmeterical Airfoil-3X
29	Stone	118S	8	0	-	Tailless Aircraft Tumbling-Model 13
30	DeLeo - Huerta	10D	2	1.50	.28	Profile No. 1
31				1.75		1
32				2.00		1
33	DeLeo - Huerta	10D		Rectangle		1 Tip Plate No. 10
34	Kuklewicz-Tissue	37S				A 75
35						A 74
36						A 71
37						A 72
38						A 73
39						B 71
40						C 71
41						D 74
42						D 75
43						D 71
44						D 72
45						D 73
46						E 71
47	Kuklewicz-Tissue	37S	2	Rectangle	.28	Profile No. P Tip Plate No. 51
48	Brunk	86B	8.0			Mod. Rectangle with Driving Vanes
49	Brunk	86B	4.0			Mod. Rectangle
50	Yelmgren	3Y	5.0	1.5		Mod. Rectangle
51	Yelmgren	3Y	5.0	1.5		Triangle
52	Yelmgren	3Y	5.0	1.5		Cylinder with Driving Vanes
53	Iverson	131	2.0			Diamond - Double Wedge
54		131	1.0			
55		131	1.0			
56	Iverson	131	0.5			Diamond - Double Wedge

Table III lists the characteristics of all unclassified data relating to autorotating wing rotors. Performance is plotted in Figures 17 and 18.

Figure 17 shows that the maximum theoretical performance of an autorotating wing rotor, $C_{Lmax} = 12.56$ at $U/V = 2$, is far from being found in practice. The best C_{Lmax} is found (case 12) for $U/V = 0.95$ and is $C_L = 2.5$. The maximum U/V found in tests is $U/V = 1.75$, and the corresponding C_{Lmax} is 2.2. As can be seen from Figures 17 and 18, a systematic correlation of test data for wing rotors in autorotation is not possible at the present time. One has a feeling that higher C_{Lmax} than have been actually measured are possible with new shapes.

It was first noticed by Trancon in 1909 (Reference 39T) that the addition of large circular tip plates to a flat plate airfoil model would greatly enhance glide performance. All models of Figures 17 and 18 have tip plates. It would seem that a rotating airfoil without end plates acts as a curious sort of centrifugal pump which sucks secondary air in at the tips and ejects it radially in the midspan region. The process may be efficiently checked by the end plates.

It may also be noted that shapes with considerable thickness ratios, from the standpoint of fixed-wing airfoils, can have very good aerodynamic characteristics (maximum lift coefficient or lift-drag ratio) when used as rotating airfoils. They can thus be used as aerial delivery containers, the payload being contained within the shape.

It has been known since Maxwell (Reference 41M) that wing rotors are dynamically stable; i.e., Maxwell's oblong card would always stabilize in steady autorotation about an axis parallel to the longest dimension. However, only in the last four years have the dynamic equations of a special type of wing rotor, the "bomblet", been written and solved. Recent developments in this area were reported at the Conference on Dynamics and Aerodynamics of Bomblets, held at the Air Force Armament Laboratory, Eglin Air Force Base, Florida, on 26-28 September 1967. Significant work was done by Zipfel at Fort Detrick, Stilley at Honeywell, Brunk at Alpha Research, and Nicolaides at Notre Dame University. Their work is either classified or contains distribution restrictions and therefore is not discussed in detail here. Suffice it to say that the dynamics of wing rotors are understood analytically and that criteria for dynamic stability of specific configurations are available.

Boehler and Foshag demonstrated in 1964, by means of flight tests of models, that wing rotors could be made to be controllable. Means of controlling wing rotors are summarized in Reference 52B.

The properties of wing rotors can thus be summarized by saying that, as free gliding bodies, they are lifting devices that possess a high maximum lift coefficient ($C_L \approx 3$), high lift-drag ratio ($L/D \approx 4$), good dynamic stability, and good controllability.

d. Application of Wing Rotors to Aerial Precision Delivery Missions

The previously cited characteristics of isolated wing rotor devices (high lifting and glide performance, good stability, and good controllability) make them natural candidates for aerial delivery missions, for example, as precision drop gliders. Some typical applications are as follows:

Long Range - delivery of personnel rescue kit; for example, in a package carried externally by the OV-10A COIN aircraft, as shown in Figure 19

- pilotless convertible glider cruising as a fixed wing and landing as a wing rotor, as shown in Figure 20

- delivery of cargo in remote areas, the rotor being stacked in the cargo hold of an aircraft, such as the C-130 Hercules. A design study shows that the C-130 cargo hold could contain 17,820 pounds of wing-rotor-deliverable fuel. The concept is shown applied to the C-119 aircraft in Figure 21

Short Range - delivery of supplies over the battlefield or to counterguerillas, using the cargo hold of the C-130 aircraft as above

- underslung delivery of supplies with wing rotor towed behind a helicopter. The concept is illustrated in Figure 22

- ordnance applications: delivery of clustered bomblets autorotating in shallow glide for maximum dispersion

e. Gliding Performance of a Wing Rotor

The gliding performance of a wing rotor depends upon three parameters: the lift-drag ratio, L/D; the maximum lift

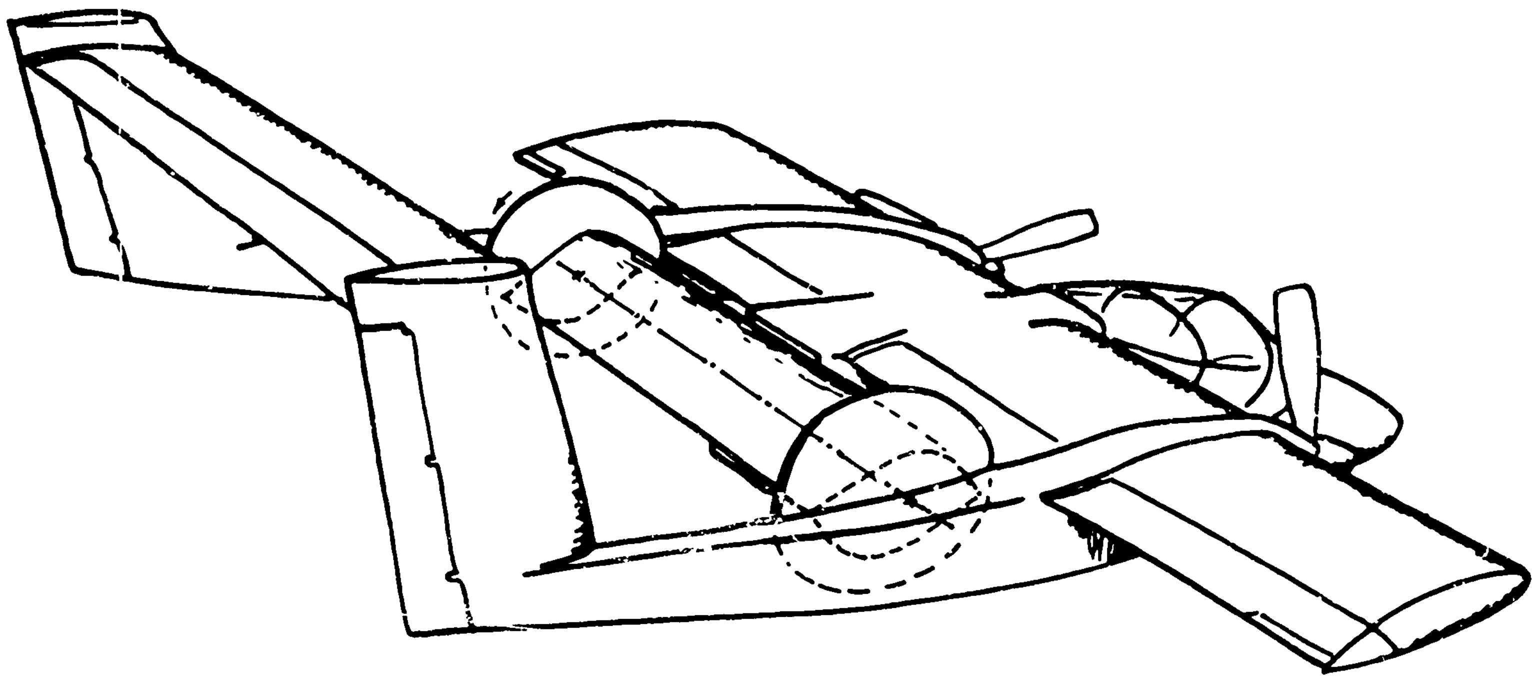


Figure 19. Wing Rotor Aerial Delivery Precision Glider Carried Externally by the OV-10A COIN Airplane.

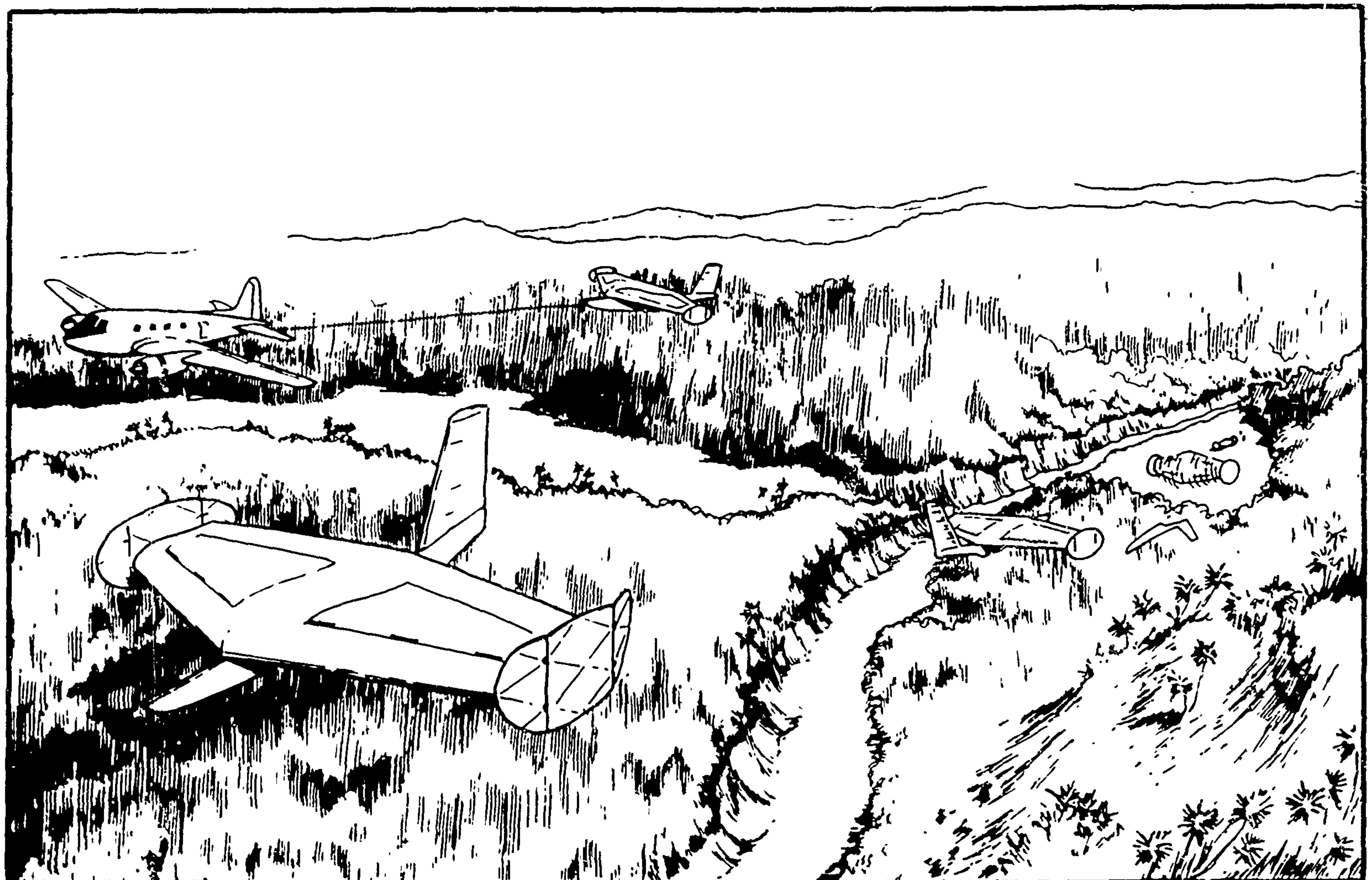


Figure 20. Pilotless Convertible Glider Cruising as a Fixed Wing and Landing as a Wing Rotor.

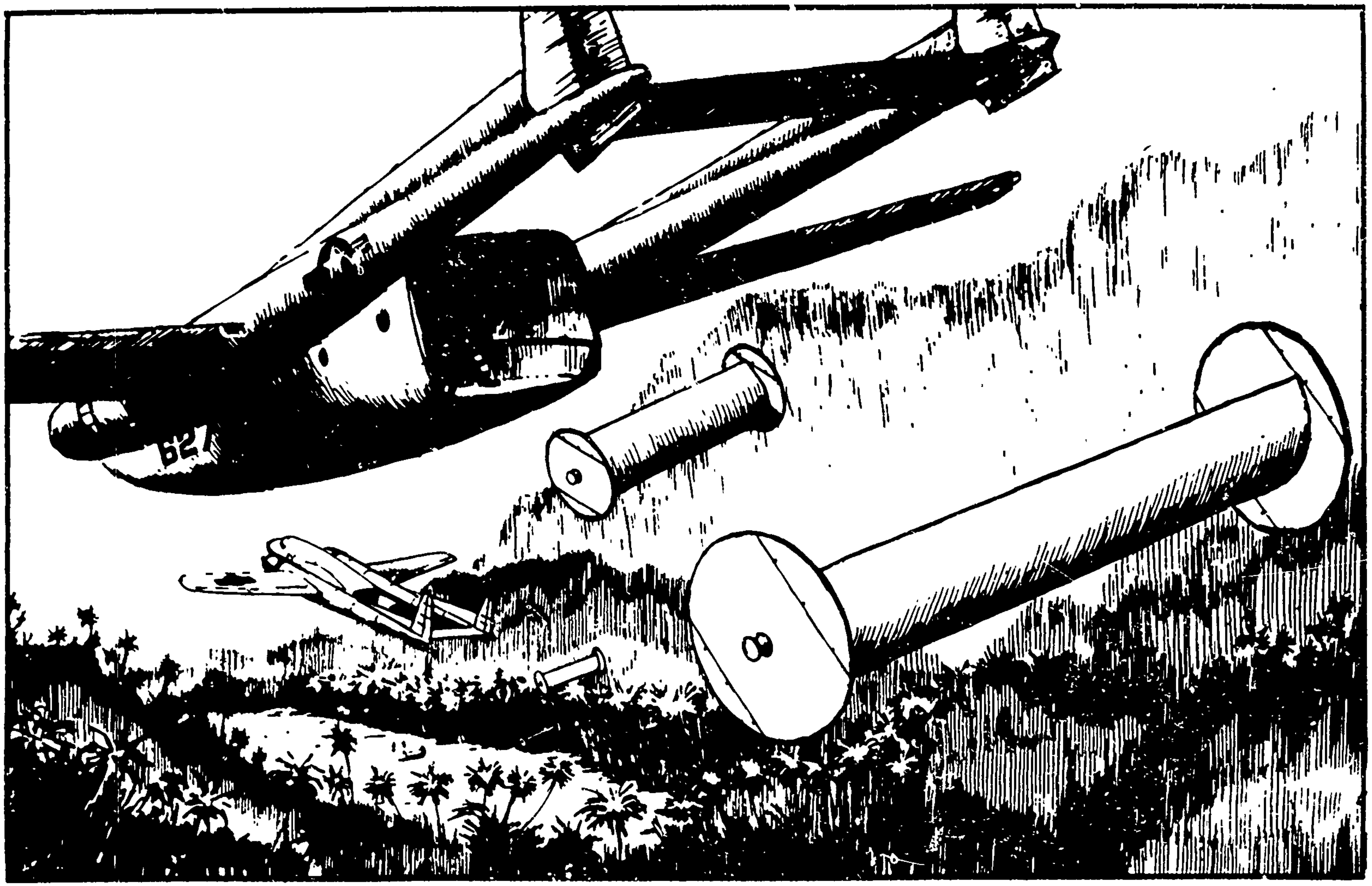


Figure 21. Aerial Cargo Delivery Autorotating Wing Rotor System, Carried Inside C-119 Aircraft.

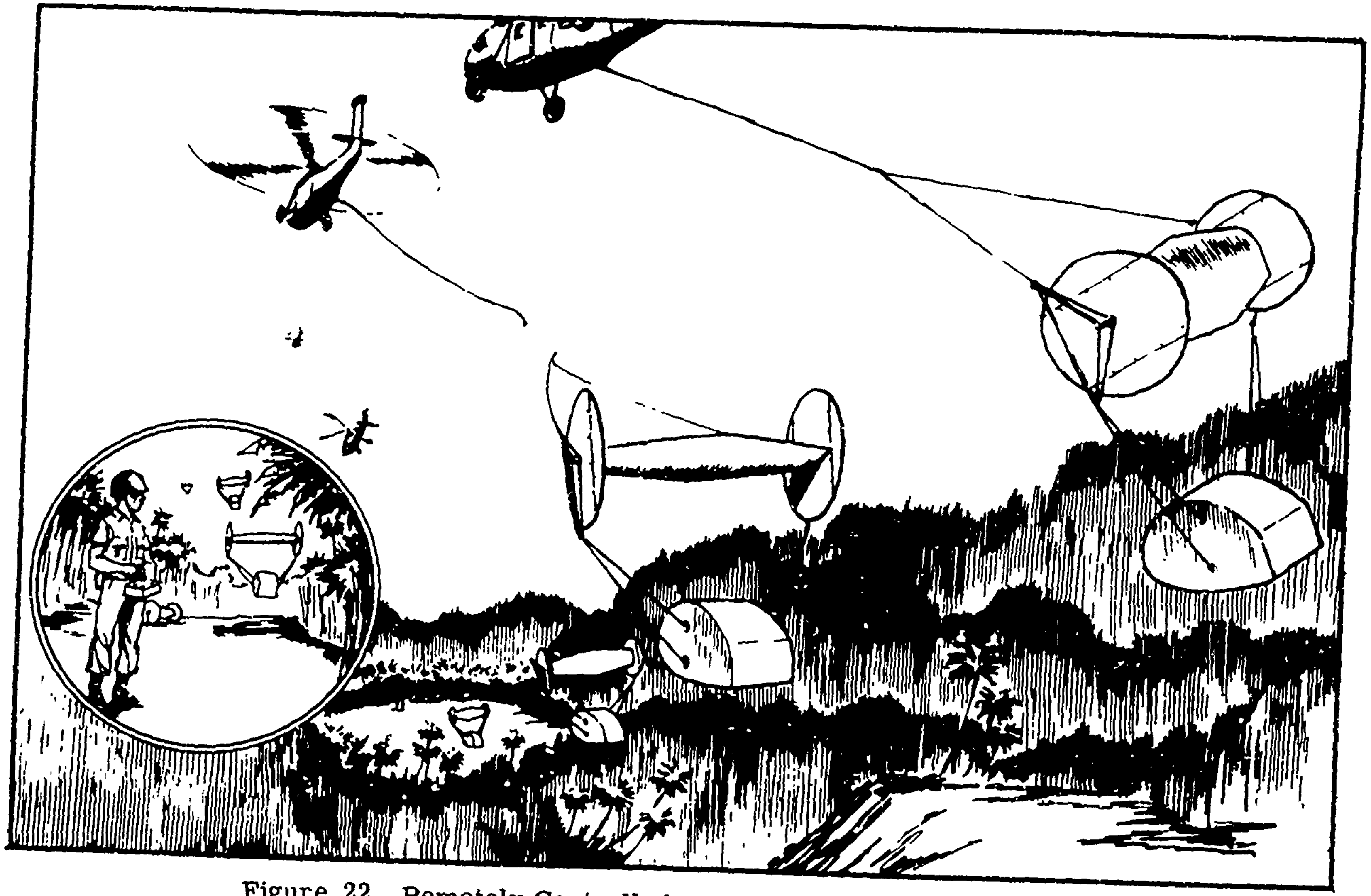


Figure 22. Remotely Controlled, Helicopter-Towed Wing Rotor Aerial Delivery System With Underslung Payload.

coefficient, C_{Lmax}; and the wing loading, W/S. The gliding equations are well known, as follows (W is the gross weight, Θ the glide angle, and V_z the vertical sink velocity):

$$L = W \cos \Theta \qquad V_z = V \sin \Theta$$

$$D = W \sin \Theta$$

$$L/D = \cot \Theta$$

$$V_{mph} = \sqrt{\frac{W/S}{0.00256\, C_{Lmax} \left(\cos \Theta + \frac{\sin \Theta}{L/D} \right)}}$$

This performance is plotted in Figure 23 as V_z versus L/D for various values of W/S and various values of C_L.

With the values of C_{Lmax} and L/D known to be feasible today, it can be seen that acceptable values of V_z, for example, V_z = 20 ft/sec, can be achieved with wing loadings of 15 to 20 pounds per square foot, resulting in acceptable payloads. One problem with the internally contained payload is the dissipation of the angular momentum of the payload following impact. This may be minimized by using the proper flare-out technique.

A comparison of the glide performance of a typical wing rotor with that of competitive systems is illustrated in Figure 24. It can be seen that the wing rotor compares favorably with such systems.

2. Rotating Airfoil Convertible to Fixed Wing (RACW)

The idea of allowing a fixed-wing airfoil to autorotate or to be power driven about its midchord spanwise axis has intrigued innumerable inventors and engineers alike for a long time. The flight of aircraft with the continually autorotating wing rotors is possible if one is willing to pay the price of the high resulting drag. The drag penalty in cruise is removed in the concept in which the wing is fully rotated in Magnus effect fashion during takeoff and landing and braked to a fixed-wing position for cruise flight.

The previously mentioned Chappedelaine "Aérogyre" (Figure 9) has been the only full-size RACW convertible aircraft built. The characteristics of this unique project are described here:

Powerplant:	Renault 90 HP (100 HP Max.)
Transmission:	The wings could be driven through a clutch engagement of the powerplant.
Wings (Rotors):	Two rotors (or one wing) Total area - 129 Sq. Ft.

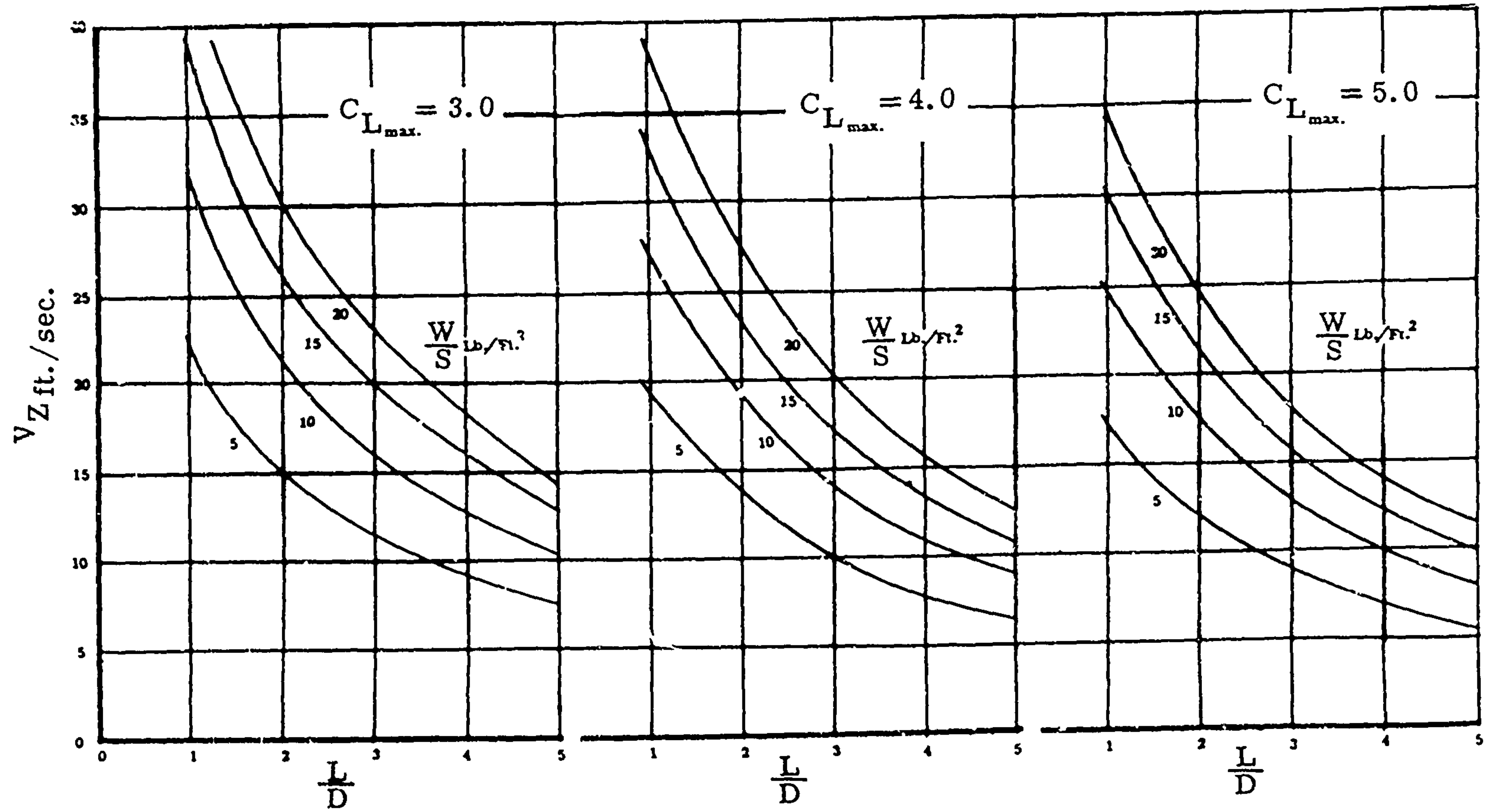
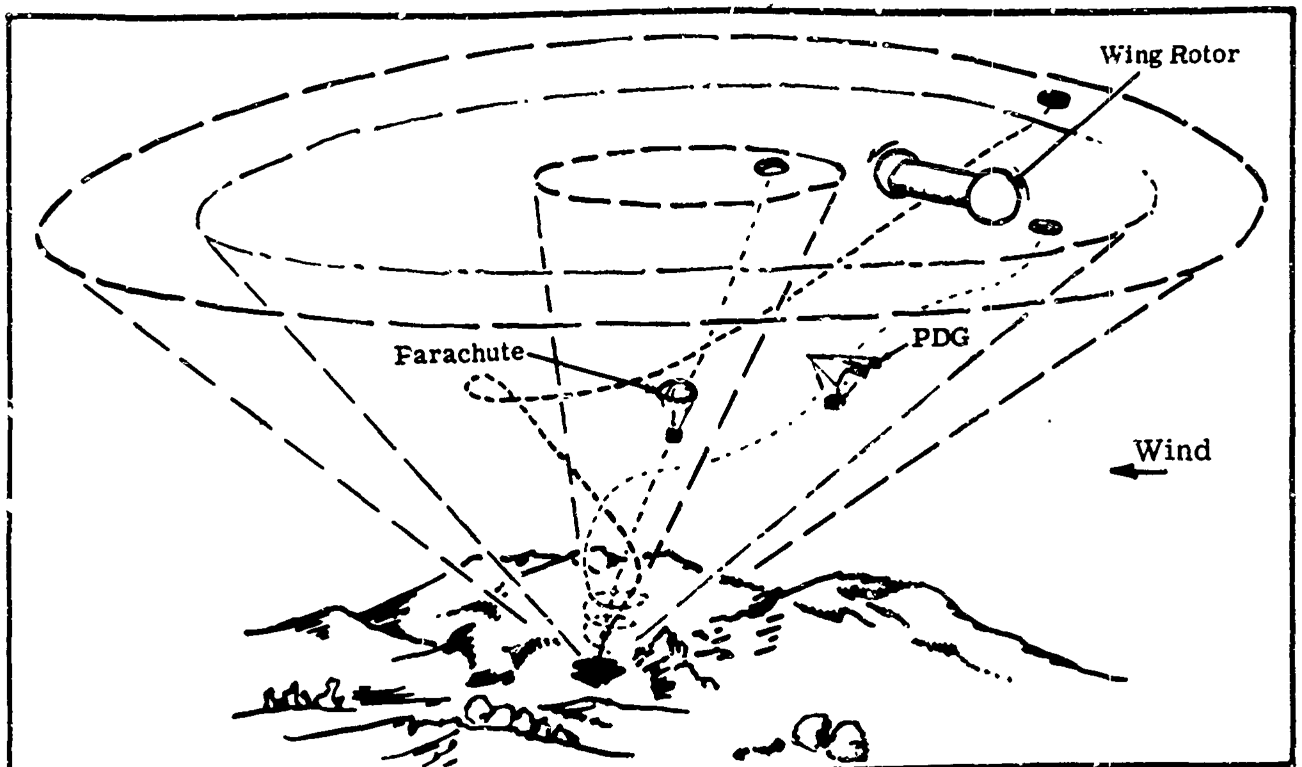


Figure 23. Wing Rotor Sinking Speeds at Various Loading as a Function of Hypothetical Maximum Lift Coefficients and Lift-Drag Ratios.



GENERAL AERODYNAMIC PERFORMANCE COMPARISON OF ABOVE SYSTEMS

SYSTEM	L/D max.	C_L	COMMENT	REFERENCE
Wing Rotor	3.6	2.2	With Payload Enclosed	Fig. 21 and 23
Parafoil	4.0	.3-.4	Without Payload Attached	Aviation Week, 7-1-68, p. 67
PDG	3.1	.6	With Payload Attached	TRECOM TR 63-64
Cloverleaf	2.1	.83	Without Payload Attached	AFFTC, TDR-64-12, v. 2
Hemisphere	1.4	.78	Idealized Parachute. No payload	Hoerner, S. F., "Aero. Drag"

Figure 24. Relative Glide Range and "Drop Cones" for Five Systems of Aerial Delivery.

	Span - 13.1 Ft. (each panel)
	Max. chord - 5.25 Ft.
	End plate diameter - 4.9 Ft.
	Wing spread - 29.8 Ft.
Wing (Fixed:	Area - 64.5 Sq. Ft.
Fuselage:	Originally from a Caudron airplane
	Overall - 25. Ft.
Weight:	Gross - 1540 Lbs.

Performance based on model wind tunnel tests were estimated to be:

Item	Aerogyre (Fixed Wing)	(Autorotating Wing)	(Powered Wing)
Cruising Speed (MPH)	87		
Landing Speed (MPH)	40.3	21.7	17.4
Landing Run (Ft.)	490	148	162

Structural failure of this craft in flight brought the project to an end. Other than the following comments (Reference 50L), the flight tests were inconclusive:

- The mechanical device for disengaging the wings was imperfect, and consideration should have been given to the deflections produced in flight.
- The rotor RPM was too low, inducing vibrations in the structure. These vibrations did not show up in wind tunnel tests because the RPM was seven times greater than in full-scale tests.
- The means for increasing the RPM consists of increasing the aspect ratio of wings and then using several wings adequately located.

The RACW concept is only a STOL vehicle. There is insufficient evidence for a complete evaluation, but the complexity of rotating the wing hardly seems worth the STOL performance advantage.

3. Rotating High-Lift Devices on Wings

The demands of flight speed range flexibility of modern aircraft would appear to have taxed the flap designer's resources to the limit. It has become not too far from the usual to incorporate on a single craft tracked and mechanically complex flap installations with multiple slots, spoilers, tabs, and vortex generators. Figure 25 shows one such example. While nothing but praise is due the designers of such an arrangement, the question may be well asked if there is not a simpler way. To this end we will examine here

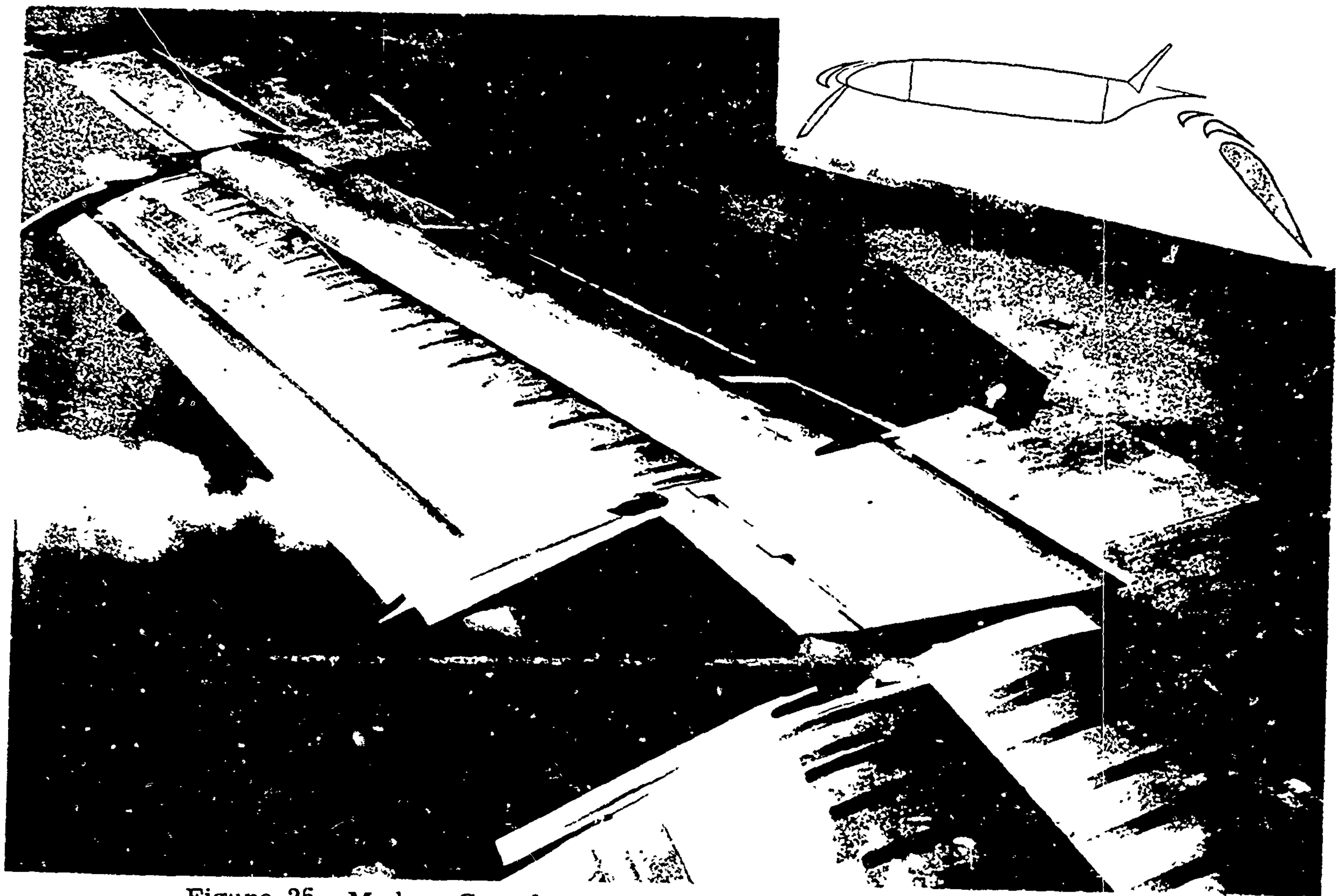


Figure 25. Modern, Complex Wing-Flap System With Multiple Flaps Partially Extended, Deflected; Spoilers Up, Slats Open.

several proposals and some background material on alternate flap systems of a possibly simpler design.

The rotating flap and slat devices to be described are basically STOL high-lift systems. These devices may be considered to be part of a VTOL arrangement only when they are used in a deflected slipstream system in conjunction with a thrust propeller slipstream. The rotating and activating elements may be located in or at the fixed wing's leading edge, aft, either in the wing or externally near the upper surface, or in or near the trailing edge. Certain arrangements place the rotating element in the leading edge of a deflected flap. These elements may be either cylindrical or airfoil-shaped, and they function to energize the boundary layer of the wing's upper surface and/or to act as a means of mechanically enhancing the wing's natural circulation. All of the cylindrical rotor elements naturally require external power, but the airfoil systems may or may not be powered. In some proposed applications, airfoil or vaned rotors arranged in conjunction with the main fixed wing may be driven as impellers in a manner to cause an energized transverse flow of air over the wing or flap. Other near-rotating flap devices are the cross-flow fan flap and the Schmidt orbiting flap. These will be discussed briefly. It may be mentioned that proposals and patents continue to describe the full chord airfoil endless circulating belt system (References 44H, 1N, etc.).

The use of the rotating cylinder as a boundary-layer energizer has been suggested for several non-aeronautical uses. Two of these arrangements would be the use of the cylinders at the entry of a very wide divergent angle diffuser and at the trailing edge of high-speed bluff bodies (vehicles).

The following discussion is organized following a classification of the flap by its type and its location with respect to the wing. Note that the main objective of the rotating flap and slat system is generally to produce high C_L's. Other arrangements are described for glide path control (negative C_L's and/or large C_D's) and low-speed flight lateral control.

a. Rotating Cylinder Leading-Edge Slat (RCLE)

With the announcement of Flettner's rotor ship and the popularization of the Magnus effect in the 1920's (Reference 31F), the technical community and innumerable inventors initially proposed the use of the full rotating cylinder for aircraft sustentation (Reference 22F). The published three-dimensional Flettner rotor (Curve 3 on Figure 14) indicated the high drag penalty associated with the high C_L's of the rotating cylinder. The first step taken to reduce the drag, with the hope of still keeping the high lift coefficients, was to fair in the trailing area aft of the cylinder. The first test in this direction was by Reid at

NACA (Reference 12R). The results, shown in Figure 26, yield maximum lift coefficients in excess of 2.

The final and most conclusive tests of this era were carried out at the N. V. Instituut Voor Aero en Hydro-Dynamiek of Amsterdam through a series of four reports (Reference 49W through 52W) by Wolff. Results of these tests are summarized in part in Figure 26. Again, these tests were conducted at low Reynolds numbers and are useful only on a comparative basis. The curves of Figure 26 show this rotating flap system with the cylinder stopped and in rotation for two profiles. The effect of rotation is roughly to triple the lift coefficient.

More recently (1963), a study was made of incorporating rotating cylinders of various surface textures in the leading and trailing edges of a hydrofoil. Results of these tests (Reference 66B) by Brooks are also shown in Figure 26. The resulting hydrofoil system was intended for an undersea vehicle control device. The poor performance may be due to the test aspect ratio ($<$ 1). With an expenditure of about 1/10 HP to rotate the leading cylinder, only slightly more than 1 pound of lift was developed at 35 F.P.S. forward speed. This is equivalent to the lift developed by the hydrofoil without a rotating cylinder when placed at less than $1/2^{\circ}$ angle of attack. Two-dimensional tests were conducted at NASA/Ames of a NACA 23018 airfoil incorporating both leading-edge and rotating-cylinder flaps (Reference 18A).

A renewed interest in the leading-edge systems was shown by Alvarez-Calderon (Reference 20A); his proposed configurations are described in Figure 27. Several ingenious means are shown for uncovering the leading-edge rotating cylinder for V/STOL application. Note that the leading-edge cylinder may double as the cross shafting for the interconnected multipropeller V/STOL airplane.

One must come to the conclusion that until more systematic and higher Reynolds number tests are made, the rotating cylinder leading-edge slat system does not evidence significant performance potential for STOL application, in comparison with other arrangements discussed later.

b. Rotating Cylinder in Wing (RCIW)

Several investigators have studied the arrangement of locating the cylindrical rotor element in the thicker section of the wing profile, thus providing a stationary airfoil entry to the rotor. Wind tunnel tests were carried out to this end by Frey (Reference 59F), but these may be considered to be inconclusive due to the very low Reynolds numbers and general irregularities. Wolff and Koning (Reference 51W) also

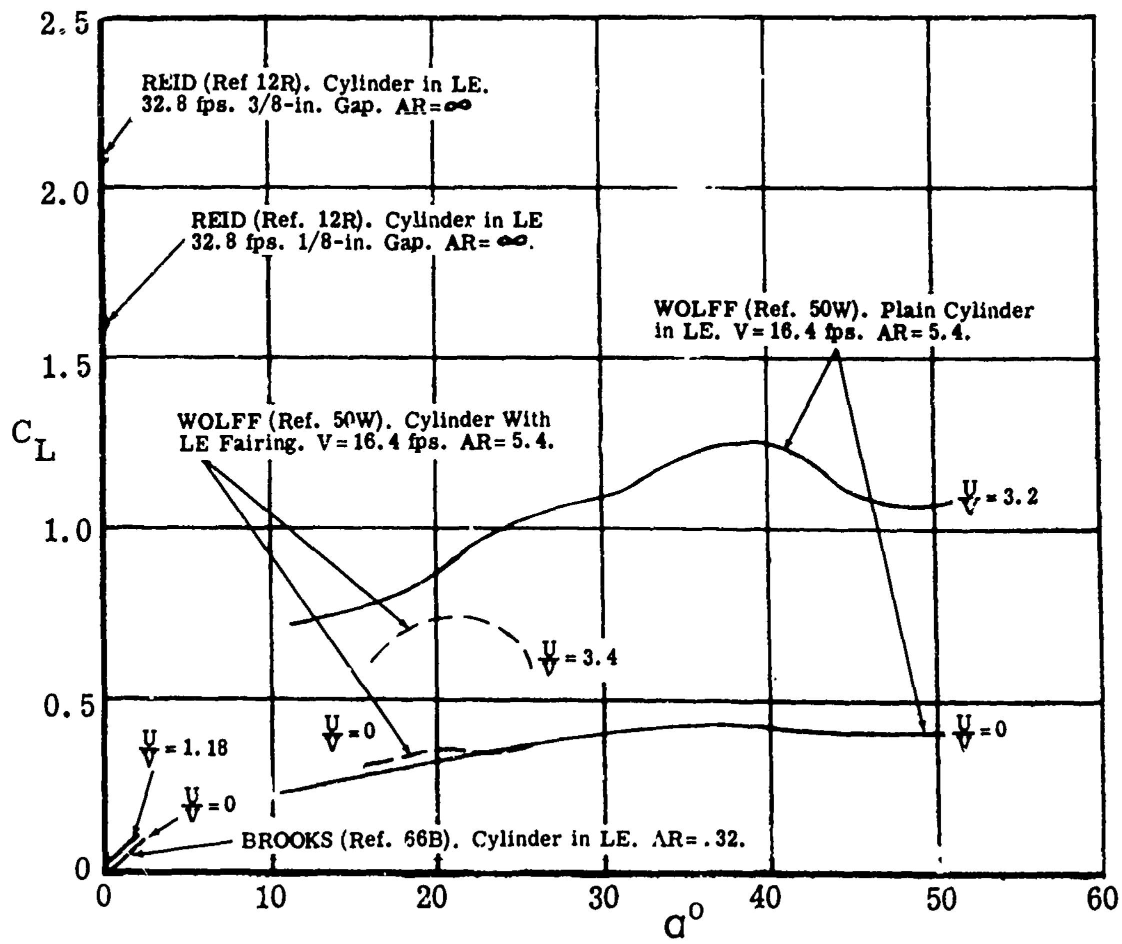


Figure 26. Measured Lift Coefficients Plotted Against Angles of Attack for a Collection of Combination Fixed Wing and Rotating Cylinder Slat System. Cylinder in the Leading Edge.

wind-tunnel-tested such a system with a fixed leading-edge fairing (Figure 26). R. Thompson built an electric-powered model capable of tethered STOL (kite) flight (Figure 28 and References 50L and 29T). Such systems do not appear to have merit as STOL devices.

c. Rotating Cylinder at the Trailing Edge (RCTE)

The rotating cylinder system located at the trailing edge may be considered to act as a circulation-augmenting device. Tests have been conducted by Longo (Reference 19J) and, more systematically, by Regenscheit (Reference 10R). Although both tests were run at low Reynolds numbers, their performance with and without a rotor is comparatively interesting because of the use of a reference-fixed airfoil. Partial results of the tests are shown in Figures 29 and 30. It is interesting to note that the Longo trailing-edge cylinder was rotated by an integral and auxiliary lenticular-shaped autorotating driving rotor. The Regenscheit tests were carried out with a broader range of rotor test positions. More recent, and also shown in Figure 29, is the Brooks rotating cylinder hydrofoil. Its performance, though quite superior to the similar arrangement in the leading edge, does not compare well with the other referenced RCTE arrangements.

Except when used as a control device, in which case the trailing-edge rotor would continually rotate, the adaptation of the cylinder to the trailing edge would require it to be retracted in some manner during cruise flight. Such an arrangement is suggested by the Tino patent (Reference 33T) and is shown in Figure 31.

The optimistic results of an analytical treatment for the rotating cylinder at a wing's trailing edge by Schmidt and Reichstein are shown in Figure 30 (Reference 42S). This simple theory may serve as an approximate method for locating the rotor axis with respect to the fixed wing.

Figure 29 also includes a comparison of the trailing-edge cylinder airfoil with that of one configuration of the NASA/Ames rotating airfoil flap (Reference 8D).

d. Rotating Cylinder in Flap (RCIF)

The RCIF is uniquely the invention of Alvarez-Calderon, whose patent coverage (References 19A, 20A, 21A, 23A, and 24A) on this system is quite comprehensive. Basically, the rotating cylinder is located in the flap's leading edge and is uncovered and put into rotation upon the flap's deflection. The RCIF is fundamentally a boundary-layer energizing system;

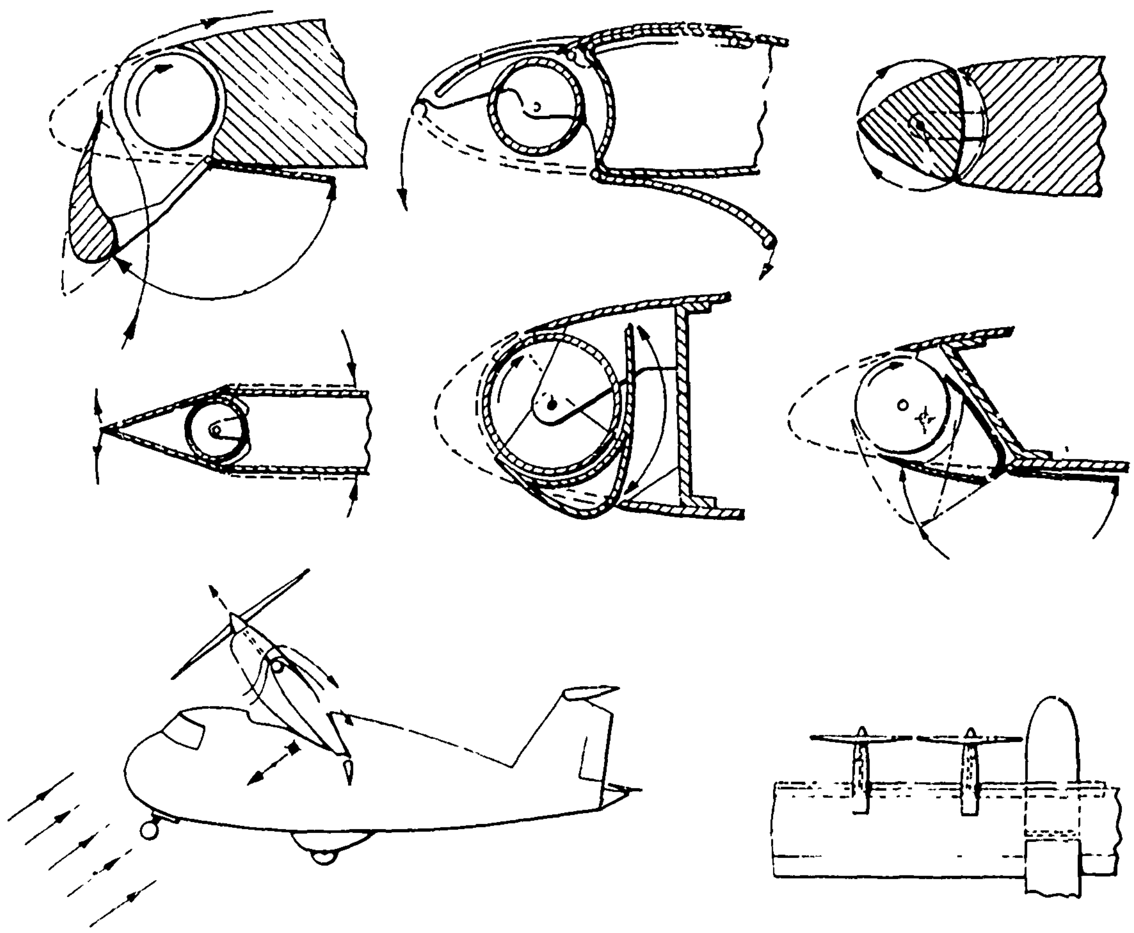


Figure 27. Various Leading-Edge Rotating Slat Systems as Applied to Tilt-Wing V/STOL. Also Shown as Cross Shaft Interconnecting Power System (Ref. 20A).

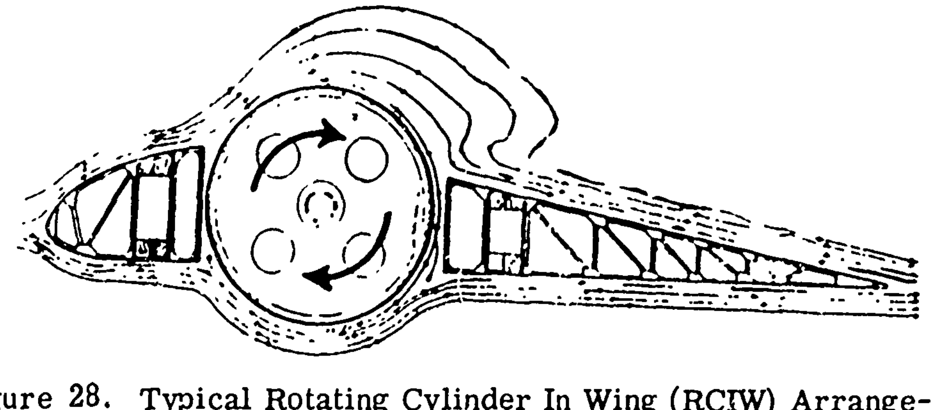


Figure 28. Typical Rotating Cylinder In Wing (RCIW) Arrangement by Thompson (Ref. 29 T).

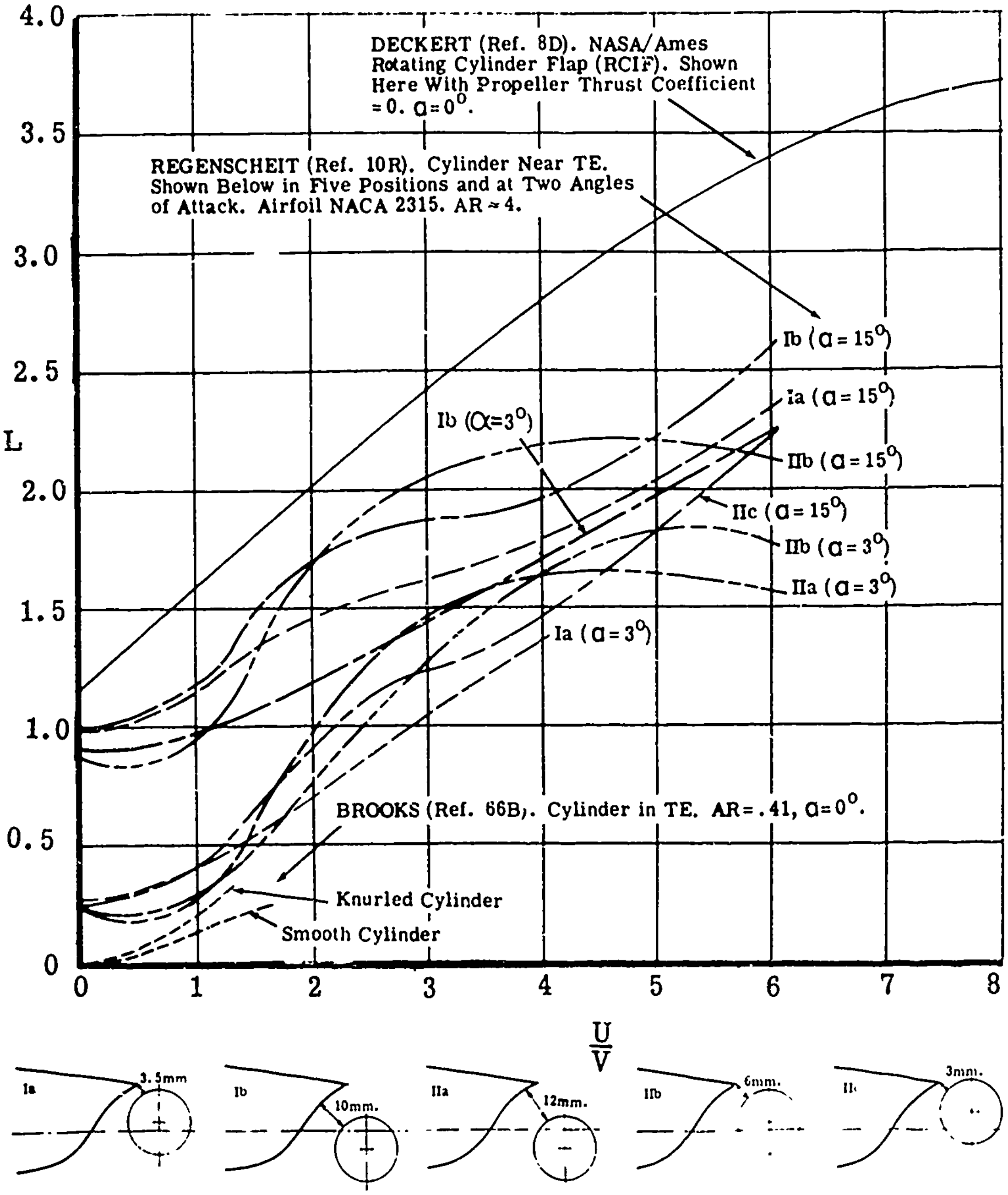


Figure 29. Measured Lift Coefficient Plotted Against Rotor Spin Ratio for a Collection of Combination Fixed-Wing and Rotating Cylinder Flap Systems. Cylinder at or Near Trailing Edge. May be Used in Conjunction With a Nonrotating Fixed Flap.

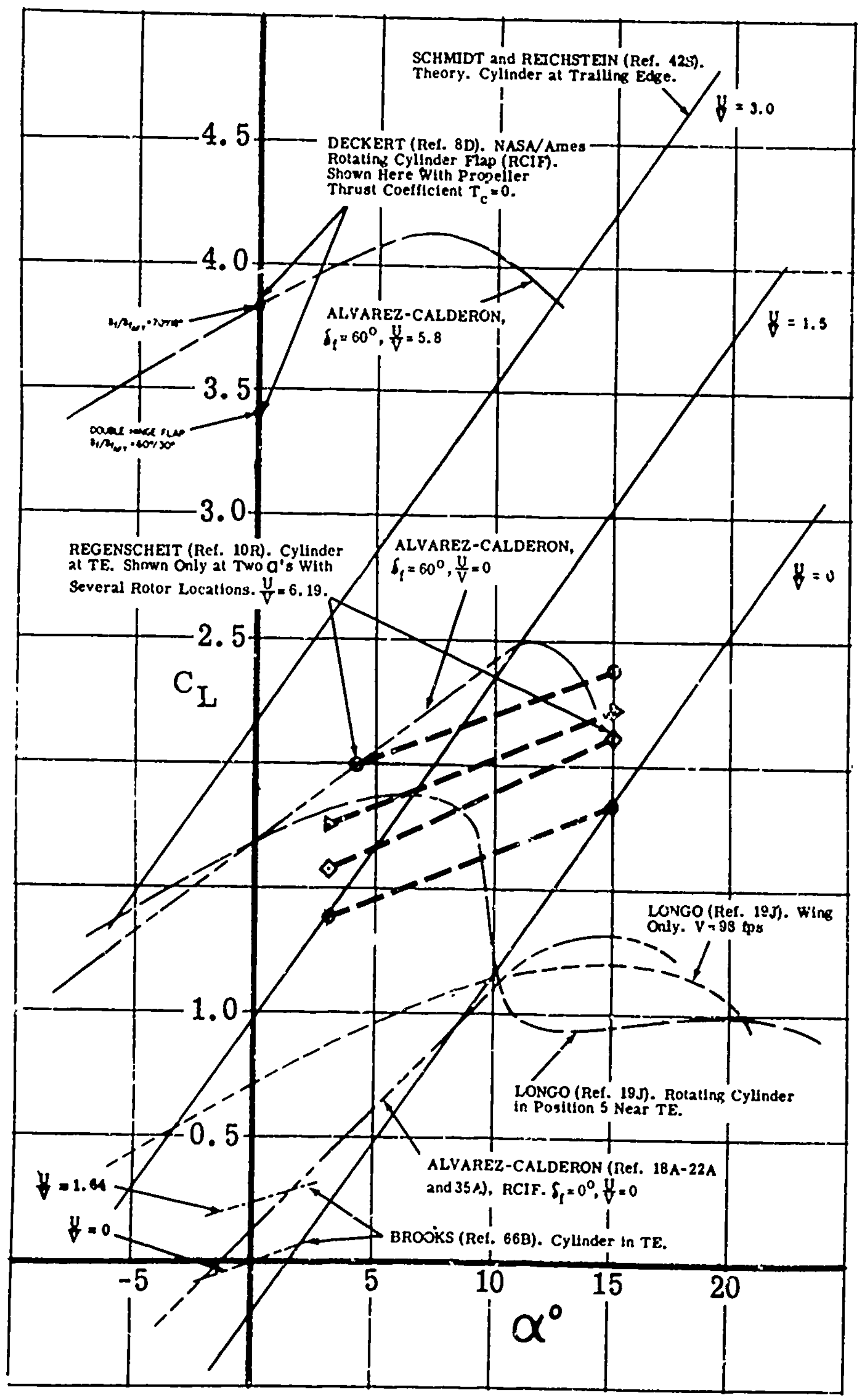


Figure 30. Theoretical and Measured Lift Coefficients Plotted Against Angles of Attack for a Collection of Combination Fixed-Wing and Rotating Cylinder Flap Systems. Cylinder at or Near Trailing Edge.

i.e., the rotor is to be considered as providing the means of energizing the boundary layer at the flap "knee" to insure the negotiation of curvature and the penetration against adverse pressure gradients existing for the flow at the deflected flap. As such, the RCIF may keep the wing's upper surface flow effectively attached when the flap is positioned through angles greater than 60° from the horizontal (Figure 32). Such an arrangement suggests an ideal system for the deflected-slipstream V/STOL application. To this end, semifree flight model and wind tunnel tests were made by Alvarez-Calderon at Stanford University (Reference 22A) to determine the potential and performance of the RCIF.

The results of these initial tests led to the prototype installation of an RCIF in a small aircraft (Reference 22A) and to studies of the adaptability of the system to the Ryan VZ-3RY and Fairchild M-224I flying deflected-slipstream test-beds. More significantly, large-scale two- and three-dimensional tests have recently been performed in the NASA/Ames wind tunnel, at Reynolds numbers of 2.1 to 2.9 million. These tests provide realistic information for deflected-slipstream VTOL and STOL aircraft (Figures 33, 34, 35, and 36).

It was initially suggested (Reference 18A) that it might be possible to aerodynamically balance the RCIF over a wide range of flap deflections and to transmit all flap loads through its hinge axis located at the aircraft center of gravity. It was felt that flap forces, regardless of magnitude or direction, could thus be eliminated. In a deflected-slipstream configuration, such an arrangement would be very attractive in minimizing the usual large pitch-down moment. Though this has not worked out exactly in practice, this approach has shown a significant reduction in pitching moment. Figure 37 shows such a change taking place, especially for flap hinge axis position 2, and also a reduction when compared to the fixed deflection flap.

Powering and driving the RCIF rotor present some points for further discussion. The power required may be treated as a part of the overall drag picture and is not included, as such, in any of the published data. It is interesting to discover that the torque reaction of the rotor-driving source would be resolved as a part of a pitch-down moment either on a free-flying model rig or on the NASA/Ames wind tunnel balance. It should be noted that this driving torque is included as a very small component of the overall pitching moment of the NASA/Ames tests.

A summary of some results of the NASA/Ames full-scale tests is presented in Figure 33. These tests are described as follows:

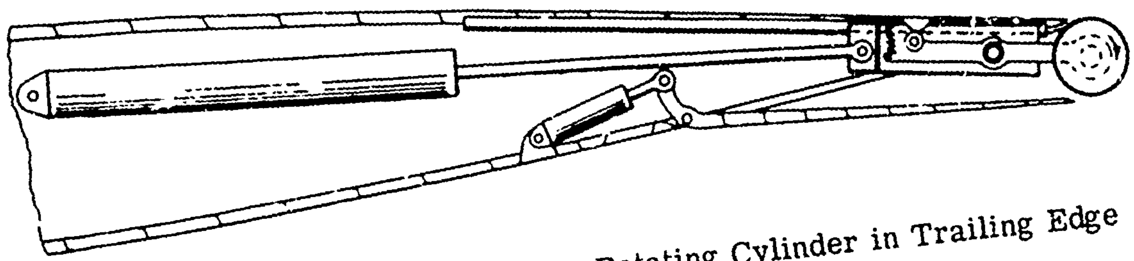


Figure 31. Retraction System for Rotating Cylinder in Trailing Edge (RCTE) by Tino (Ref. 33T).

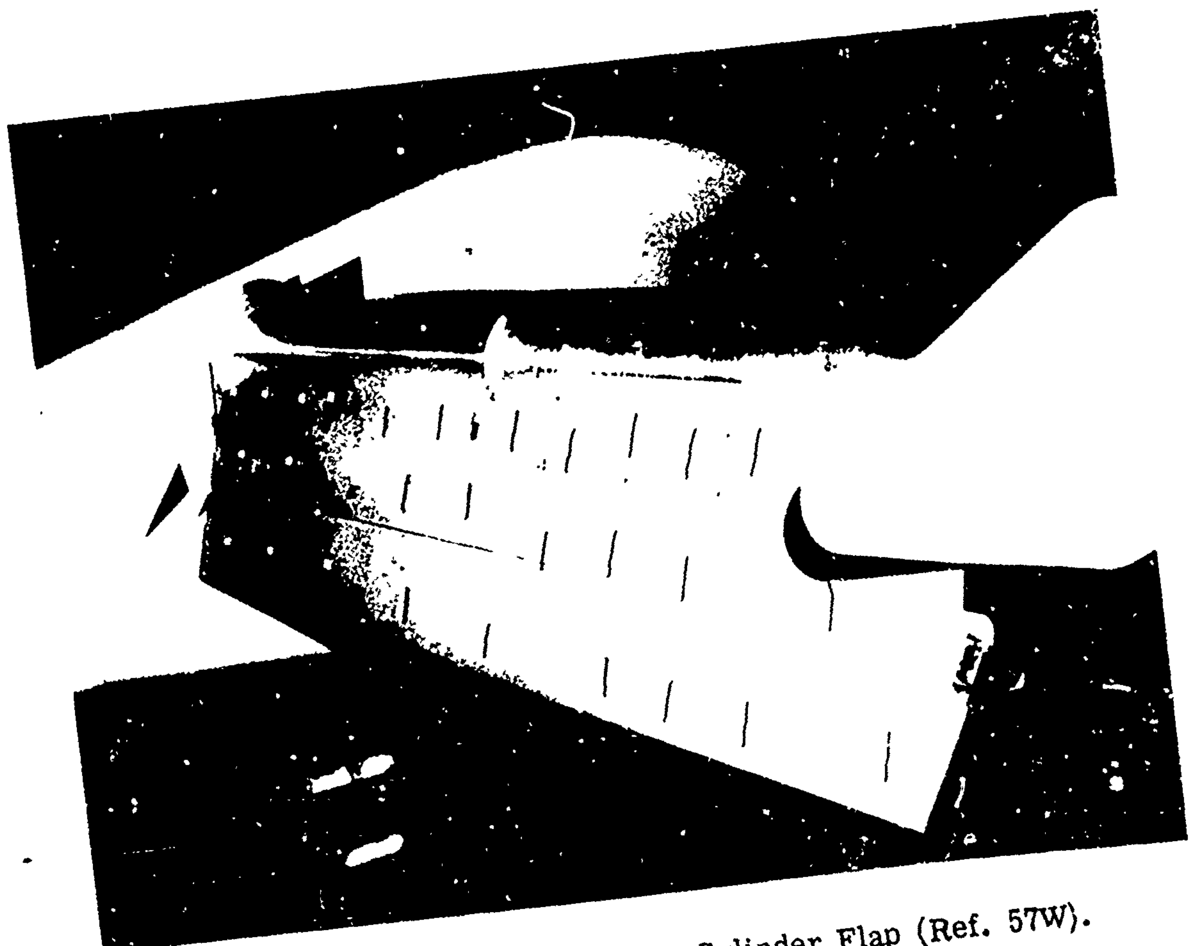


Figure 32. NASA/Ames Rotating Cylinder Flap (Ref. 57W).

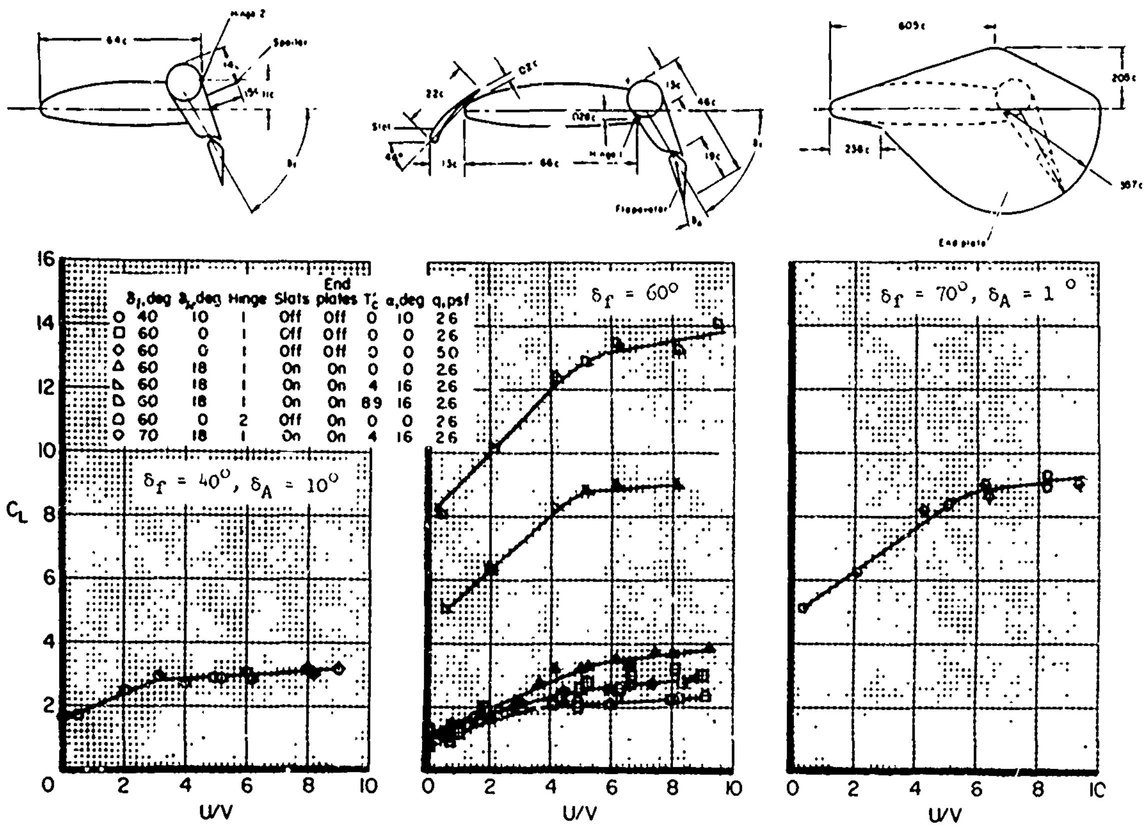


Figure 33. Lift Performance Summary of NASA/Ames RCIF-
Various Geometries.

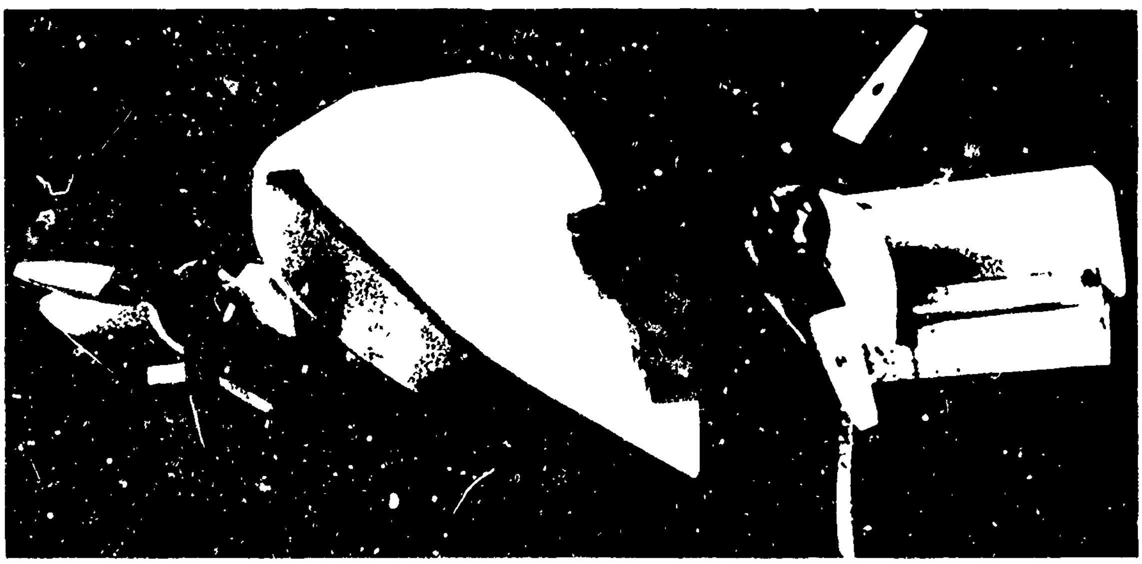


Figure 34. Full-Size Wind Tunnel Model of NASA/Ames RCIF Aircraft.

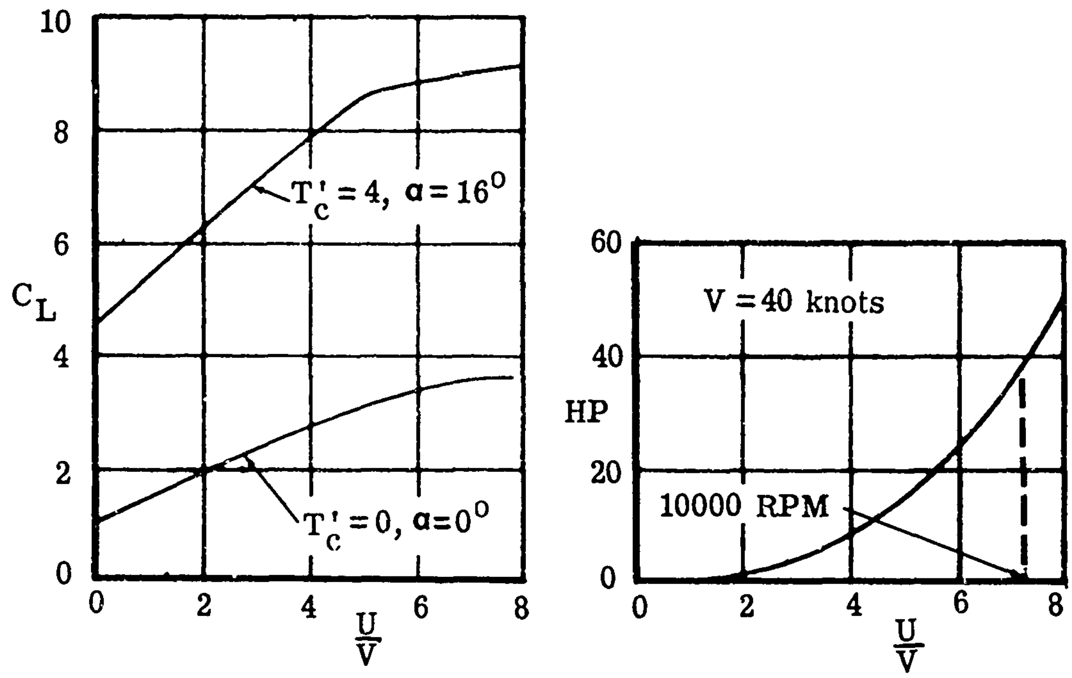


Figure 35. Cylinder Speed and Horsepower Requirements for the NASA/Ames (Ref. 8D) Rotating Cylinder Flap

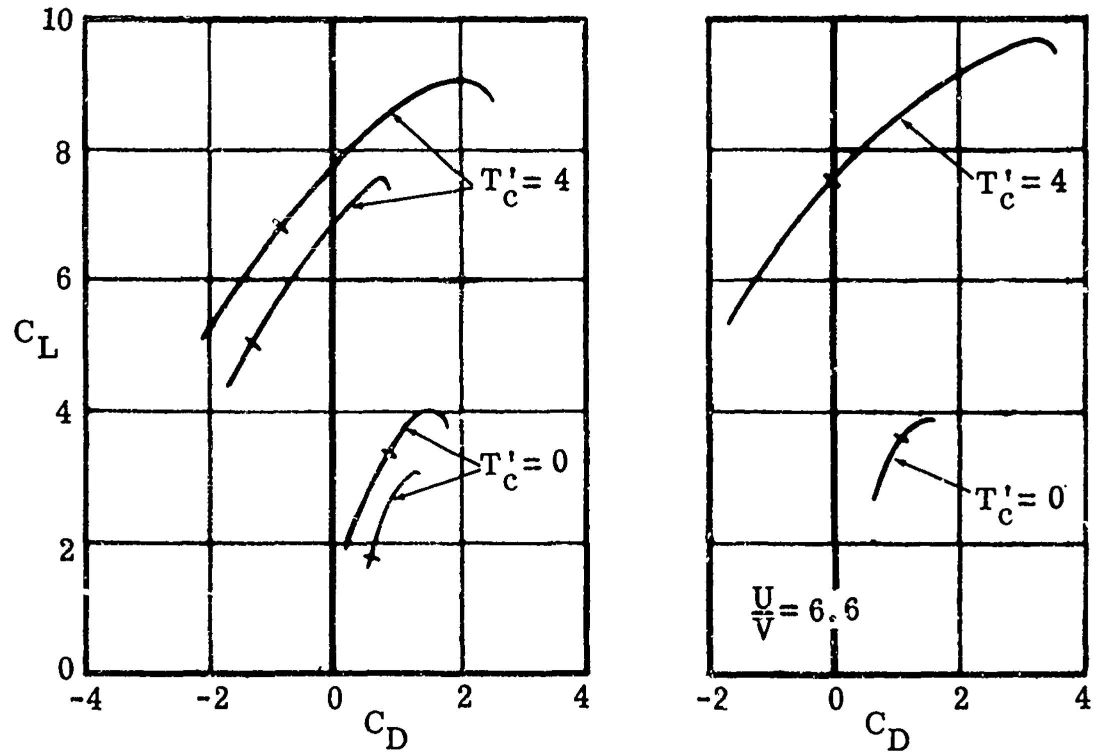


Figure 36. Lift-Drag Polars for the NASA/Ames (Ref. 8D) Rotating Cylinder Flap.

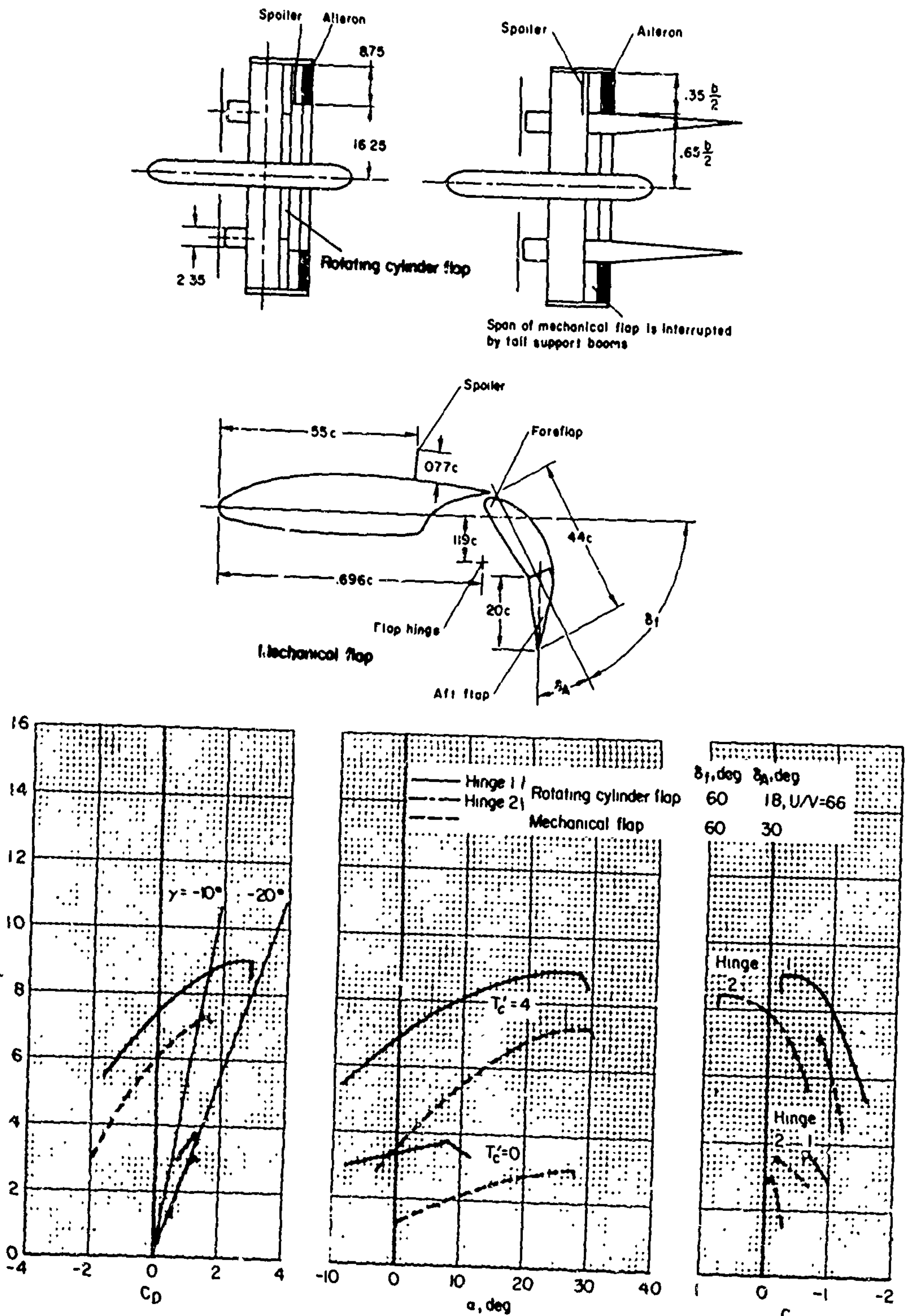


Figure 37. Comparative Performance of RCIF With Mechanical Flap (Ref. 57W).

> "Wind-tunnel tests were made of a model of a twin turbo-propeller airplane with rotating cylinder flaps. The model had a straight untapered wing of aspect ratio 3.57 equipped with end plates. Cylinder rotation provided a lift coefficient increment of 2.0 and a maximum lift coefficient of 4.0 with 60° flap deflection and zero propeller thrust. A maximum lift coefficient of 9.1 was obtained with a thrust coefficient of 4. The cylinder rotational speed required for the test was varied with flap deflection and was independent of angle of attack and slipstream velocity. For a flap deflection of 60° and a free-stream velocity of 40 knots, the cylinder power required was approximately 0.7 horsepower per foot of cylinder length."

Some conclusions drawn from this particular configuration have been:

> "This study has shown that the rotating cylinder flap can be an effective and efficient high lift device in the operating regions investigated. Cylinder rotational speed required is a direct function of airspeed and an inverse function of airfoil thickness (cylinder diameter limitation). The power required is proportional to the cube of the velocity; therefore, the mechanical requirements for rotating cylinder flaps will rapidly become more stringent if airspeed is increased, and detailed design efforts will be required to establish the feasibility of the device when used on aircraft with high approach speeds. However, the power requirements are less than for a comparable blowing flap BLC system. Proper choice of hinge line about which the rotating cylinder flap pivots can result in substantially lower pitching moments and flap hinge moments than those for a conventional mechanical flap."

Full-size four-propeller deflected-slipstream model tests continue at this time (Figure 38). Provisional results have indicated a greater lift performance enhancement due to the comparatively larger ratio of flap chord to propeller diameter.

In conclusion, the RCIF high-lift device appears to be extremely promising.

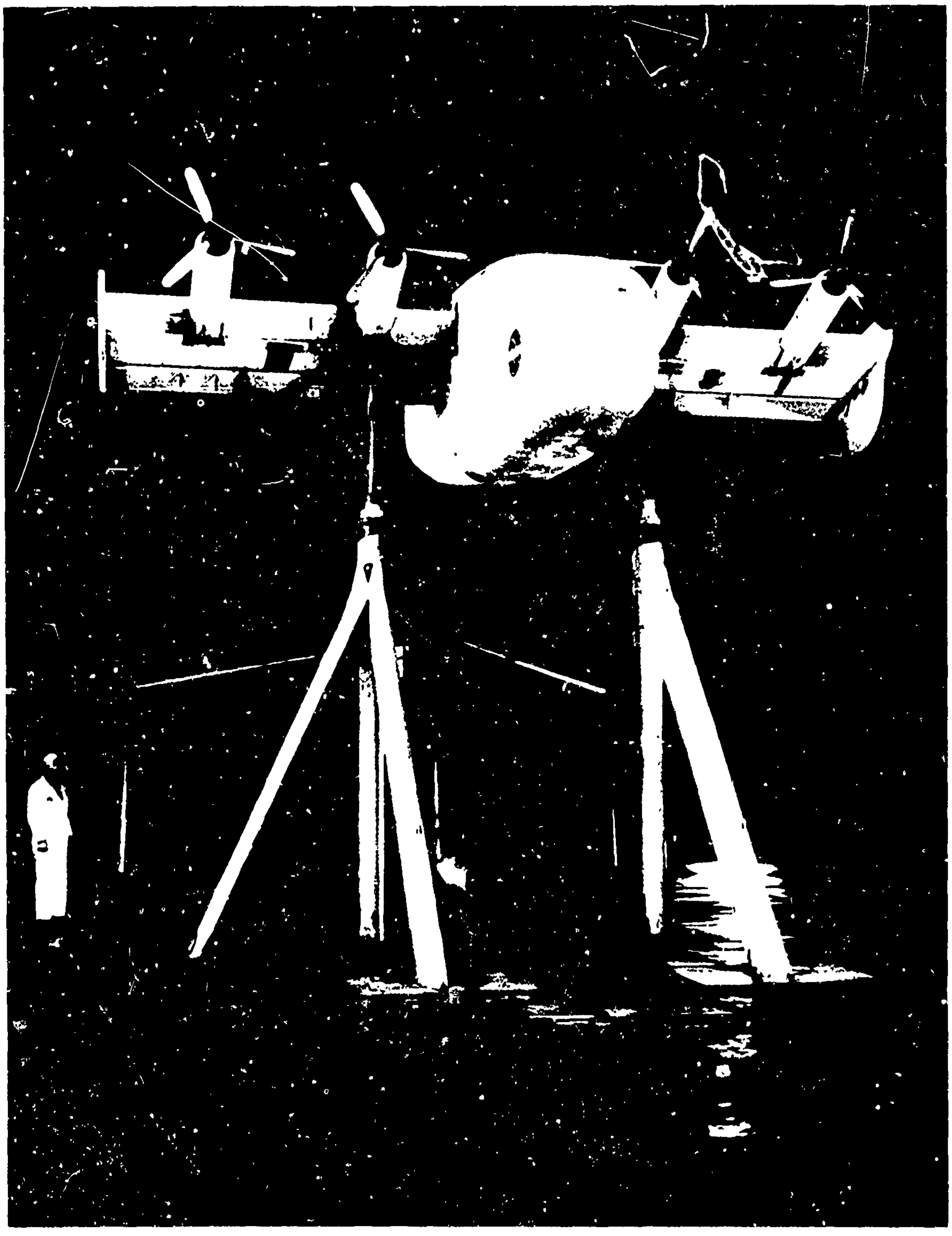


Figure 38. Deflected-Slipstream V/STOL Full-Size Model in Ames Wind Tunnel.

A typical application to a VTOL aircraft is shown in Figure 39.

e. Rotating Airfoil in Wing (RAW)

Various proposals have described the use of a rotating airfoil device, fairing or retracting into the upper surface of a fixed airfoil. It may be shown in a very preliminary fashion that the location of the rotating element in this area of the wing is far from being the optimum position for a circulation-enhancing device, but it could have some beneficial effect on energizing a weak boundary layer.

f. Rotating Airfoil Slat (RAS)

Auxiliary rotor devices of an airfoil, cruciform, or multivaned shape, located immediately in the leading edge of a fixed airfoil, are considered in this category (Figure 40). Such a rotor may be considered to be of the boundary-layer energizing type. Although such arrangements continue to be suggested from time to time, no practical tests have even been reported. It is interesting to note that a patent filed by F. W. T. Taylor (Reference 12T) as early as 1909 clearly shows an understanding of the installation of an autorotating leading-edge airfoil system for lift "enhancement" and longitudinal control. Like some subsequent arrangements, an installed vaned rotor may be driven over the full wing semispan in the manner of a transverse-flow fan (Reference 35M) and thus perform a means of direct blowing for a BLC system.

g. Rotating Airfoil Flap (RAF)

Encouraging analyses and tests have demonstrated that an auxiliary airfoil rotating near or at the trailing edge of a fixed main airfoil is a definite and attractive means of obtaining high lift coefficients and dramatic lateral and glide path aircraft control.

Fortunately, several investigators have tested this flap system (Figure 41). Initially, the phenomenen of a driven flat plate rotating behind a fixed surface was investigated in the wind tunnel by Riabouchinski in 1909 (Figure 42); it was subsequently tested in 1926 and reported in 1940 (References 27R and 28R). The arrangement of these experiments is shown in Figure 42, and the meager results are shown in Figure 41. The Brothers Longo in Italy extensively patented a convertible RAF system as early as 1925 (Reference 60L), and the results of their comparative wind tunnel results were published by Jona (Reference 19J). These tests were conducted with one basic 23% thick fixed wing, utilizing several lenticular-shaped,

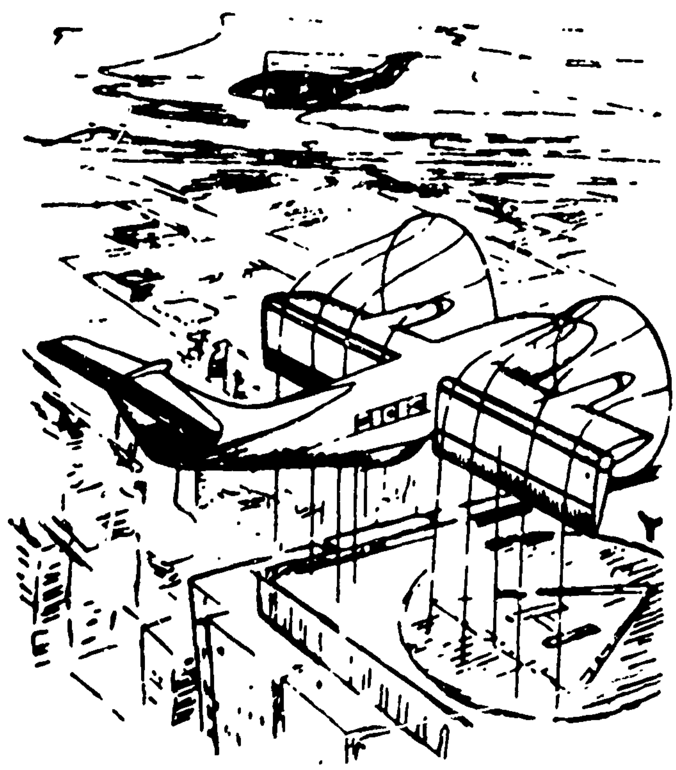


Figure 39. Proposed Application of Alvarez-Calderon's Rotating Cylinder Flap (RCIF) to a VTOL Airplane.

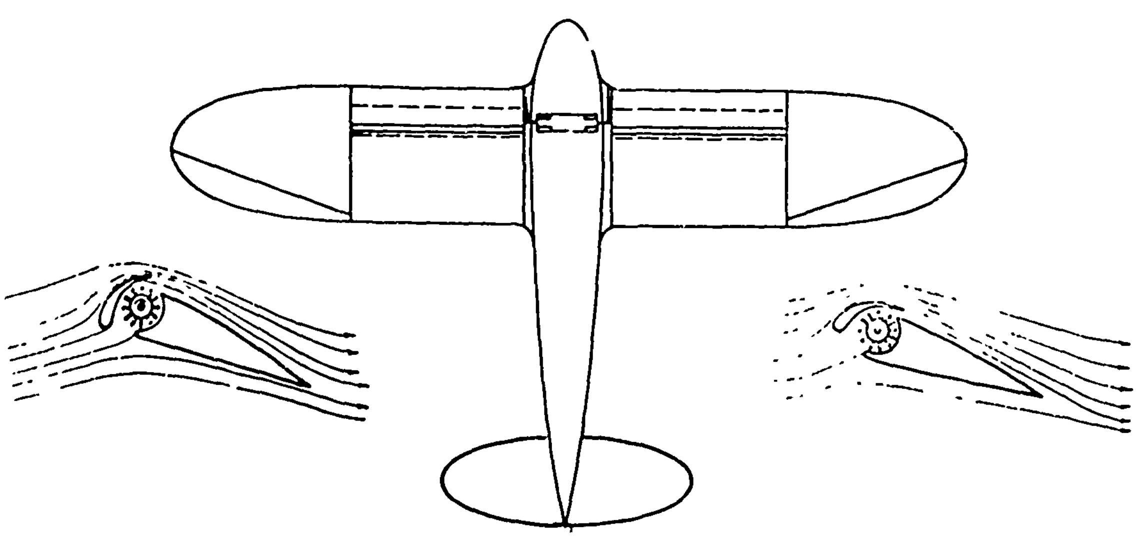


Figure 40. Lippisch Patent (Ref. 56L) Describing Rotating Airfoil Slat (RAS) Device and Boundary Layer Energizer.

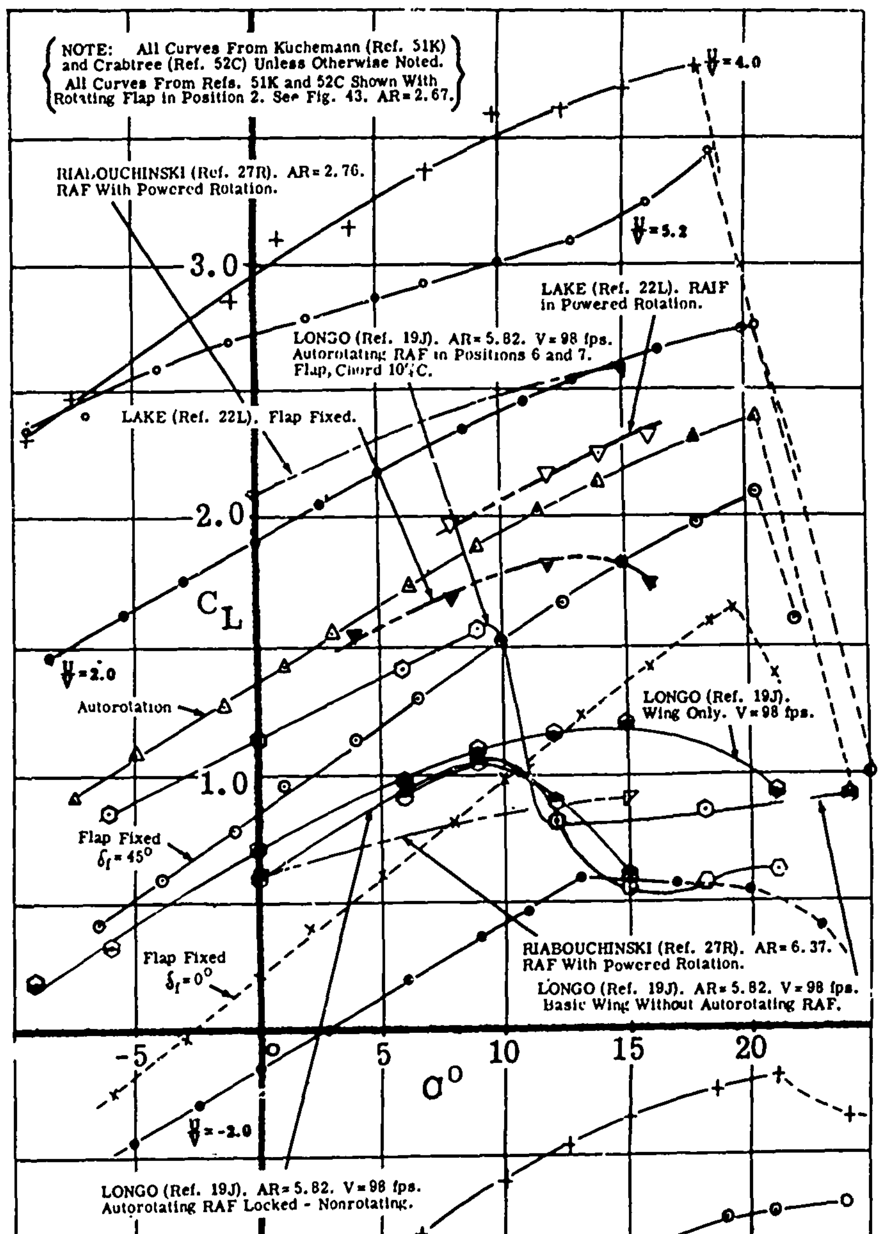


Figure 41. Measured Lift Coefficient Against Angle of Attack for a Collection of Combination of Fixed-Wing and Rotating Noncircular Airfoil Rotating Flap Systems; Rotating Flap at or Near the Trailing Edge.

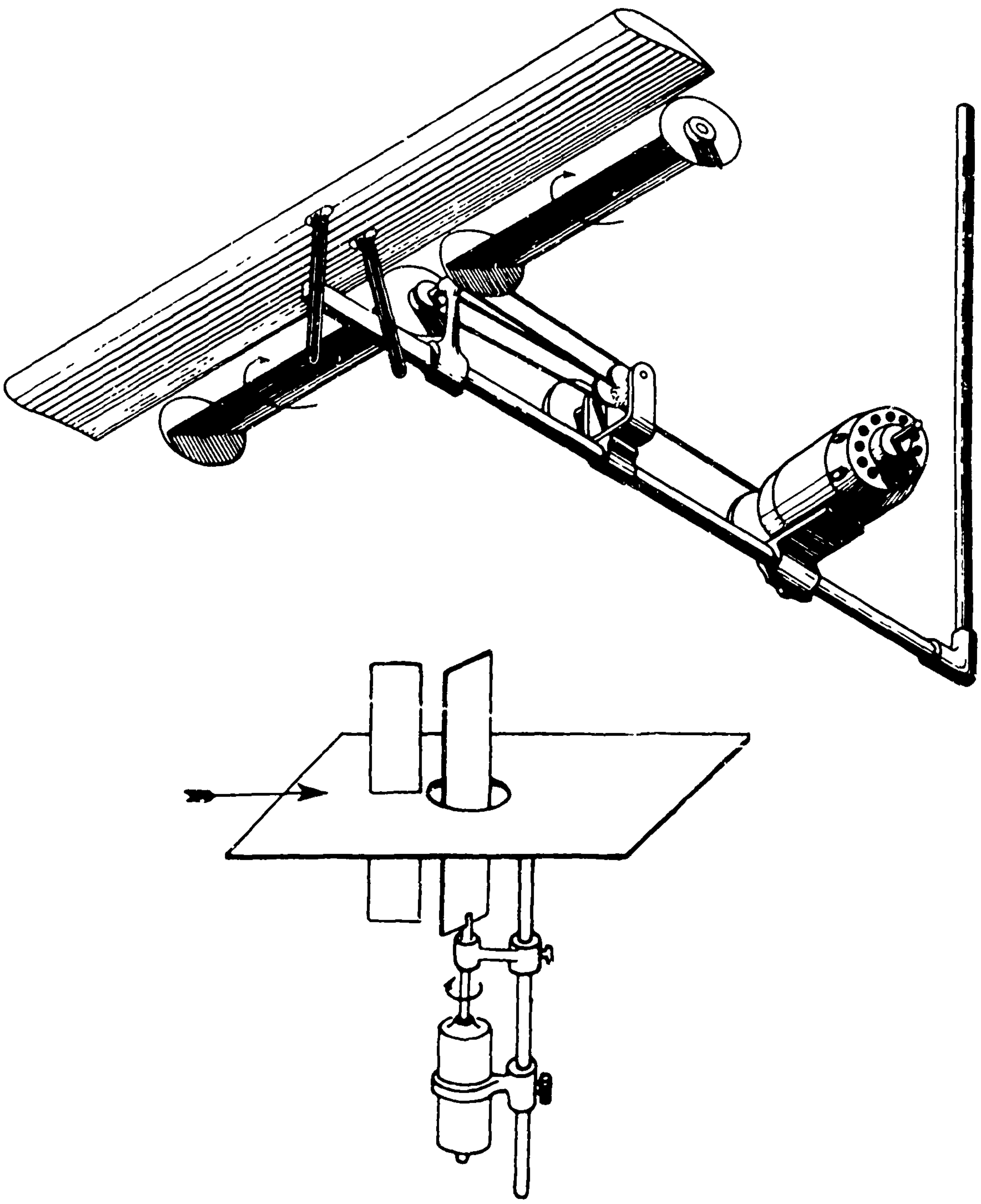


Figure 42. Early Experiments by Riabouchinski To Determine the Performance of the Trailing-Edge Rotating Airfoil Flap. (Ref. 19R).

trailing, fixed, and autorotating flaps and several wind-rotated cylinders--at various angles of attack and at several tunnel speeds. The selection of that test airfoil is inappropriate for modern applications.

The most useful background information for the application of the RAF was generated during World War II by Holst (Reference 48H) and Küchemann (Reference 51K) and later reviewed by Crabtree (Reference 52C) and Neumark (Reference 20N). The wind tunnel tests by Küchemann are relatively comprehensive and were carried out in a Reynolds number range from 60 x 10^6 (flap in autorotation) down to .14 x 10^6 (flap operating at U/V = 4).

These tests were carried out on a 30- x 80-cm fixed wing located between two large stationary elliptical tip plates. The rotating flap was an airfoil with a chord 25% of the fixed-wing chord, with a profile not too unlike that of the main wing. Two smaller circular tip plates were rotated with the flap element. The axis of the flap was tested in three positions, below and in the vicinity of the fixed-wing trailing edge. Parameters varied in these tests were: rotating flap position, angle of incidence, tunnel speed, peripheral speed of RAF (autorotation, powered and stopped), direction of rotation. Lift, drag, and moment coefficients were determined. Some of these results are presented in Figures 41, 43, 44, and 45.

The arrangement of the RAF in these tests suggests adaptation of the flap in an external manner, as was often done in a wide variety of aircraft types by Junkers. If this is done, it is well to review the past experience of NACA/Langley in the wind tunnel and full-size flight tests of this external adjustable flap (NACA Reports 541, 573, 679; NACA TN 524, 604).

It would now become possible to combine these two separate devices, the RAF and the external flap, and to put them to practical use. Such a study, using the existing DeHavilland DHC-4 "Caribou" STOL aircraft, is later described on page 219. If one considers the installation simplicity of such a flap arrangement, as is shown, for example, on the Boeing XL-15 aircraft (Figure 46), then this adaptation to an existing design may not present too many problems.

It is suggested that the main fixed wing should be constructed continuously and that the external flaps also be rigged to serve as ailerons. The external flap would be supported to the trailing edge of the fixed wing through a series of hangers extending to the 50% chord or spin axis of the airfoil flap. These hangers would partially contain the

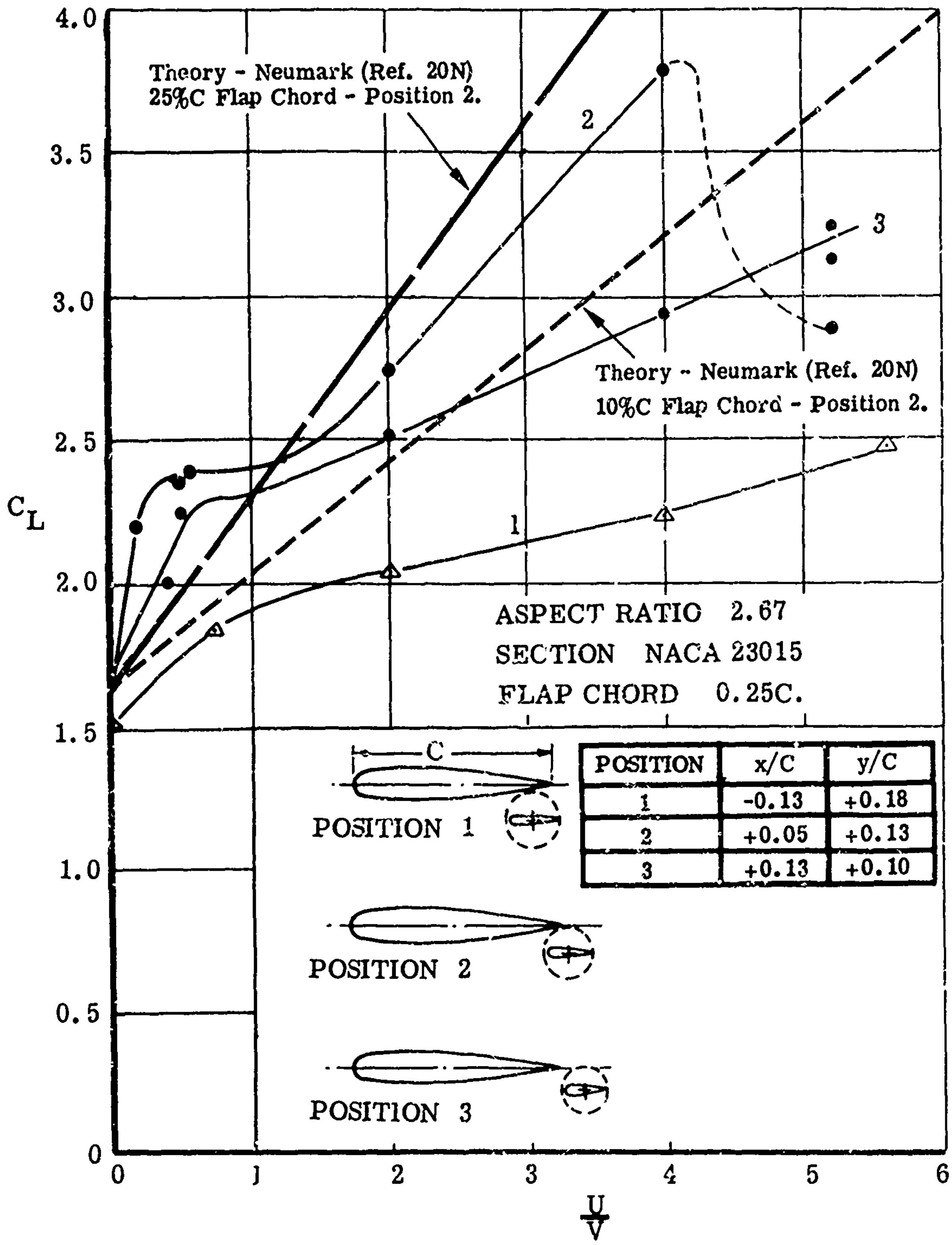


Figure 43. Wind Tunnel Results and Optimization of Rotating Airfoil Flap Position With Respect to Fixed Airfoil. From Küchemann (Ref. 51K) and Crabtree (Ref. 52C).

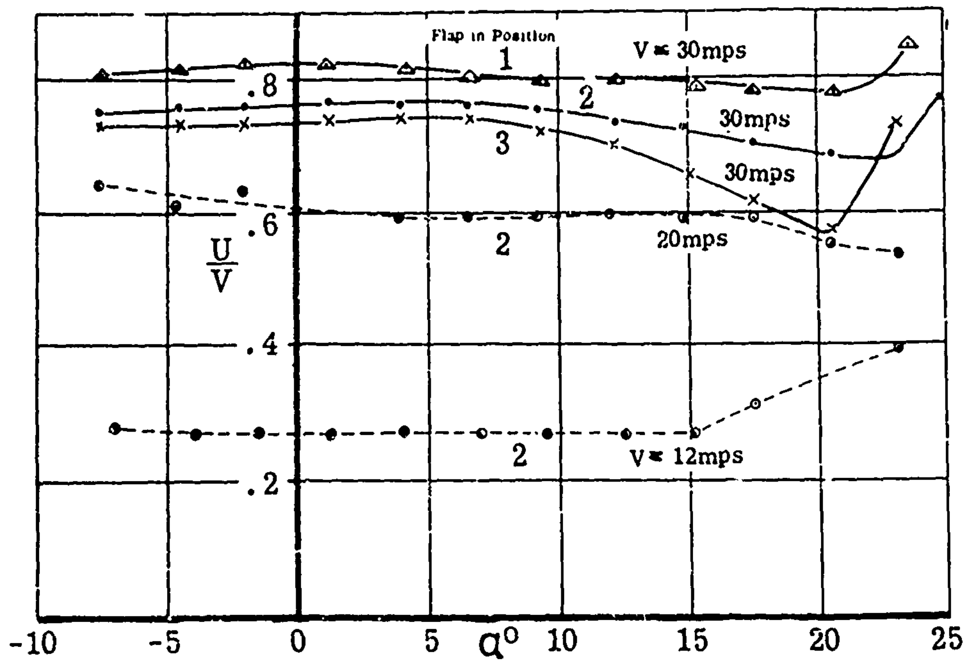


Figure 44. Autorotation of a Trailing Edge Airfoil Flap at Various Positions (See Fig. 18) and for Different Free-Stream Velocities. From Crabtree (Ref. 52C) and Küchemann (Ref. 51K).

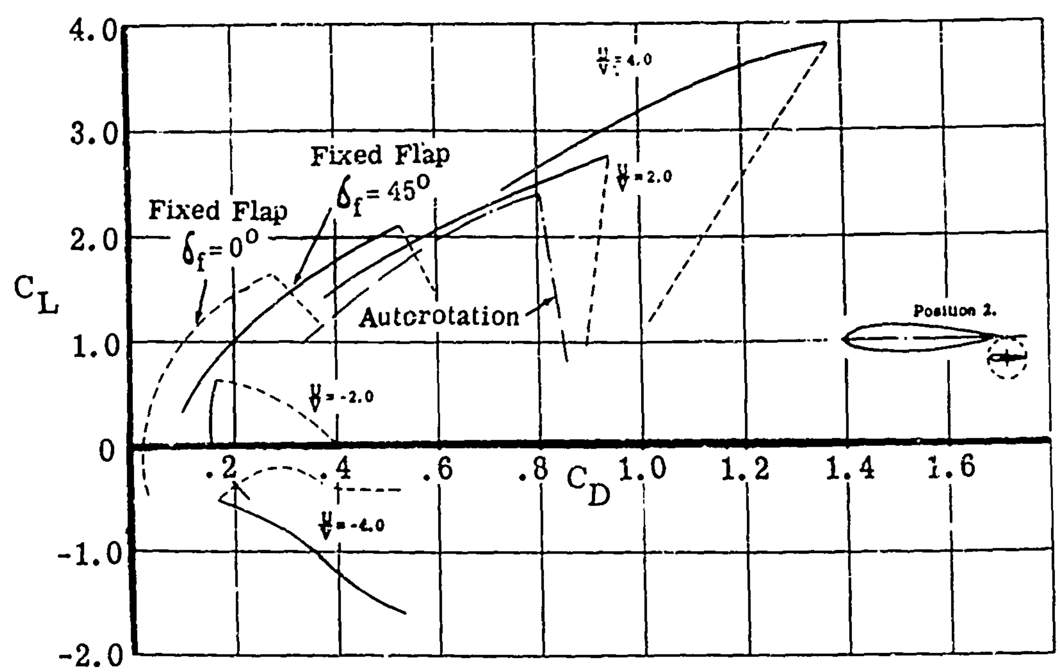


Figure 45. Lift and Drag Polars of a Fixed Wing with Trailing-Edge Rotating Airfoil Flap. Flap in Powered Rotation, Autorotation, and in Braked (Spoiler) Rotation. From Crabtree (Ref. 52C) and Küchemann (Ref. 51K).

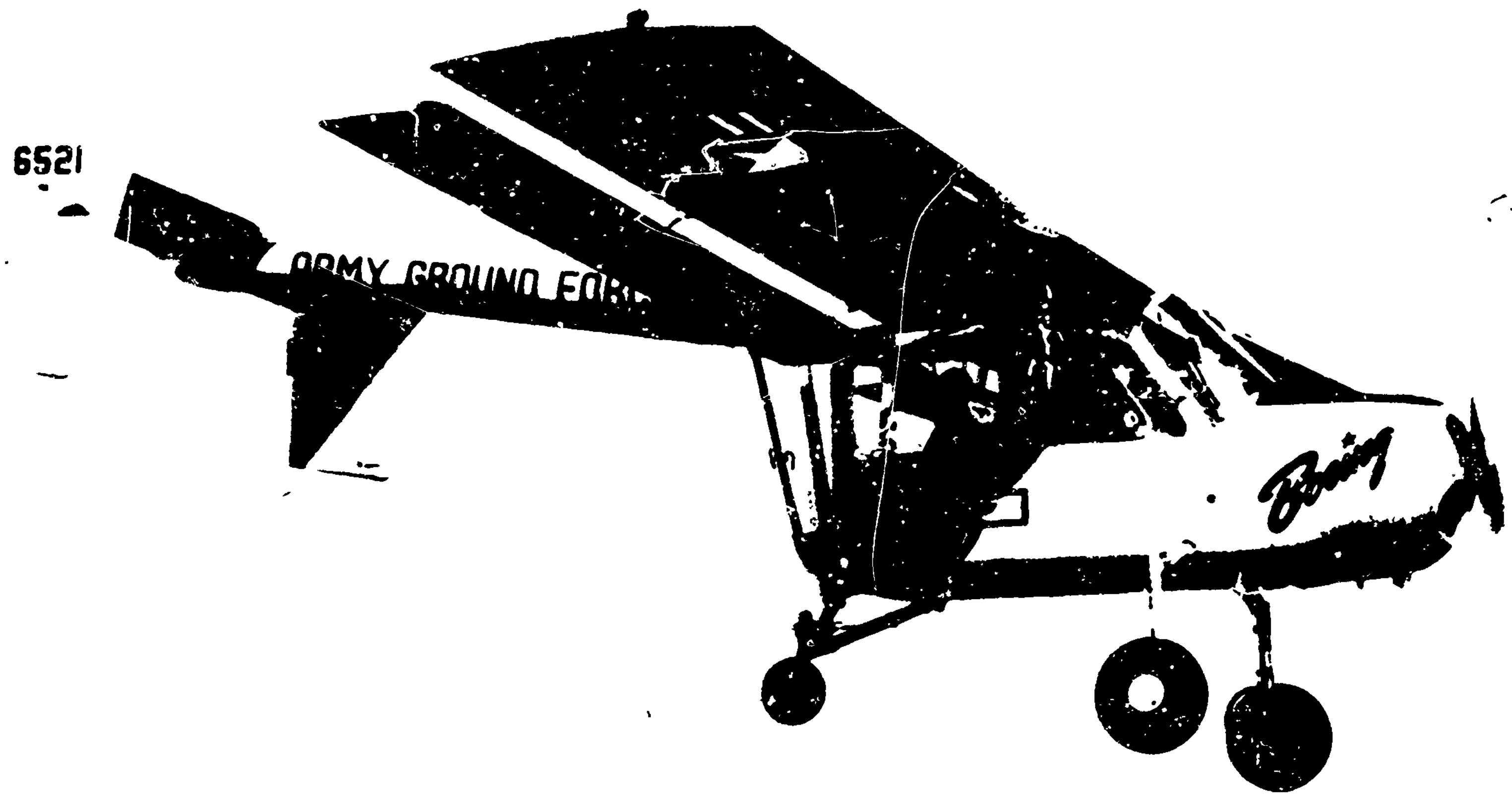


Figure 46. Boeing XL-15 Liaison Aircraft With Full-Span External Airfoil Flaps (1949).

drive shaft, axle housing, angle gearing, clutching, and flap angle locking mechanisms.

With a suitable flap thus installed, the following flight regimes and corresponding flap operations may be considered:

1. As a fixed wing - cruise. Airfoil flap is locked at its best cruise position. Flap area may be considered to be a part of the total fixed-wing area (Figure 41).

2. Flap deflected at various angles - operating as an external fixed flap for trim flight control or as a safety power-off backup system (Figure 41).

3. Flap rotated 90° to airstream and fixed as a (dive) brake or glide path control device.

4. Airfoil flap unlocked in free autorotation about its axle. Lift and drag now in excess of that of the fixed airfoil (Figure 41). As a safety backup, no shaft power required.

5. Airfoil flap unlocked and in powered rotation. Power may be practically applied to the flap axle at its junction in the support hangers, or the axle may be conveniently extended directly into the side of the fuselage. Lift and drag can be modulated by increases in power and peripheral speed of the airfoil flap. Note that the torque reaction required to drive the powered RAF appears, in part, as a component of the pitch-down moment on the aircraft.

6. Figure 41 shows that reverse rotation of the RAF produces negative lift coefficients. Thus, by rotating the flap backward, one may produce a negative lift. This may be employed as a glide path control system.

7. The RAF should be capable of being uniformly braked from the rotational state to the fixed-flap condition.

The flexibility of the RAF arranged in this manner is attractive. Before exploring the effects of flap in rotation, let us review the characteristics which have been determined for the fixed external flap.

Consideration of the external airfoil flap as a high-lift device indicates that it may be generally applied to improve

V/STOL aircraft performance. Previous investigations by NACA/Langley have shown that this device is capable of developing high lift coefficients and that it gives lower drag at these coefficients than ordinary flaps. Thus, it may be more favorable to such items of performance as takeoff and landing. At low lift coefficients, the external flap gives very nearly as low values of profile drag as a good plain airfoil of comparable thickness. Stability problems associated with large negative pitching moments occurring at high lift coefficients may be slightly greater than in the case of ordinary and split flaps. If the maximum lift coefficient of the wing with the external airfoil flap is referenced to the chord of the fixed wing, as is customary for other types of flaps, the resulting values would be about the same as those for single-slotted flaps. Generally, the full-span external flap has not been used extensively in this country. Some question arises as to the icing hazard between the flap and the wing.

Returning to the Küchemann RAF data of Figures 41, 43, 44, and 45, initial testing sought to determine the optimum position of the RAF to obtain $C_{L_{max}}$ (Figure 43). It is interesting to note that the determined optimum position 2 also satisfies the simple theories of Küchemann and Neumark and is also within the "optimum" position of the fixed external flap. The collapse of the lift curve of position 2 beyond U/V = 4 may be due to the fact that the test Reynolds number ($.14 \times 10^6$) at this U/V is causing an early transition to turbulence. Note that in these tests the Reynolds number varied from each U/V value as the flap peripheral speed (U) was held constant while the tunnel speed (V) was varied. It would be of interest to repeat a similar experiment in which the test Reynolds number could be raised to that of full-size aircraft landing and takeoff velocity and the U/V parameter could be held constant by varying the RPM of the rotating flap.

Several preliminary analytical attempts have been made to establish the theory of a wing with rotating flap (References 42S, 52C, 19N, and 20N). The theoretical attempts have been to represent a two-dimensional flat plate together with a straight line vortex at the axis of rotation of the flap. Thin airfoil theory can be developed for this ideal case, permitting solution by the potential flow method of conformal transformation. It may be noted that this is not too unlike the case of the two-dimensional jet flap airfoil, where the jet may be represented by a continuous distribution of vorticity in contrast with the axially concentrated vortex of the RAF theory.

A practical conclusion of Neumark's paper (Reference 20N) indicates a way to determine the contribution of the airfoil flap lift to the fixed-wing lift in the form of an incremental lift coefficient:

$$C_{L_1 S \Gamma} \approx \sqrt{\frac{L^2}{C^2} + \frac{2L}{C(1+\epsilon)}} \cdot \cos \frac{\beta}{2} \frac{U}{V}$$

where

$C_{L_1 S \Gamma}$ = incremental lift coefficient (referenced to fixed-wing chord)

ϵ = gap parameter, in which $d_2 = 1/2\ L\ (1+\epsilon)$

L = chord of airfoil flap

C = chord of fixed wing

β = angle between horizontal (x) and reference line passing through wing trailing edge and flap axis

U = peripheral velocity of flap

V = free-stream velocity

As a practical check, assume a wing chord to flap chord ratio (L/C) = 1/4 and the axis location angle $\beta = 52^o$. This corresponds roughly to the "optimum" theoretical locus of Neumark (Reference 20N, Figure 6). The incremental lift coefficient is determined for a range of values and added to the measured data of Küchemann (Reference 51K), and the resulting theoretically adjusted curve is shown in Figure 43 for the "optimum" position 2. The agreement between the measured and the adjusted curves of flap position 2 is surprisingly good.

It would be of further interest to determine the influence of slipstream effects and combined propeller thrust coefficients on enhancing the lift potential of the RAF.

Recent technological advances in the operational use of lightweight, high-speed drives and shafting supported over long lengths would be useful for adaptation of the rotating flap system to aircraft. Further, extensive operational experience by Junkers with the external flap is useful in understanding the problems of support structure, icing, etc. Some questions not yet answered might be the effect of the gyroscope couple of rotation flaps on structure and flight control and wake and buffeting problems created by the trailing-edge rotating airfoil flap.

h. Rotating Airfoil in Flap Leading Edge (RAIF)

The arrangement of a rotating airfoil in the leading edge of an adjustable fixed flap, as in the RCIF, is not a new suggestion. The patents of Henter and Kaser (Figure 47), filed in Germany in 1929, clearly indicate the application of a deflected slipstream over an RAF (Reference 28H) or a rotating airfoil ahead of, and adjacent to, a fixed flap (Reference 29H). The patent by Lake (Reference 22L) describes various adaptations of the RAIF to aircraft (Figure 48). This patent is of interest because it clearly suggests means of airfoil flap installation, drive, collective and differential control, and electromagnetic braking. The patent is also unusual in that it provides brief data on the power required to rotate the RAIF and the lift developed (Figure 41). The use of intermediate folding, rotating, flap tip plates is also suggested to prevent spanwise flow of air. The flap is also capable of autorotation. A more recent patent by Brunk (Reference 84B) describes a similar RAIF system in which, as the fixed flap is deflected, it uncovers fully autorotating airfoils in its leading edge. Like the RCIF, the arrangements are to be considered to be boundary-layer energizers to encourage flow attachment over a sharply deflected fixed flap. The Brunk system (Figure 10) suggests the use of two of the better bomblet or windmill sections. It should be noted that this system could benefit from improvements and adaptation in past and current bomblet profile studies. Note again that the autorotation system is self-contained, requiring no shaft power. Like the RAF system, the only preliminary flap power estimates that are available are those determined by Wiese (Reference 56W), and these are applicable only for an isolated lenticular rotor. The RAIF holds interest in that the retraction and stowage of the flap rotor could be more compact and simpler than that required for a comparable cylinder rotor. The RAIF should be capable of power-off autorotation.

i. Rotating Flap Systems in Ground Effect

The effect of the ground on general V/STOL performance is indicated in Figure 49, which shows the power required for a tilt-wing airplane, in and out of ground effect, as a function of takeoff speed. This shows that the airplane requires considerably more speed to produce a given lift with a given power in ground effect than out of ground effect. This indicates a greater takeoff speed and distance required within ground effect than outside it. For the deflected-slipstream RCIF NASA/Ames aircraft (Reference 57W), test data show the deterioration of lift performance in ground effect (Figure 50). This adverse ground effect is probably due to a collection of difficulties arising when the high-velocity deflected slipstream flows forward upon striking the ground circulation. The power-on characteristics ($T_C{}' = 4$) are most affected by the ground.

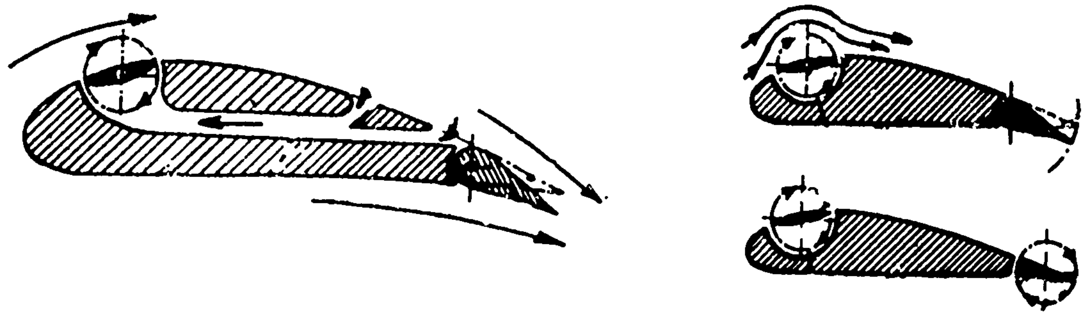


Figure 47. Rotating Airfoil Flap in Leading-Edge High-Lift RAS System by Henter and Kaser (Refs. 28H and 29H).

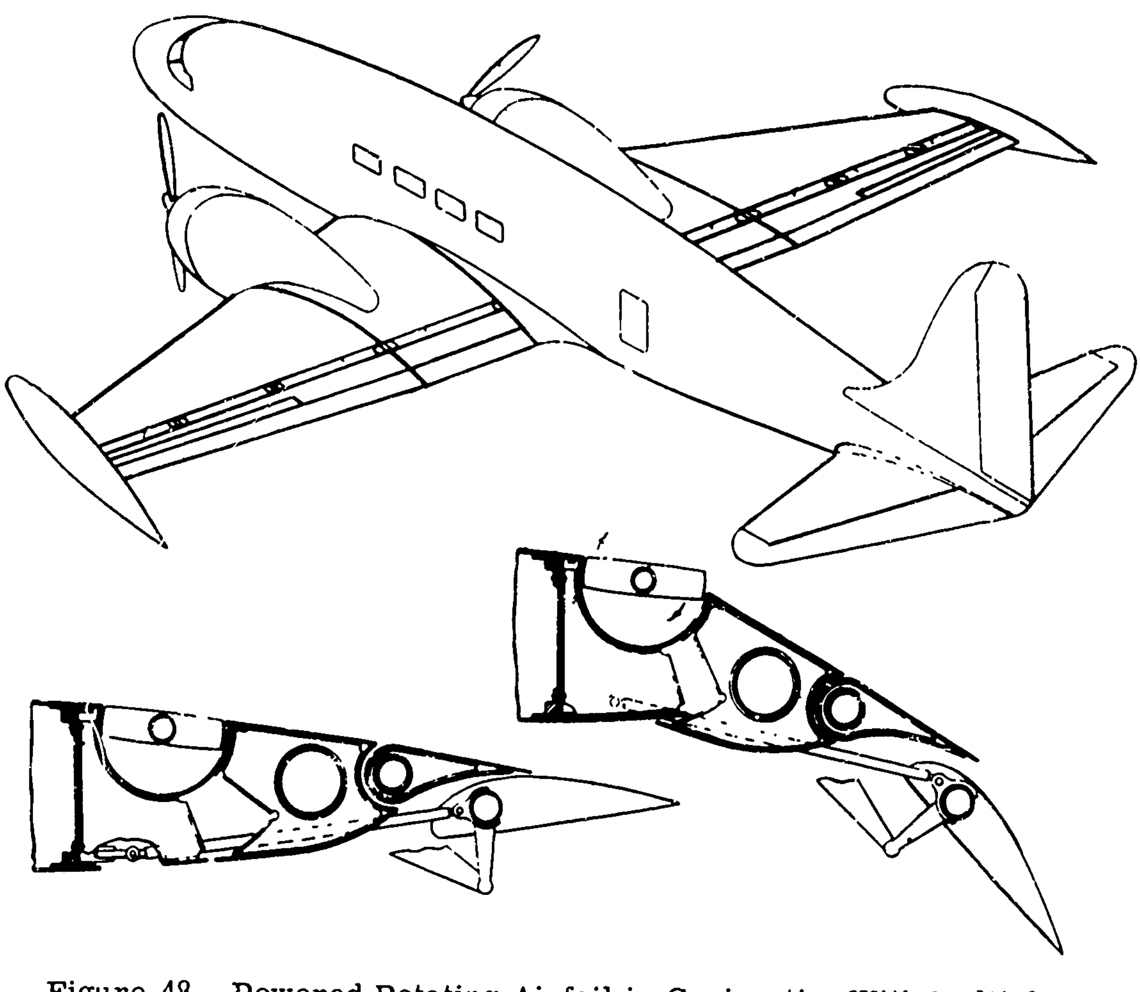


Figure 48. Powered Rotating Airfoil in Conjunction With Multiple Flap by Lake (Ref. 22 L).

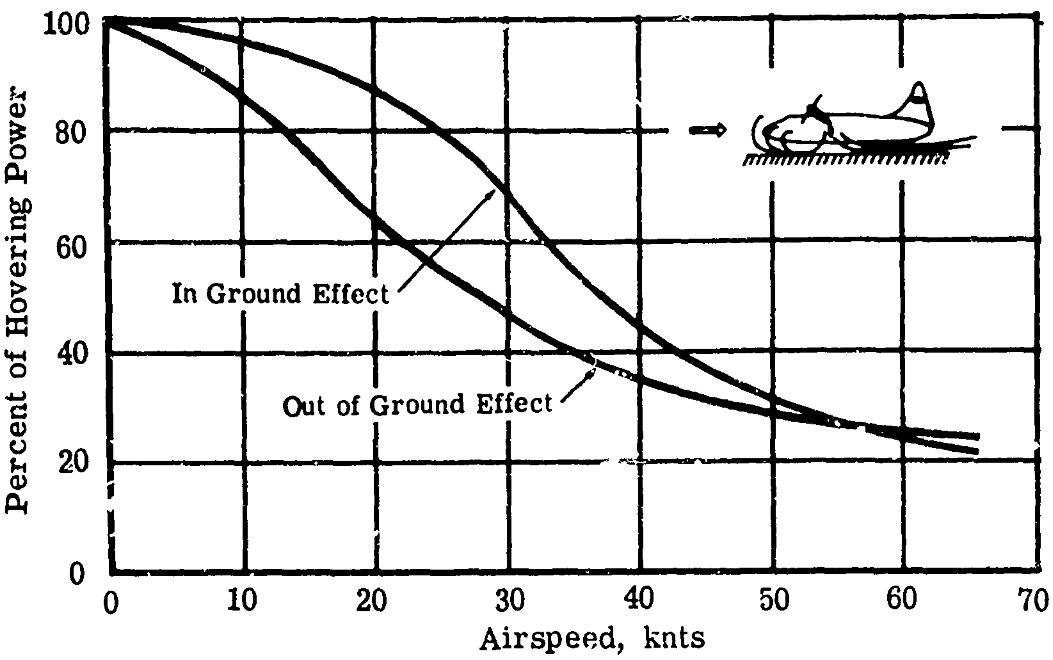


Figure 49. Influence of the Ground on a General Tilt Wing V/STOL.

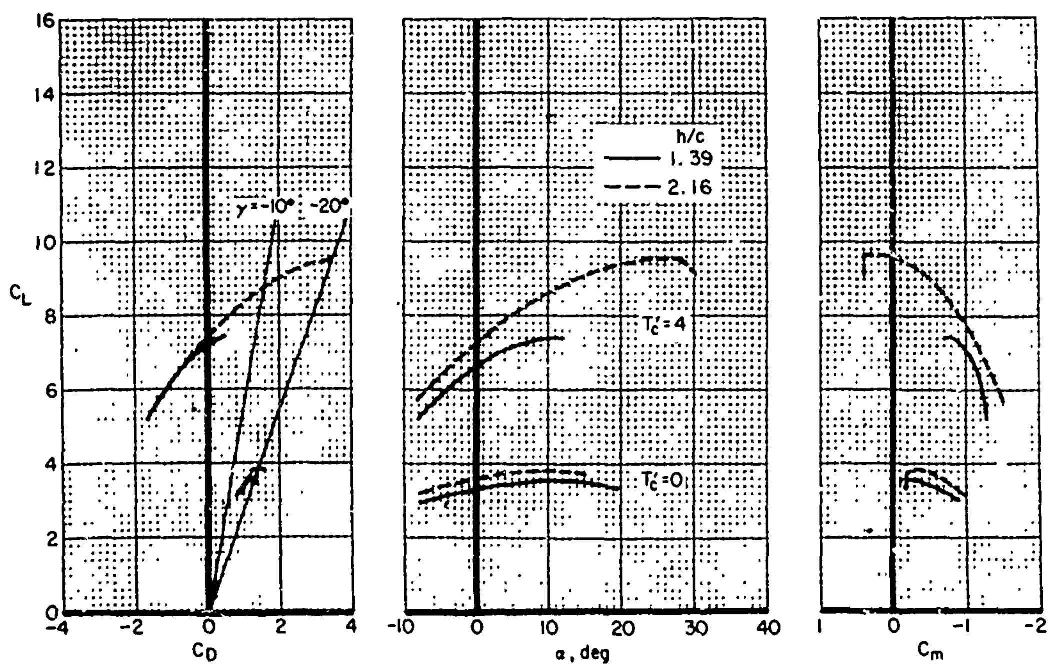


Figure 50. Effect of Ground Height (h/c) on the Aerodynamic Characteristic of the NASA/Ames RCIF Aircraft. $\delta_f = 70^0$ $\delta_A = 18^0$, Slats and End Plate on, Hinge 1 (See Fig. 75 and Ref. 57W).

No direct data exist on the influence of the ground on the Magnus effect or the circulation enhancement of the RAF arrangement. Experimental and analytical studies have been made on the attraction of flow with circulation toward a boundary or the ground (Reference 72R). This attraction or loss of lift, called the Raimondi effect, does not necessarily need forward speed to become effective. Data are shown here (Figure 51) for the attraction force between a rotating cylinder or between a rotating flap plate, and a ground board. This phenomenon may be expected to cause a decay in lift of Magnus effect systems when operating in ground effect. Further applicable analytical techniques are available for the study of the influence of ground effect on wing performance. These techniques have been cataloged and summarized in David Taylor Model Basin Report 2179, March 1966.

j. Rotating Flaps for Lateral Control

Taylor, Holst, and Neumark have suggested the use of small auxiliary wing rotors or rotating flaps as a means to obtain aircraft longitudinal or lateral control.

The results of the 1967 NASA full-size wind tunnel and flight test of the external flap system (Figure 37) indicate that when the full-span external flap is used also as an aileron, the rolling action is good; but the resulting adverse yaw is undesirable, and the stick forces (without boost) required to operate them increase too rapidly with speed.

It is suggested that, in a practical application of the RAF, the flap be split into an outboard and an inboard section. The inboard RAF would be driven at its highest and/or optimum RPM, while the powered rotation of the outboard portion (now considered as ailerons) would be driven through a differential and variable RPM system. Modulation of these outboard rotation aileron systems might be trimmed to provide very large and controllable low-speed roll forces. Here the problem is to program the control system of the outboard rotation ailerons to provide the proper roll characteristics without introducing the adverse yaw forces that were found in the full-span arrangement of the NASA flight tests.

The rotating cylinder and airfoil slat suggestions are not without interest as roll-producing or quasi-aileron devices. In the use of very thin high-speed wings, it is desirable to minimize elastic wing deflections originating from the trailing-edge aileron. In a thin wing, these deflections tend to act in a direction opposite to that of the desired roll motion and may produce undesirable aeroelastic problems. It is suggested that a controlled RCS or RAS in the wing leading edge may produce the desired roll couple and also deflect the elastic wing in the desired direction.

4. Orbiting Flap and Undulating Propeller

Schmidt (References 41S, 43S, and 54S) has evolved a unique trailing-edge rotating flap which capitalized, in part, on the Knoller-Betz or Katzmayr effect. Essentially, it is a system of thrust augmentation, drag reduction, or thrust production, depending upon the configuration of the orbiting airfoil and/or fixed airfoil(s). The basic arrangement is shown in Figure 52, in which a leading airfoil or "undulator" is orbited ahead of an aft stationary airfoil or "deundulator". The combined system experiences an overall thrust as a result of the undulator's rotation.

Further, if the undulator and deundulator are submersed in the airstream of a propeller or jet, the effect on the system is an overall drag reduction or, effectively, a thrust augmentation (Figure 54). Figure 53 also indicates how further variations in the geometry and mechanical motion can be made to obtain not only thrust augmentation but also lift. The number of parameters needed to be manipulated to seek an optimum performance are innumerable. Schmidt has carried out many tests on several special configurations; the results of one arrangement are presented as a lift and drag polar in Figure 54. Note that:

α = angle of attack of main forward body (note range from 0° to 25°)

ϵ = angle of incidence (constant) of undulator in orbit with respect to main body reference

β = angle of incidence of deundulator with respect to main body reference

U = peripheral speed of undulator

V = wind speed

n = RPM of undulator

The results, as explained in Reference 54S, are the wind tunnel results on an air and land vehicle (Figure 55). Note the very thick forward stationary airfoil body, the trailing and orbiting undulator, and the final stationary elevator-like deundulator.

Other innumerable adaptations of the orbiting airfoil flap have been suggested. One system proposed by Schmidt is the adaptation of the undulator airfoil as a thrust device and conventional flap.

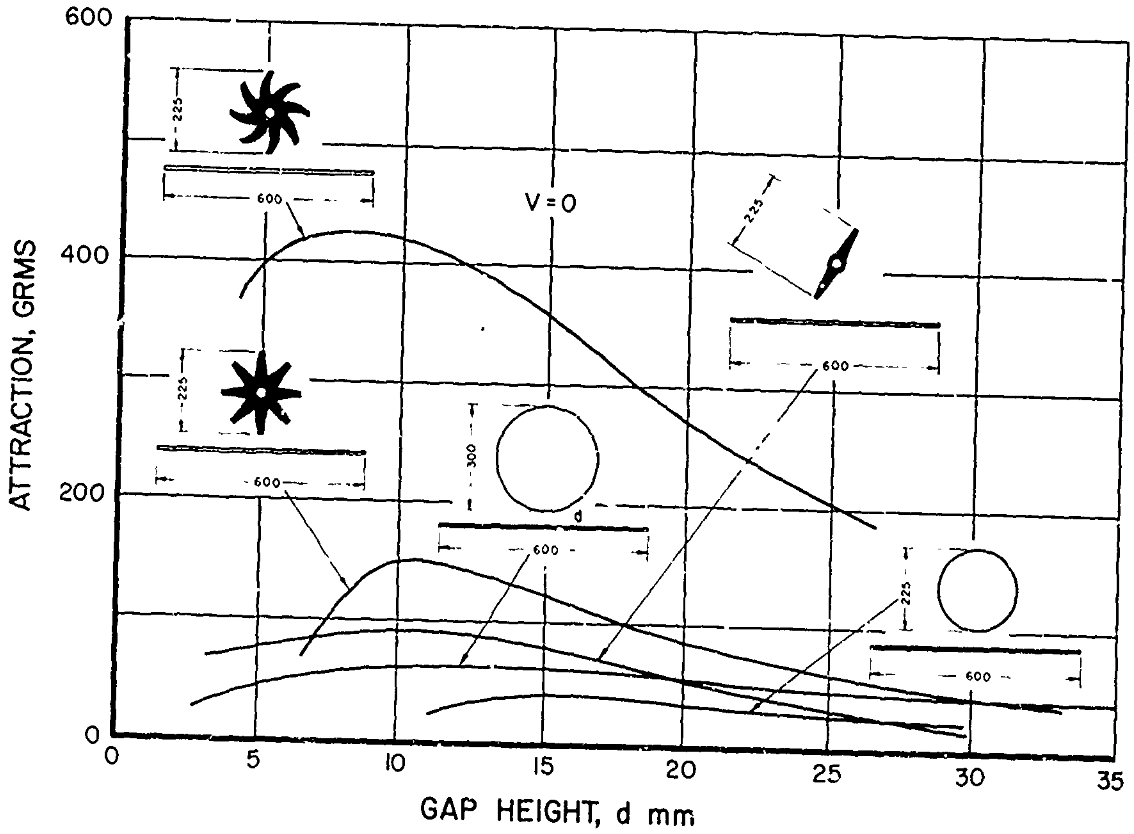


Figure 51. Attractive Force of Various Wing Rotor and Cylinder Devices Rotating in Proximity to a Ground Board (Ref. 72R).

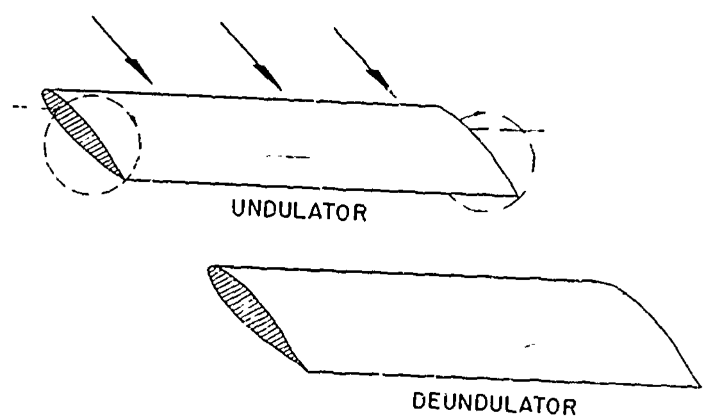


Figure 52. Basic Arrangement of Orbiting Flap Undulator and Deundulator.

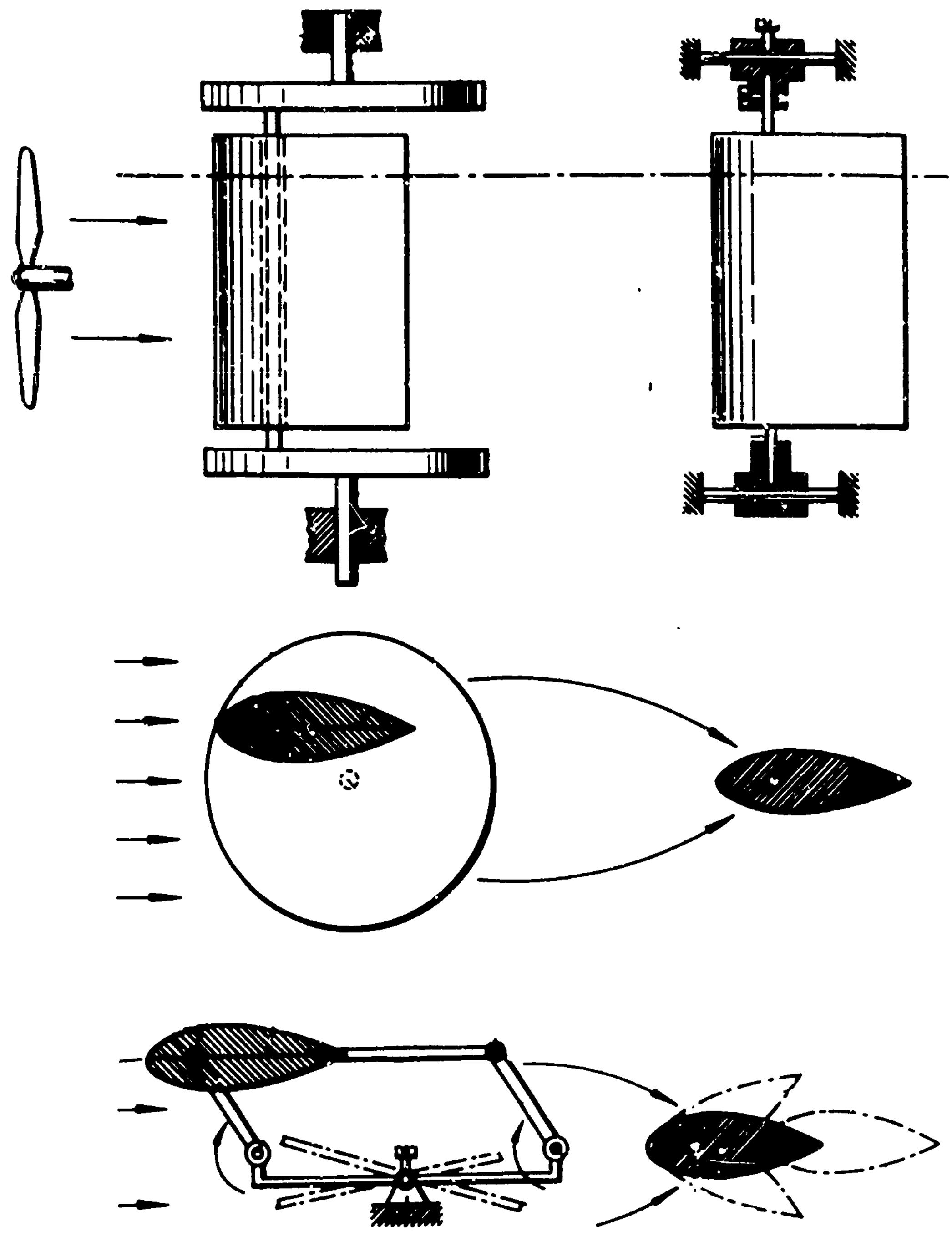


Figure 53. Schematic Arrangement of Orbiting Flap. Lower Drawing Indicates Various Geometries Possible by Varying Angles, Spacing, and Rotation.

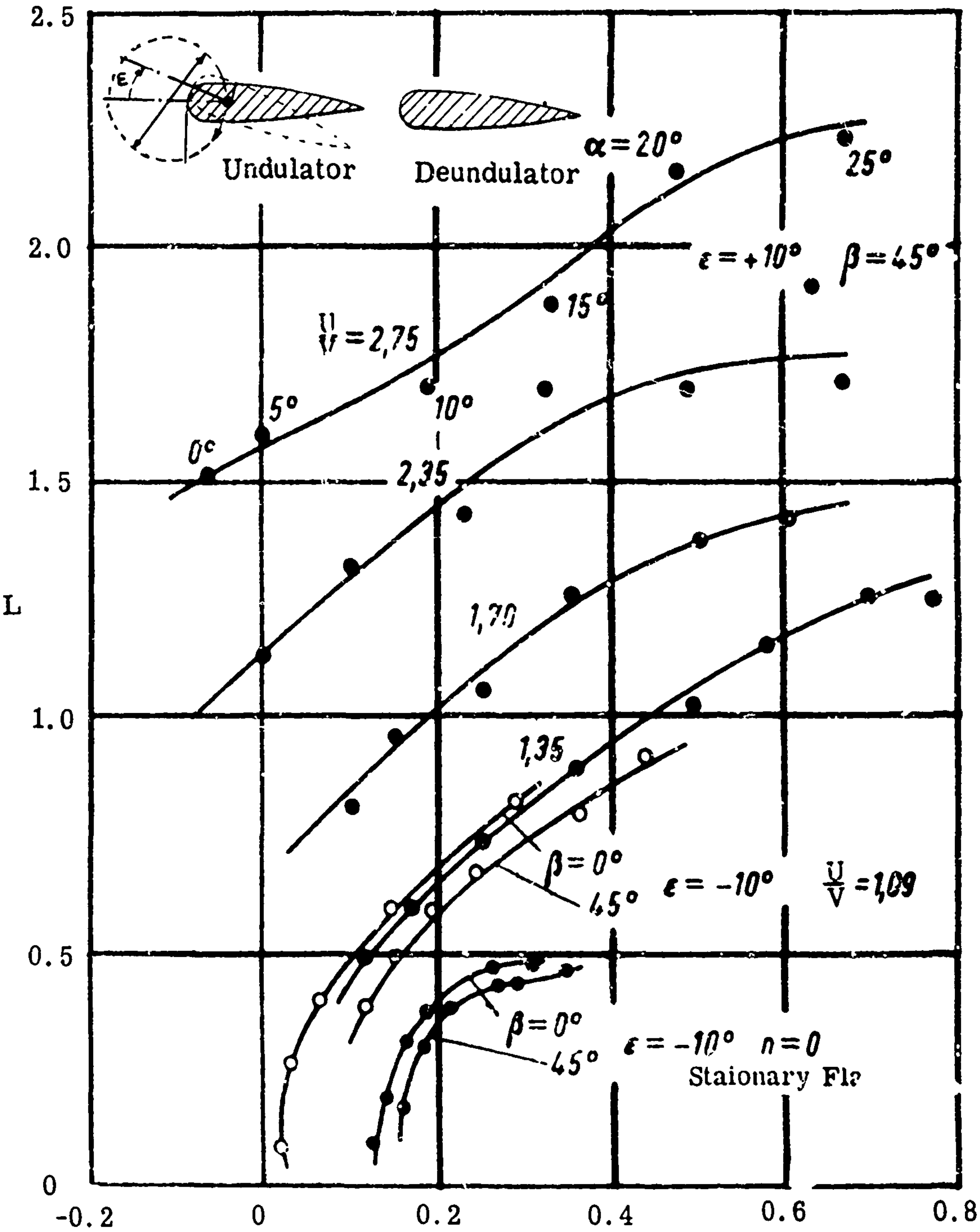


Figure 54. Wind Tunnel Results by Schmidt on Air Vehicle of Figure 55. Curves Are Aerodynamic Polars With Undulator in Rotation and Stopped. Note Thrust at U/V = 2.75, $\alpha=0^{o}$ (Ref. 54S).

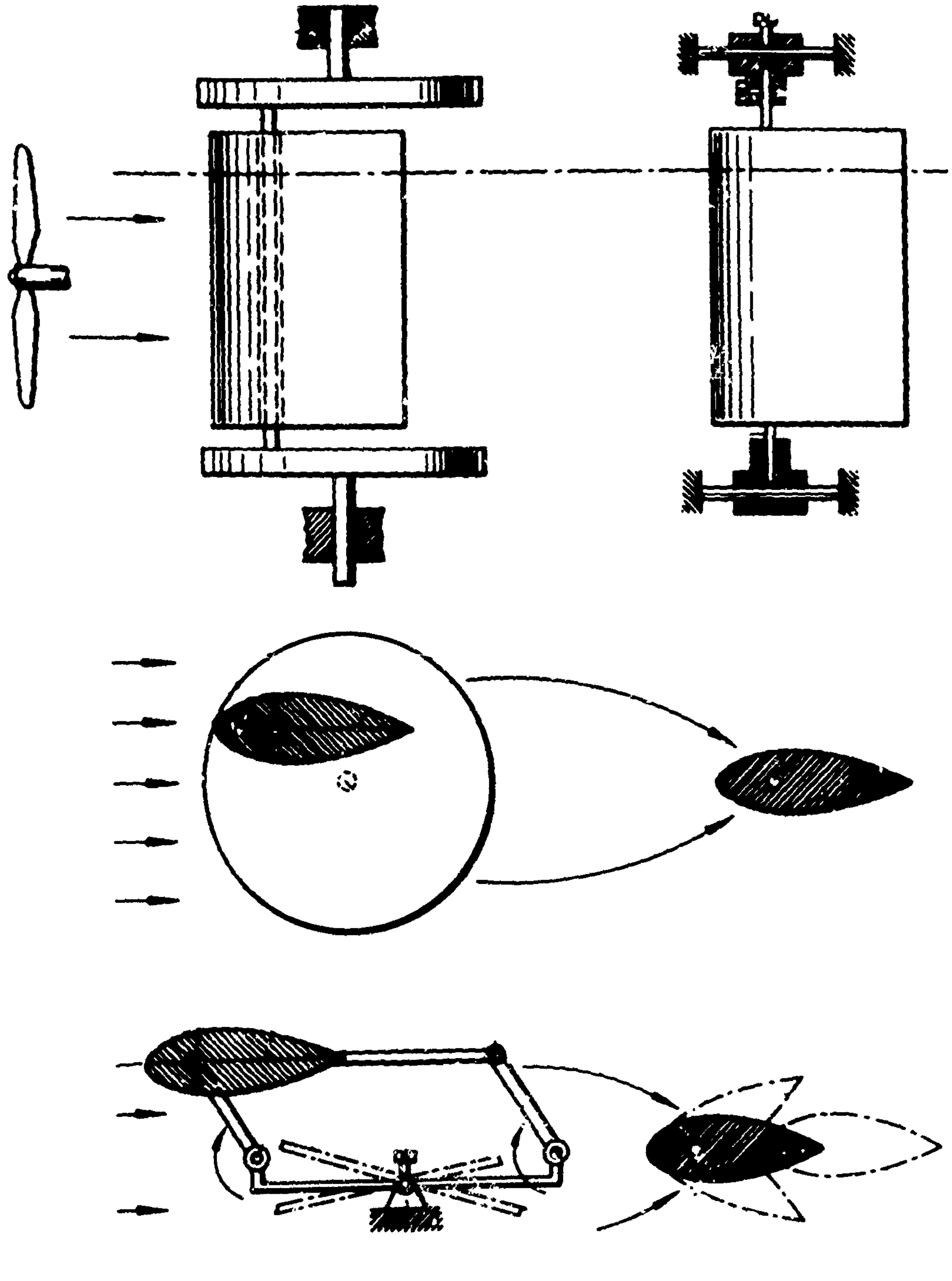


Figure 53. Schematic Arrangement of Orbiting Flap. Lower Drawing Indicates Various Geometries Possible by Varying Angles, Spacing, and Rotation.

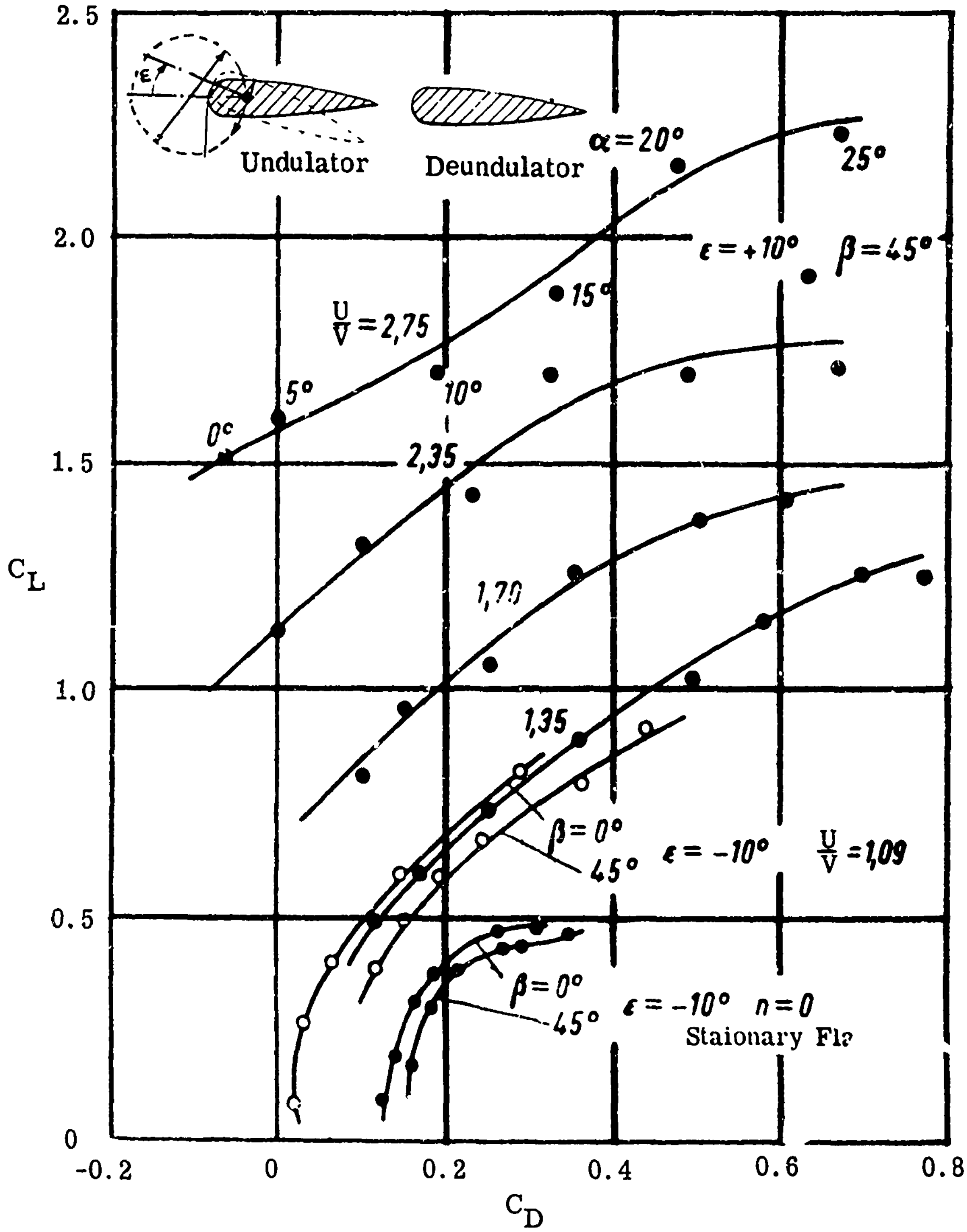


Figure 54. Wind Tunnel Results by Schmidt on Air Vehicle of Figure 55. Curves Are Aerodynamic Polars With Undulator in Rotation and Stopped. Note Thrust at U/V = 2.75, $\alpha=0^{\circ}$ (Ref. 54S).

This arrangement, as applied to a sailplane (Figure 56), for example, strongly resembles the RAF. Schmidt suggests the use of the tailplane as a possible undulator for this system. This, of course, must take into account tail buffeting problems and the like. This would further suggest an intriguing mechanical combination of the external, rotating, and orbiting flap for flight control and propulsion augmentation.

The background for the orbiting flap is summarized from Reference 54S:

> "The Knoller-Betz effect has given rise to investigations of a flapping wing with rear-wing. Already in the 1940's, the efficiency of a flapping wing at higher frequencies could be proved to be doubled by the presence of a rigid wing behind it. Model experiments in air and water confirmed this theoretical knowledge. Because of the unavoidable movement to and fro of masses in the case of a flapping wing, considerably restricting the frequency of flapping, a rotating "undulator" has been developed which, in conjunction with the rigid rear wing, constitutes the novel "undulating propeller". This new propulsion mechanism is proved by experiments on the rotating arm and by experiments with the model of a ship also to produce a static thrust. Wind tunnel experiments have rendered good efficiencies. They especially have shown that the undulating propeller is able to produce good thrust, and to increase the lift considerably, even in the case of operation behind a thick wing, and have given the first polar diagrams [Figure 54] for it. The undulating propeller prevents separation of flow, even at very high angles of incidence. Finally, examples of application for the undulating propeller are given. As this propeller rendered most favourable values of lift also behind a very thick wing, the chord of which was twice its span, there is some hope that the "flying car" will be realized."

5. Cross-Flow or Transverse-Flow Fan and Flap

In 1891, Mortier patented in France a type of fan which entrains and discharges air along its entire axial length. Referring to Figure 57, taken from the original U.S. Patent (No. 507445), air enters the inlet at L, passes through the inlet face and the blading of the fan at a-b, crosses the center portion and axis area, is pressurized through the outlet blading c-d, and is diffused to its service at K. The intriguing fact of this fan is that the volume flow that it can handle is limited only by practical considerations of the rotor length. The flow inlet and exhaust are usually rectangular. Although patent coverage is extensive, the technical and analytical evolution of the

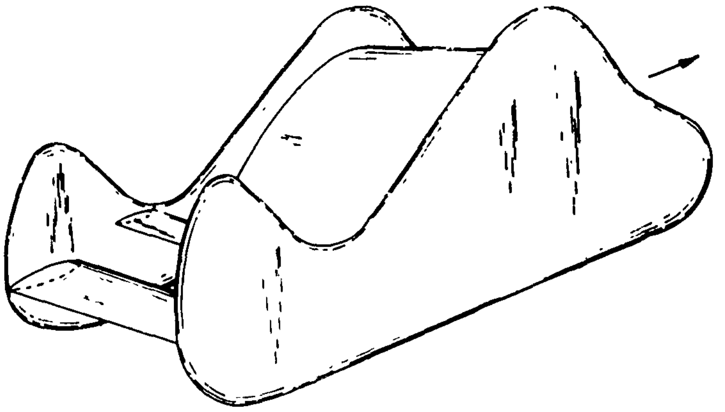


Figure 55. Aerodynamic Body of Orbiting Flap Test. Note Main Body Airfoil Ahead of Undulator and Deundulator.

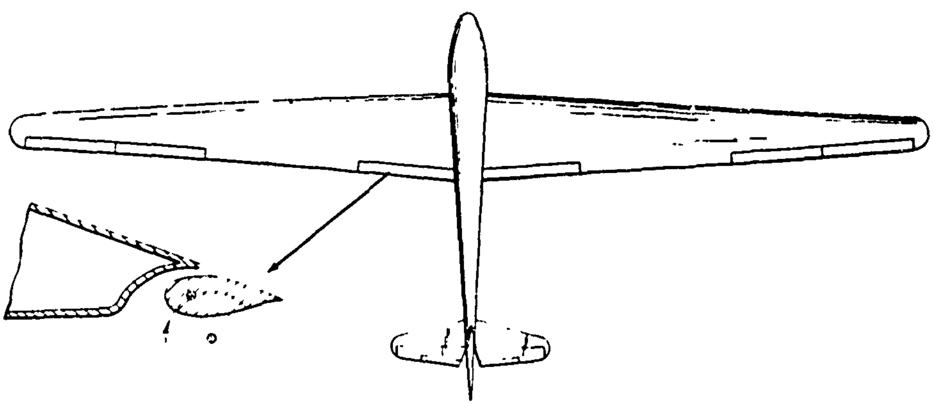


Figure 56. Suggestion by Schmidt (Ref. 53S) for Aircraft Drag Reduction or Auxiliary Propulsion.

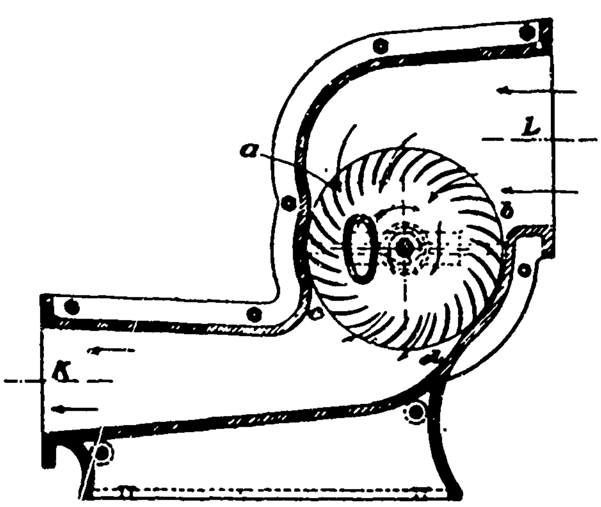


Figure 57. Basic Cross-Flow Fan by Mortier, 1891 (U.S. Patent, No. 507445).

transverse fan is just beginning to be understood. A survey of this particular system has been published by Eck (Reference 4E). Many parameters affect the performance of this fan system. The geometry of the outside stationary housing is found to be critical. Slight changes in the shaping of this shroud can give a very wide variety of pressure, flow, efficiency, and power selections.

The adaptation of crude linear cross fans to aircraft has been patented from time to time (References 35M, 36M, etc.). The fan is usually located spanwise in conjunction with a fixed wing and directs its exhaust over the wing surface in some manner to increase or control wing performance.

Only very recently has an intelligent attempt been made to combine the cross-flow fan with various arrangements of BLC, jet flap, and propulsive-wing aircraft systems. The combination of fan and aircraft systems has been given recent exhaustive patent coverage by Laing (References 12L through 21L). Two examples of this are presented here. Figure 58 shows a STOL propulsive-wing system which features a jet flap arrangement. In the cruise and thrust mode, the spanwise fans are deflecting flow essentially aftward and are also helping to maintain an attached boundary layer by the upper wing surface inlet suction area. In the STOL mode, the fan deflects considerable flow downward with the use of direct blowing and aft flap inlet suction. The wing is displaced upward and forward in such a manner as to help alleviate the pitch-down movement usually associated with the jet flap when operating in this manner. Going one step further, Laing also proposed to use the shrouded full-span cross-flow fan as a pure VTOL, as seen in Figure 58. Although it is believed that wind tunnel tests are being carried out to determine the feasibility of these basic ideas, no data have been published to date. At first glance, the cross-flow fan may offer certain attractive features, as it would eliminate the blower and the duct losses in a jet flap arrangement. Question has arisen as to the ability to make the fan rotors structurally sound, lightweight, and aerodynamically efficient.

B. CYCLOGIRO SYSTEMS

1. General Description

The cyclogiro aircraft which will be discussed in this section result from the application of the cycloidal propulsion principle to wings rotating in air about a horizontal axis while absorbing power. Another important application of the cycloidal propulsion principle is the cycloidal propeller, which is used for the propulsion and steering of ships; in the latter case, the blades operate in water and usually revolve around a vertical axis. The latter case will be discussed on pages 204 to 208.

A typical cyclogiro aircraft rotating-wing system is shown in Figure 59. The rotor consists of several blades rotating uniformly

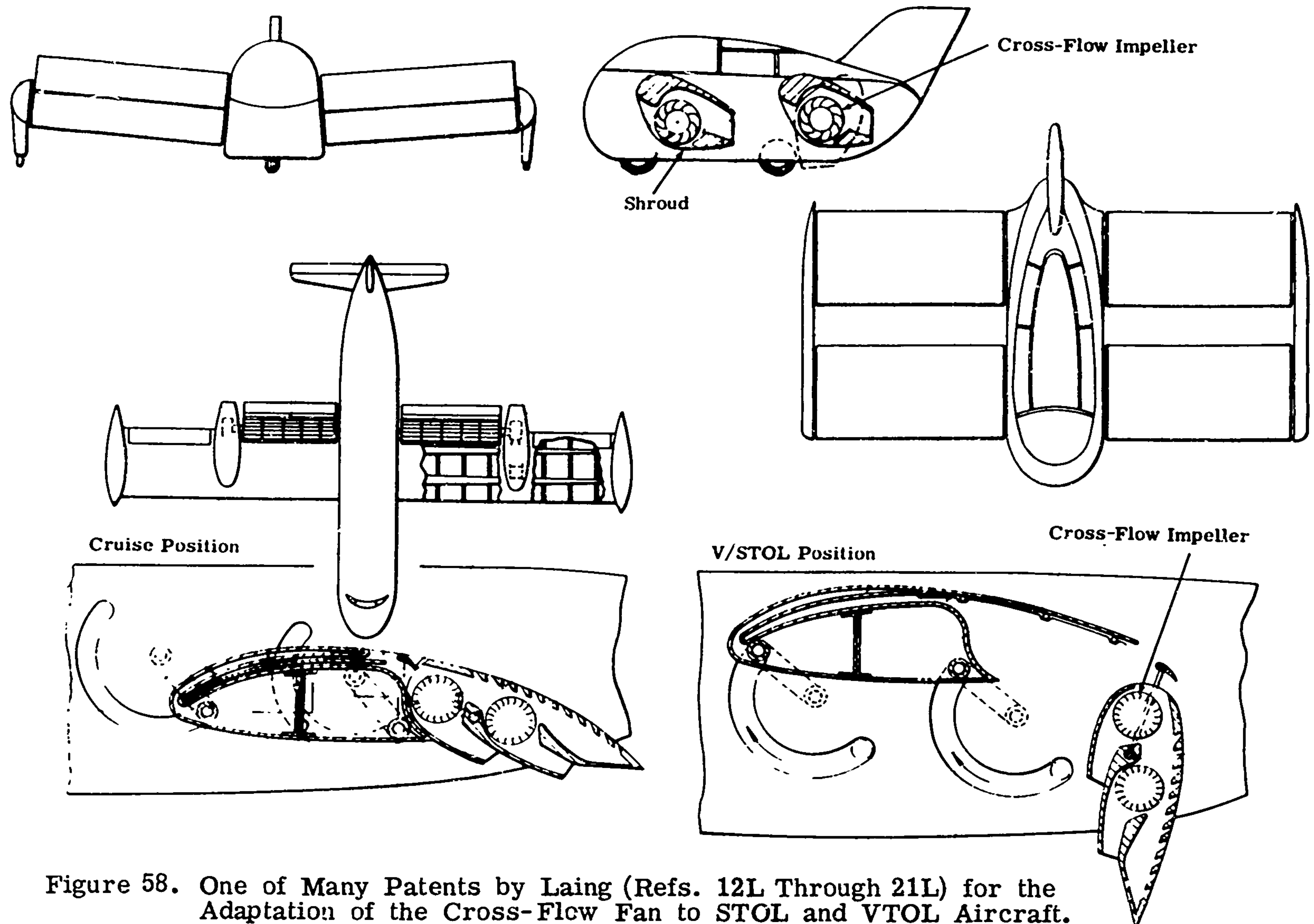


Figure 58. One of Many Patents by Laing (Refs. 12L Through 21L) for the Adaptation of the Cross-Flow Fan to STOL and VTOL Aircraft. Shown are Two Means of Maintaining Pitch Trim With Such a System.

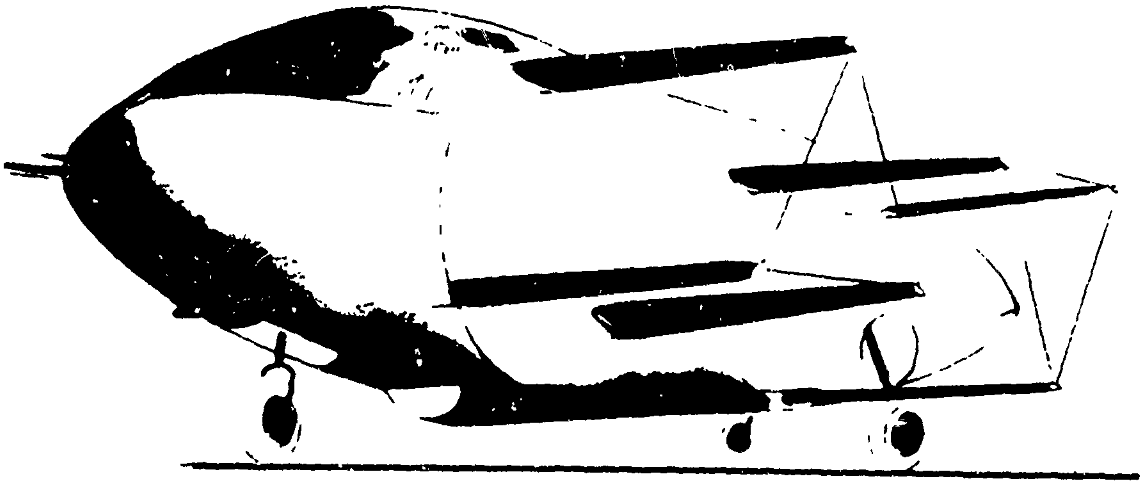


Figure 59. U.S. Army Air Forces, Wright Field Fighter Cyclogiro Project (1943-1945). Wt., 3900 Lbs.; LOA, 25 Ft.; Rotor Dia., 5 Ft.; HP Instal., 490. See Refs. 30H and 31H.

about a horizontal axis usually perpendicular to the direction of flight. The angle of the individual blades to the tangent of the circle of the blade's path is varied by a double-cam arrangement, so designed that the periodic oscillation of the blades about their span axis may be changed both in amplitude and in phase angles. The net force on the rotor may thus be varied in magnitude and direction by movements of the cam. In particular, cyclogiro aircraft are capable of hovering flight. In forward flight, lift and propulsion are integrated.

2. Pictorial Review

The original "Aerial Carriage" man-powered cyclogiro was proposed by William Congreve in 1828 and is shown in Figure 60.

Another antique cyclogiro aircraft, proposed by Herard in the 1880's, is shown in Figure 61.

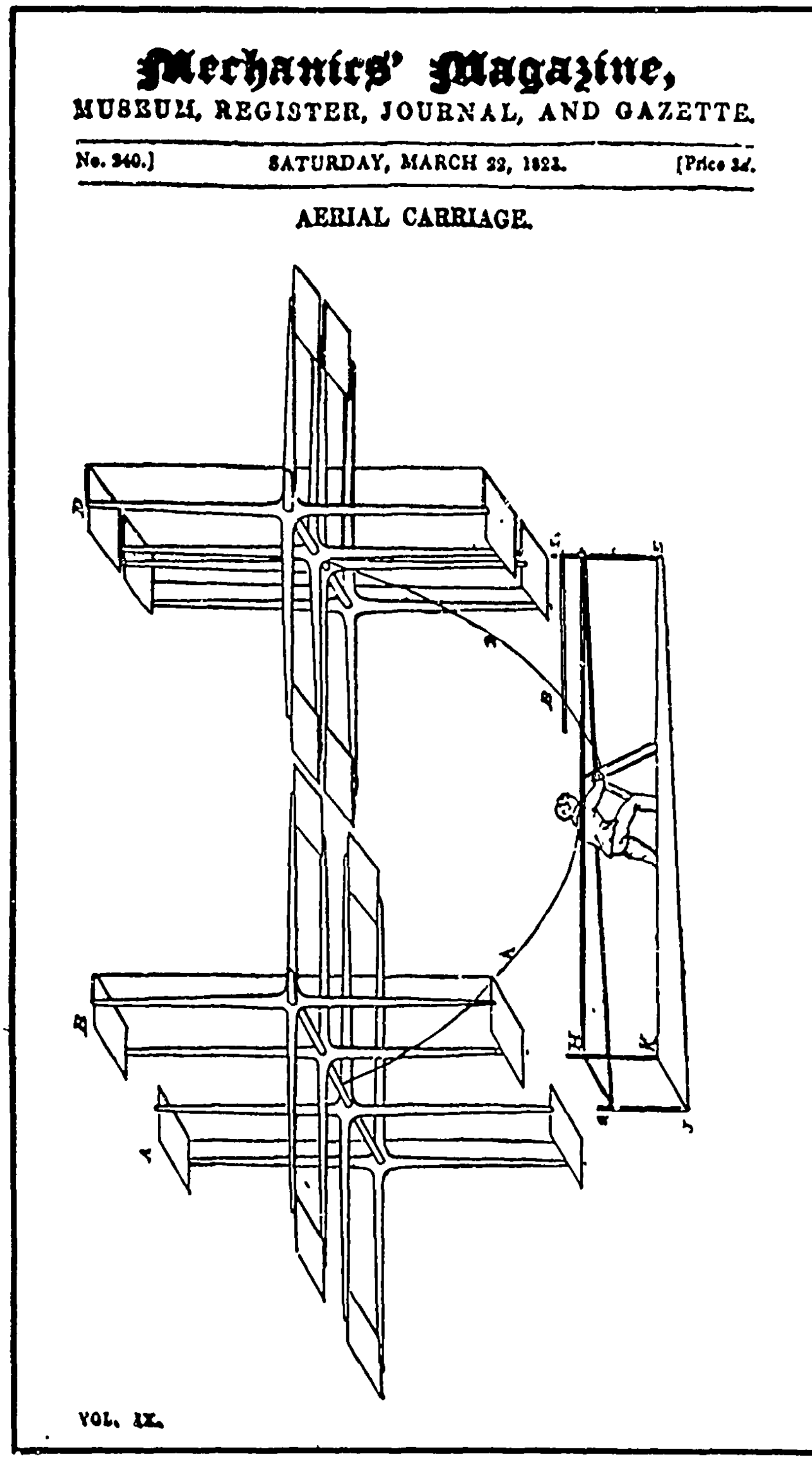
In the 1920's, still in the pioneering age of aviation, many efforts at building cyclogiros were started: Nemeth (the machine shown in Figure 62 is believed to be his design; moving pictures of that machine do exist); McWorter (Figure 63); in France, Pichou and Moineau (Figure 64).

Dr. Klemin, at New York University, became interested in cyclogiros and tested both Platt's (Figure 65) and Laskowitz's designs (Figure 66).

In Europe, in the 1930's, two engineers attracted major attention: Rohrbach in Germany (Figures 67 through 69) and Strandgren in France (Figures 70 through 72). Strandgren's basic paper was translated as NACA TM 727 (Reference 130S).

At the same time, NACA started investigating at Langley Field, Virginia, the fundamental claims of the cyclogiro as a VTOL or a STOL. This work was done by the same Wheatley who was responsible for the fundamental investigations of the autogiro and of the helicopter. Wheatley was responsible both for wind tunnel tests (Figure 73 and Reference 28W) and for a theoretical approach (Reference 25W). His work was not continued at NACA after the outbreak of World War II.

The towering figure in cycloidal propulsion and cyclogiros in the United States was Professor F. K. Kirsten of the University of Washington (Reference 28K). Kirsten (References 17K through 31K) became interested in cycloidal propulsion in the 1920's (Figure 74), built the wind tunnel model shown in Figure 75 in the early 1930's, and was responsible for a school of thought to develop at the University of Washington which resulted in the work done during World War II for the U. S. Army Air Forces. Kirsten's



Mechanics' Magazine,
MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 240.] SATURDAY, MARCH 22, 1828. [Price 3d.

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Figure 60. First Concept of the Cyclogiro by Sir William Congreve, 1828 (Ref. 44C). The Feathering System Is That of the Valved Pusher Arrangement.

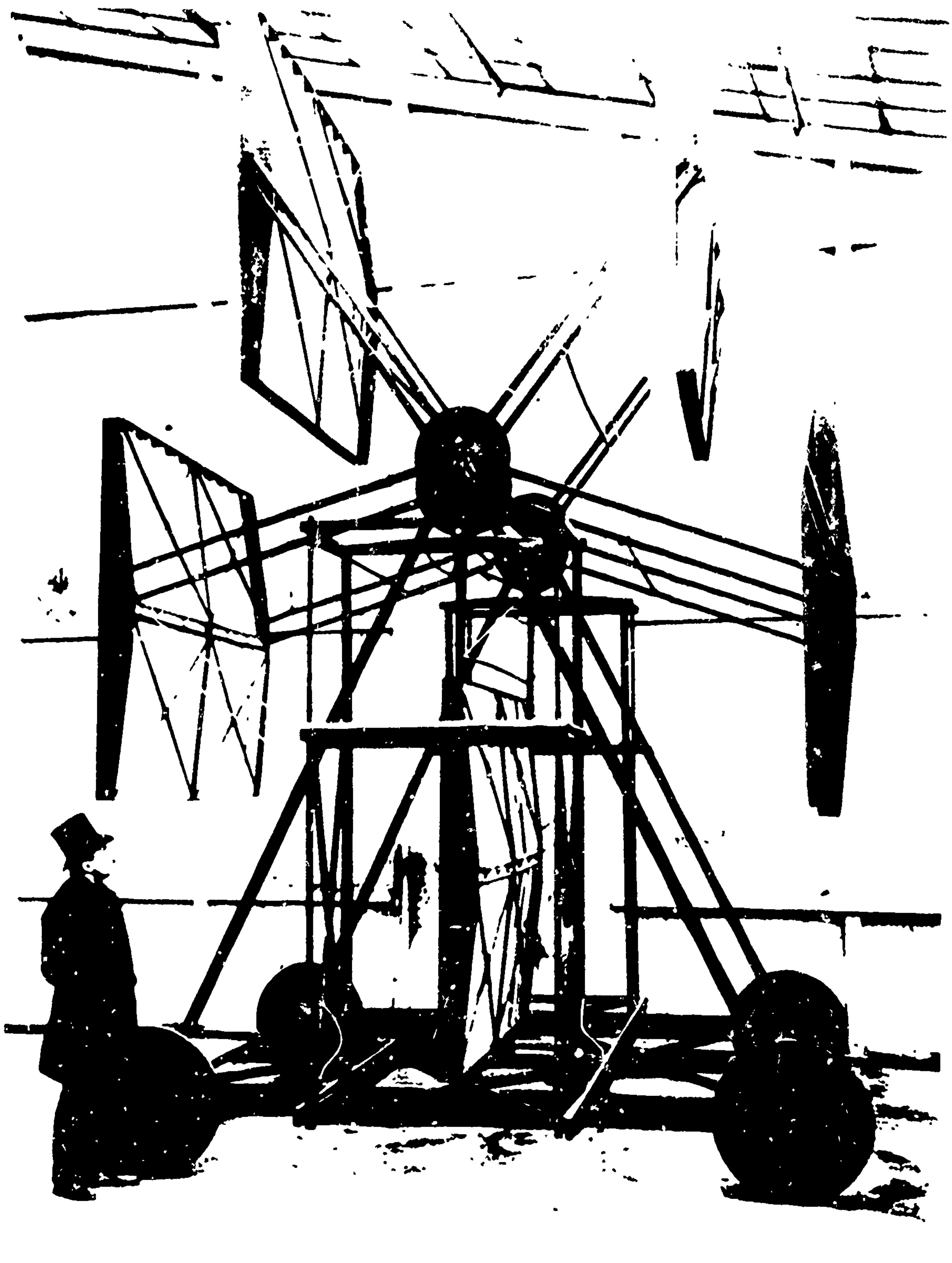


Figure 61. Antique Cyclogiro System by Herard in the 1880's. This Feathering Arrangement is Typical of Class 6 Type (Fig. 92).

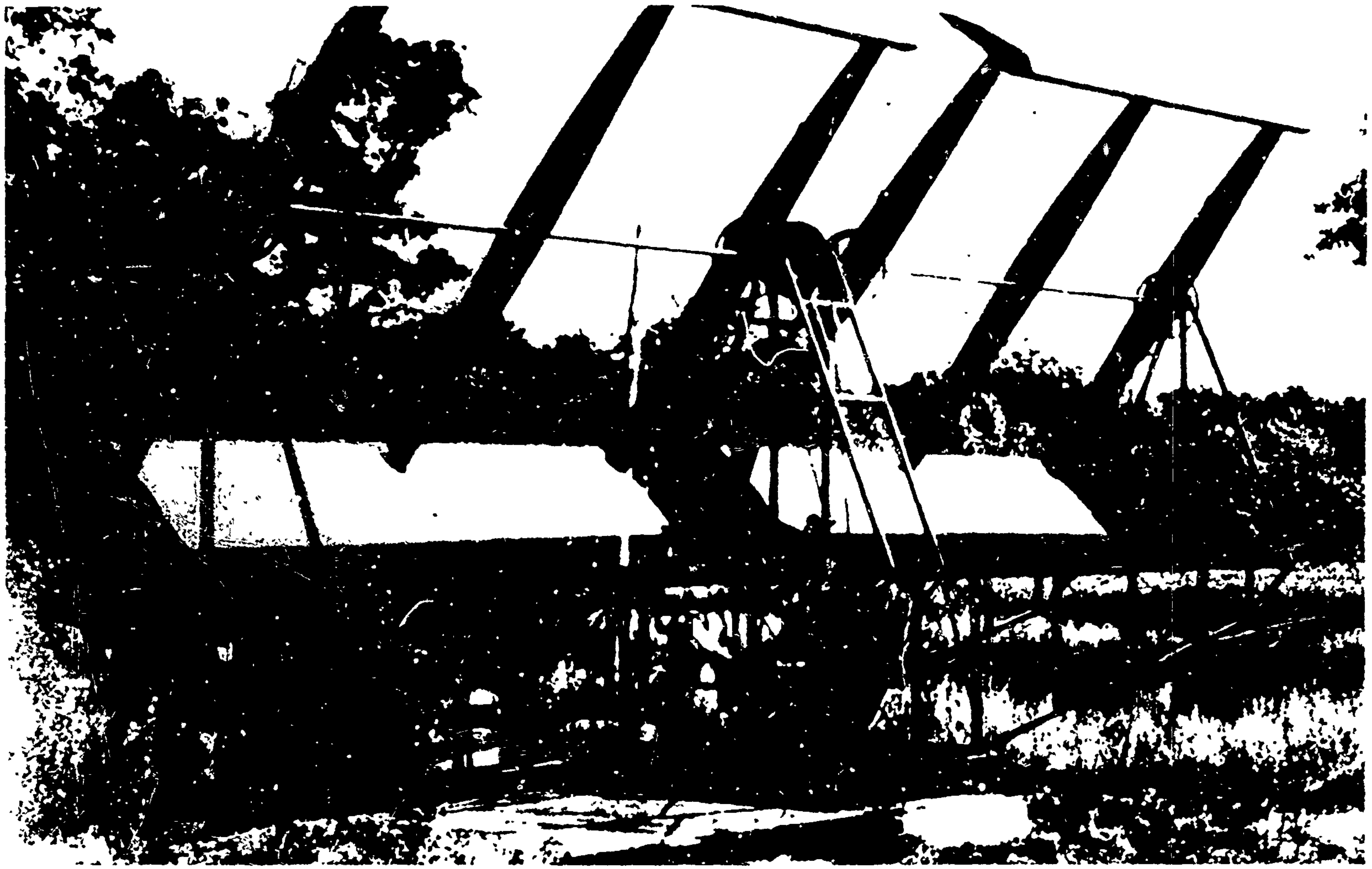


Figure 62. Unidentified (Nemeth, Ref. 12N) Full-Size Cyclogiro of the 1920's. Note Rotary Engine and Direct Chain Drive.

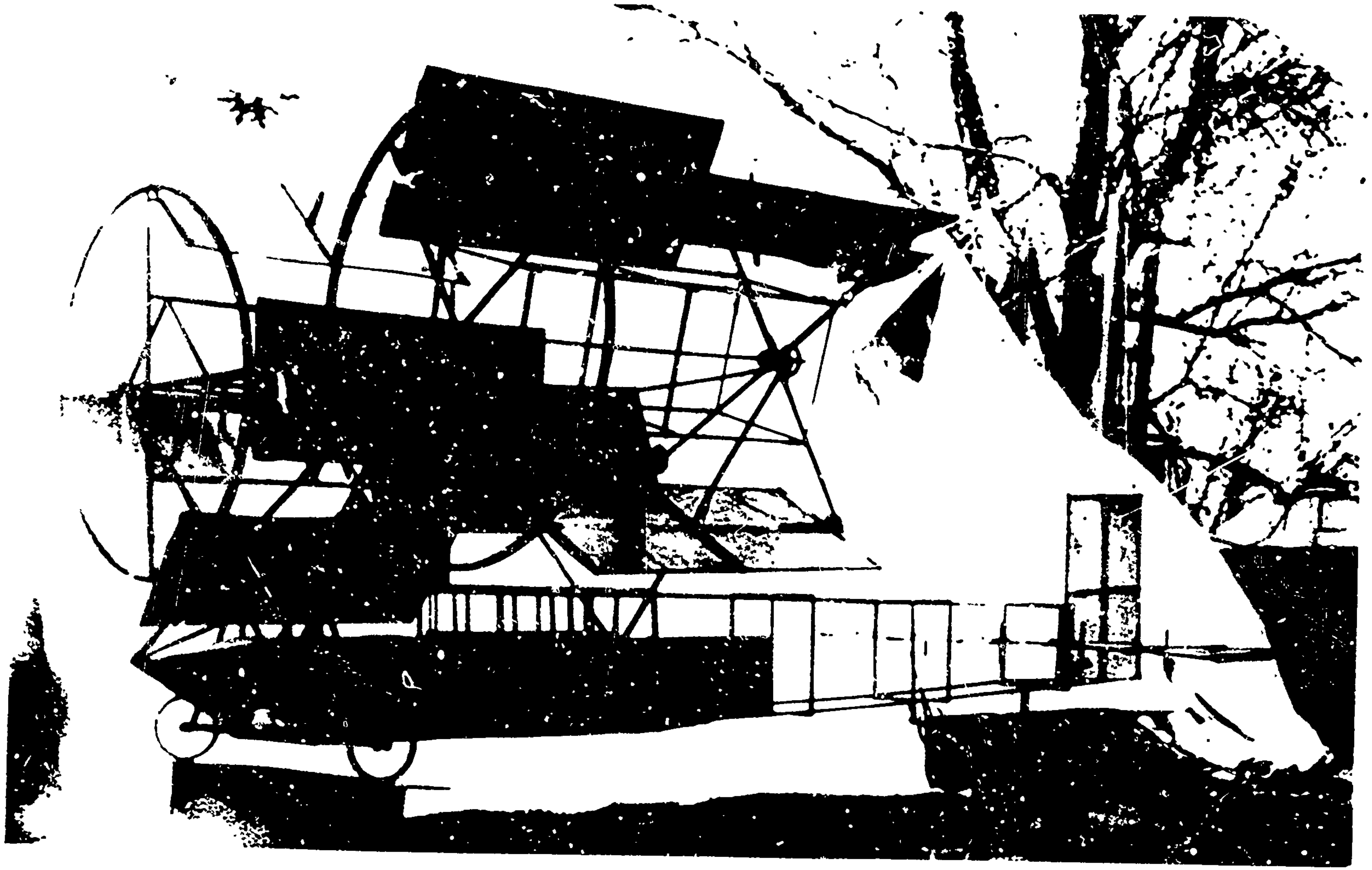


Figure 63. McWorter "Autoplane" Quarter-Scale Model Cyclogiro, Evaluated by the U.S. Army Air Service, McCook Field, 1919. Blade Feathering Scheme That of Class 2 Type (Fig. 92). Item 24). Refs. 13Mc Through 16Mc.

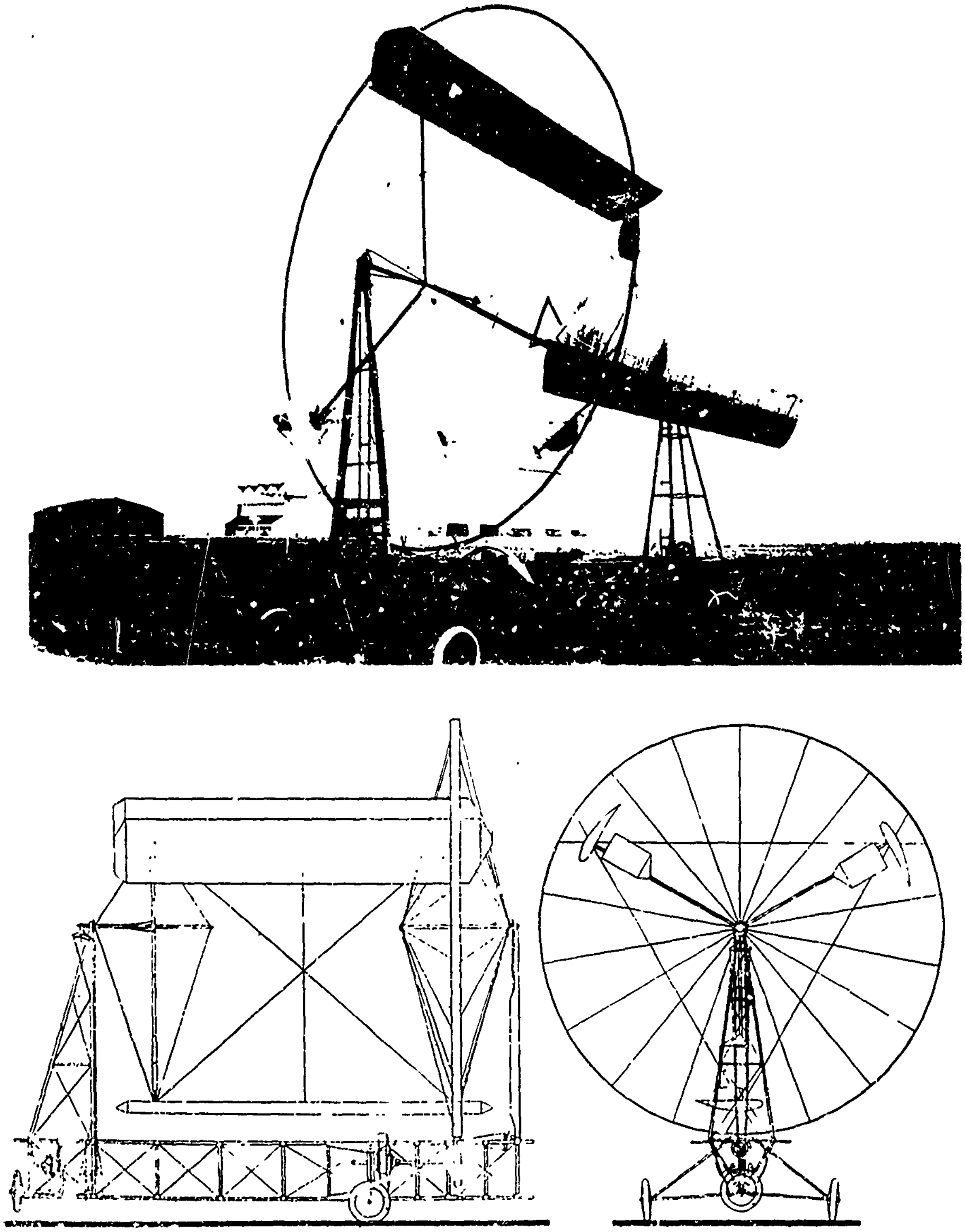


Figure 64. Moineau Low Pitch Cyclogiro Project of the 1920's in Which Direction of Flight Is Along Axis of Rotation. 1/10th-Size Model Test in Wind Tunnel. See Refs. 54M Through 57M.

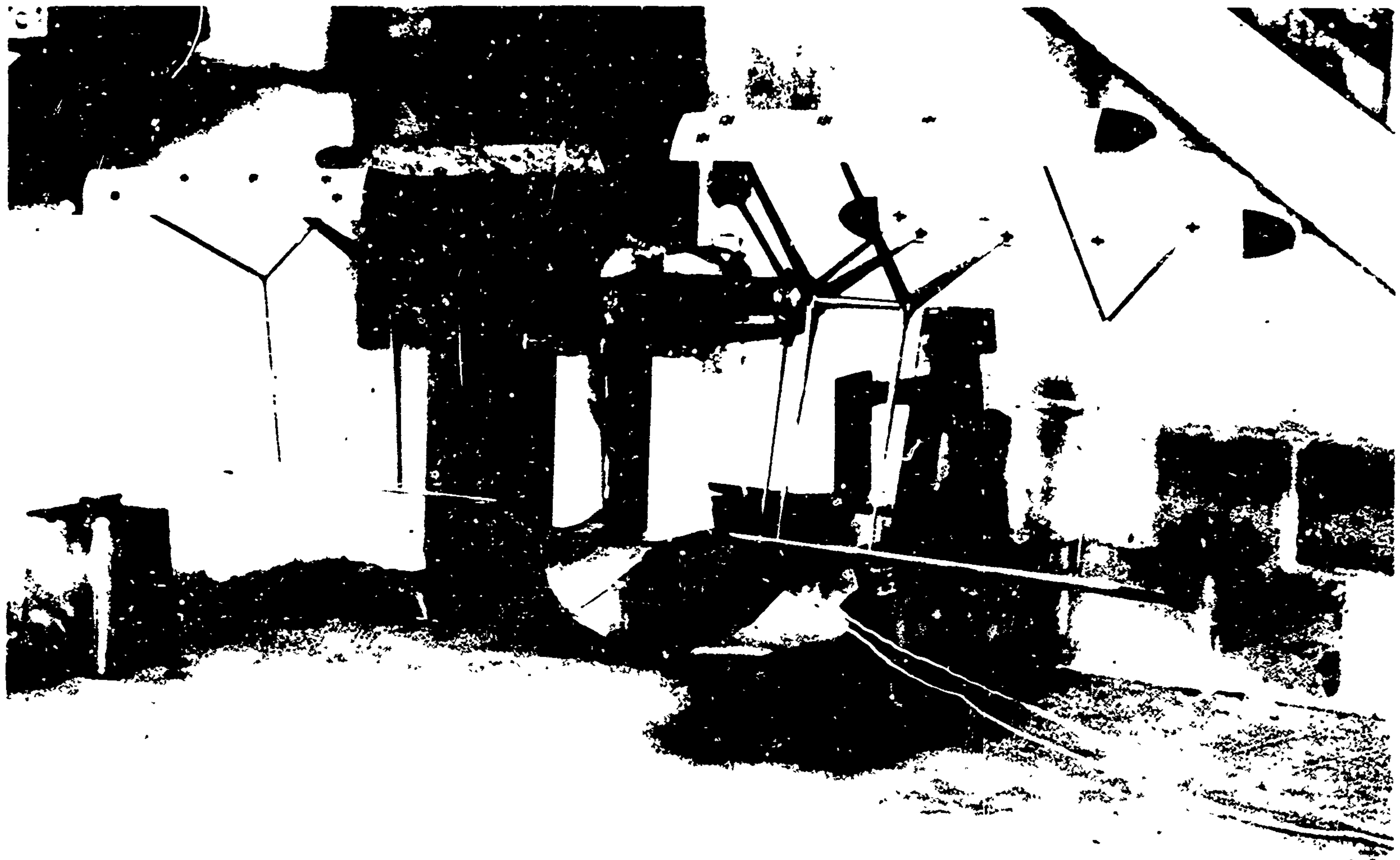


Figure 65. Platt Cyclogiro Wind Tunnel Model (1929-1930) Tested at The Daniel Guggenheim School of Aeronautics, New York University. See Refs. 24P Through 28P.

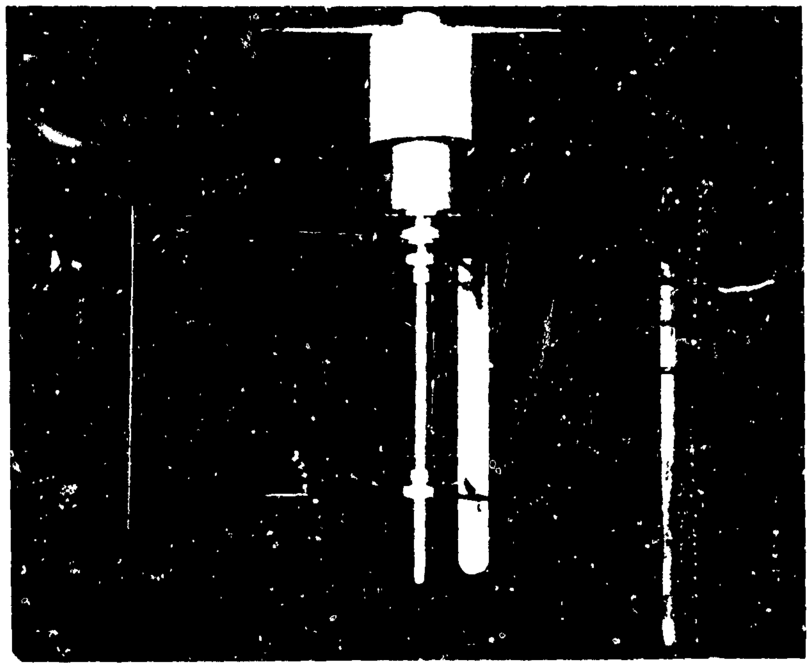


Figure 66. Laskowitz Three-Blade Low-Pitch Cyclogiro Rotor in the New York University Wind Tunnel. Rotor Dia. 3 Ft., Span 2 Ft. See Ref. 32L.

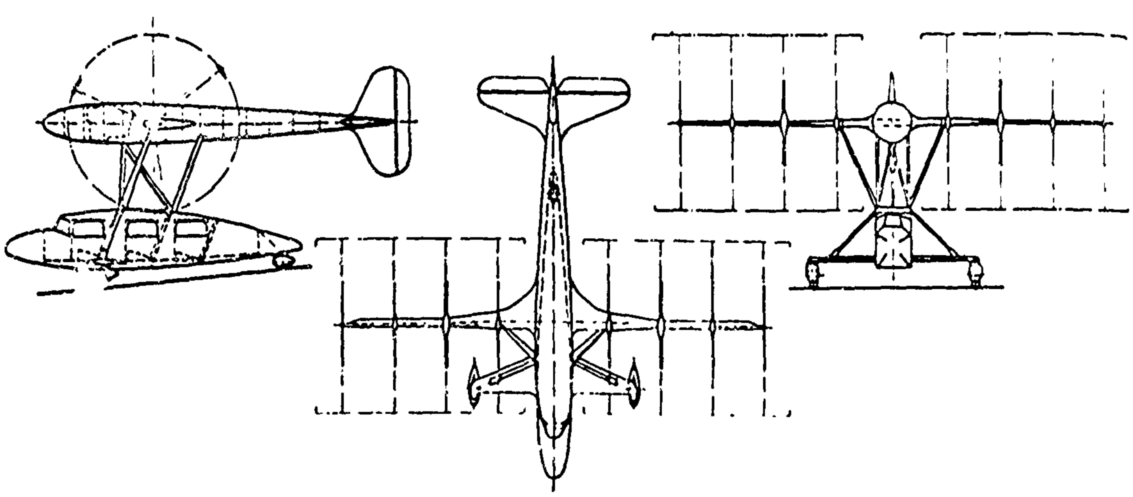


Figure 67. Rohrbach Project "B" Cyclogiro, Three Views (1934).

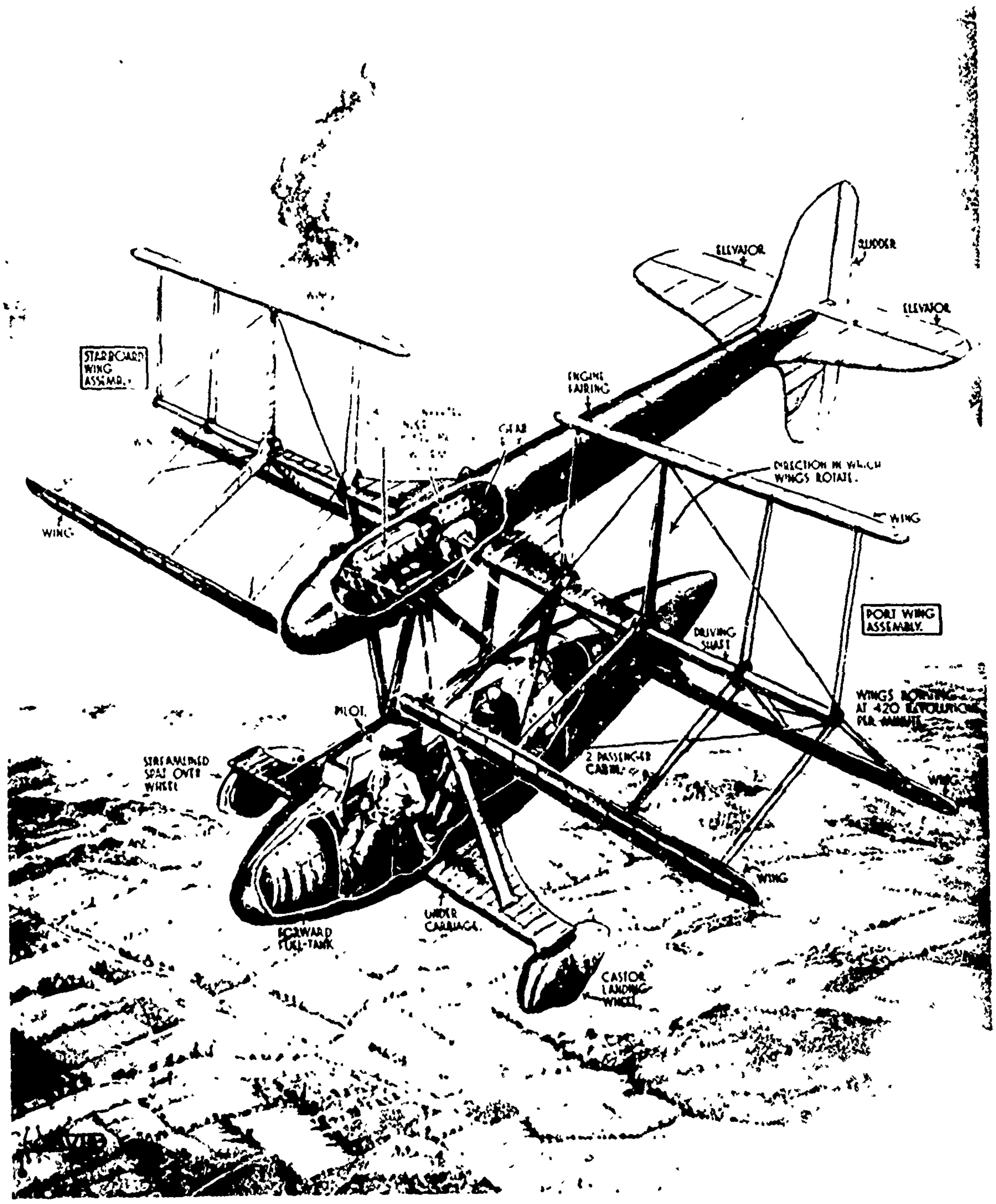


Figure 68. Comprehensive View of the 1934 Rohrbach Cyclogiro. Although Extensively Studied, Outcome of This Project Is Not Known. See Refs. 58R, 59R, and 79S. From Ref. 55R.

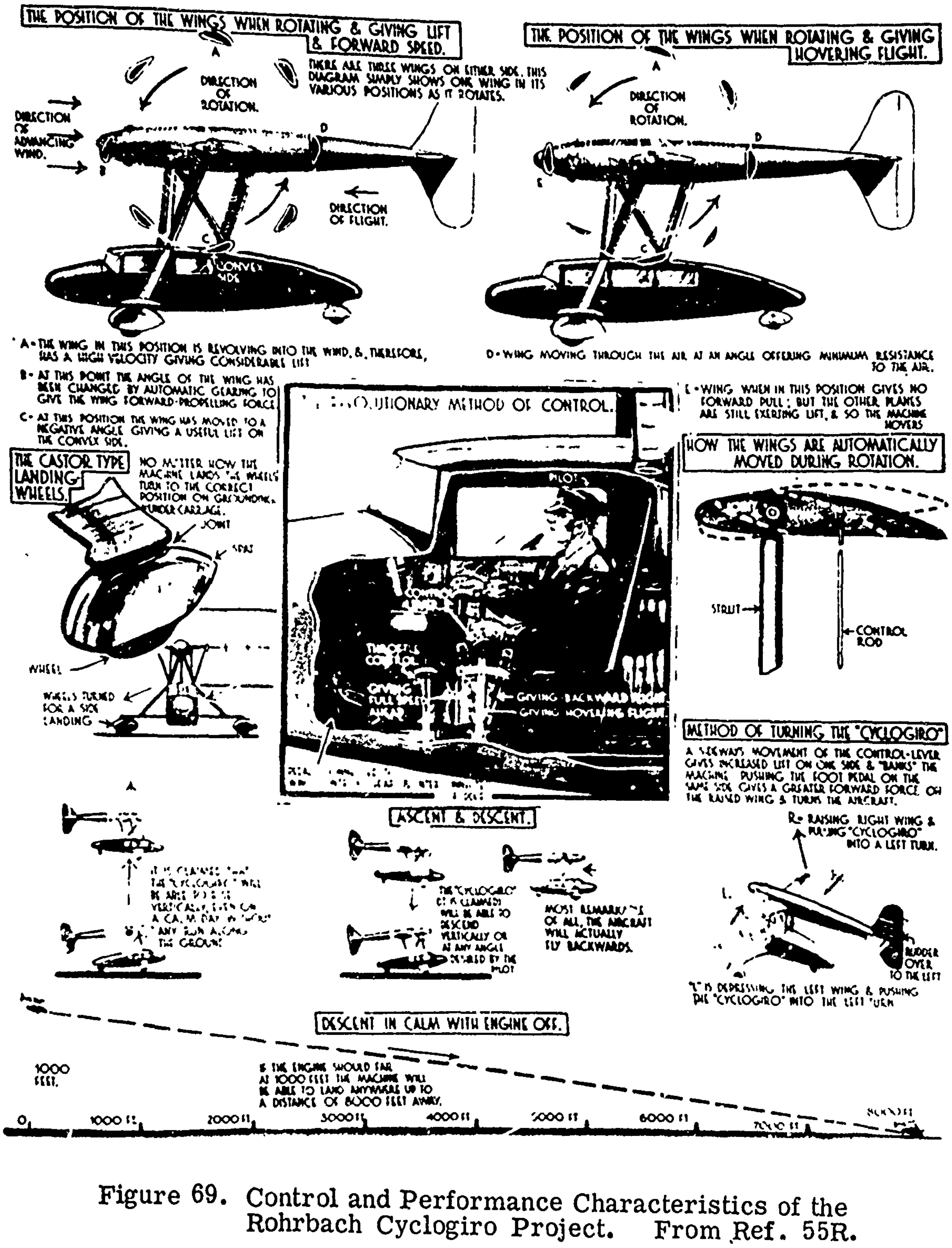


Figure 69. Control and Performance Characteristics of the Rohrbach Cyclogiro Project. From Ref. 55R.

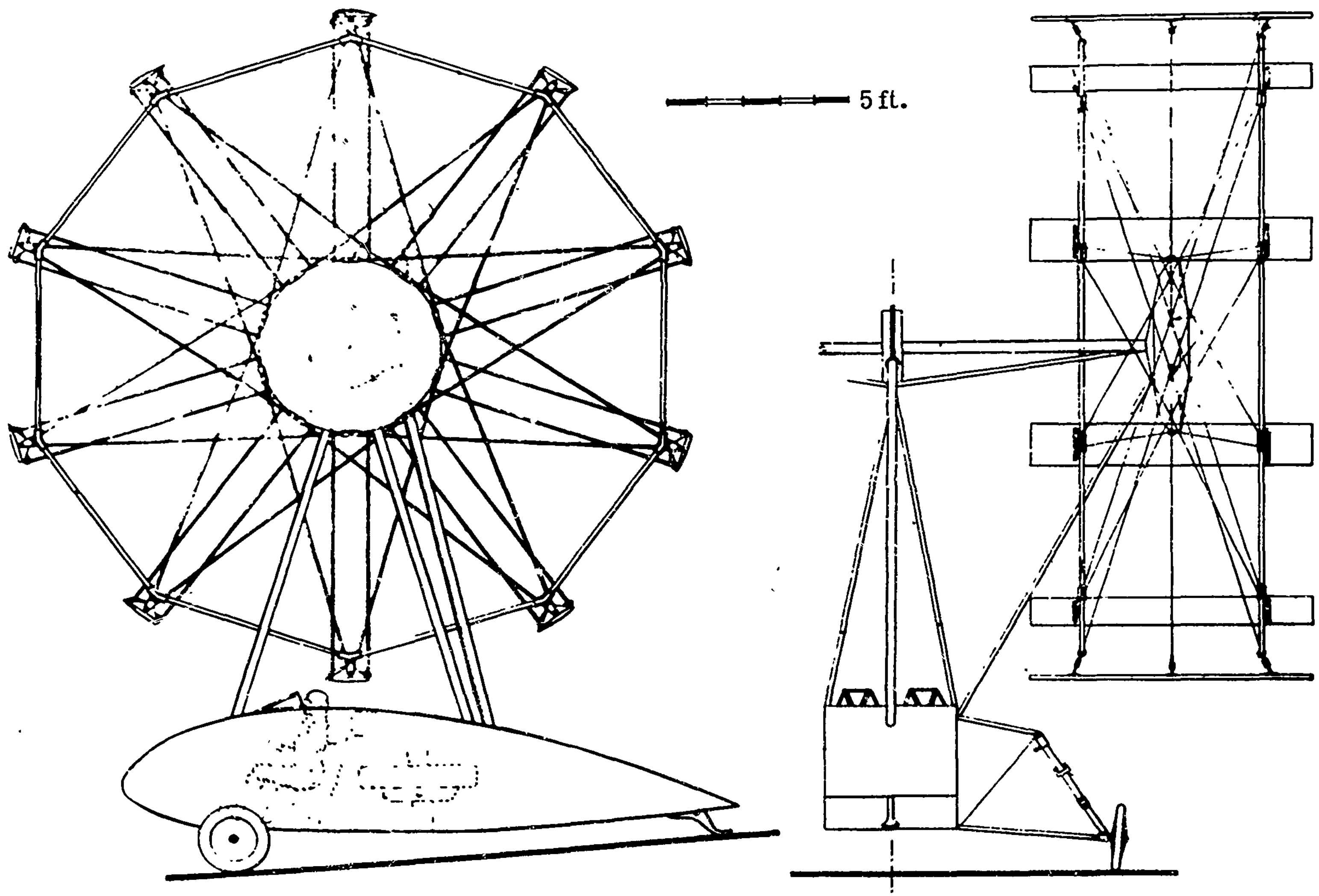


Figure 70. Two Views of the Strandgren Project (1932) Showing Method of Generating Lightweight Spoked Rotor Wheel System. See Ref. 122S.

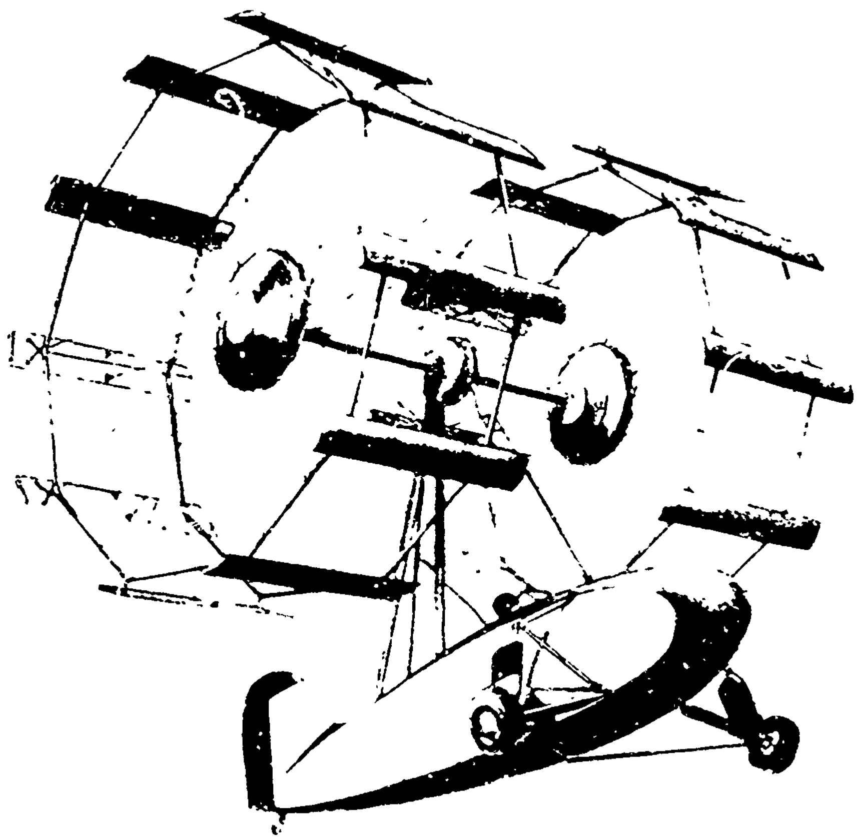


Figure 71. Artist's Impression of the Strandgren Low-Pitch Cyclogiro in Flight.

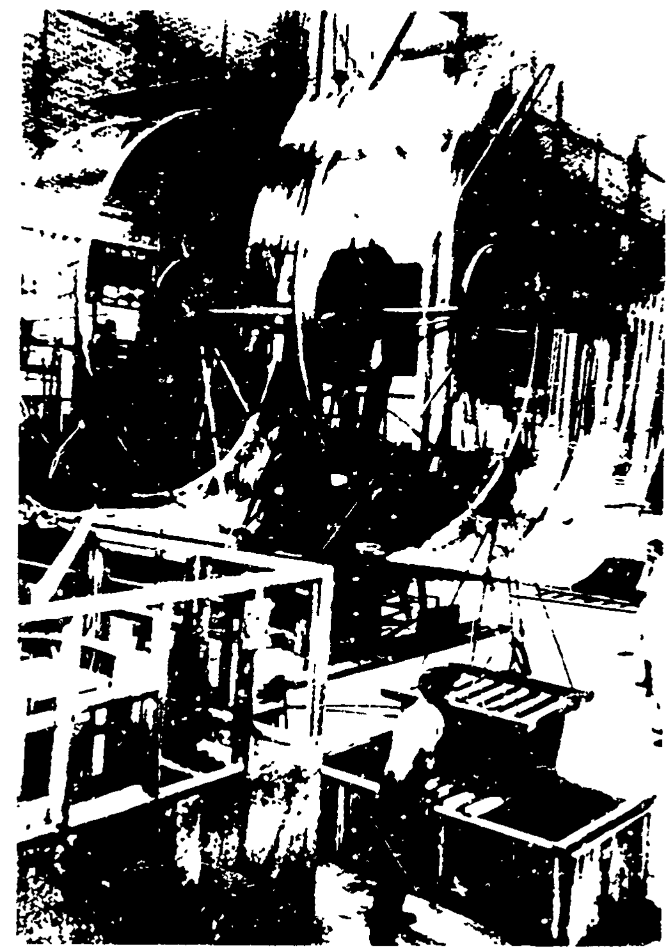


Figure 72. Full-Size 19.6-Ft.-Dia. Strandgren Low-Pitch Cyclogiro Wheel on Test Stand at Lioré et Olivier Co. (1933). Functional and Static Lift Test. See Refs. 119S Through 135S.

Figure 73. NACA (1934) Low-Pitch Cyclogiro Model in the Langley 20-Foot Wind Tunnel. 8-Foot Diameter, 8-Foot Span. See Ref. 28W.

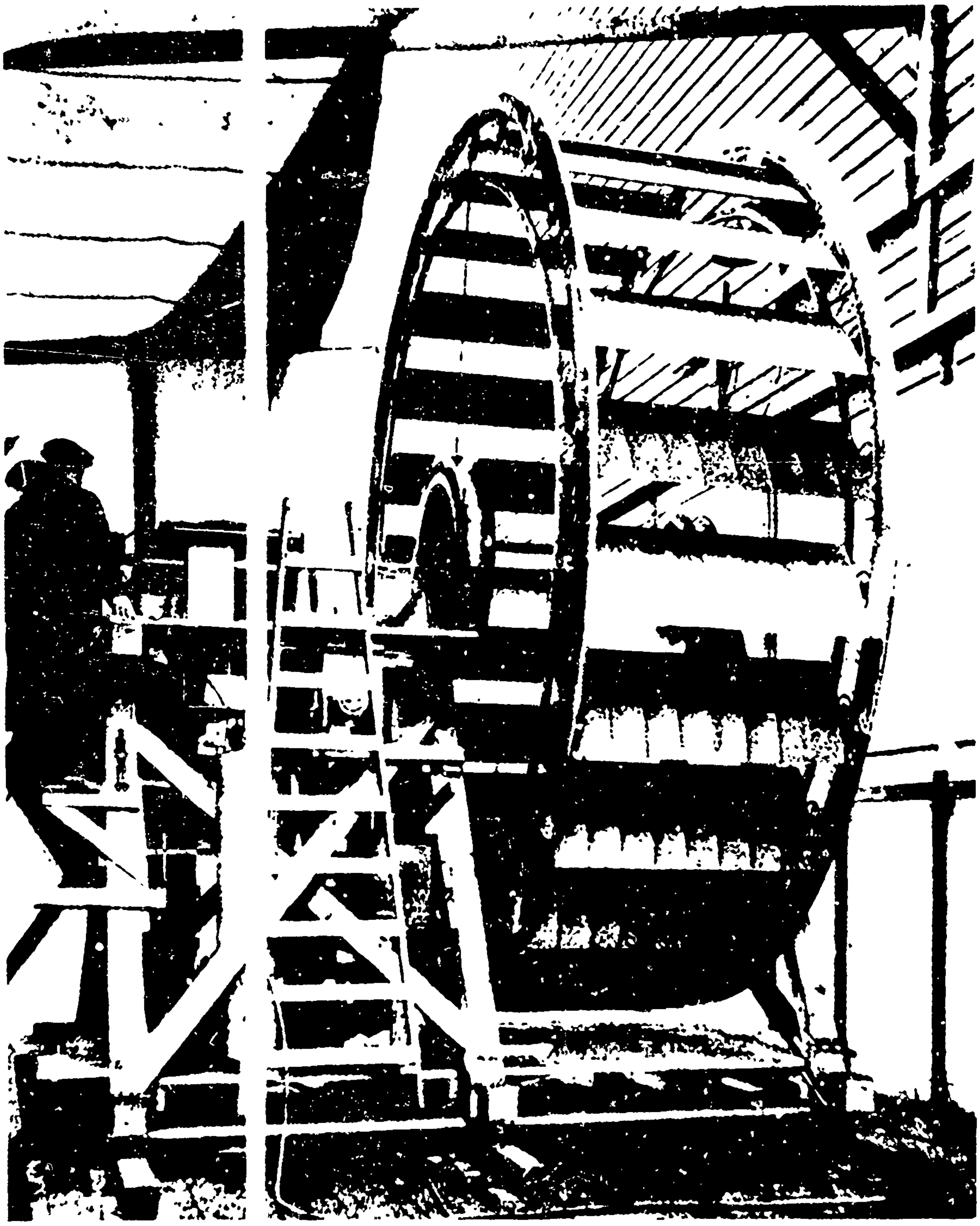


Figure 74. 15-Foot-Diameter Kirsten-University of Washington Pi-Pitch Cyclogiro Wheel. Designed and Constructed During 1922. Number of Blades Variable up to 24. See Ref. 24K.

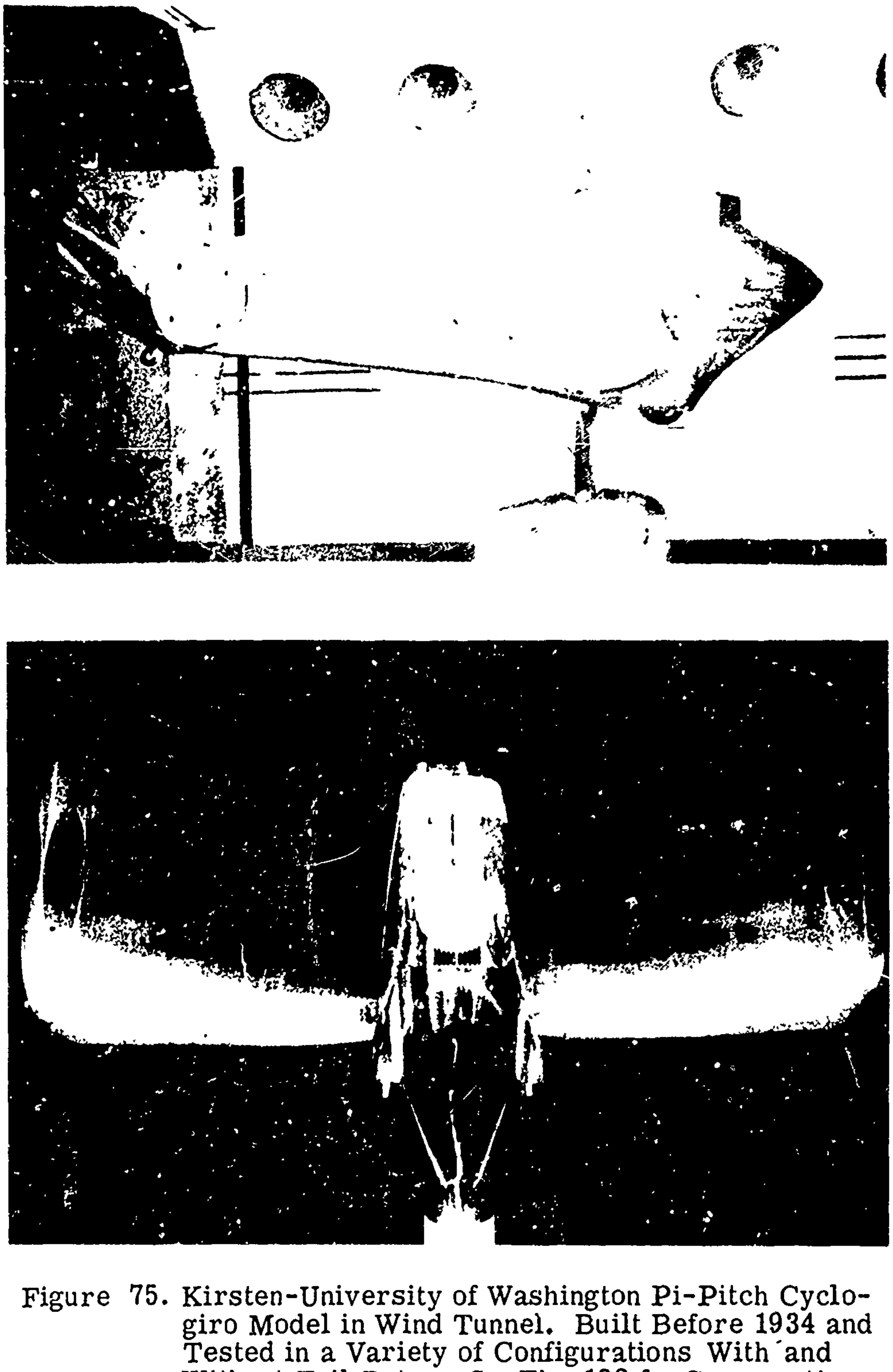


Figure 75. Kirsten-University of Washington Pi-Pitch Cyclogiro Model in Wind Tunnel. Built Before 1934 and Tested in a Variety of Configurations With and Without Tail Rotor. See Fig. 102 for Comparative Tunnel Installations. Also See Ref. 27K.

high-pitch cyclogiro wind tunnel model rotor is shown in Figures 76 and 77. The corresponding overall design is shown in Figure 78.

The U. S. Army Air Forces, during World War II, recognized the potential advantages of the cyclogiro aircraft (Reference 4H, for example) and supported work with Kirsten and Eastman. The result was a proposed fighter, shown in Figure 59.

Several investigators have recognized the advantages of the cyclogiro in low-speed flight and the corresponding disadvantage of a relatively high drag at high speed, and they have proposed to stop the rotors in high speed; this approach is shown in Figure 79, in a Wiessler 1950 patent. This is not necessarily the best approach, as Kirsten claimed on his high-pitch model that it was not desirable to stop the rotor at high speed, but only to slow it down.

In the 1960's, there has been no known active effort on cyclogiros, except for one inventor: Dave Cook. Cook was able to do limited static testing at Boeing-Wichita around 1959 (Figure 80). His latest proposed design is shown in Figure 81. Like Moineau (Figure 64), Cook chooses to have the axis of the rotor in the direction of flight.

3. Configuration

The cyclogiro rotor applied to an aircraft rotates about a horizontal axis. Despite the recurrent patent and proposal suggestions to the contrary, the arrangement of the rotor axis perpendicular to the fuselage in a spanwise direction appears to be the most adaptable and natural geometry. Those cyclogiro rotor arrangements with the rotor and blade axis parallel to the fuselage and general direction of flight introduce the very large aerodynamic problem of an additional spanwise airflow component due to forward-flight speed, and the problem of providing an independent forward propulsion. The only obvious advantage to such an arrangement would possibly be structural; that is, the rotor could be supported at both its root and its tip as suggested by Moineau (Figure 64). The discussions that follow will consider only the spanwise orientation of the cyclogiro rotor axis.

The rotor blades will also be considered to be revolving in a parallel manner about the rotor axis, and thus the longitudinal axes of the blades sweep out the surface of a right cylinder in hover. There are many suggestions for configurations in which the blade describes a conical surface, the vertex of the cone being located at the fuselage and the inboard end of the rotor system. Such an arrangement, as suggested by Richard (References 30R, 32R, 33R) and by Piskorsch (Figure 82, References 16P through 19P), would allow the rotor blade roots, feathering system, and transmission to be collected and unified at the focus of the rotor cone (Figure 83). The conical rotor system is not without aerodynamic interest, and

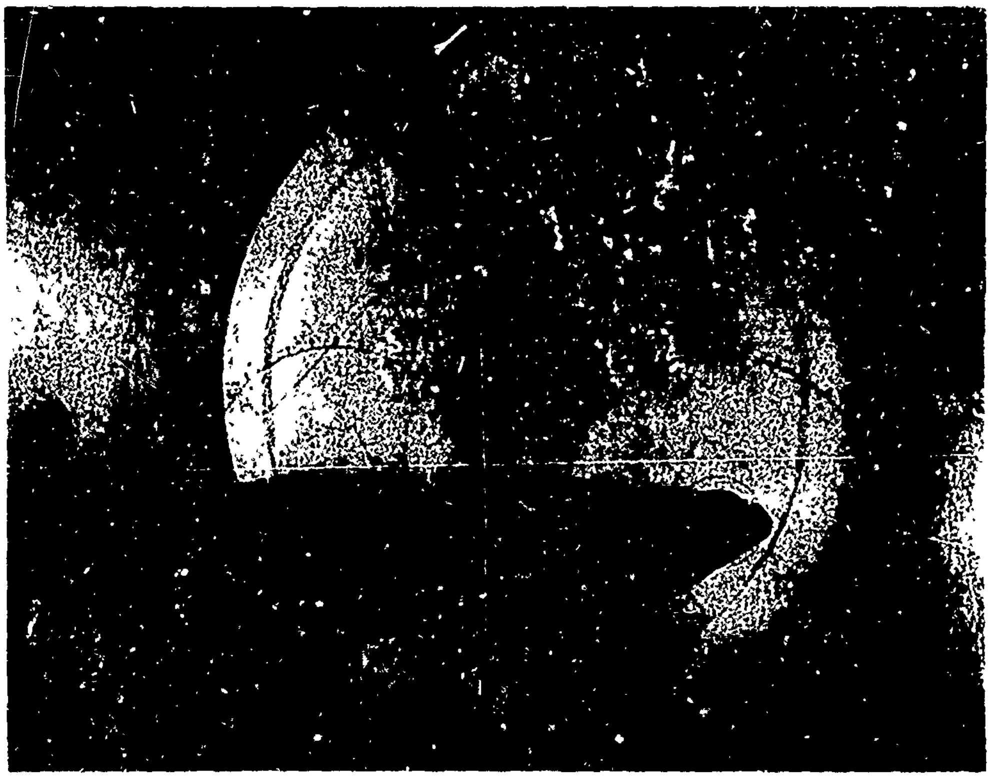


Figure 76. University of Washington Amplified High-Pitch Cyclogiro Wind Tunnel Rotor. Dia. = 3 Ft.

Figure 77. University of Washington Amplified High-Pitch Cyclogiro Wind Tunnel Rotor Blade. See Ref. 8B.

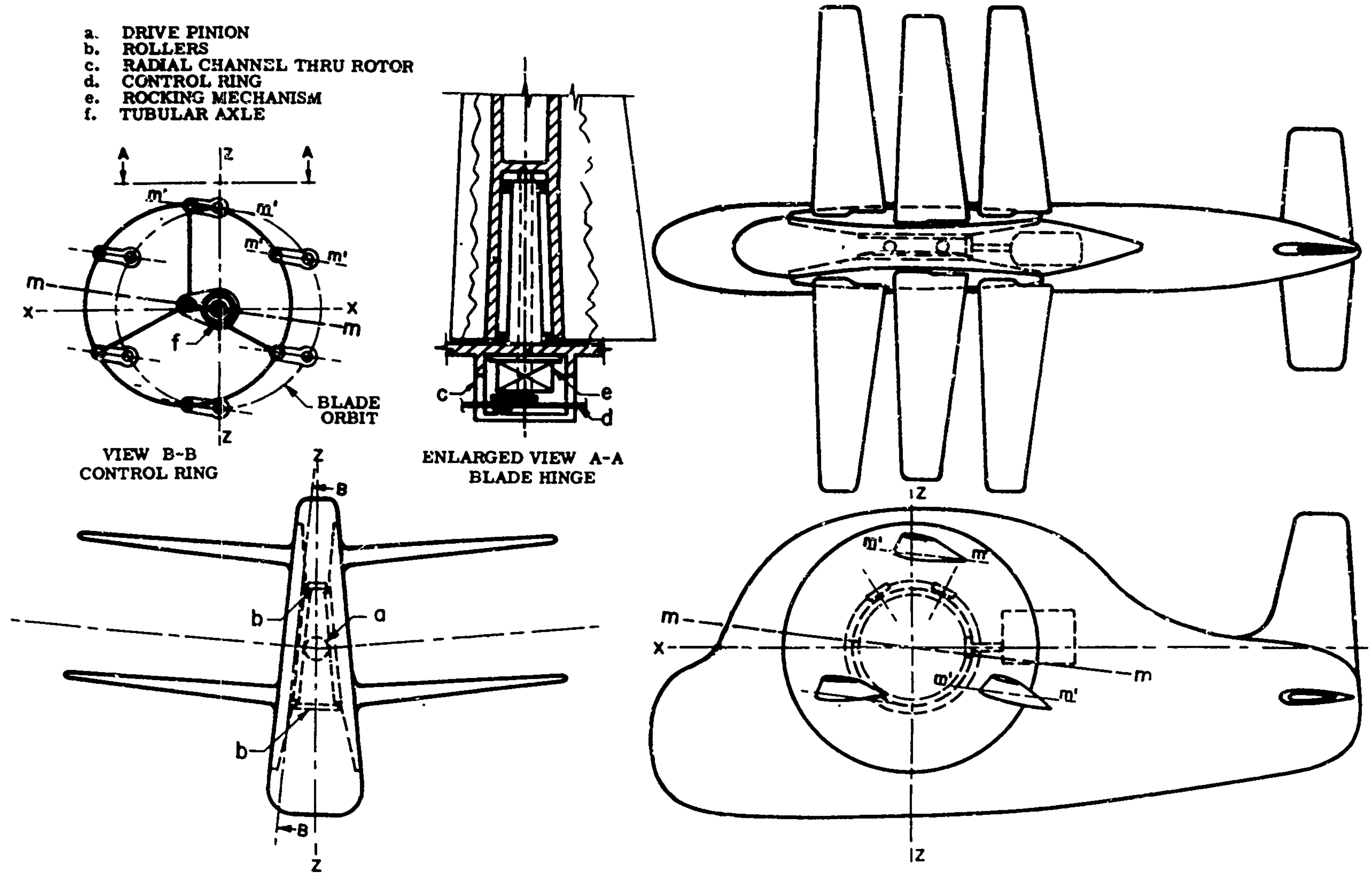


Figure 78. Hypothetical Full-Feathering Cyclogiro and Pitch Change Mechanism. Rotor System as Shown Tested in University of Washington Wind Tunnel. See Eastman, Ref. 2E.

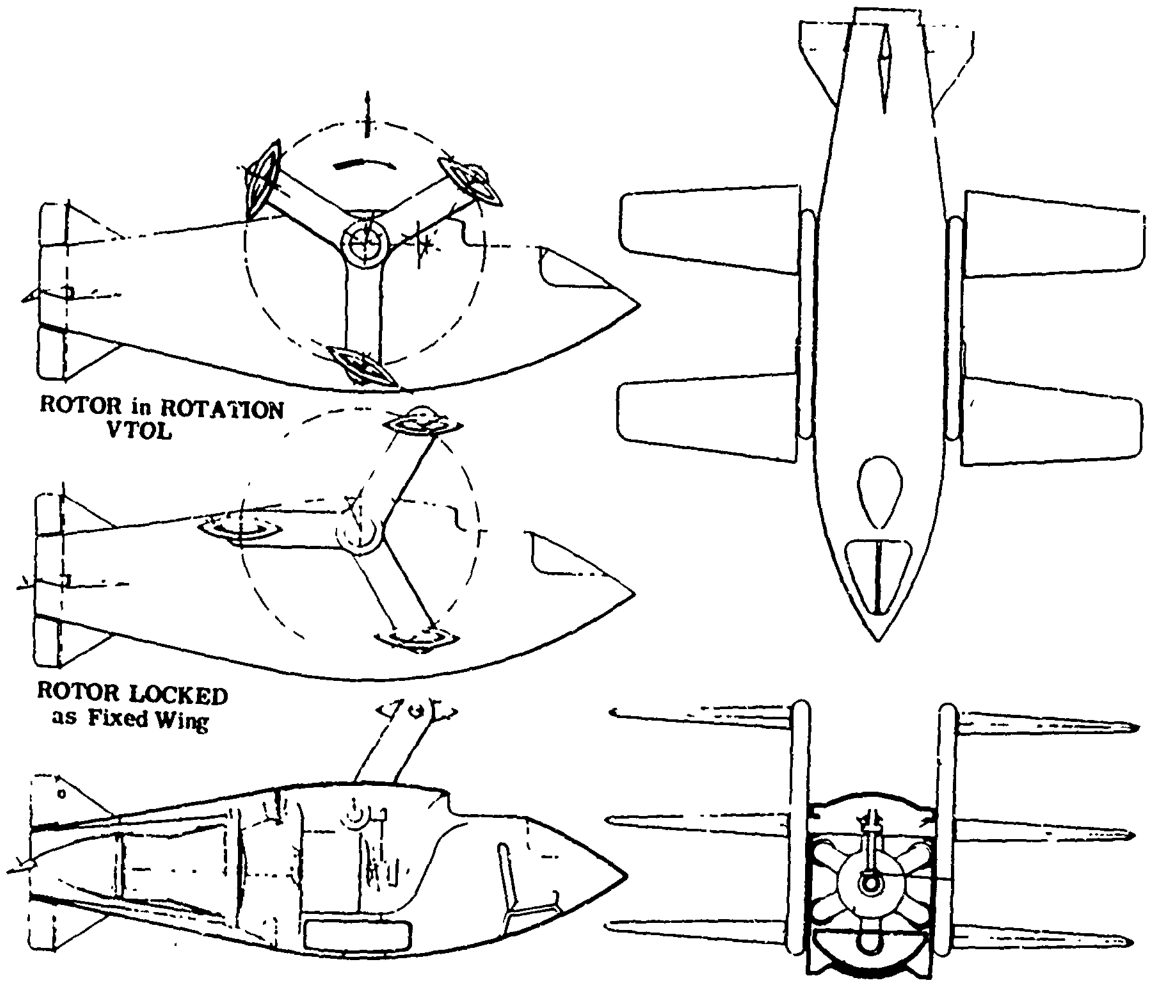


Figure 79. Wiessler Patent (1950) for a Convertible and Compound Cyclogiro in Which the Rotor May Be Stopped in Flight. Patent Further Describes Conversion of Turbine Means To Produce Shaft Power or Jet Thrust. See Ref. 31W.

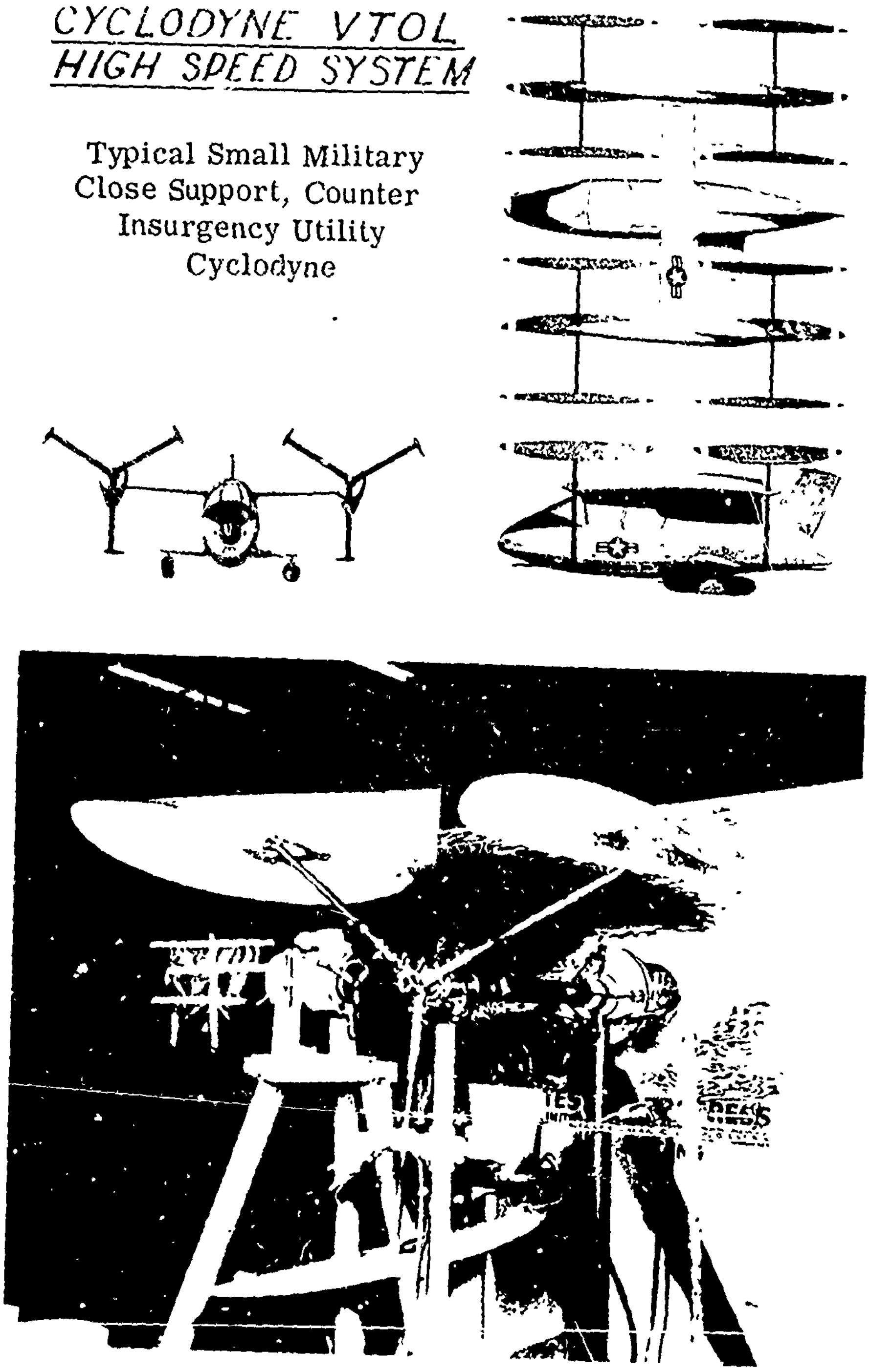


Figure 80. Cook "Cyclodyne" Project (1958-1968) Pictorial Presentation and Vibration Test Arrangement of Three-Bladed Wind Tunnel Model. Rotor Dia. 4 Ft., Span 4 Ft.

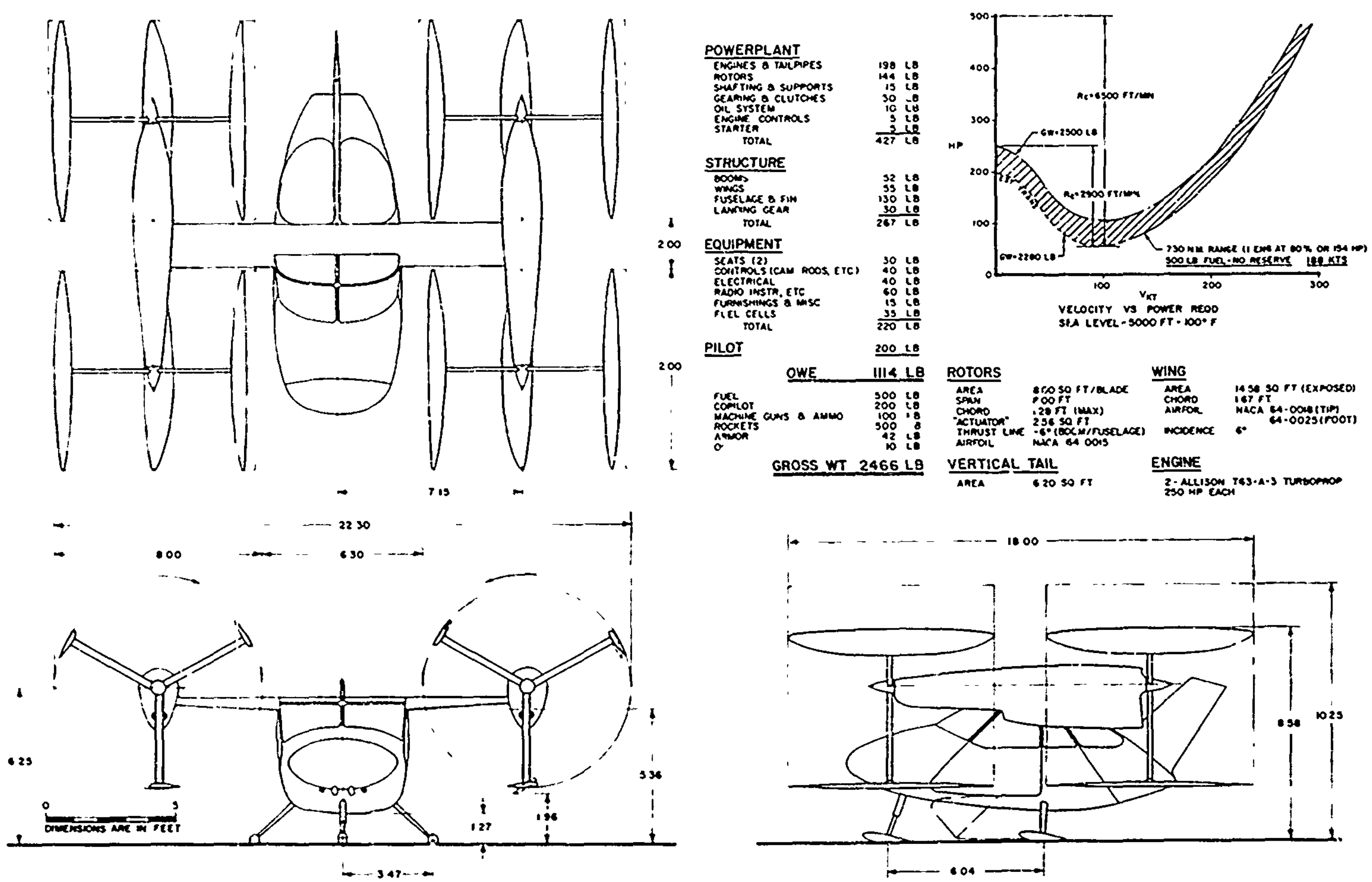


Figure 81. Cook "Cyclodyne" Project (1958-1968). Three Views. Weight Breakdown and Estimated Performance.

Figure 82. Cyclogiro With Conical
Rotor. See Ref. 19P.

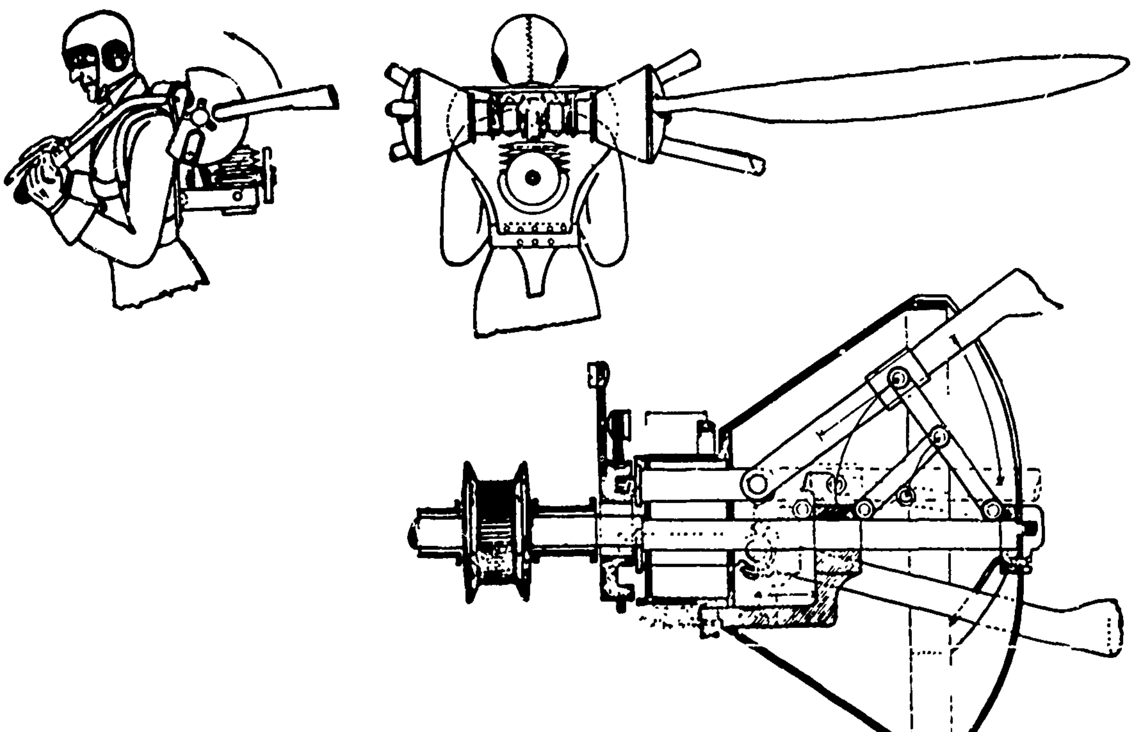


Figure 83. Conical Rotor Cyclogiro Reflecting
Compactness See Ref. 15B.

it would be premature to discount its merits, especially when one considers the evolutionary flight excellence of insects, which do quite well with exactly this form of cyclogiro geometry.

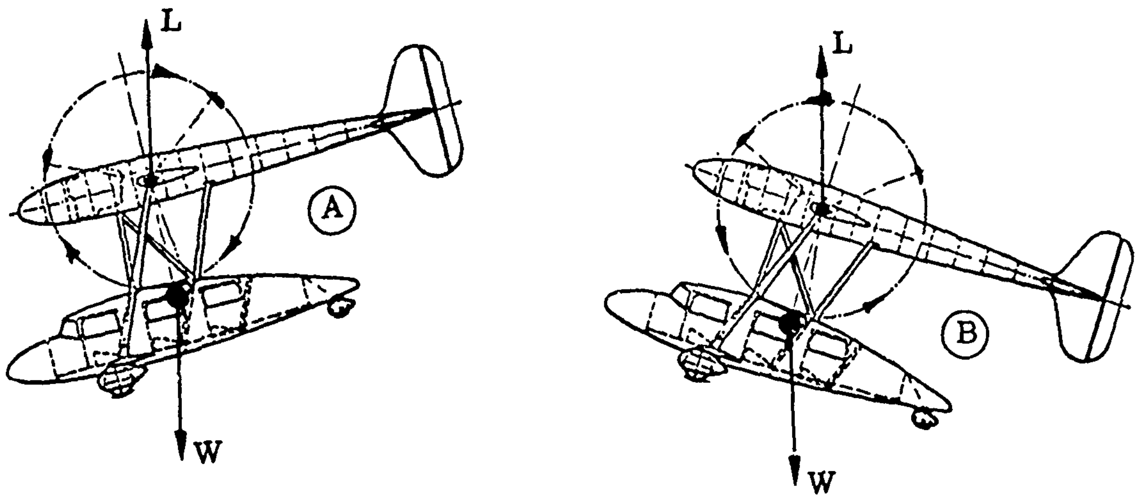
The number of rotor systems per aircraft installation is dependent upon several considerations. Rotor torque compensation, though not as serious a problem as in the helicopter, must be reckoned with. The method suggested most often for torque compensation is to place the aircraft center of gravity sufficiently below the rotor axis so that the reaction couple between the rotor lift and aircraft weight (Figure 84) will cause the craft to seek an offset equilibrium trim position. The trim will pitch the aircraft either nosedown or -up depending upon the direction of rotation of the rotor. At first glance, it seems that the nosedown arrangement (A) would be desirable, as this also directs the rotor rotation in a suitable "Magnus effect" direction. Stability considerations might favor scheme (B), as the advancing blade of the rotor at forward speed would be passing over and through the upper rotor quadrant. Other aerodynamic drag forces on the rotor, upper structure, and fuselage, as well as trim forces originating in a horizontal stabilizer, may modify this general discussion.

Other means of torque balance have been tested by having the opposite concentric pair of rotor systems rotate in opposite directions; that is, the port rotor would rotate counter to the starboard rotor. Such is the case of the University of Washington cyclogiro of Figure 78. Such an arrangement allows the rotor system to be made more integral with the fuselage.

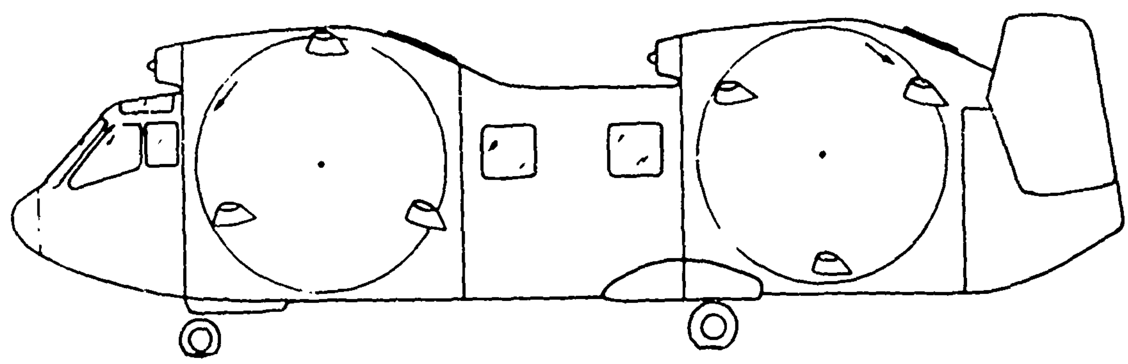
A third suggested means of absorbing the rotor torque is in the use of a fore and aft pair of rotors rotating in opposite directions (Figure 84C). This configuration is analogous to the tandem helicopter. This arrangement also offers the advantage of increasing the overall total rotor disc (cylinder) area by keeping the rotor span short and distributing the area over four rotors. There is a suggestion from marine cycloidal propeller practice that the gap area between the fore and aft rotors may partially contribute to the overall momentum "disc" area (see page 138 and Reference 30K).

4. Kinematic Discussion of Cycloidal and Trochoidal Motion

In forward flight, the path followed by the longitudinal axis of any single cyclogiro rotor blade closely approximates a cycloid or a trochoid. It is therefore useful to review first the kinematics of cycloidal and trochoidal motion.



A and B - Single Rotor, Concurrent Rotation.



C - Tandem Fore and Aft Rotors, Opposite Rotation.

Figure 84. Cyclogiro Rotor Torque Compensation Methods.

Consider (Figure 85) a circle of radius b rolling without slipping along a straight line. Any point P on the circumference of the circle describes a cycloid. Any point on a radius of the rolling circle, at a distance b from the center, describes a trochoid. If $e > b$, it is a curtate trochoid, also sometimes incorrectly referred to as a "curtate cycloid"; if $e < b$, it is a prolate trochoid, also labelled a "prolate cycloid". When $e = 0$, this corresponds to the center of the rolling circle, the trajectory of which is obviously a straight line.

The equation of the trochoid may be established in a straightforward manner and is given, for example, in Marks' Handbook. Taking the origin of coordinates, as shown in Figure 85, at the upper point on the trochoid, defining a system of rectangular coordinates Ox, Oy as shown, and calling ψ the angle by which the generating circle has turned from the initial position, the parametric representation of the trochoid is

$$x = b\psi + e \sin\psi$$

$$y = b + e \cos\psi$$

Values of ψ are shown on the trajectories of Figure 85. The tangent at any point is given by

$$\frac{dy}{dx} = -\frac{e \sin\psi}{b + e \cos\psi} = -\frac{\sin\psi}{b/e + \cos\psi}$$

To understand the passage from the geometrical problem of the trochoid to the aerodynamic problem of the cyclogiro rotor, consider the sketch of Figure 86. Though it represents the special case of a cycloidal propeller with thrust in the x direction only, it will suffice for the time being. The general case in which both thrust and lift (in the y direction) are considered will be presented later.

The same point P, shown in Figure 85, revolves in Figure 86 in a circular orbit having a radius e and a center at O. This corresponds to the relative motion of the cyclogiro rotor with respect to the aircraft's fuselage. The coordinate system is shown in the same direction as in Figure 85 (Ox positive to the left). The orbit of P moves through a fluid with a velocity V directed in the negative direction along the x axis, i.e., toward the right. The velocity V corresponds to that of the rolling circle of Figure 85. Thus, the trajectory of point P in space is a cycloid or a trochoid. The case shown in Figure 86 corresponds to a curtate trochoid.

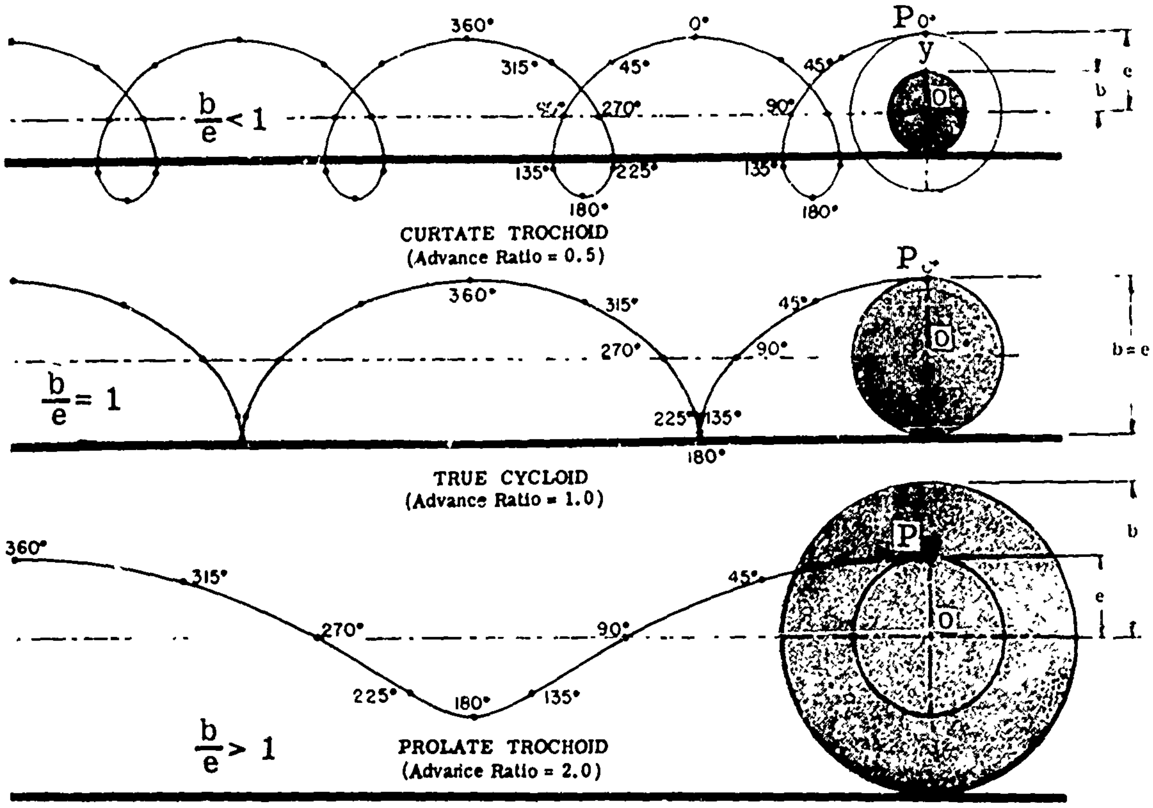


Figure 85. Kinematic Representation of Cycloidal and Trochoidal Motion. Numbers Show Angle thru which Generating Circle has Rotated.

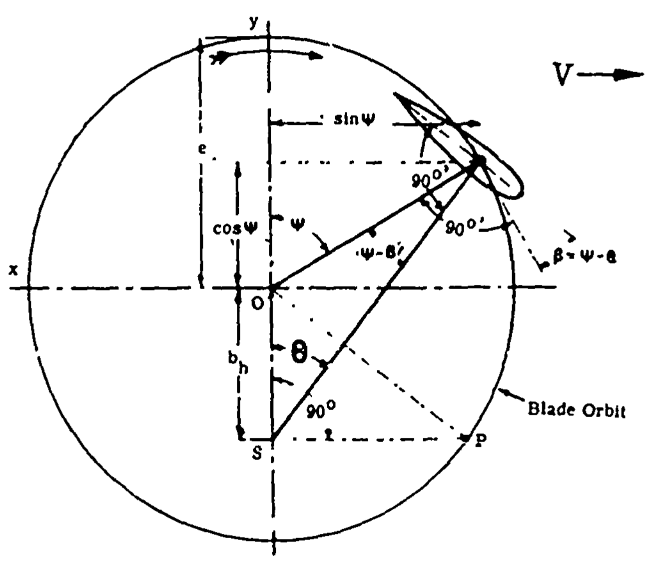


Figure 86. Geometrical Representation of Curtate Trochoidal Motion for a Cycloidal Propeller With Thrust and No Lift.

For a conventional axial propeller, pitch is defined as the linear advance along the axis of rotation in one revolution, and pitch ratio is defined as the ratio of the pitch to the propeller diameter. This definition is extended to the cycloidal propeller or rotor. The pitch ratio is thus defined as the ratio of the advance per revolution (of point P) at zero slip to the diameter 2e of the orbit. Calling the pitch ratio p, one has

$$p = \pi \frac{b}{e}$$

For a curtate trochoidal trajectory, $p < \pi$. This is called low-pitch motion. For a cycloidal trajectory, $p = \pi$. This is called pi-pitch motion. For a prolate trochoidal trajectory, $p > \pi$. This is called high-pitch motion.

The definition of the advance ratio (j) of a cyclogiro rotor is also similar to the corresponding definition for an axial propeller. It is the ratio of the speed of advance V of the orbit to the circumferential speed of point P. The velocity V should be based on local air; therefore, it may not be exactly equal to the forward velocity of the aircraft. A slipstream correction factor may be required. However, for normal flight conditions, the velocity V is assumed to be steady and uniform throughout the rotor cylinder.

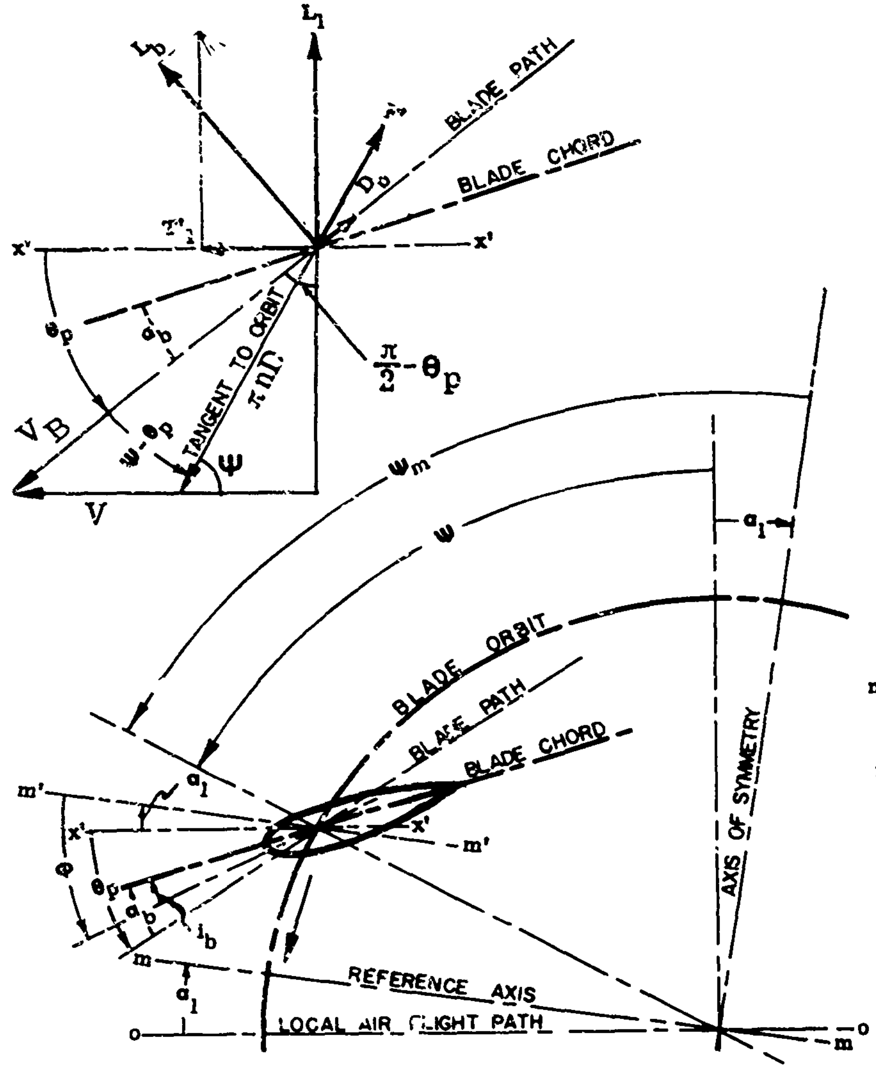
If n is the speed of rotation of the rotor, in revolutions per second, the circumferential speed of point P is πnD, where $D = 2e$.

Hence,

$$j = \frac{V}{\pi nD}$$

When a cyclogiro blade such as that shown in Figure 86 rotates about O in a circular orbit which itself translates with a velocity V, aerodynamic forces originate on the blade, and these forces have a resultant which usually is not zero. Two special cases are when the resultant is horizontal, in which case the rotor acts as a thrusting device, and when the resultant is vertical, in which case the rotor is a lifting device. In the general case, the cyclogiro rotor has both a lifting and a thrusting component, the magnitude of which depends upon the prescribed rocking motion of the blade about its feathering axis P.

Figure 86 exemplifies low-pitch curtate trochoidal motion for a purely thrusting rotor. The general case, in which both lift and thrust resultant forces exist, is shown in Figure 87. Note that, in Figure 87, the orbital motion is counterclockwise, while it was chosen clockwise for Figure 86, to agree with the direction of rotation of Figure 85. Both Figures 86 and 87 will be used to explain rocking motion.



Where:

D_b = Blade Drag Parallel to Blade Path.

F' = Blade Force Tangent to Orbit.

L_b = Blade Lift Perpendicular to Blade Path.

L_1 = Mean Lift Perpendicular to Local Air Flight Path.

T_1 = Mean Thrust Parallel to Local Air Flight Path.

i_b = Incidence Angle Determined by Orientation on Control Shaft.

α_b = Rotor Blade Angle of Attack in Local Air.

α_1 = Rotor Angle of Attack Relative to Local Air.

θ_p = Inclination of Blade Path to the Local Air Flight Path.

Φ = Blade Angle as Introduced by the Rocking Mechanism.

ψ = Orbit or Phase Angle for θ_p.

ψ_m = Orbit or Phase Angle for Φ.

Axes:

m - m = Reference Axis Through Rotor Center.

m' - m' = Reference Axis Parallel to m - m.

o - o = Local Air Flight Path.

x' - x' = Local Air Flight Path other than Passing through Rotor Center.

Figure 87. Cyclogiro Blade Angle Diagram and Resolution of Blade Forces.

If only a thrust force is desired, the blade orientation is easy to determine, as shown in Figure 88. The upper sketch corresponds to the curtate cycloidal propeller blade setting. Six positions of the blade are shown, both as seen from the fuselage or as seen in their spatial motion. All lines normal to the blade chord at the rotational axis of the blades meet in a common point within the orbit, a distance b from the propeller center. The blades in this configuration oscillate but do not rotate about their axes. However, with respect to the vehicle to which the propeller is attached, the blades make a full revolution, though at variable speed, while the propeller makes one revolution at constant speed. By tracing a blade on its path through a cycle, it is observed that the leading edge always remains the leading edge. By moving the point of convergence of the normals to the blade chords along the vertical axis of symmetry inside the orbit circle, the propeller can operate along any curtate cycloidal path.

The middle sketch of Figure 88 shows that, for pure cycloidal motion of a thrusting propeller, the blade chord must always be normal to a line passing through point 4 and the rotative axis of the blade. The leading edge of the blade becomes the trailing edge every other propeller revolution. The condition of tangency of the blade is easily achieved by giving the blade a rotation about its center axis of one-half the rotational speed of the blade orbit.

The lower sketch of Figure 88 shows the blade settings for prolate cycloidal propellers. All lines normal to the blade chords converge in a point on the axis of symmetry <u>outside</u> the blade orbit of radius e, at a distance b from its center. It can be noted that the blades make one full revolution, though at variable speed, while the propeller makes one revolution at constant speed. However, the blades oscillate only with respect to the vehicle to which the propeller is attached.

A cyclogiro rotor, of which the cycloidal propeller discussed above is a special case, may thus be defined as a mechanism, the blade chords of which are tangent to a cycloidal or trochoidal curve at zero slip in all positions of their orbital travel.

Cyclogiro rotor usefulness would be greatly enhanced if the rotors could be designed so that a complete pitch-ratio variation of from O to ∞ could be obtained by a simple mechanism, or by any mechanism at all. It has been shown that low pitch or pi-pitch is desirable for hover and low-speed flight and that high pitch is essential for high-speed aircraft flight. As will be seen later, Eastman and Heuver have proposed mechanisms that cover certain ranges of both low pitch and high pitch and that can convert from one to the other in flight. However, there are two factors that militate against the universal pitch system: (1) for the pure cycloid, a blade profile with leading and trailing edge symmetrical about the 50-percent station, is an absolute requirement, whereas for the curtate and prolate cycloid, a streamlined blade seems to be

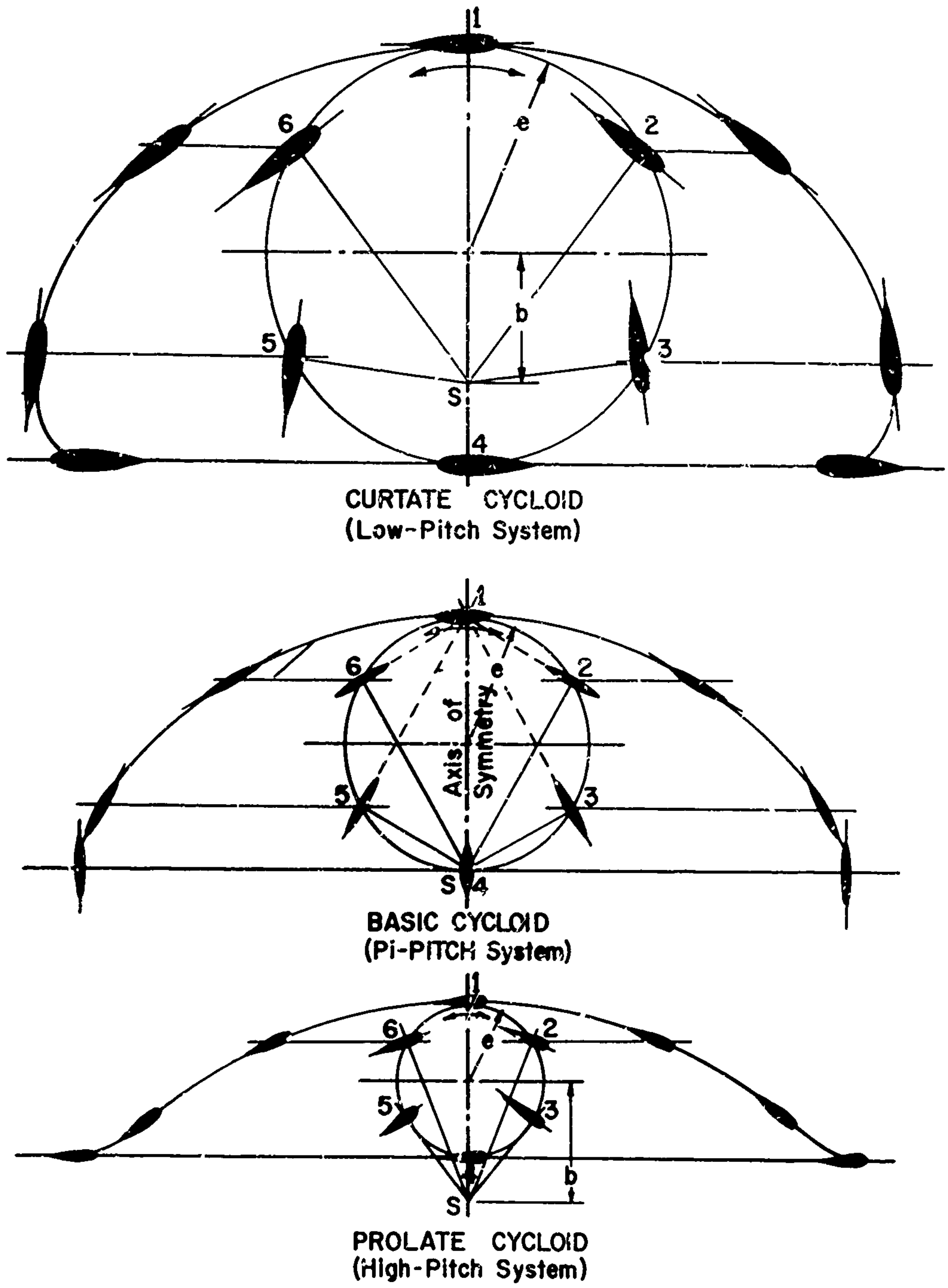


Figure 88. Ideal Path Trajectories of Cyclogiro Rotor Blade for a Full Range of Pitch Ratio Systems, for a Thrusting Propeller.

desirable for good efficiency; (2) the high acceleration forces required for both the curtate and prolate ranges in the close proximity where b/e approaches unity prevent a close approach to the pure cycloid. Only the ranges of pitch ratios from 0 to 0.8π and from 1.2π to ∞ can be covered by safe mechanical means.

From an observation of Figures 86 and 88, it is concluded that thrust control of a cyclogiro rotor is achieved by blade pitch changes, obtained themselves by moving, by the proper mechanical linkage, point S of Figures 86 and 88 up and down.

It is interesting to compare the pitch-change mechanisms for the conventional propeller and for the cycloidal propeller. The pitch changes in cycloidal propellers are brought about by mechanically varying the eccentricity of the blade control mechanisms. The entire cycloidal blade--from its tip to the base--is thereby realigned to follow a new cycloidal path. The mechanisms of variable-pitch screws also turn the entire blade--from tip to base--so that each blade element receives the same amount of angular displacement. However, since every blade element of the screw follows a different helix, the angular displacement of each blade element should be different for every pitch adjustment and should vary from zero at the propeller center to a maximum at the tip. Such a variation of angle would be possible if the blade could be mechanically distorted by twisting, but not by turning it about its base. The mechanical difficulties of creating a blade twist are quite apparent. If the variable-pitch screw is designed for a certain fixed pitch and this pitch is increased by turning the blade in its socket, the blade loading shifts toward the blade tip for low-pitch screws and a small angular turn of the blades. For high-pitch propellers and large angles of blade turn, the converse is true; namely, the blade loading shifts toward the propeller center. Hence, the accommodation of the variable-pitch screw from normal pitch to a different pitch setting is accomplished at the expense of efficiency. The problem is particularly severe for a convertible aircraft of the tilt-rotor type, as is well known. Here, the cyclogiro rotor presents an enormous conceptual advantage.

5. Analysis of Cyclogiro Blade-Rocking Motion

The purpose of the rocking motion is to keep the blades properly aligned with the airstream throughout their wave-shaped paths. The type of rocking motion that permits the blade to maintain constant angle of attack along a chosen path is called <u>ideal motion</u>. For practical reasons, i.e., to reduce blade accelerations in the critical portions of the orbit, it may be expedient to digress from ideal motion into what is referred to as "<u>amplified motion</u>". Both ideal and amplified motion will be discussed here.

Consider the blade angle diagram of Figure 87. However, the diagram of Figure 86, though covering a more restrictive case, is equivalent and could be used.

The angle of inclination of the blade path, Θ_p, can be calculated from the velocity triangle, in the upper left corner of Figure 87:

$$\tan\left(\frac{\pi}{2} - \Theta_p\right) = \frac{V + \pi nD \cos\psi}{\pi nD \sin\psi}$$

or

$$\tan\Theta_p = \frac{\sin\psi}{j + \cos\psi}$$

$$\Theta_p = \tan^{-1}\frac{\sin\psi}{j + \cos\psi}$$

The variation of Θ_p with ψ (ideal motion), for various values of the advance ratio j, is plotted as the solid lines of Figure 89.

When $j > 1$ (shown as $1/j < 1$ on Figure 89), the curves oscillate about the zero axis; but when $j < 1$, they oscillate about a 45-degree axis. The type of oscillation is identical in the two cases, since Θ_p determined for a given value of $1/j$ is equal to $\psi - \Theta_p$ determined for the same value of j (this is proved by Kirsten in Reference 30K). In other words, a line tangent to the blade path rocks about the rotor path if $j > 1$, but it rocks in an identical manner about the rotor structure of $j < 1$. The sudden transition from one type of rocking motion to the other leads to the sharp distinction between a high-pitch cyclogiro and a low-pitch cyclogiro. It also follows from the geometrical definition of the trochoid, in Figure 85. The high-pitch machine is suitable for high advance ratios because its blades rock relative to the fuselage, but the low-pitch machine is limited to low advance ratios because its blades rock relative to the rotor structure, as seen previously.

A study of Figure 89 shows that, as j decreases from infinity and approaches the transition value, $j = 1$, the maximum value of Θ_p becomes larger and occurs later in the cycle. In the limit, the maximum is 90 degrees, and it occurs when $\psi = 180^\circ$. At this point, Θ_p suddenly changes 180 degrees in either the positive or the negative direction, depending upon whether or not the transition is made. Since to turn the blades 180 degrees instantly is impossible, ideal motion becomes impossible as the transition is approached. Nevertheless, as stated before, the pi-pitch propeller meets the requirement of ideal motion when $j = 1$.

Apparently, ideal motion is impossible when j is slightly less or slightly greater than one. However, since blade "effectiveness",

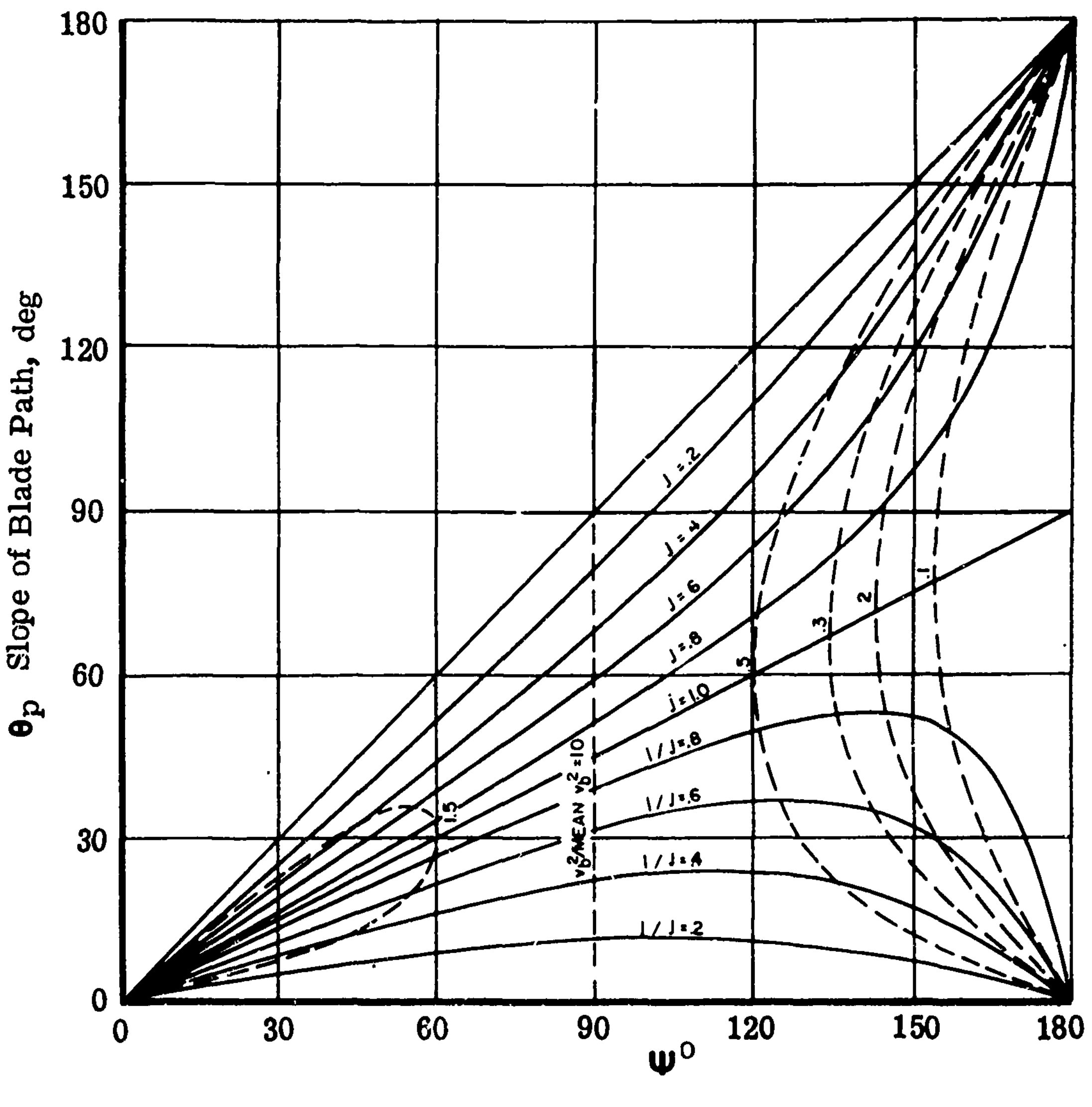


Figure 89. Orbital Variations of the Slope of the Blade Path With Variations in the Rotor Advance Ratio. Auxiliary Curves Indicate Blade Effectiveness.

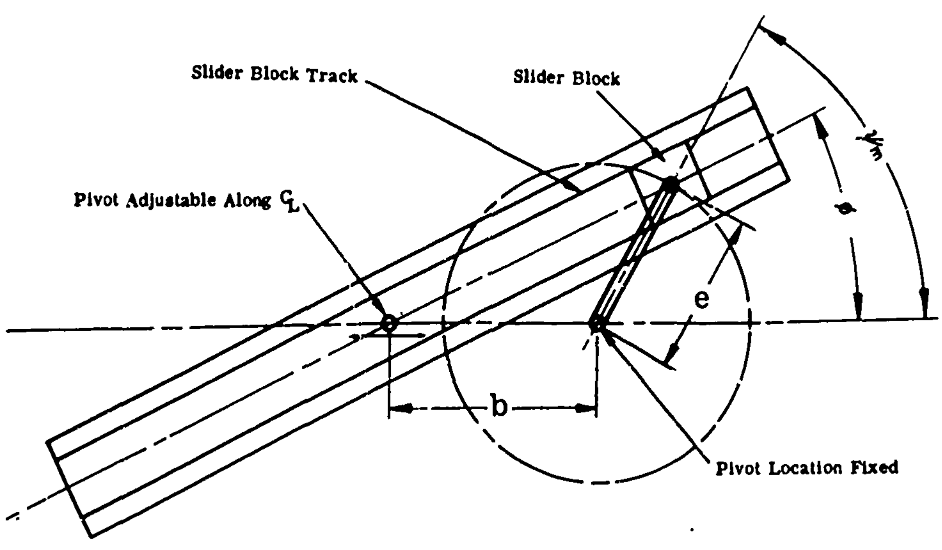
i.e., the lifting ability of the blade, approaches zero at the same time that the angular acceleration becomes excessive, a distorted ideal or "amplified" motion can be substituted without appreciably affecting rotor characteristics. The reduction in effectiveness arises from the variation of the blade resultant velocity v_b throughout the orbit. Blade lift is proportional to v_b^2, and therefore v_b^2/ mean v_b^2 can be taken as a measure of blade effectiveness. Eastman, in Reference 2E, shows that the effectiveness is given by the equation

$$\frac{v_b^2}{\text{mean }(v_b^2)} = \frac{1 + 2j \cos \psi}{1 + j^2}$$

The dashed curves in Figure 89 are drawn through points of equal v_b^2/mean (v_b^2), and the number on each curve indicates the value of the effectiveness ratio, between 0.1 and 1.5. It can be seen that greatest blade effectiveness occurs at small values of ψ and becomes very small around $\psi = 180^o$. With this information, a blade motion may be selected which conforms closely with the blade path throughout the effective part of the orbit, but which is distorted to reduce angular acceleration throughout the part where even a stalled blade will have little influence.

Blade angular velocity and angular acceleration can be plotted also as a function of ψ and j. However, their values will depend upon the type of blade-rocking motion.

Kirsten, in Reference 30K, calculates both for the configuration of Figure 86, i.e., the pure thrusting propeller. Eastman, in Reference 2E, notes that a simple swinging block linkage, in common use for quick-return mechanisms, will produce ideal motion. It consists of a block sliding in a slotted bar as it is moved by a crank of radius e. The axis of the crank is displaced a distance b



from the axis of the slotted bar. For this mechanism, one can define an ideal blade-rocking motion parameter, such as $m = b/e$. When $b > e$, the slotted bar oscillates exactly as required for ideal high-pitch motion. Similarly, $b < e$ corresponds to ideal low-pitch motion. For $b = e$, the mechanism is inoperative.

The rocking motion, being an ideal motion, is described by

$$\Phi = \tan^{-1} \frac{\sin \psi_m}{m + \cos \psi_m}$$

The angle Φ is shown in Figure 87.

The angular velocity and acceleration of the blade corresponding to the above motion are given by Kirsten and Eastman as

$$\frac{d\Phi}{dt} = 2\pi n \frac{1 + m \cos \psi_m}{1 + 2m \cos \psi_m + m^2}$$

$$\frac{d^2\Phi}{dt^2} = (2\pi n)^2 \frac{m(1-m^2) \sin \psi_m}{(1 + 2m \cos \psi_m + m^2)^2}$$

These equations are obtained by straightforward differentiation of the equation for Φ.

Angular velocity and acceleration are plotted in Figure 90. Consider first the angular velocity curves. The parameter against which they are plotted is the rocking motion parameter. This parameter replaces the advance ratio of Figure 89. As in Figure 89, there is a correspondence between a value of m corresponding to low-pitch motion and the corresponding value $1/m$ that gives high-pitch motion. Actually, the two curves are symmetrical with respect to the line $d\Phi/dt = 0.5$. From the earlier definition of the pitch ratio, it is equal to π times the rocking parameter.

An examination of the angular velocity and acceleration curves (Figure 90) reveals the large magnitude of the accelerations, for ideal motion, for m near 1, and for large values of ψ. These curves, plus the effectiveness curves of Figure 89, serve as a guide to the design of amplified-pitch mechanisms.

The limitation imposed by angular acceleration is best illustrated by comparing the maximum acceleration for ideal motion with that for harmonic motion having the same amplitude. The equations show that the maximum for ideal motion is essentially the same as for harmonic motion when m is either very small or very large, but that the acceleration increases more and more rapidly as m approaches unity. The acceleration is nearly four

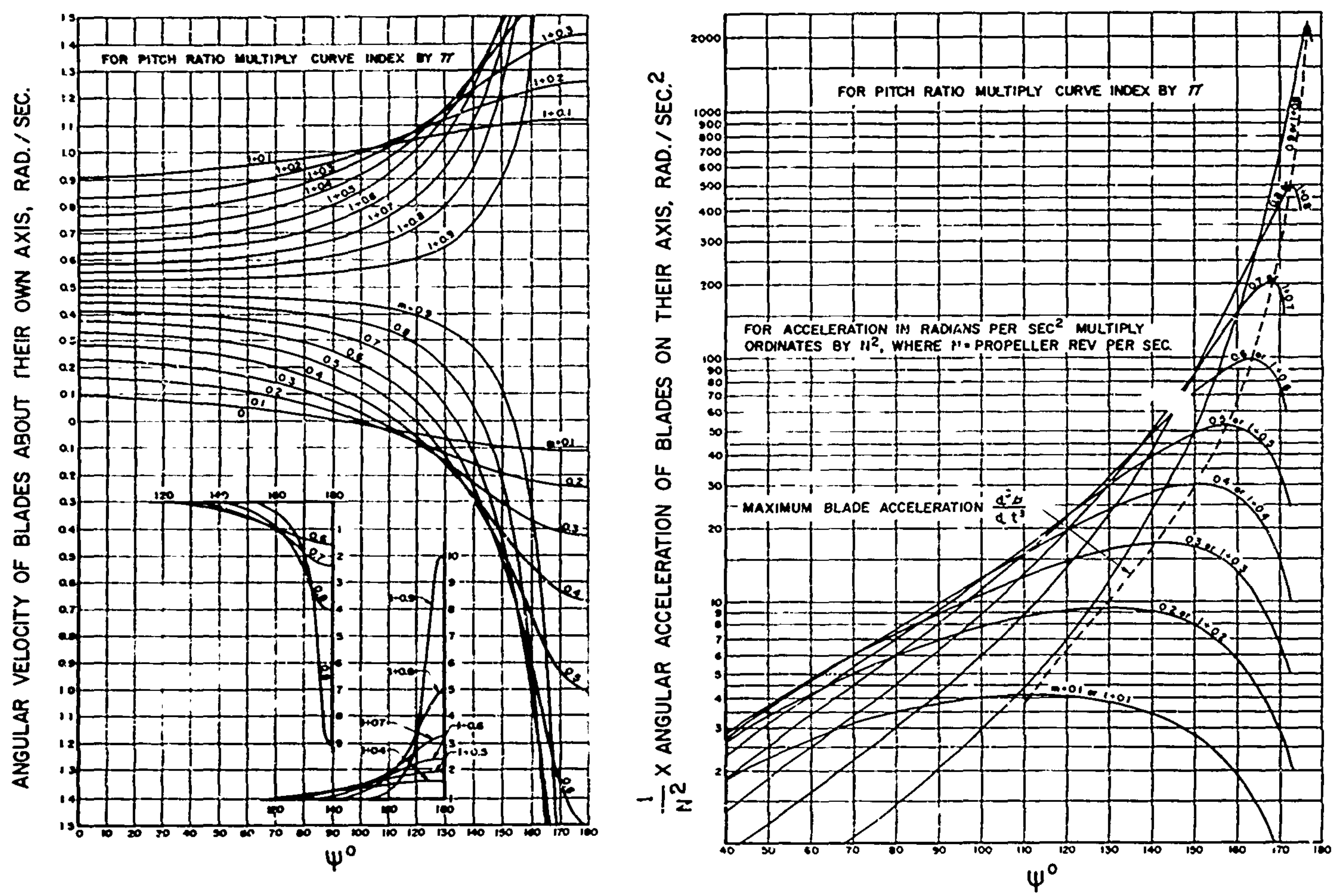


Figure 90. Angular Velocity and Acceleration of the Cyclogiro Blade About its own Feathering Axis Throughout the Rotor Orbit With Variations in the Blade Rocking Parameter.

times that for harmonic motion when m or $1/m$ becomes 0.8. This acceleration is considered to be a practical maxumum value for m or $1/m$. Eastman (Reference 2E) suggests a maximum value of 0.6.

The transition from low-pitch to high-pitch motion cannot be made by changing at once from $m = 0.6$ to $1/m = 0.6$, because this would require an instantaneous change in the angular velocity of the blades. However, a distorted ideal motion can conform to the blade path for $j = 1$ throughout the effective part of the orbit without introducing excessive angular acceleration in the ineffective part. Since the blade angle for high-pitch motion will be identical to that for the low-pitch motion throughout the effective part of the orbit, transition is possible. Such a mechanism is shown schematically in Figure 78. This subject will be brought up again later.

Distortion of ideal blade motion introduces an orbital variation in pitch which corresponds in a sense to the radial variation defining the pitch distribution of a screw propeller. Following screw-propeller terminology, a reference blade angle, β, will be used. It is the angle through which the blade turns relative to the rotor structure, while ψ_m increases from 0 to 90 degrees. As for the screw, $\tan \beta$ is the advance ratio at which the blade angle of attack becomes zero at the reference position. For pure harmonic rocking motion, β is the amplitude in the low-pitch range for which the rocking is relative to the rotor structure, but it is 90 degrees minus the amplitude in the high-pitch range for which the rocking is relative to the reference axis. For ideal motion, $\beta = \tan^{-1} m$.

Preferred rocking motion will approach ideal motion throughout the effective part of the orbit, but to relieve inertia stresses it will approach constant angular acceleration throughout the ineffective part. Amplified ideal motion is a step in this direction, and it is easily obtained with gears or other means. Wind tunnel tests using this motion were made by Baker (Reference 8B). Using Φ_b for the rocking angle of the blade and using k for the amplification factor, amplified high-pitch motion is described by

$$\Phi_b = k\Phi \; , \quad \frac{d\Phi_b}{dt} = k \frac{d\Phi}{dt} \; , \quad \frac{d^2\Phi_b}{dt^2} = k \frac{d^2\Phi}{dt^2}$$

and

$$\beta = 90^\circ - k \tan^{-1} \frac{1}{m}$$

Since the mechanism must rock the blades, but not turn them through a complete revolution, m must be greater than unity.

Amplified low-pitch blade motion can be obtained by applying the same rocking motion relative to the rotor structure. In this case,

$$\Phi_b = \psi_m - k\Phi, \quad \frac{d\Phi_b}{dt} = 2\pi n - \frac{kd\Phi}{dt}, \quad \frac{d^2\Phi_b}{dt^2} = -k \frac{d^2\Phi}{dt^2}$$

and

$$\beta = k \tan^{-1} \frac{1}{m}$$

Again, m must be greater than unity.

For smooth transition, the two motions must have the same angular velocity as well as the same angular positions. This will be satisfied at $\psi_m = 0$, for $k = 1.33$. Therefore, smooth transition is possible at this point in the orbit.

The amplified motion defined by Φ_b can be approximated with the ideal motion mechanism by using an "equivalent" value of m, say, m'. Then,

$$\Phi_b = \tan^{-1} \frac{\sin \Phi_m}{m' + \cos\Phi_m}$$

Obviously, there will be a different value of m' for every position of the rotor. However, a value of m', where $\psi_m = 90^\circ$, gives a close approximation to the actual motion. For this condition,

$$\tan^{-1} \frac{1}{m'} = K \tan^{-1} 1/m$$

Letting $\Phi' = K \tan^{-1} 1/m$, then

$$m' = \cot \Phi'$$

With $K = 1.5$ and $m = 4$, one finds $m' = 2.6$.

The curves in Figure 91 illustrate the amount of discrepancy for two different values of m when the amplification factor is 1.5. The difference is quite pronounced when the equivalent m becomes less than unity. However, the wide variation occurs in the most ineffective part of the orbit. By computing the equivalent m at a larger rotor angle, better agreement could be obtained at the larger rotor angles but the curves (of $K = 1.5$) would show much less coincidence at the smaller rotor angles in the most effective region.

The total rotor force is unsteady, owing to orbital variations in blade velocity and in angle of attack. If it is assumed that there are three blades per rotor, that ideal motion is used, and that the velocity through the rotor is uniform, the computed pulsation in lift reaches

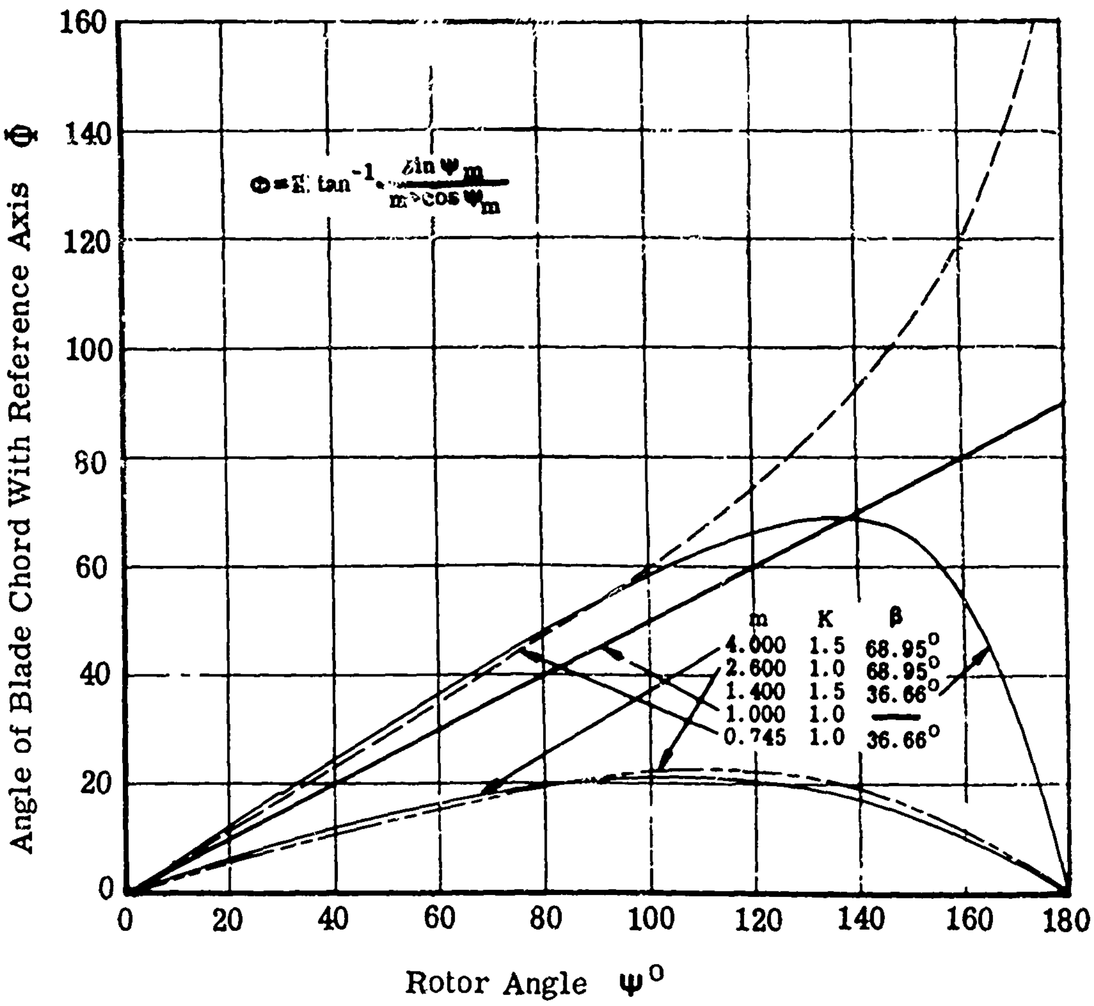


Figure 91. Cyclogiro Rotor Blade Angularity With and Without Amplification ($K \neq 1$ and $K = 1$ Respectively) and Variations in the Ideal Rocking Motion (m) (Ref. 8B).

a maximum of about 5 percent at low advance ratios and decreases to zero as the advance ratio approaches infinity. Actually, the maximum will not be attained, because low advance ratios will be employed only for near-hovering flight in which the pulsation will be subdued by prominent induced velocity. Nevertheless, Black has shown (Reference 39B) that the pulsation can be reduced or eliminated by proper choice of the blade-rocking motion. This may lead to a slightly modified ideal motion which will produce steady lift under normal flying conditions.

Preferred blade motion may be outlined as follows: Between cruising and maximum forward speed, high advance ratios will be used, and the only advantageous modification of ideal motion is that which will produce steady lift. Any other modifications will produce objectionable variations in blade load, and increased power losses. At near-hovering speed, on the other hand, low advance ratios will be used, and the blade velocity will be so low that aerodynamic loads cannot become excessive. In addition, a moderate increase in parasite power will be inconsequential, compared with the high slipstream loss, which is unavoidable at low speed. In this range, therefore, preferred rocking motion will be determined as much by the merits of the mechanism as by the slope of the blade path. The latter will be influenced by the nonuniform flow through the rotor. Nevertheless, even at low advance ratios, ideal motion establishes the pattern which should serve as a guide toward establishing the ultimate blade motion.

6. Classification and Further Discussion of Cyclogiro Systems

A complete classification of cyclogiro systems into eight classes was prepared in connection with the cross-index tables of Appendix II and is shown in Figure 92. The classification rests upon a distinction between the various types of blade-rocking motion. There are eight classes; each cyclogiro reference of the bibliography of Appendix I is identified with one of the eight classes, as shown in item 23 of the cross-index table. No attempt is made to fully describe, in Figure 92, the feathering motion corresponding to each rotor class. Rather, additional discussion of these classes will be given below using additional figures.

It will be noted first that the blade feathering motions discussed in the previous paragraph, e.g., low pitch, pi-pitch, and high-pitch systems, cover only the first three classes. Actually, most of the early proposed cyclogiro systems (before 1920) belong to classes 4 through 8 and use "pusher" feathering systems. It is anticipated that any future cyclogiro aircraft would utilize the "full-feathering" system; i.e., one in which the pitch ratio of the rotor blades can be changed at will as a function of the flight condition. Because of its importance, this system will be discussed separately on pages 128 to 131.

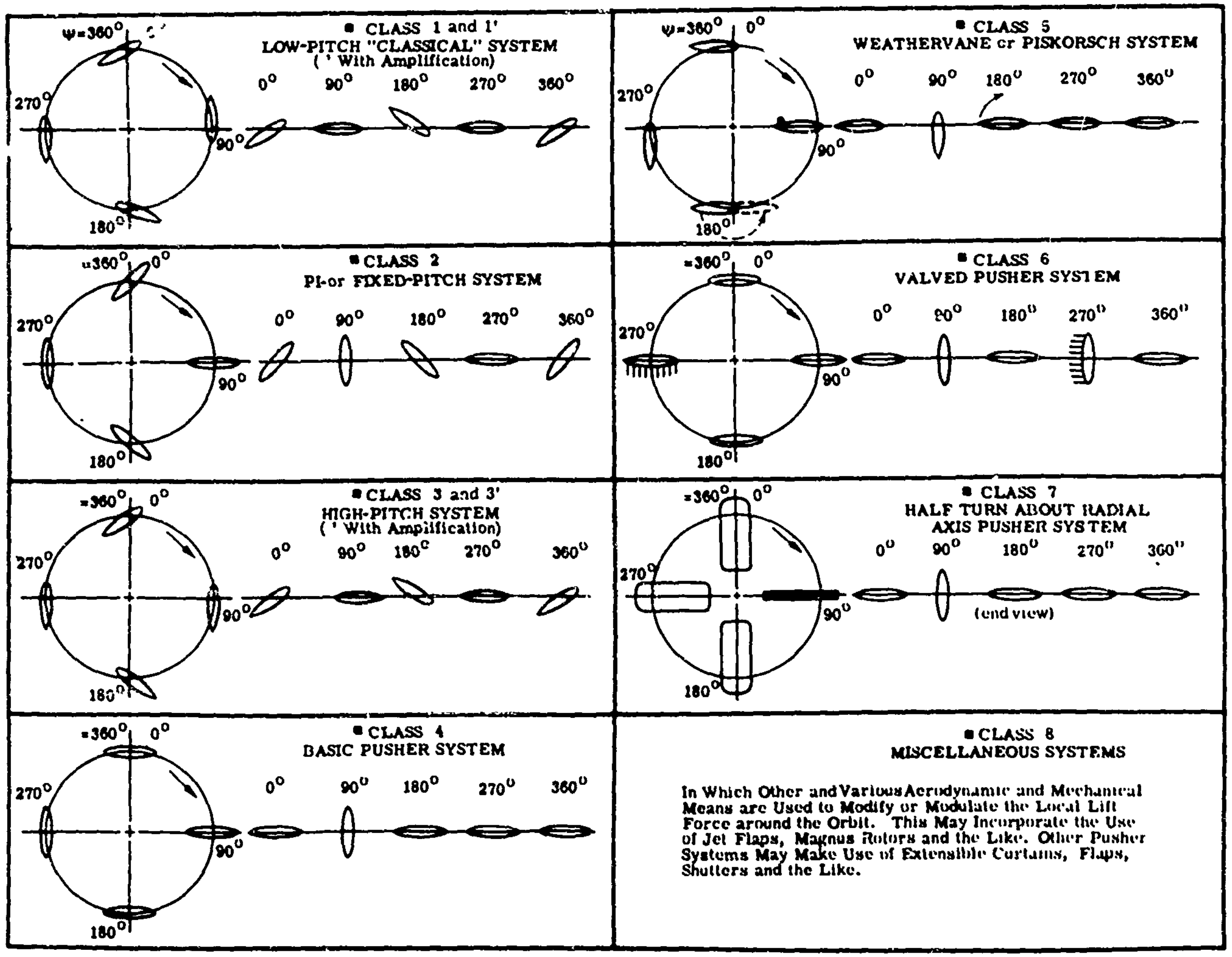


Figure 92. Classification of Cyclogiro Feathering Systems by Blade Motion and Position Relative to Rotor Axis of Rotation. Note That Only Blade Settings Are Shown for Hovering or Vertical Flight. Also See Item 23 of the Cross-Index Table of Appendix II.

Some additional details on the mechanical arrangements of the rotors of the different classes are given below:

Class 1: Low-pitch and amplified low-pitch systems

This has been the most exhaustively studied arrangement, witnessed by the number of references in the bibliography. Blade-feathering motion is invariably sought from a simple offset crank or excentric relative to the rotor axis, which feathers the blade through radial push rods. Such was the arrangement of the early NACA tests (Figure 73 and Reference 28W). The use of these linkages produces a blade motion which conforms closely with the ideal low-pitch motion when the amplitude is small, but which becomes progressively less satisfactory when the amplitude is increased to accommodate larger advance ratios. In addition, as shown in the previous paragraph (Figures 89 and 90), as the pitch ratio and advance ratios increase, blade accelerations can become excessive.

In 1935, Wheatley concluded from the NACA cyclogiro tests done on a low-pitch system (Reference 28W) that "the probable performance of the cyclogiro is very poor for normal power loadings". His indictment of the cyclogiro was really that of the low-pitch system at high advance ratios. These limitations of the low-pitch system were first recognized by Rohrbach in 1938 (Reference 58R). It is recognized today, as a result of the work done at the University of Washington, that the low-pitch system is well suited--actually is the best--at hover and low advance ratios.

A schematic demonstration of the operation of a typical low-pitch system is shown on the left side of Figure 93. (It was conceptually shown in Figures 86 and 88.)

The rationale for the amplified low-pitch system was given in a previous paragraph. A practical way to achieve amplified low pitch, according to Kirsten, is shown in Figure 94.

Class 2: Pi-pitch systems

The pi-pitch system was defined in a previous paragraph. It was shown that, by using a doubly symmetric airfoil profile, the need to rotate the airfoil instantaneously by 180° at ψ = 180° was alleviated. A schematic diagram of a pi-pitch mechanism is shown

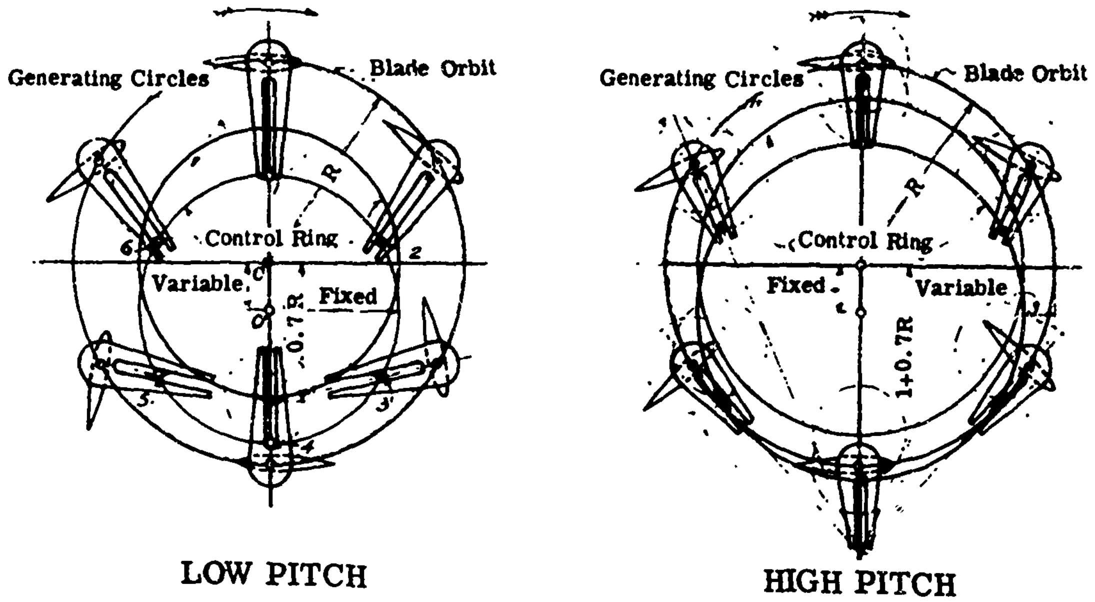


Figure 93. Schematic Demonstrating Cyclogiro Blade-Feathering Means and Similarity in the Low-Pitch (Left) and High-Pitch Regimes. Note Opposite Orientation of Slider Arm at $\psi = 180^{\circ}$.

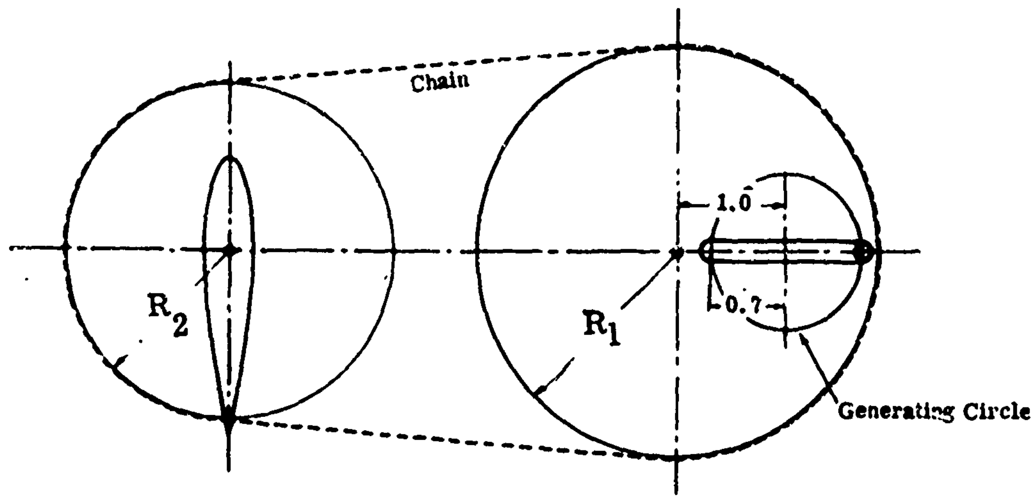


Figure 94. Schematic of Cyclogiro Blade-Feathering Mechanism To Introduce Pitch Amplification Into Basic Blade Motion (Ref. 30K).

in Figure 95. The relative simplicity of this arrangement makes it attractive. However, the doubly symmetric airfoil has fewer good aerodynamic characteristics than the cambered airfoil which is best adapted to low- or high-pitch systems. Also, the pi-pitch system has a good aerodynamic efficiency only at moderate advance ratios. Altogether, the pi-pitch system does not adapt well to aeronautical applications.

Class 3: High-pitch systems

A schematic demonstrating the operation of a typical high-pitch system is shown on the right side of Figure 93 (it was conceptually shown in Figure 88). In the limit, when the pitch ratio becomes infinity, the high-pitch cyclogiro rotor takes on a fixed-wing configuration. It stands to reason, therefore, that the high-pitch system is well suited for high-speed aircraft configurations. The advantage of the high-pitch cyclogiro over the fixed-wing airplane, independent of the VTOL argument, comes from the fact that in the cyclogiro, lift and thrust functions are integrated.

The rationale for the amplified high-pitch system was also discussed previously. Amplified high pitch is useless for operation of an aircraft at high speeds, but it may be useful for low-speed operation. An amplified high-pitch system makes possible a broader speed range than the pure high-speed system, which has a very poor aerodynamic efficiency at low speeds or in hover.

Classes 4 Through 7: Pusher feathering systems

The basic idea is a variation of the familiar paddle wheel: in the hover situation, for example, the descending blade ($\psi = 90^o$) adjusts its position so as to create a maximum resistance or "push" ($C_D \geqslant 1$), while the opposite ascending blade ($\psi = 270^o$) is set at the angle of minimum resistance (C_{Dmin}). The net effect is an acceleration of the system in a direction opposite to that of the "push". The blades travelling in the remaining quadrants of the orbit ($\psi = 0^o$ and 180^o) usually remain in the position corresponding to C_{Dmin}. Horizontal thrust is obtained by inclining the lift vector by varying the feathering mechanism. Lift and thrust magnitudes were also changed in these older configurations by changing the rotor RPM.

Although such systems may be mechanically simple and are capable of producing lift as demonstrated

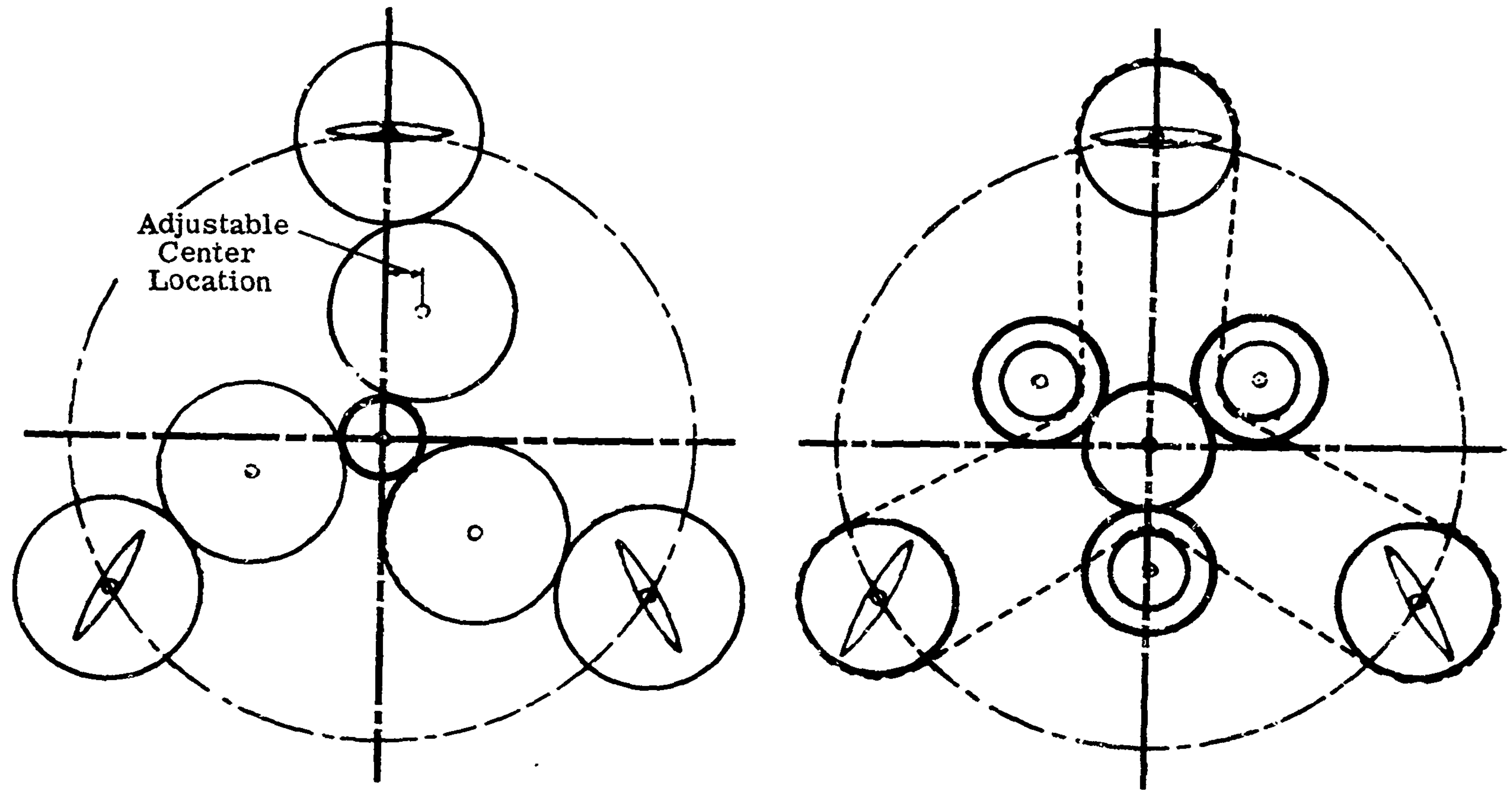


Figure 95. Simplicity of Obtaining Fixed, Ideal Pi-Pitch Blade-Feathering Motion by Gearing (Left) or Chain and Sprockets (Right).

by Pichou (Reference 13P), the fact that the effective blade is influencing only the local air and not the air through the entire swept cylinder demonstrates the lack of aerodynamic refinement. A corollary is excessive power requirements. Such systems can be defended for hovering flight, but their highspeed potential is nonexistent.

There may be an exception to this generalization in the form of a convertible "pusher" to fixed-wing cyclogiro arrangements. A patent by Wilcox (Reference 33W) shows a very straightforward system for changing from a hovering "pusher" cyclogiro to a multiplane fixed-wing high-speed aircraft. The simplicity of such an arrangement may offset the limitation on the aircraft's hovering capability.

Class 8: Miscellaneous systems

An unusual system was proposed by Hill and Nicholas (Reference 36H), the "jet flap cyclogiro". They proposed that the cyclogiro wheel be rotated by a reaction jet at the trailing edge of the blades and that the lift of the blades, assumed fixed (nonfeathering), be modulated by "jet flap" action. This in turn suggests rotor control by fluidics rather than by mechanical means. This particular proposal compounds the difficulties inherent to the jet flap phenomenon to those proper to the cyclogiro. Other indescribable cyclogiro systems are also to be found in this category.

7. Full-Feathering Universal Pitch Systems

It has been shown in the preceding discussions that each cyclogiro pitch regime operates efficiently only within a specific and related rotor advance ratio range; that is, the low-pitch system is very effective at low forward speeds and at hover, while, conversely, the high-pitch system excels at high forward speeds but suffers in the near-hover condition. Thus, in order to evolve a completely efficient full-flight-range high-speed cyclogiro, a system must be determined that will allow the rotor blade feathering motion to operate at its best efficiency regardless of its advance or pitch ratio. The full-feathering VTOL cyclogiro thus will be able to operate at nearly any pitch ratio between zero and infinity. The background, kinematics, aerodynamics, and mechanism required to obtain this system will be briefly discussed here.

The initial "discovery" of the need for a full-feathering universal pitch cyclogiro mechanism was explained and detailed by Rohrbach in a remarkable patent first filed in Germany in 1932 (Reference 58R). Although often described to the contrary, The Rohrbach Project "B" cyclogiro (Figures 67 through 69) was probably intended to make use of the full-feathering system as reflected in the patent (Reference 58R). The yet-to-be-understood mechanical requirements for a full-feathering mechanism, the political difficulties of the time (1932-1935), and the reorganization of the Rohrbach Company (Reference 48R) probably were responsible for lack of completion of this advanced VTOL system. In his patent, Rohrbach discusses the simple and inadequate feathering mechanisms proposed for the low-pitch cyclogiros of his and previous times.

He then demonstrates the need for the efficient universal pitch feathering arrangement and describes a mechanism and control to obtain such a system. What is of further interest is that the patent anticipates the need for the blades to translate through the regime of low-pitch high blade accelerations to pi-pitch and thence through the area of high-pitch blade accelerations. The patent also anticipates the need for a means to relieve the blade accelerations in the vicinity of pi-pitch. The means was later to be called by Eastman "pitch amplification".

The patent describes pitch amplification in this manner:

> "With a ratio of $U/V \doteq 1$ (pi-pitch), the wing (blade) has to perform a sudden turn in the lower apex of the circle of revolution (orbit angle $\psi = 180^{\circ}$). Because of the smallness of the aerodynamical forces which are occuring in the lower portion of the circle of revolution, with a ratio of U/V = nearly one, this 180° turn of the revolving wings could be performed much more gradually (lower and constant blade accelerations about its feathering axis) while a good deal of the lower part of the circle of revolution is transversed without noticeable aerodynamical loss."

The critical problem of the full-feathering system is to obtain the smooth passage of the rotor blade across the pi-pitch area. Eastman (Reference 2E) was able to demonstrate the quasi-mechanical and structural means to perform this transition and to insure efficient aerodynamic performance at the same time.

To understand kinematically how this is done, consider Figure 96. It is, in effect, a repetition of Figure 89, in which the x-x axis has been given the slope of 1/2 in order to place the curve of $p = \pi$ (a straight line) at right angles to the y-y axis. Thus, the Θ_p vs. ψ curves for the low- and high-pitch systems become geometrically symmetrical about the $p = \pi$ line. This fact will become significant in the design of the full-feathering cyclogiro control mechanism.

In Figure 96, the dot-dash curves show amplified low- and high-pitch blade motions for the pitch ratios of $\pi \times .7$ and $\pi / .7$,

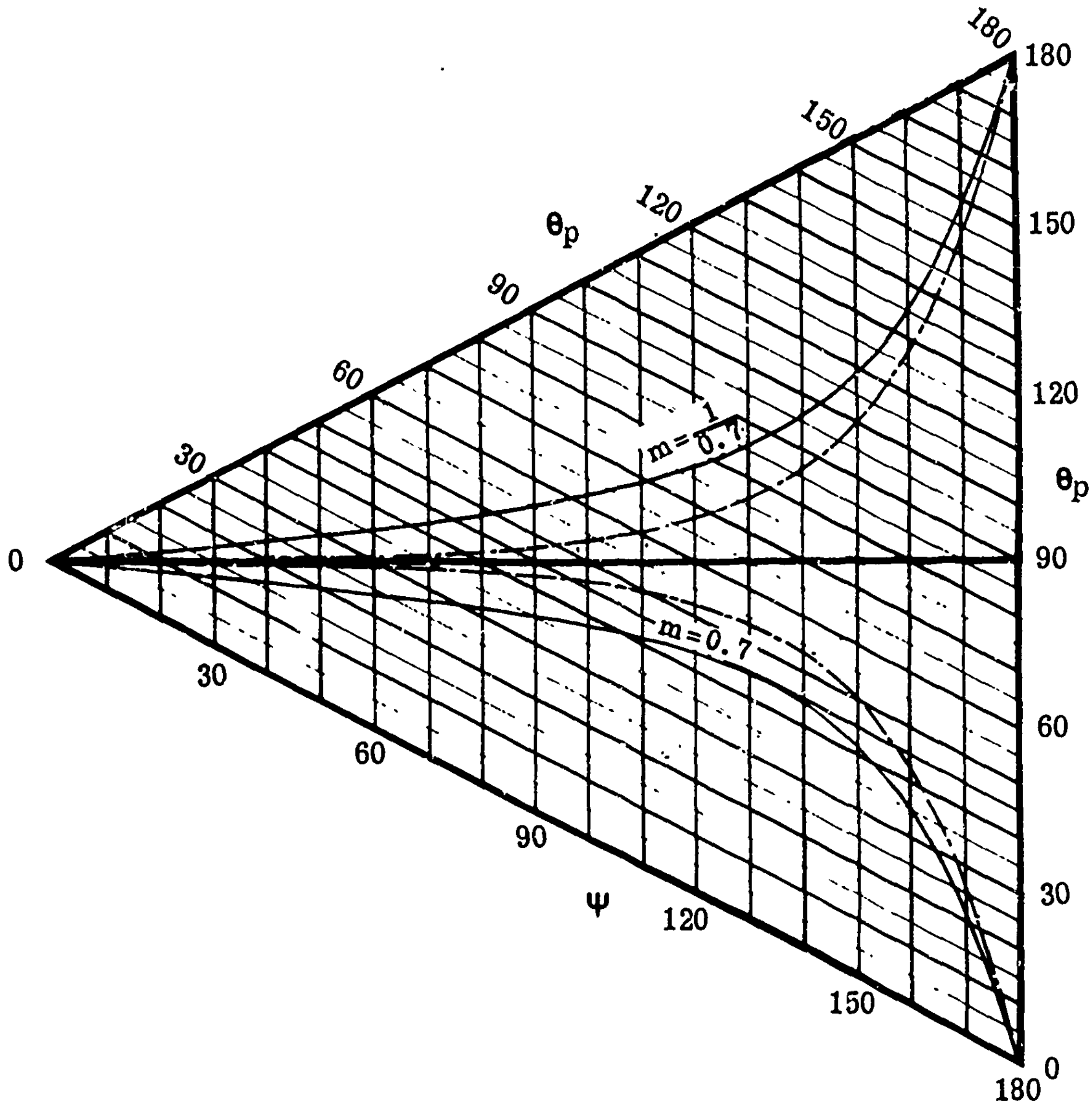


Figure 96. Modification of Figure 89 to Demonstrate Change-Over From Low- to High-Pitch Regime Through Pitch Amplification.

respectively. The appropriate blade motions are obtained by multiplying all ordinates by a constant of such a magnitude that the resultant curves are tangent to the $p = \pi$ line at the point where $\Theta = 0$ or at the top of the rotor orbit. Thus, the angular velocity $d\beta/dt$ when $\Theta = 0$ is exactly the same for $p = .7$ and for $p = 1/.7$. Consequently, if a mechanism can be designed to switch the pitch ratio from $.7\pi$ (low pitch) to $\pi/.7$ (high pitch) at the exact moment when the blade passes through the $\Theta = 0$ top position, no shock would result upon the rotor blade or mechanism. Thus, for a multiblade rotor system, the blade could be switched successively from the low-pitch to the high-pitch range. By this means, a smoothly progressive aerodynamic performance is produced which would be the equivalent of the performance of the pi-pitch system when half of the number of blades are operating in the low-pitch range and the other half in the high-pitch range. It may be shown (Reference 30K) by this arrangement that the critical blade accelerations may be less than those developed by the isolated amplified-pitch system.

A full-feathering rotor system is described in some detail by Kirsten (Reference 30K). This system involves a system of clutches and differentials at each rotor blade root plus several eccentric devices required to obtain the desired pitch motion. In the schematic of the full-feathering cyclogiro (Figure 78), Kirsten indicates the "rocking mechanism" only in the schematic of the universal pitch mechanism (view A-A, item "e"), and it is in this specific area of the rocking mechanism that the full-feathering system is open to criticism.

Although the aerodynamic performance potential of the full-feathering cyclogiro is unquestionable, a simpler and less delicate mechanism must be evolved which will safely produce universal pitch feathering. Such a system remains to be developed.

8. Aerodynamic Analysis of Cyclogiro Rotors

Background

Simplified aerodynamic analyses of cyclogiro rotors are straightforward enough that they appeared in the early 1930's. Analyses by Strandgren (Reference 130S) and Wheatley (Reference 25W) appeared simultaneously in 1933. Heuver and Hage presented a more refined analysis in Reference 30H (1943). The most recent analysis available today is that of Eastman (Reference 2E), last revised in 1951. Actually, the Heuver and Eastman analyses are quite similar and serve as a basis for the discussion which follows. These analyses are not by far as rigorous as they might be since unsteady effects are ignored, uniformity of the induced velocity components is assumed, and two-dimensional airfoil characteristics are used, with no really adequate provisions for stall. Much work thus remains to be done to produce a satisfactory aerodynamic analysis of the cyclogiro rotor.

<u>Aerodynamic Characteristics Based on Local Air, for Forward Flight</u>

The angular relationships and velocity triangle for a blade element are shown in Figure 87, which shows a blade element section by a vertical plane parallel to the direction of flight. Conditions are assumed to be uniform in the spanwise direction. The velocity V is not the aircraft forward speed, but it is the local velocity at the rotor cylinder, assumed to be uniform throughout the cylinder. V will be related to the forward velocity in the developments that follow.

From Figure 87, local rotor blade angle of attack α_b is given by

$$\alpha_b = \alpha_1 + \theta_p - (\Phi - i_b)$$

where

α_1 = the rotor angle of attack based on local air. The magnitude of α_1 determines the amount of lift (in the vertical direction of the rotor). Thus, α_1 is also the angle between the local air flight path and the rotor axis of symmetry. If $\alpha_1 = 0$, the cyclogiro has no lift; it has only thrust. α_1 is controlled by the pilot.

θ_p = the inclination of the blade path to the local-air flight path. Its expression was given on page 114 as

$$\tan \theta_p = \frac{\sin \psi}{j + \cos \psi}$$

j = the advance ratio, $j = \dfrac{V}{\pi n D}$ where V is the local, not the forward-flight velocity.

Φ = the blade angle introduced by the rocking mechanism.

i_b = the incidence angle determined by the orientation of the blade on the control shaft.

Φ_b = $\Phi - i_b$ defines the amplitude of the rocking motion. This angle is determined graphically or analytically from the pitch-change mechanism characteristics. A typical graphical plot is given in Reference 30H. A typical analytical determination is given in Refer- 30H. For the mechanism shown on page 116, one has

$$\tan \Phi = \frac{\sin(\psi + \alpha_1)}{m + \cos(\psi + \alpha_1)}$$

When both α_1 and i_b are zero, the rotor has no lift and exerts pure thrust. One has then

$$\alpha_{bt} = \tan^{-1} \frac{\sin \psi}{j + \cos \psi} - \tan^{-1} \frac{\sin \psi}{m + \cos \psi}$$

$$\alpha_{bt} = \tan^{-1} \frac{(m - j) \sin \psi}{1 + mj + (m + j) \cos \psi}$$

This periodic variation governs the thrust, as α_1 governs lift. It can be measured by the thrust angle of attack, obtained by letting $\psi = 90^\circ$ in the above equation.

$$\alpha_T = \tan^{-1} \frac{m - j}{1 + mj} \approx \frac{m - j}{1 + mj}$$

To obtain any desired thrust action, the pilot controls the blade-rocking motion, which is defined by m. This in turn controls the value of α_T.

When $m > j$, α_T is positive and the rotor exerts thrust.

When $m < j$, α_T is negative, and the rotor generates power by windmill action. In either case, the action can be visualized by observing the direction of the blade-lift vector at $\psi = 90^\circ$ and $\psi = 270^\circ$ on one of the paths in Figure 85. When α_T is positive, both vectors have a forward component, and their vertical components produce a retarding torque. When α_T is negative, however, both vectors have a rearward component and they produce a driving torque.

In general, rotor forces may be computed by resolution of the blade loads into three components, as shown in the upper left-hand corner of Figure 87. The three forces--L', normal to the local-air flight path; T', parallel to the path; and F', tangential to the orbit--are instantaneous values of the desired rotor forces and must be averaged over one complete cycle to provide mean values. Actually, the blade angle of attack α_b is calculated at twelve points equally spaced around the orbit, and the corresponding instantaneous values of the three rotor coefficients are computed.

Symbols and coefficients are used as follows:

Blade Lift Normal to Blade Path: $L_b = C_{L_b} S \, 1/2 \, \rho V_b^2$

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θ_p = the inclination of the blade path to the local-air flight path. Its expression was given on page 114 as

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j = the advance ratio, $j = \dfrac{V}{\pi n D}$ where V is the local, not the forward-flight velocity.

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$$\alpha_{bt} = \tan^{-1} \frac{(m-j) \sin \psi}{1 + mj + (m+j) \cos \psi}$$

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Symbols and coefficients are used as follows:

Blade Lift Normal to Blade Path: $L_b = C_{L_b} S \, 1/2 \rho V_b^2$

Blade Drag Parallel to Blade Path: $D_b = C_{D_b}\ S\ 1/2\,\rho V_b^2$

Mean Lift Normal to Local-Air Flight Path: $L_1 = C_{T_1}\ S\ 1/2\,\rho V^2$

Main Tangential Force: $F = C_F\ S\ 1/2\,\rho V^2$

Power Input: $F\ V/j \quad P = (C_{F/j})\ S\ 1/2\,\rho V^3$

Effective Power: $T_1 V = C_{T_1}\ S\ 1/2\,\rho V^3$

Parasite Power, $P - T_1 V$, $P_p = (C_{F/j} - C_{T_1})\ S\ 1/2\,\rho V^3$

S is the total blade area.

The instantaneous values are defined as follows:

$$L' = C_L'\ S\ 1/2\,\rho V^2 = L_b \cos \Theta_p + D_b \sin \Theta_p$$

$$C_L' = C_{L_b}\,(V_b/V)^2 \cos \Theta_p + C_{D_b}\,(V_b/V)^2 \sin \Theta_p$$

$$T' = C_{T'}\ S\ 1/2\,\rho V^2 = L_b \sin \Theta_p - D_b \cos \Theta_p$$

$$C_{T'} = C_{L_b}\,(V_b/V)^2 \sin \Theta_p - C_{D_b}\,(V_b/V)^2 \cos \Theta_p$$

$$F' = C_{F'}\ S\ 1/2\,\rho V^2 = L_b \sin(\psi - \Theta_p) + D_p \cos(\psi - \Theta_p)$$

$$C_F' = C_{L_b}\,(V_b/V)^2 \sin(\psi - \Theta_p) + C_{D_b}\,(V_b/V)^2 \cos(\psi - \Theta_p)$$

Blade interference is disregarded. Blade coefficients are those for any chosen airfoil, for a chosen aspect ratio; for example, 6 (as in Reference 30H) or 10 (as in Reference 2E). The ratio $(Vb/V)^2$ is calculated from the equation

$$\left(\frac{V_b}{V}\right)^2 = \frac{1}{j^2}\,(1 + 2j \cos \psi + j^2)$$

The rotor coefficients C_L and C_T are the arithmetic averages of the instantaneous values calculated as described above.

The aerodynamic performance of the rotor can be presented in the form of lift-thrust polars (C_L against C_T curves), which are comparable with constant RPM polars for a conventional wing-and-powered-nacelle combination. It is of interest to note the very large thrust which can be obtained without rocking the blades;

i.e., with m = ∞. In this case, the propelling action is essentially the same as for a flapping and oscillating airfoil, analyzed by Garrick in NACA TR No. 567.

Figure 107 shows a good efficiency of the cyclogiro rotor, when used as a propeller exerting thrust, but not lift. An additional advantage of the cyclogiro over the equivalent screw-propelled wing must be noted. Screw-propeller efficiency is based on a useful thrust which includes that required to overcome wing drag. In contrast, the efficiency shown for the cyclogiro rotor is based on net thrust, so that the power to overcome the drag of the lifting surfaces contributes to the propulsion losses instead of being recognized as useful thrust action. If blade drag is added to the net thrust, according to the 12-point average, the maximum efficiency will be at least 98 percent. In keeping with this figure, Garrick has shown in NACA TR No. 567 that for an infinite wing in pure flapping motion, the efficiency approaches 100 percent.

The approach to 100 percent propulsive efficiency can be explained as follows. In horizontal flight, propulsion results from the gliding action of the descending blade. The torque applied to the rotor simply shifts some of the weight from the ascending to the descending blade. Consequently, the only power loss attributable to propulsion results from a slight increase in overall blade drag. The increase, caused by higher blade velocity as compared with forward velocity, vanishes as j approaches infinity, but that due to concentration of lift on the descending blade remains.

Forward-Flight Theory Based on the "4-Point Average"

Eastman, in Reference 2E, after developing the "12-point average" theory, remarks that one gets a clearer physical picture by not attempting to follow the blades through 12 positions, but by looking at things globally and assuming that the effect of blade action is to uniformly deflect and accelerate the air passing through the rotor. He found that rotor coefficients, based on the local velocity V, can be expressed mathematically and with reasonable accuracy by averaging the four instantaneous coefficients existing at the quarter-turn points.

Expressions for rotor lift, thrust, and tangential force coefficients are obtained by adding the expressions for their instantaneous values at the quarter-turn points and dividing by four. At the position ψ = 180°, the blade velocity reverses when $j < 1$. As a result, the coefficients below may have different expressions for low and for high pitch. These expressions are given below, together with the equations of Table IV.

$$C_{L1} = \frac{dC_{L_b}}{d\,\alpha_b}\left[G\,i_b + M\,\alpha_1\right]$$

$$C_{T1} = \frac{dC_{L_b}}{d\alpha_b} \frac{\sqrt{1+j^2}}{2j^2} \alpha_T - G\, C_{D_{b_o}} - \frac{dCdb}{d\ \ b^2} \left[\frac{\sqrt{1+j^2}}{2j} \alpha^2{}_T + H \alpha^2{}_1 \right.$$

$$C_F = \frac{dC_{L_b}}{d\alpha_b} \frac{\sqrt{1+j^2}}{2j} \alpha_T + Q\, C_{D_{b_o}} + \frac{dC_{db}}{d\alpha_b{}^2} \left[\frac{\sqrt{1+j^2}}{2j^2} \alpha^2{}_T + R \alpha^2{}_1 \right.$$

where

$$C_{L_b} = (dC_{L_b}/d\alpha_b)\ \alpha_b$$

$$C_{D_b} = C_{D_{b_o}} + (dC_{Db}/d\alpha^2{}_b)\ \alpha^2{}_b$$

The parasite power coefficient is given by

$$C_{F/j} - C_{T_1} = E\, C_{D_{b_o}} + \frac{dC_{Db}}{d\alpha^2_b} \left[\frac{(1+j^2)^{2/2}}{2j^3} \alpha_T{}^2 + (H + R/j)\, \alpha_1{}^2 \right]$$

$dC_{Db}/dC_L{}^2$ represents only the variation in blade profile drag, the relationship of induced drag effect being considered separately.

This is usually so small that the second turn on the right-hand side of the above equation can usually be disregarded. Eastman shows that, should greater accuracy be required, one can use

$$C_{F/j} - C_{T_1} = K_p\, C_{D_{b_o}},$$

where

$$K_p = E + \frac{1}{C_{D_{b_o}}} \frac{dC_{Db}}{dC_{L_b}{}^2} \left[2j\sqrt{1+j^2}\, (C_{T_1} + G\, C_{D_{b_o}})^2 + B\, C_{L_1}{}^2 \right]$$

Eastman compared, in Reference 2E, the results of the "12-point average" and of the "4-point average" methods. He found fairly good agreement, except when the coefficients were large. The discrepancy was due to blade stalling, which is accounted for in the 12-point method and not in the 4-point method.

Induced Velocity Effects

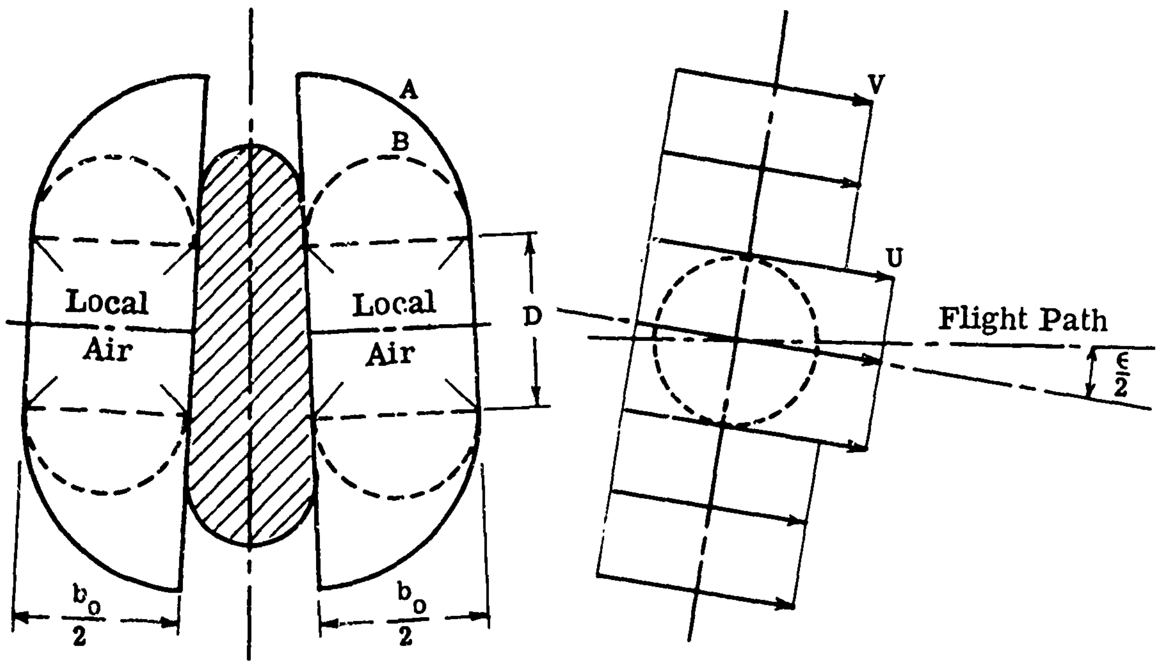
In the foregoing study, the assumed uniform flow through

TABLE IV. COEFFICIENT OF EQUATIONS ON PAGES 135 AND 136

	$j > 1$	$j = 1$	$j < 1$
B	$\frac{2\sqrt{1+j^2}}{j+\sqrt{1+j^2}}$	← Use Either →	$\frac{2j\sqrt{1+j^2}}{j^2+\sqrt{1+j^2}}$
E	$\frac{1}{2} + \frac{3j+(1+j^2)^{3/2}}{2j^3}$	← Use Either →	$\frac{1+3j^2+(1+j^2)^{3/2}}{2j^3}$
G	$\frac{1+j^2+j\sqrt{1+j^2}}{2j^2}$	← Use Either →	$\frac{2+\sqrt{1+j^2}}{2j}$
M	$\frac{m}{2}\left[\frac{m(1+j^2)-2j}{j^2(m^2-1)} + \frac{\sqrt{1+j^2}}{1+mj}\right]$	$\frac{m}{2}\left[\frac{(1+j)^2}{2j^2(1+m)} + \frac{\sqrt{1+j^2}}{1+mj}\right]$	$\frac{m}{2}\left[\frac{1+j^2-2mj}{j^2(1-m^2)} + \frac{\sqrt{1+j^2}}{1+mj}\right]$
H	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 + \left(\frac{j-1}{m-1}\right)^2 + \frac{2j^3\sqrt{1+j^2}}{(1+mj)^2}\right]$	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 + \frac{2j^3\sqrt{1+j^2}}{(1+mj)^2}\right]$	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 - \left(\frac{1-j}{1-m}\right)^2 + \frac{2j^3\sqrt{1+j^2}}{(1+mj)^2}\right]$
Q	$\frac{2j+\sqrt{1+j^2}}{2j^2}$	← Use Either →	$\frac{1+j^2+\sqrt{1+j^2}}{2j^2}$
R	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 - \left(\frac{j-1}{m-1}\right)^2 + \frac{2j^2\sqrt{1+j^2}}{(1+mj)^2}\right]$	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 + \frac{2j^2\sqrt{1+j^2}}{(1+mj)^2}\right]$	$\frac{m^2}{4j^2}\left[\left(\frac{1+j}{1+m}\right)^2 + \left(\frac{1-j}{1-m}\right)^2 + \frac{2j^2\sqrt{1+j^2}}{(1+mj)^2}\right]$

the rotor cylinder provided the reference velocity V. Both the direction and the magnitude of this local velocity must be determined before the theory can be applied to an actual cyclogiro.

When the rotor is producing lift without thrust, it acts like a multiplane. This suggests that the area of the equivalent airstream, which is assumed to be deflected by lift action, may be that shown in the sketch below. This assumption was used by Wheatley (Reference 25W), and it is justified by tests of the high-pitch models.



CROSS SECTION OF THE DEFLECTED FLOW

VELOCITY THROUGH ROTOR CYLINDER

On the other hand, pi-pitch model tests seem to indicate that the area becomes smaller when the advance ratio approaches unity. There are also indications that the fuselage width may add to the equivalent span. Thus,

$$\pi b_o^2/4 < A_L < b_o D + \pi b_o^2/4$$

The area of the equivalent uniform flow, which is accelerated by thrust action, is much larger than that for an equivalent screw-propelled wing. Wheatley (Reference 25W) used the projected area of the rotor cylinder, and experimental evidence seems to justify this assumption. Thus,

$$A_T = b_o D$$

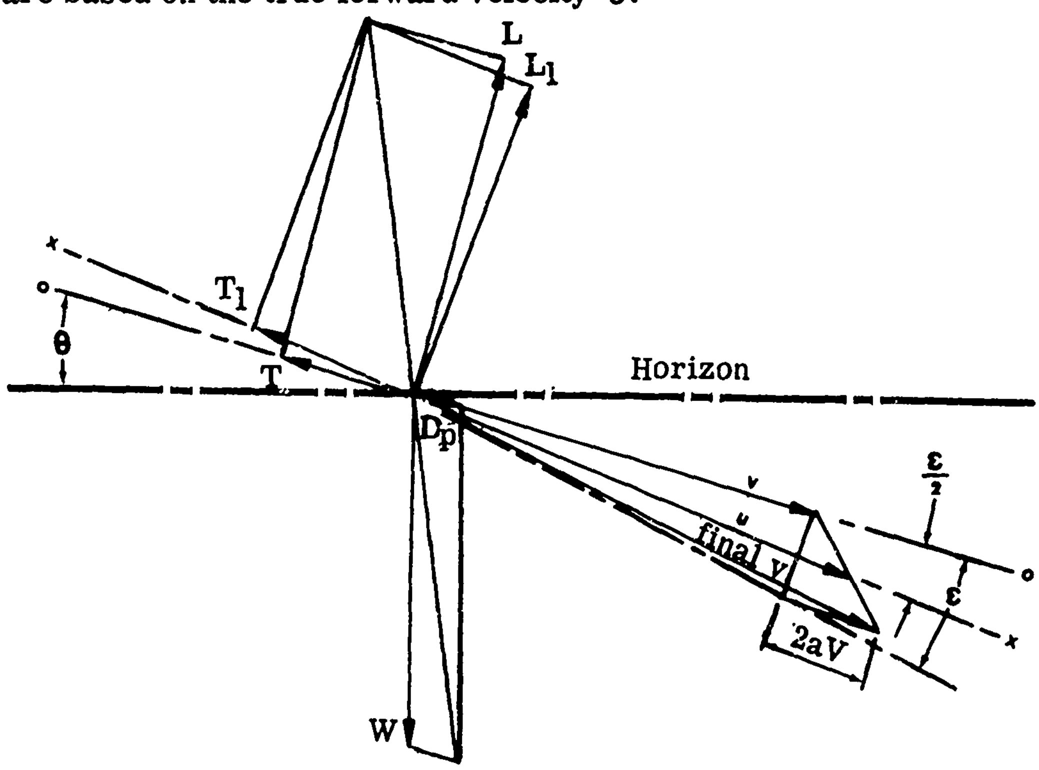
The combined equivalent flow pattern may be described as follows. An air stream having an area A_L and a velocity U is deflected by the force L_1 through an angle ϵ. Following accepted wing theory, the air is assumed to be deflected through half of this angle when it reaches the rotor. Therefore, $\epsilon/2$ determines the direction of the local air. If δ is the rotor angle of attack measured to the reference axis (angle between m - m and x - x in Figure 78), α is related to α_1 (page 110), rotor angle of attack relative to local air, by

$$\alpha = \alpha_1 + \epsilon/2$$

Superimposed upon the deflected flow is a region of area A_T, which is accelerated by the force T_1. Following accepted propeller theory, the assumed total change in velocity is $2aU$, half of which is attained when the air reaches the rotor. Therefore,

$$V = U(1 + a)$$

In the sketch below, the forces T and L are the true thrust and lift, acting parallel and perpendicular to the flight path 0 - 0. D_p is the residual drag. The forces T_1 and L_1 act parallel and perpendicular, respectively, to the local-air flight path x - x. They will be expressed in terms of new coefficients, C_X and C_N, which are based on the true forward velocity U.



The momentun theory for lift gives the relation between C_N and sin ($\epsilon/2$); that for thrust gives the relation between C_X and the slip-stream factor, a.

$$L_1 = (\rho A_L U) 2U \sin \epsilon/2$$

$$C_N = \frac{L_1}{S\,1/2\,\rho U^2} = \frac{4A_L}{S} \sin \frac{\epsilon}{2}$$

$$T_L = \rho A_T U (1 + a) (2a U)$$

$$C_x = \frac{T_1}{S\,1/2\,\rho U^2} = \frac{A_T}{S} (a + a^2)$$

$$a = 1/2 \left(-1 + \sqrt{1 + \frac{C_x S}{A_T}}\right)$$

From the sketch above

$$C_N = C_L \cos \frac{\epsilon}{2} - C_T \sin \frac{\epsilon}{2}$$

$$C_x = C_T \cos \frac{\epsilon}{2} + C_L \sin \frac{\epsilon}{2}$$

Hence, by straightforward substitution

$$C_N = \frac{C_L (4 A_L/S)}{\sqrt{C_L^2 + (C_T + 4 A_L/S)^2}}$$

$$C_x = \frac{C_L^2 + C_T (C_T + 4 A_L/S)}{\sqrt{C_L^2 + (C_T + 4 A_L/S)^2}}$$

The effective power, T_1V, may be expressed in terms of C_x, since

$$T_1 = C_x S\,1/2\,\rho U^2 \quad \text{and} \quad V = U (1 + a)$$

$$T_1 V = 1/2\, C_x \left(\sqrt{1 + C_x S/A_T}\right) S\, 1/2\, \rho U^3$$

The equations for C_N, C_x, and T_1V establish the relation among lift, thrust, and effective power. The relation is important, because it determines cyclogiro performance when induced velocity effects predominate, as in near-hovering flight.

The gliding condition may be approximated by letting $C_x = 0$, because this means that only rotor parasite power will be supplied by the engine. In this case,

$$C_L^2 + C_T^2 + 4\, A_L/S\; C_T = 0$$

The slope of the flight path is obtained from

$$\tan \Theta = C_T/C_L$$

The procedure for the complete cyclogiro performance calculations is as follows. For assumed values of j, α_1, and m, one calculates first local-air lift, thrust, and parasite power coefficients. Then the conversion to free-stream coefficients C_N, C_x, and C_{pp} (C_{pp} is the parasite power coefficient: $C_{pp} = P_p/Sq\,U$) may be made after the velocity ratio, V/U, is known. This ratio, equal to $1 + a$, is obtained by substituting

$$C_x = C_{T_1}\,(1 + a)^2$$

into the equation

$$C_x = \frac{4\,A_T}{S}\,(a + a^2)$$

Hence,

$$1 + a = \frac{1}{1 - S/4\,A_T C_{T_1}}$$

For convenience, the other relations used to complete the analysis are listed below:

$$C_x = C_{T_1}\,(1 + a)^2$$

$$C_N = C_{L_1}\,(1 + a)^2$$

$$C_{pp} = K_p\; C_{D_{b_o}}\,(1 + a)^3$$

$$C_p = C_{pp} + C_{T_1} (1 + a)^3$$

$$\epsilon/2 = \sin^{-1} (C_N S/4 A_L)$$

$$C_T = C_x \cos \frac{\epsilon}{2} - C_N \sin \frac{\epsilon}{2}$$

$$C_L = C_x \sin \frac{\epsilon}{2} + C_N \cos \frac{\epsilon}{2}$$

$$C_{Di} = C_P - C_T$$

$$\alpha = \alpha_1 + \frac{\epsilon}{2}$$

$$V/\pi nD = j/(1+a)$$

The coefficient C_{De} is called the extended-drag coefficient, because it represents a drag which, when multiplied by U, gives the entire power which does not contribute to the net thrust. In addition to parasite drag and induced drag, it includes an equivalent drag which accounts for propulsion losses. Its components may be separated as follows:

$$C_{D_e} = C_{pp} + C_{T_1} (1 + a)^3 - C_T = C_{pp} + C_x (1+a) - C_T$$

or

$$C_{D_e} = K_p \, C_{D_{b_o}} (1 + a)^3 + (C_x - C_T) + a \, C_x$$

The first term accounts for parasite power. The second term accounts for induced drag, and, when ϵ is small, it may be approximated by the familiar expression $SC_L{}^2/4 A_L$. The last term accounts for slipstream power. Parasite power may be separated into three parts, by observing the components of the K_p equation

$$K_p = E + \frac{1}{C_{Dbo}} \frac{dC_{Db}}{dC_{Lb}{}^2} \left[2j \sqrt{1 + j^2} \, (C_{T_1} + G \, C_{Dbo})^2 + B \, C_{L_1}{}^2 \right]$$

The first term, E, accounts for the effect of minimum blade profile drag. The second term accounts for the increase in profile drag with C_{Lb} and is in two parts: that due to thrust action and that due to lift action.

When the rotor is autorotating with the torque equal to zero, C_{DC} is truly comparable with wing drag. Neglecting the slight retarding influence of blade profile drag, $a = 0$ and $C_{T1} + GC_{Dbo} = 0$. As a result, the drag coefficient of a cyclogiro rotor is expressed, in the above equation, in the conventional manner. The first two terms are profile drag; the last term is induced drag and must be replaced by $C_x - C_T$ when ϵ is large.

$$C_D = E\, C_{Dbo} + B\, C_L^2\, dC_{Db}/dC_{Lo}^2 + C_L^2\, S/4\, A_L$$

The efficiency of a cyclogiro rotor used for propulsion alone is $\frac{TU}{p}$ or simply C_T/C_p. Therefore,

$$e = \frac{C_T}{C_x + K_p\, C_{Dbo}\,(1 + a)^3 + a\, C_x}$$

As has been pointed out, the propulsive efficiency of a cyclogiro must include blade drag as part of the useful thrust, if it is to be compared with the propulsive efficiency of a screw-propeller airplane. The 12-point average method indicated that this efficiency might be as high as 98 percent. Now it is possible to be more specific. The additional useful thrust is that which would be required to overcome the drag of the blades if they were used in the conventional manner, thereby providing lift but not thrust. This is the drag which exists when $m = \infty$ and $j = \infty$. Therefore,

$$\text{Equivalent efficiency} = \frac{C_T + C_{Dbo} + C_L^2\, \dfrac{dC_{Db}}{dC_{lb}^2} + (C_x - C_T)}{C_p}$$

This efficiency increases as the lift action increases, but its conservative zero lift value will be used for simplicity.

$$\eta = \frac{C_T + C_{Dbo}}{C_p} = e\, \frac{(C_T + C_{Dbo})}{C_T}$$

Representative values of η are as follows. Let $S/A_T = 1$, $m = \infty$, and $C_T = 0.04$. Then $\eta \approx 0.97$. Representing a steep climb by using $m = 2$ and $C_T = 0.2$ gives $\eta \approx 0.92$.

Aerodynamic Characteristics in Hover

In the hovering condition, rotor force coefficients become infinite, and a separate use of the momentum theory determines the value of V, C_{T1}, and P.

The momentum area being assumed to be $A_T = b_0 D$, one has

$$W = \rho A_T V (2V)$$

Hence,

$$V = \sqrt{\frac{W}{2\rho A_T}}$$

Also,

$$C_{T_1} = \frac{W}{S\,1/2\,\rho V^2} = 4\,A_T/S$$

and

$$P = P_p + WV$$

$$P = \frac{K_p\,C_{Dbo}\,S}{4\sqrt{2p}} \left(\frac{W}{A_T}\right)^{3/2} + W\,\frac{1}{2p}\left(\frac{W}{A_T}\right)^{1/2}$$

9. The Wright Field World War II Cyclogiro Project

It would seem that Heaver, who had been associated with Dr. Kirsten at the University of Washington in the 1930's, promoted interest in the cyclogiro at Wright Field at the beginning of World War II. As a result, analyses and preliminary design studies were performed and wind tunnel tests sponsored at the University of Washington. This effort was stopped, like many others, following the end of World War II.

The culmination of the Wright Field effort was the design of a fighter aircraft, designed on the same basis as the Bell XP-77. An artist conception of the cyclogiro aircraft is shown in Figure 59. Its general characteristics (taken from Reference 30H) are as follows:

Rotor

- High-Pitch System
- Range 1.25-20 Pi Pitch
- 3 Blades per Rotor
- Tandem Sets of Rotor
- Counterrotation of Fore and Aft Rotor Systems
- Total Blade Area = 90 ft.^{2}
- Area of One Blade = 7.5 ft.^{2}
- Span of One Blade = 6 ft.

Rotor Span = 15.5 ft.
Blade Taper = 7.3
Blade Section: NACA 0012 Series

Fuselage
Length - 25 ft.
Width - 3.5 ft.
Height - 6 ft.

Engine
Type W770-9
Normal - 465 HP @ 12,000 ft.
Military - 450 HP @ 27,000 ft.
515 HP @ 12,000 ft.
500 HP @ 27,000 ft.

A weight estimate is shown in Table V.

Estimated performance, calculated in accordance with the 12-point average method, discussed in the previous paragraph, is shown in Figure 97.

A performance comparison (estimated) with the Bell XP-77 airplane is as follows:

	XP-77	Cyclogiro
High Speed at Sea Level	327 MPH	340 MPH
High Speed at 27,000 Feet	420 MPH	428 MPH
Max. Rate of Climb, Sea Level	3,050 ft/min	2,900 ft/min
Max. Rate of Climb, 27,000 Feet	2,020 ft/min	2,000 ft/min
Speed Range (V max/V min)	4.5	8.5
Gross Weight	3,700 lbs	3,900 lbs

The cyclogiro and the XP-77 have the same engine, same armament, and approximately the same gross weight.

It will be noted that the above cyclogiro was not designed for hovering flight. However, its speed range is substantially in excess of that of the fixed-wing fighter.

The Wright Field conclusions (Reference 30H, 1943) were as follows:

1. The aerodynamic efficiency of the cycloidal propeller (rotor propulsion-lift device) appears to be superior to that of the conventional screw propeller and wing system.

TABLE V. WEIGHT ESTIMATE, WRIGHT FIELD CYCLOGIRO FIGHTER (Reference 30H)			
Design Gross Weight			3,900 lbs
Weight Empty		2,686	
Rotor Group			
12 Blades	282		
12 Spindles	92		
2 Rotor Structures	258		
2 Rotor Mechanisms	140		
Body Group		275	
Alighting Gear			
Main Landing Gear	202		
Auxiliary Landing Gear	90		
Powerplant Group (Less Propeller)		994	
Engine (As Installed)	835		
Engine Accessories	47		
Powerplant Controls	5		
Starting System	22		
Lubricating System	10		
Fuel System	75		
Fixed-Equipment Group (Less Surface Controls)		523	
Instruments	39		
Electrical	105		
Communicating	144		
Armament Provisions	183		
Furnishings	37		
Service Pickup	15		
Useful Load		1,014	
One Crewman Plus Chute		180	
56 Gallons Gasoline		336	
4.6 Gallons Oil		35	
Two 50-Caliber Guns		135	
50 Caliber - 400 Rounds Ammunition		125	
One 20-mm. Camera		135	
20-mm. Ammunition (100 Rounds)		62	
Gun Sights (N-7)		3	
Gun Camera (ANN-4)		3	

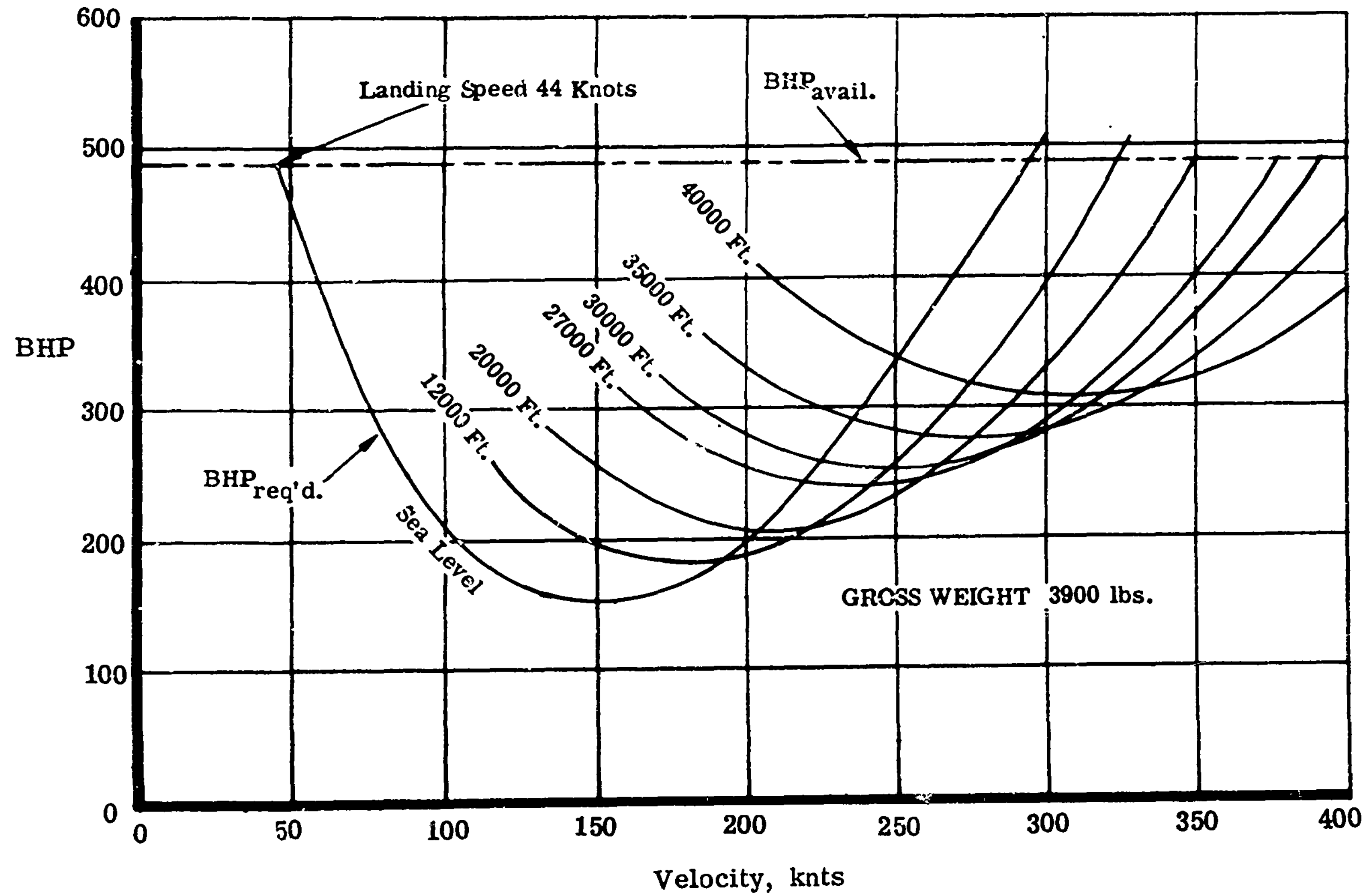


Figure 97. Theoretical Performance and Power Requirements of The Wright Field WW II Cyclogiro Project (Ref. 30H).

2. For conventional fighter power loadings, hovering flight can be attained only at low wing loadings, due to the limitations of the pitch-change mechanism.

3. The following advantages and disadvantages as compared with conventional fighters of the same power and useful load can be identified:

a. Advantages

(1) possibility of greater speed range
(2) possibility of high rate of roll and lower radius of turn
(3) somewhat improved visibility from the cockpit
(4) appears to be conveniently adaptable to nose armament installation
(5) lower external noise level due to cycloidal propellers instead of screw type

b. Disadvantages

(1) increased structural problems
(2) increased flutter and vibration problems
(3) possibility of stability and control difficulties
(4) increased mechanical problems

4. In the design studied, due to the inherent size of the fuselage, it appears to be feasible to use more power than that shown in the preceding analysis with little increase in airplane drag. Hence, increased performance should be attained, giving higher speeds, higher rates of climb, and possible hovering flight.

Further analyses of the cyclogiro fighter design by the Wright Field Propeller Laboratory were reported in July 1944 (Reference 39B). The report noted the following:

1. It appears that large oscillatory aerodynamic forces and torques are present in the rotor system discussed above.

2. Oscillatory forces and torques can be eliminated by revision of blade angle changing mechanisms or by entire redesign so that blade angles will conform to those required by the theoretical analysis.

3. Experimentally determined rotor efficiencies that compare favorably with values for conventional

airplane propeller and wing systems have been obtained in recent tests.

4. The stresses, as calculated for maximum applied load factor pullout from a terminal velocity dive in a fighter aircraft, are approximately twice the allowable stresses for the assumed type of construction (1943-1945 hollow steel type of construction of propellers).

5. Mechanical and vibrational difficulties and stress considerations appear to indicate that this type of aircraft would not have been suitable for use as a fighter. It is believed, however, that this type of aircraft would be feasible for use where flight velocity and load factors were not so great.

6. This type of aircraft is capable of hovering flight.

7. Further tests of existing rotor mechanisms are necessary to ascertain the degree of oscillatory forces and torques and the magnitude of the stresses encountered.

As a result of the conclusions of Reference 39B, additional work was performed by Eastman at the University of Washington under the auspices of the Army Air Forces. This work was concentrated on the solution of the problems noted above; i.e., the development of more satisfactory cyclogiro control mechanisms and the correlation of theoretical analyses with test results (results of wind tunnel tests were the only ones available). Much of the earlier discussion of this chapter was borrowed from Reference 39B. Eastman made his own preliminary design, which is shown in Figure 78. Calculated performance (not reproduced in this report) confirmed the Wright Field results; i.e., higher maximum speed, higher rate of climb, and higher speed range for the cyclogiro than for either the airplane of similar characteristics or the helicopter.

Eastman's conclusions (from Reference 39B) regarding the major features of the cyclogiro are still essentially valid at this time. These conclusions are reproduced here:

"Although the theory is somewhat inaccurate when the rotor force is extremely large, model tests covering three different ranges of blade-rocking motion verify the theoretical trends. As a result, the theory predicts the general characteristics of a full-feathering cyclogiro rotor with certainty, and makes reasonably reliable quantitative predictions for specific applications.

"A freely autorotating cyclogiro rotor acts like a multiplane. When its blade rocking motion is adjusted so that it autorotates slowly at high forward speeds, the advance ratio becomes so high that its characteristics will be essentially the same as those of a multiplane using the same blades and the same blade spacing. The autorotating speed will be fully controllable if a full-feathering mechanism can be perfected. The resulting effect upon rotor characteristics can be compared with that of an unlimited and fully controllable anti-stall device on a wing. If the slight retarding influence of mechanical friction is disregarded, the only apparent limitation on lift coefficient arises from the limitation on downwash angle. The stall is avoided by increasing the autorotating speed. As a result, rotor profile drag becomes larger, but it can be reduced to that of the equivalent multiplane, when high lift coefficient is no longer needed.

"If power is applied gradually so that rotor rpm is steadily increased beyond the autorotating speed, the drag will diminish gradually until it becomes zero. Thereafter, thrust is exerted, which will increase as long as power input is increased. If propulsive efficiency is important, the rocking motion should be changed gradually to avoid blade stalling.

"When the thrust required is negligible, so that the propelling action is used primarily to overcome the drag of the lifting surfaces, a very high advance ratio can be used, and the equivalent propulsive efficiency can exceed 98 per cent. In practice this figure will be reduced slightly by mechanical friction.

"The efficiency based on net thrust, as for example when the rotor replaces a screw propeller on a lighter-than-air craft or on a marine vessel, can be higher than that of a screw. In such applications, however, a more prominent reduction in power required will result from the use of rotor lift action to replace an existing control surface for steering or maneuvering, or for auxiliary sustentation.

"When rotor rpm is gradually reduced below that for autorotation, the drag increases and power is generated by windmill action. Neither the drag nor the power will increase indefinitely. The drag reaches a maximum when the air passing through the rotor is retarded to about half of its original speed; the power reaches a maximum when the air is retarded to about two-thirds of its original speed. To obtain these maximums, the stall is avoided by the use of low advance ratios, and the blade-rocking motion must be adjusted accordingly.

"Within the limits of power available, any combination of lift and thrust can be obtained by adjustment in inclination of the reference axis and in amplitude of the blade-rocking motion. In every case, the optimum rotor rpm, as determined by minimum parasite losses, is only slightly higher than that necessary to avoid blade stalling. When stalling does occur, it starts at one or more points on the orbit and its gradual progress prevents any sudden change in rotor force.

"A full-feathering cyclogiro offers distinct aerodynamic advantages over the screw-propelled airplane. Its span probably will be shorter than that of the airplane, for structural reasons. Nevertheless, its greater slipstream area and the ability to use its lifting surfaces for propulsion should result in higher rate of climb and higher maximum speed with the same power loading. In addition, it should be able to hover, and it should be extremely maneuverable regardless of the flight attitude. Its control will be positive and instantaneous, and since it is provided by the rotor mechanism, no need exists for additional control devices.

"According to the theory, full-feathering motion requires a transition from high-pitch motion, which rocks the blades relative to the reference axis, to low-pitch motion, which turns the blades through a complete revolution for every revolution of the rotor. This introduces a difficult amplified high-pitch motion. The use of this substitute motion will have little influence on the performance of the cyclogiro when it is climbing or when it is in level flight. It may be a handicap, however, in power-off maneuvers at very low forward speed.

"The structural problem is not as serious as might be expected, because rotor rpm will be low when forward speed is high. The problem can be further relieved by reducing the number of blades per rotor, so that a smaller blade aspect ratio will result for the same span. The theoretical blade-rocking motion will give reasonably steady lift if three blades are used per rotor, but the use of two blades per rotor may require a special rocking motion to avoid objectionable pulsations. The advantage arising from the use of fewer blades leads to conjecture regarding the employment of only one blade per rotor. Certainly this final step can be taken in gliding flight, for which rotor rpm normally will be zero, and for which a slow rotation will serve to reduce the gliding angle. In powered flight, it may be possible to compensate for the pulsations in the lift of a single moving wing. A study of this possibility should be made, recognizing that the use of a conical, rather than a cylindrical swept surface, may lead to a machine having the advantages of a cyclogiro without sacrificing any of those of the airplane."

10. Cyclogiro Test Data

Hover

Test data show incontrovertible evidence that cyclogiro rotors are capable of hover flight. They further indicate that conventional screw momentum theory is applicable, if one uses as the area of the accelerated flow the projected area of the rotor cylinder A_T defined previously. A comparison of cyclogiro and helicopter shows that the momentum area of the cyclogiro in hover is likely to be significantly lower than that of the corresponding helicopter (two to three times). This means a higher power loading in hover for the cyclogiro than for the helicopter. For a composite aircraft application (VTOL with maximum speed greater than 300 knots), a high power loading is required for the high-speed condition; therefore, a high power loading in hover is not likely to be detrimental from the standpoint of installed power. From the standpoint of environmental effects (downwash velocity), this is another matter. The cyclogiro is not likely to be competitive for a "disc" loading of 10 lbs/ft^2; a disc loading around 30 lbs/ft^2 seems to be more appropriate.

The static thrust of several old low-pitch cyclogiros is plotted in Figure 98 in the form of C_T against C_p, where

$$C_T = \frac{T}{\rho \omega^2 R^3 b}$$

$$C_p = \frac{P}{\rho \omega^3 R^4 b}$$

T = cyclogiro rotor thrust

ρ = air density

ω = cyclogiro rotor angular velocity

R = cyclogiro blade axis distance to center of rotation

b = cyclogiro rotal span

P = power required

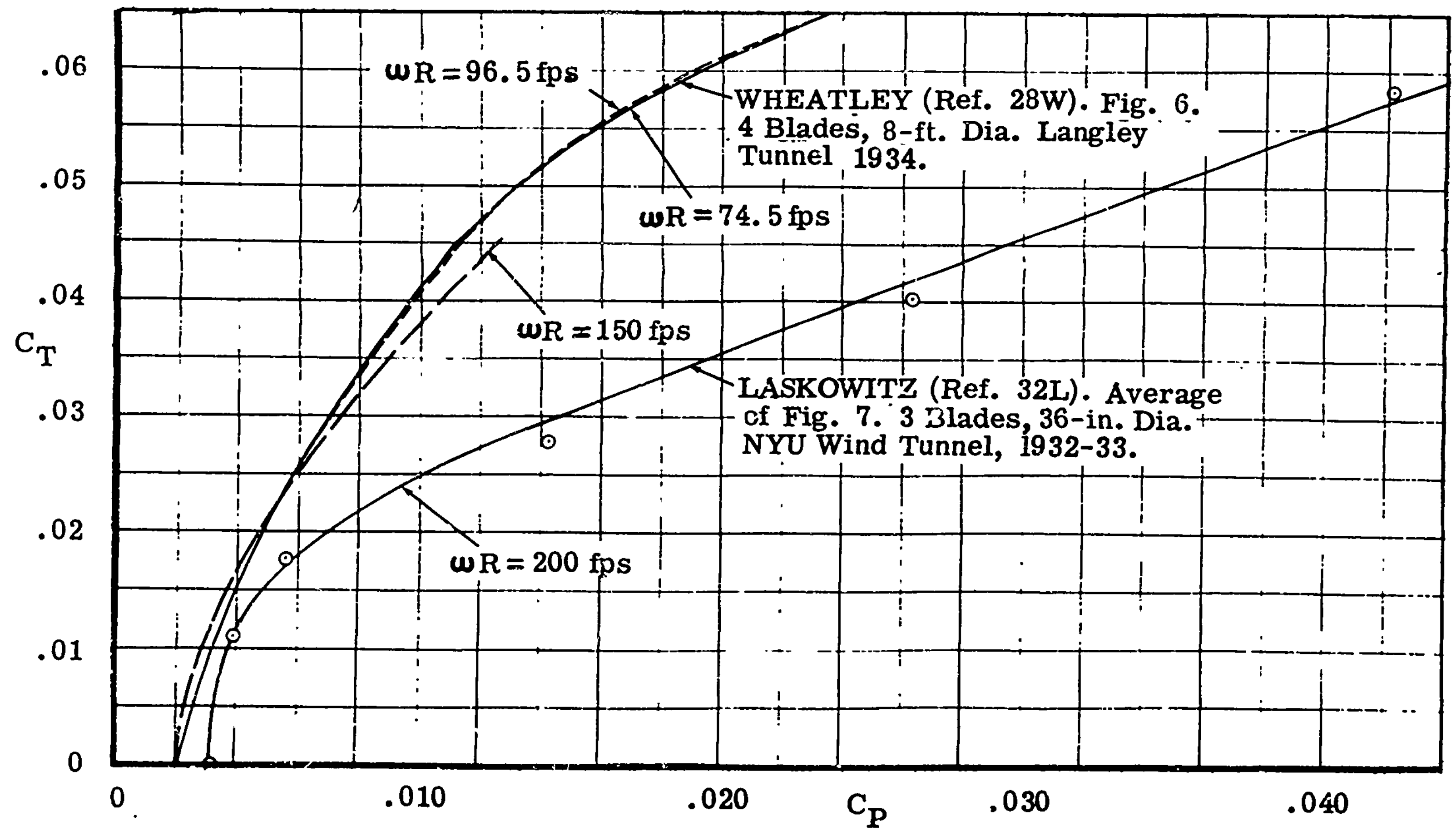


Figure 98. Comparative Static Lift Power Loading of Two Low-Pitch Cyclogiro Systems, With Variation in β and at Several Tip Speeds. Blades Alone.

The data of Figure 98 are replotted in Figure 99 in the familiar form of the figure of merit M versus the mean lift coefficient C_T/σ . C_T/σ for a cyclogiro may not have much meaning, but it is a convenient parameter σ, for a cyclogiro is defined (following Wheatley) as the ratio of the total blade chord to the peripheral length of the rotor cylinder.

$$\sigma = \frac{bc}{2\pi R}$$

where

b = the number of blades

c = the blade chord

The figure of merit is defined as usual as

$$M = .707 \frac{{C_T}^{3/2}}{C_Q}$$

All available test points are plotted and compared with typical helicopter results. It can be seen that most cyclogiros have performed in hover with a very poor efficiency. The exception is Moineau, with a figure of merit of 0.83. This definitely indicates that the hover potential of the cyclogiro is there, but the proper blade pitch mechanism is required for its exploitation.

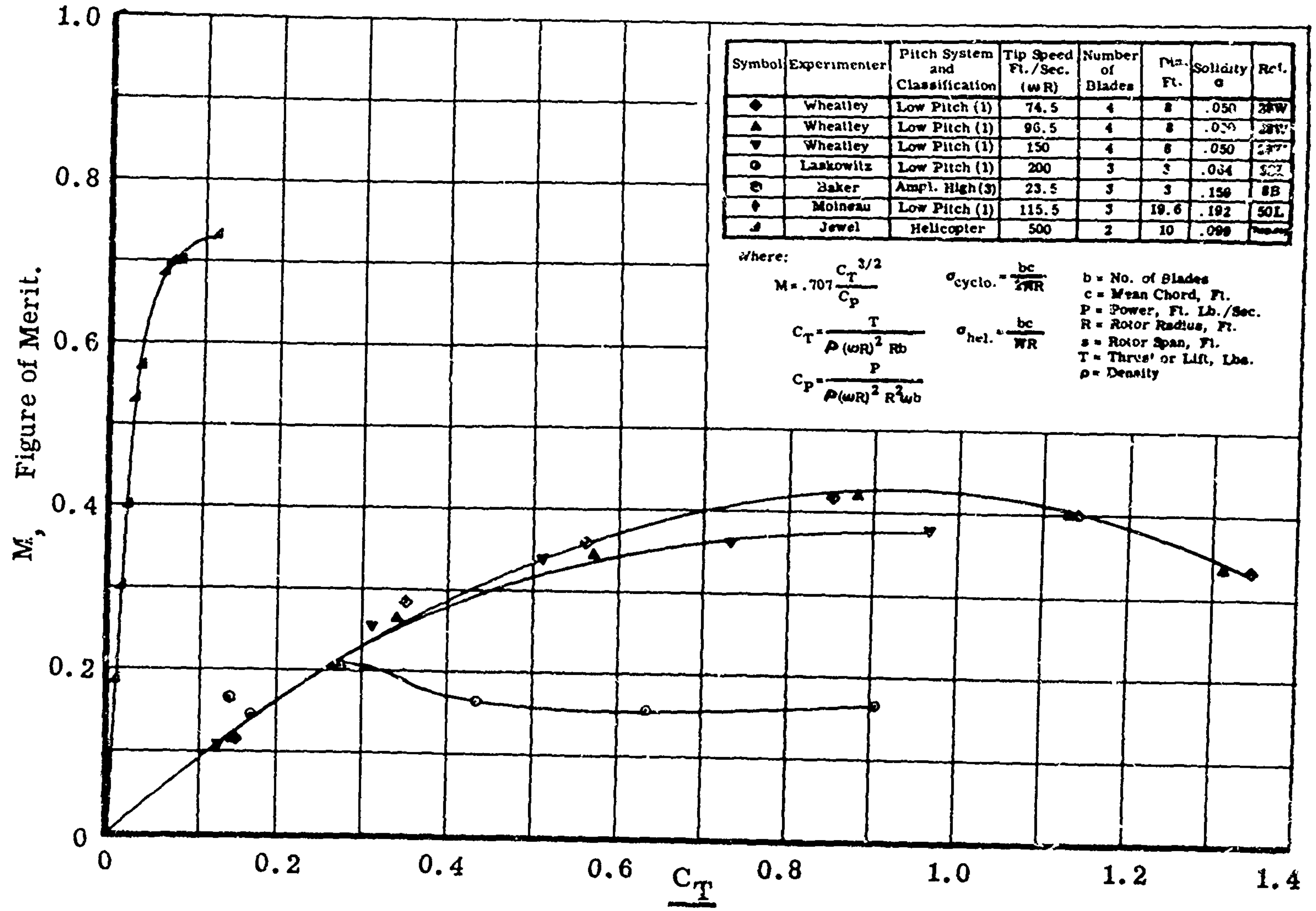
A comparison made of calculated and measured lift per horsepower by Wheatley (References 25W and 28W) is shown in Figure 100. It reveals that the measured data fall very short of the theoretical predictions, especially in hover and at high speed. Again, this indicates the use by Wheatley of a poor feathering system (see Reference 58R).

Autorotation

The ability of a cyclogiro to autorotate is also beyond question. A typical comparison of calculated and measured data is shown in Figure 101.

Forward Flight

Three series of wind tunnel tests form the basis for our experimental knowledge of cyclogiro performance in forward flight. These data were analyzed thoroughly by Eastman in Reference 2E. The significant dimensional, theoretical, and measured characteristics of these models are shown in Table VI, and the general test arrangement is indicated in Figure 102.



Symbol	Experimenter	Pitch System and Classification	Tip Speed Ft./Sec. (ωR)	Number of Blades	Dia. Ft.	Solidity σ	Ref.
◆	Wheatley	Low Pitch (1)	74.5	4	8	.050	[illegible]
▲	Wheatley	Low Pitch (1)	96.5	4	8	[illegible]	[illegible]
▼	Wheatley	Low Pitch (1)	150	4	8	.050	[illegible]
⊙	Laskowitz	Low Pitch (1)	200	3	[illegible]	.034	[illegible]
⊜	Baker	Ampl. High (3)	23.5	3	3	.159	8B
♦	Moineau	Low Pitch (1)	115.5	3	19.6	.192	50L
◢	Jewel	Helicopter	500	2	10	.099	[illegible]

Where:

$$M = .707 \frac{C_T^{3/2}}{C_P}$$

$$C_T = \frac{T}{\rho(\omega R)^2 Rb}$$

$$C_P = \frac{P}{\rho(\omega R)^2 R^2 \omega b}$$

$$\sigma_{cyclo.} = \frac{bc}{2\pi R}$$

$$\sigma_{hel.} = \frac{bc}{\pi R}$$

b = No. of Blades
c = Mean Chord, Ft.
P = Power, Ft. Lb./Sec.
R = Rotor Radius, Ft.
s = Rotor Span, Ft.
T = Thrust or Lift, Lbs.
ρ = Density

Figure 99. Hovering Figure of Merit vs. Thrust Coefficient/Solidity for Four Cyclogiro Systems and One Helicopter.

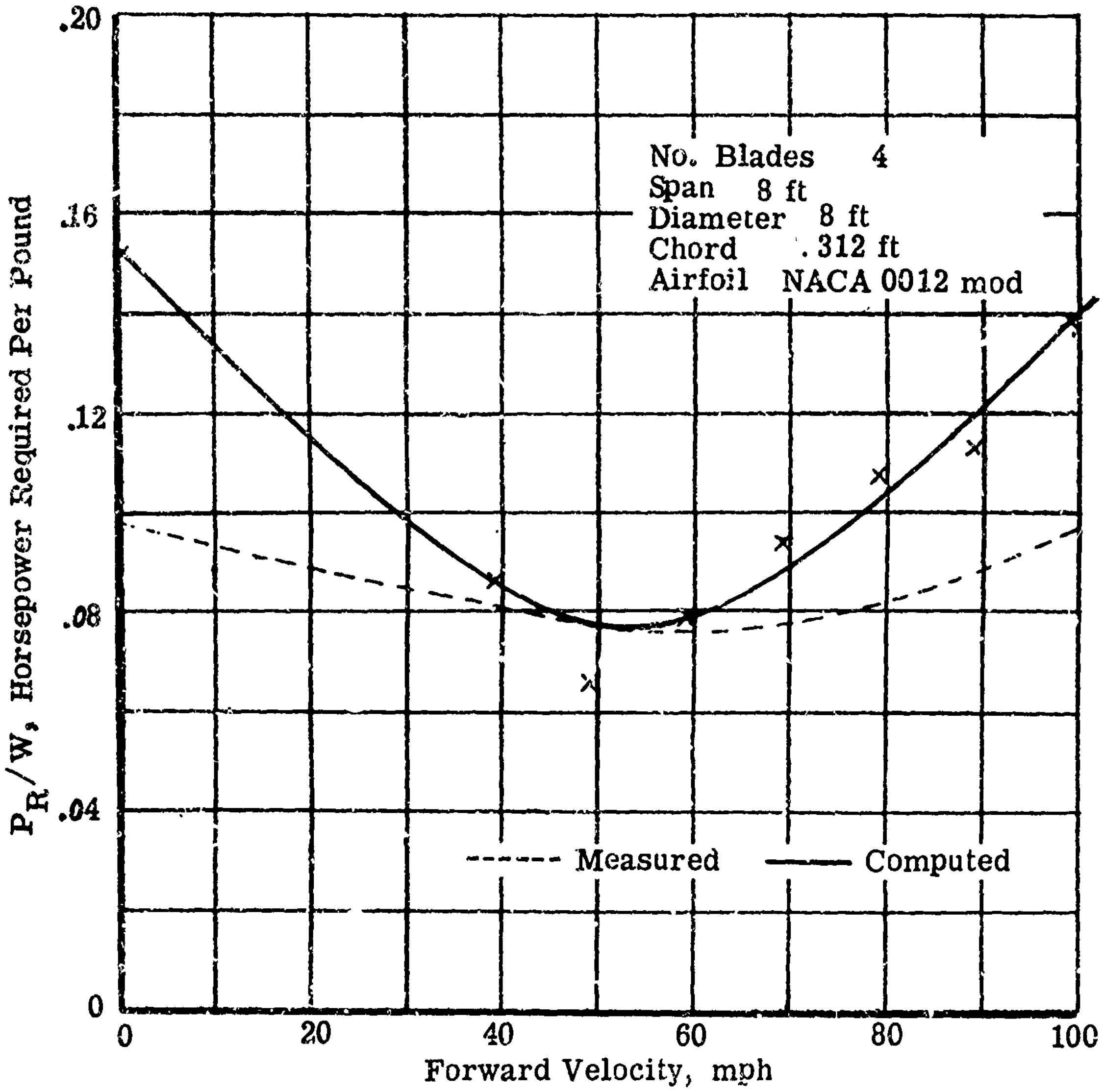


Figure 100. Theoretical and Measured Lift Per Horsepower at Forward Speed for a Low-Pitch Cyclogiro. Wheatley NACA, Refs. 25W and 28W.

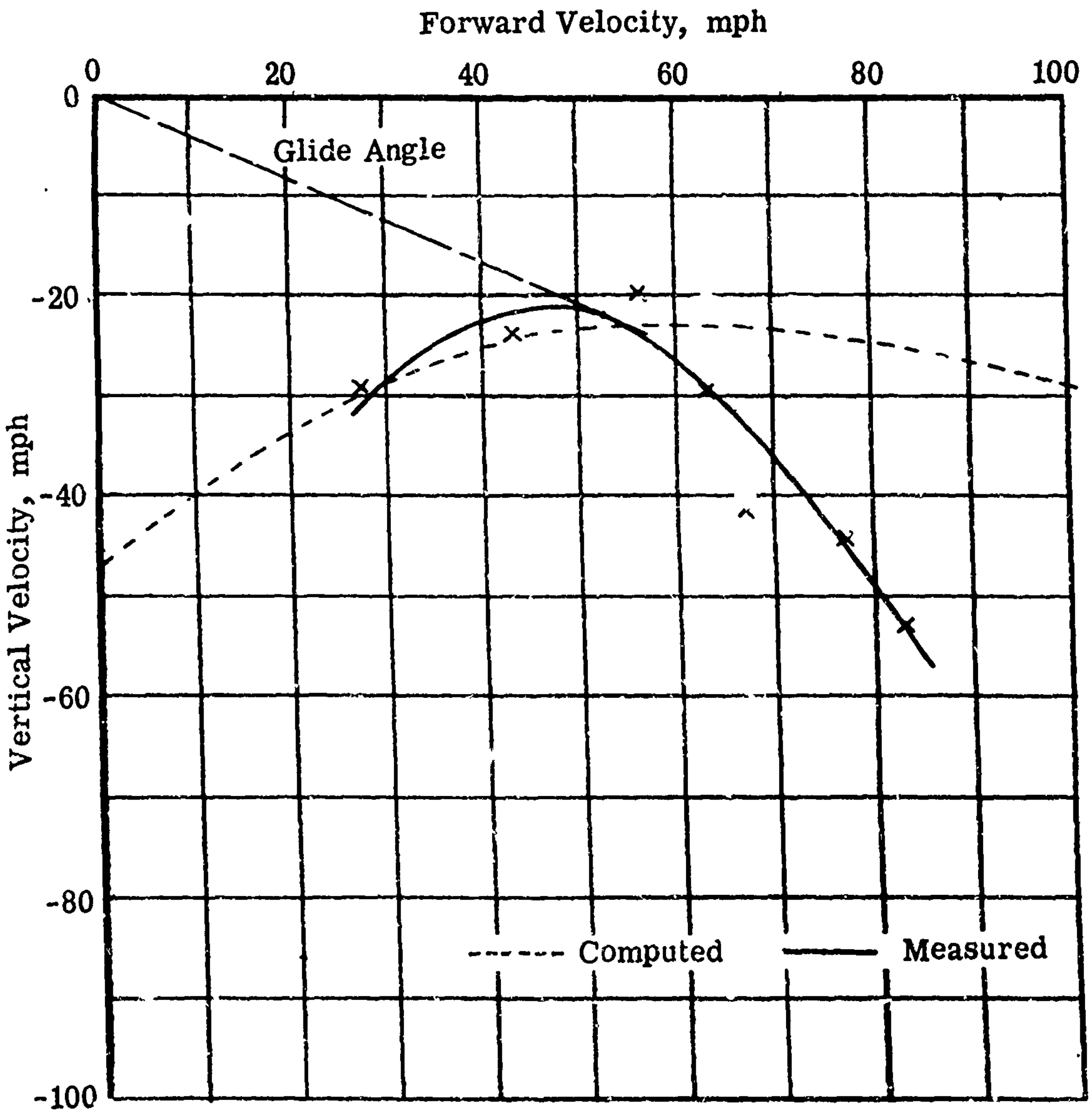


Figure 101. Theoretical and Measured Autorotation Gliding Polar Curve for a Low-Pitch Cyclogiro. Wheatley NACA, Refs. 25W and 28W.

TABLE VI. COMPARATIVE CHARACTERISTICS OF THREE CYCLOGIRO WIND-TUNNEL MODELS. See Also Figure 102.

	HIGH-PITCH MODEL			PI-PITCH MODEL			LOW-PITCH MODEL
Rotor arrangement	Two, counter-rotating			Two, with fuselage			One, both ends open
Blade rocking motion	Distorted Harmonic			Ideal, m = 1			Harmonic, relative to rotor
External bracing	None			Ties between blade tips			28 arms radiate from shaft
Root blade section	NACA 0025			Circular arcs			NACA 0012 (cambered to conform with mean blade path)
Tip blade section	NACA 0009			Circular arcs			NACA 0012 (cambered to conform with mean blade path)
Hinge position, c	1/4			1/2			1/4
Orbit diameter, ft	3			1.667 (1.5 at root, 1.833 at tip)			8
Overall span, b , ft	- - -			5.17			8
Blade span, b_0 , ft	6			4.33			8
Blade chord, ft	0.5 (0.667 at root, 0.333 at tip)			0.354 (0.312 at root, 0.396 at tip)			0.3125, no taper
Blades per rotor	3			2	3	6	4
Total blade area, S	9			3.07	4.60	9.20	10
Blade angle, $\beta°$	90	83	72	45	45	45	Variable
Air speed, v , ft/sec	99	99	44.5	33	33	33.5	Varied while $\pi nD = 150$
C_{Lbmax} , measured (and for theory)	0.78	0.78		0.75	0.75	0.75	
C_{Db0} , measured (equiv. for theory)	0.017 "	0.017 "	0.025 0.023	0.039 0.04	0.039 0.04	0.038 0.039	 0.013
dC_{Db}/dC^2_{Lb} , for theory	0.01	0.01	0.01	0.0336	0.0336	0.0336	0.01
$dC_{Lb}/d\alpha_b$: for theory	5	5	5	5	5	5	5
Reference No.	8B, 1E, 2E, 30H			20K, 24K, 30K			25W, 28W

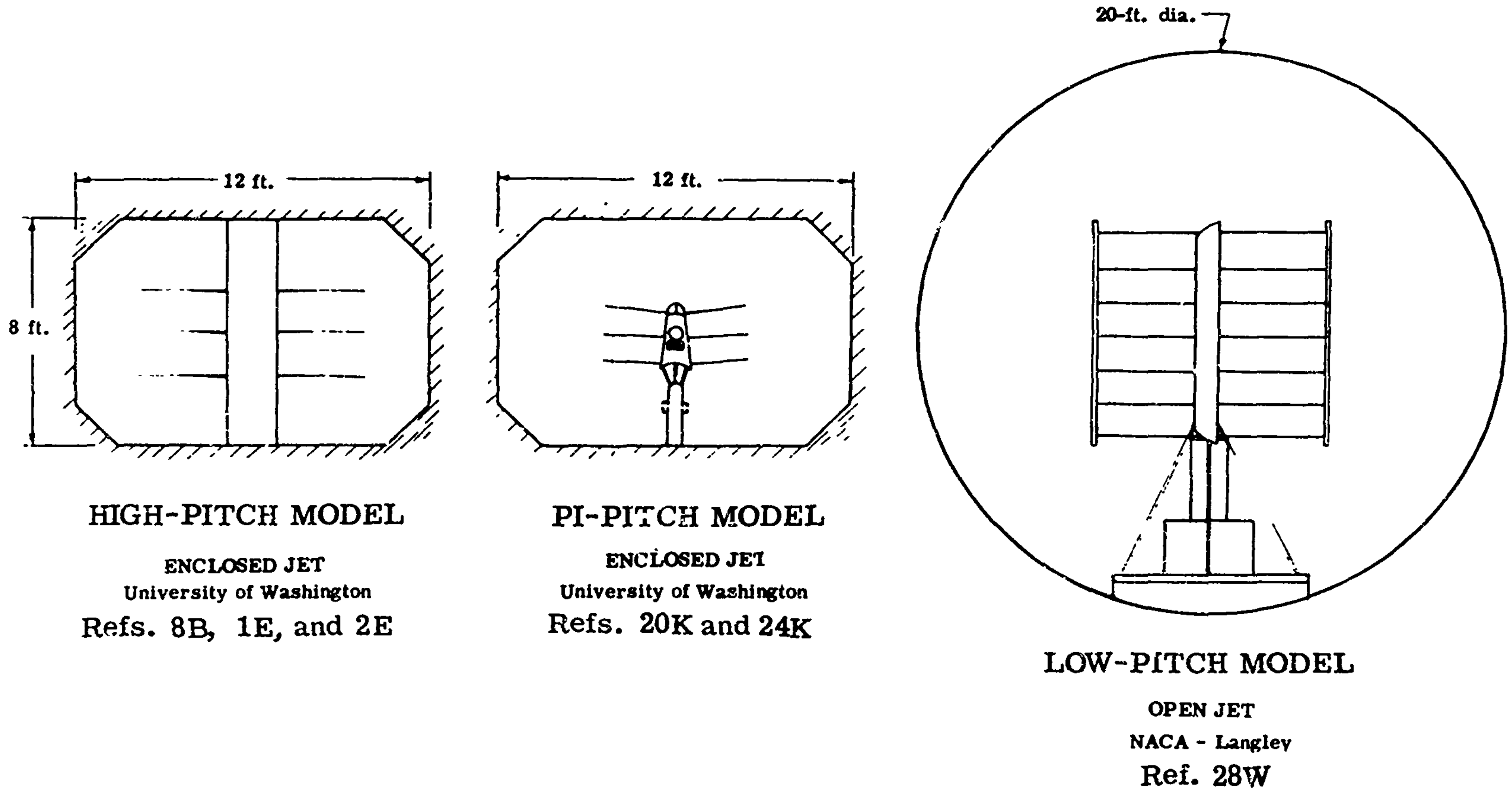


Figure 102. Wind Tunnel Arrangement of Three Comprehensive Cyclogiro Studies Covering All Pitch Feathering Types in Forward Flight. See Table IV for Details of Test Models. From Refs. 2E.

The low-pitch model consisted of the single-rotor NACA arrangement of Figure 73. It had four high-aspect-ratio blades, each attached to a central axle by means of seven radial arms. All of the arms and axles were exposed to the airstream. After the uncertain influence of this bracing is allowed for, some doubt remains regarding the true rotor characteristics. As previously mentioned, the low-pitch feathering mechanism used here became progressively less satisfactory when operating at other than small advance ratios.

The comparative pi-pitch model (Figure 75) with fuselage and three cantilevered rotor blades turns two rotor systems with the top blade advancing and moving down. The driving torque in this instance adds a positive pitching moment about the spanwise axis (Figure 84). The double-edged blades are hinged at their midchord, because the leading edge must become the trailing edge on alternate revolutions. The blades are tapered so that their chord increases while their thickness decreases toward the tips. There was also a slight increase in orbit diameter toward the tips of the blades which would result in a spanwise variation in the advance ratio, which aggravated the unfavorable influence of the blade planform on spanwise lift distribution. The lack of root fillets of the blade was considered to have a definite detrimental effect on the overall effective span of the rotor system.

Several high-pitch and amplified high-pitch models were tested at the University of Washington. A typical configuration that corresponds to Baker's amplified high-pitch configuration (Reference 8B) is shown in Figures 76 and 77. The model consisted of two rotors, with a common horizontal axis, mounted on opposite sides of a central wind tunnel fairing and turning in opposite directions (for torque compensation). Blade-rocking amplitude was adjustable by changes of a quick-throw linkage. When the amplitude of the motion was small, ideal blade motion was closely approximated; for large amplitudes, however, serious discrepancies were introduced. In addition, the lack of good blade root fillets lessened the effective rotor span.

Eastman (Reference 2E) attempted to reduce and unify the test data, in an effort to support a full-feathering cyclogiro theory. As a whole, he was remarkably successful. Some of his typical results are shown in Figures 103 through 107, which must be viewed together with the results of the earlier discussion on cyclogiro aerodynamics, since theoretical and test results are presented simultaneously. Notations of Figures 103 through 107 are the same as those used for the earlier theoretical discussion.

Figure 103 shows the cyclogiro polar curve for a pi-pitch configuration. Figure 104 shows the same curve for a

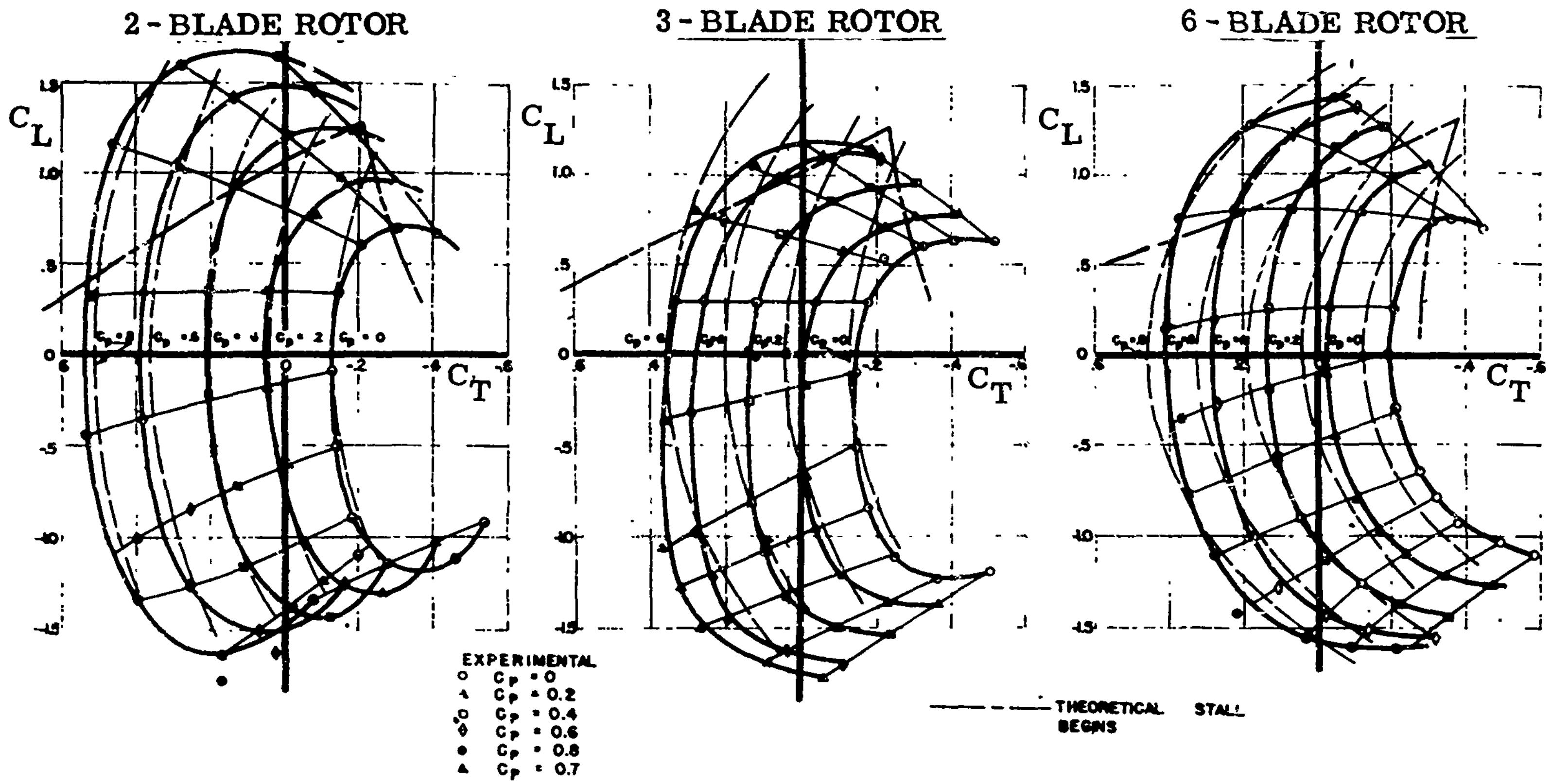


Figure 103. Experimental and Theoretical Lift-Thrust Polars for the Pi-Pitch Cyclogiro Model With Variations in the Number of Blades per Rotor. (Ref. 2E).

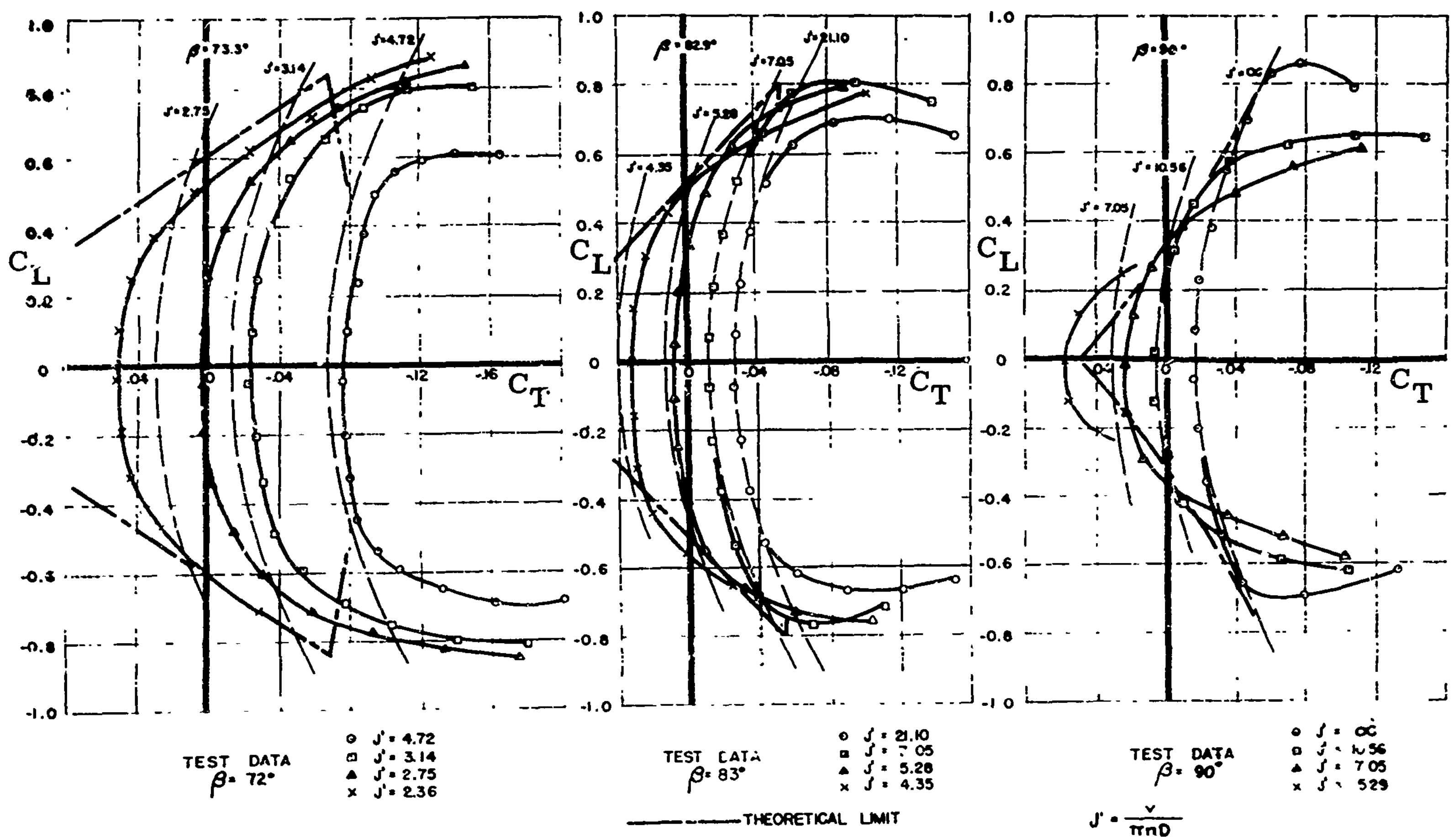


Figure 104. Experimental and Theoretical Lift-Thrust Polars for the High-Pitch Cyclogiro With Three Variations in the Rotor Blade Rocking Amplitude Angle (Refs. 1E and 2E).

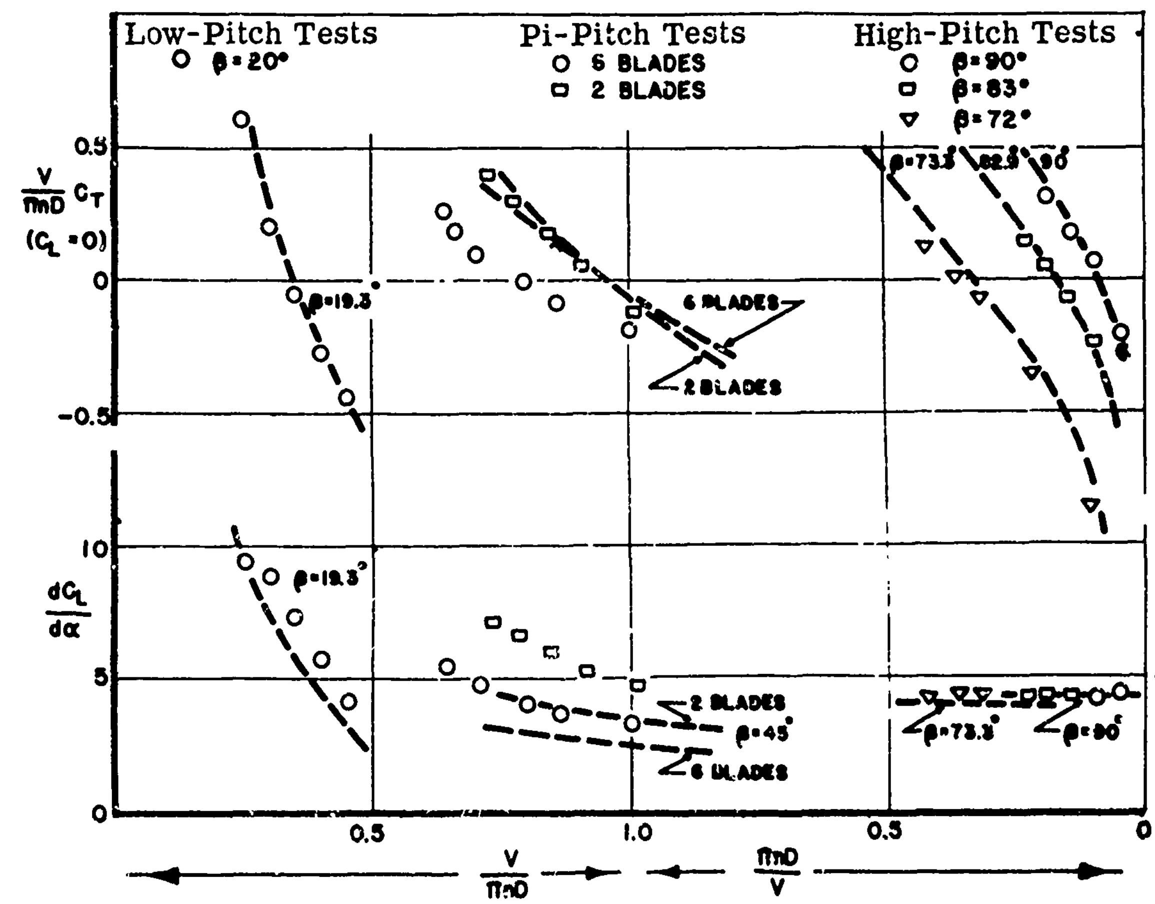


Figure 105. Experimental Values and Theoretical Variations of $dC_L/d\alpha$ and C_T at Zero Lift for Three Full Ranges of Pitch Ratios (Ref. 2E).

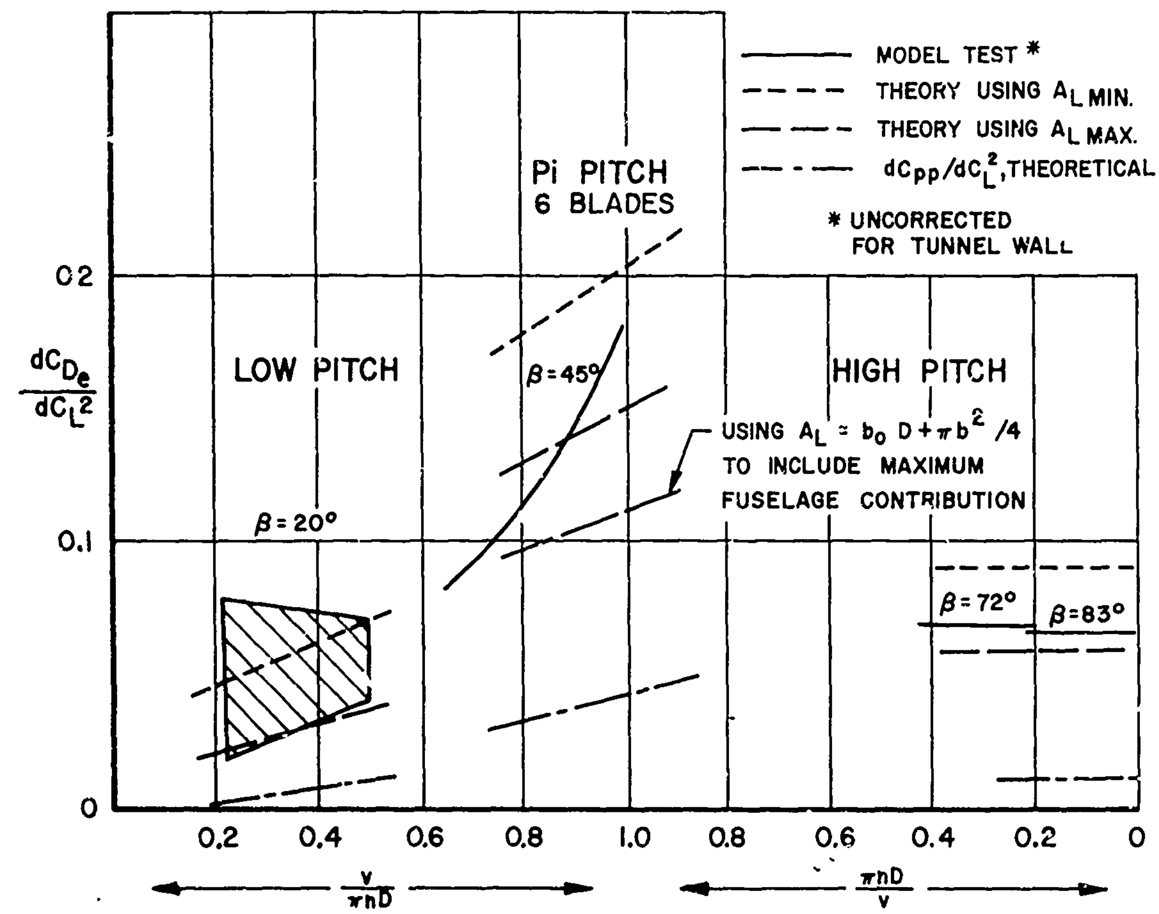


Figure 106. Experimental and Theoretical Values of dC_{D_e}/dC_L^2

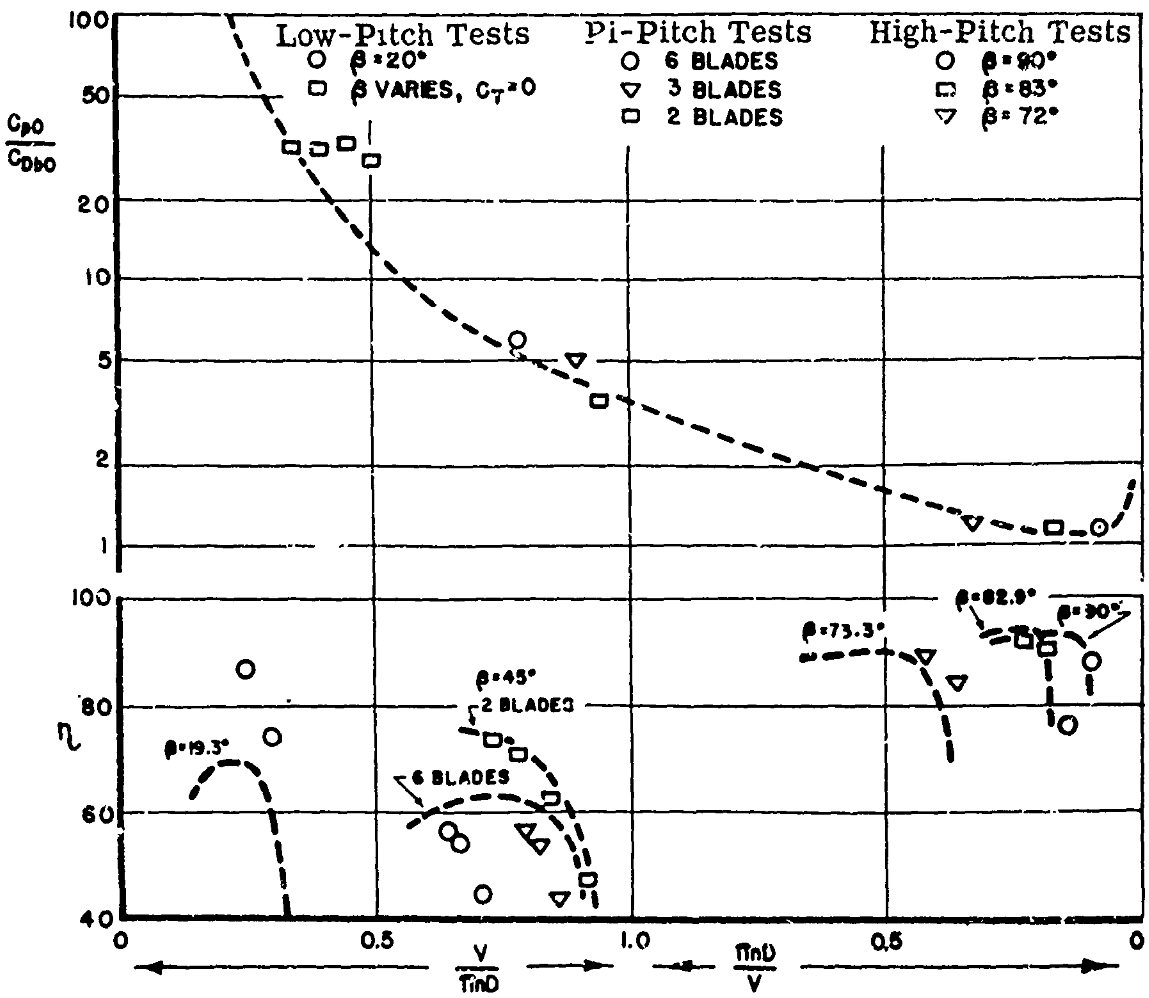


Figure 107. Experimental and Theoretical Values of Equivalent Propulsive Efficiency and of No-Load Power Coefficient for Three Full Ranges of Pitch Ratios (Ref. 2E)

high-pitch configuration. General agreement between theory and experiment can be noted in both cases, at least at low values of C_L.

In Figure 105, Eastman plots thrust (at no lift) against advance ratio in the upper figure and lift against advance ratio in the lower figure. α in the lower figure is the overall cyclogiro rotor angle of attack, which corresponds to the angle of attack of the equivalent wing.

In Figure 106, dC_{D_e}/dC_L^2, the slope of the "polar curve", is plotted versus advance ratio, the theoretical value being successively based upon several assumed values of the area A_L. In general, test data fall between extreme values of A_L.

In Figure 107, experimental and theoretical values of equivalent propulsive efficiency and of no-load power coefficient are compared.

11. Helicopter With Auxiliary Cycloidal Rotor Propulsion and Control

It has been but one thought more for several engineers to propose the perpendicular attachment of short cyclogiro-type blades to the tip of helicopter blades. If one can overlook the disturbing feeling this may cause, due to the mechanical and aerodynamic difficulties, this scheme is not without interest. The intent is that, as the untilted lifting helicopter rotor revolves, the tip cyclogiro blades feather so as to produce thrust in the azimuth plane of the rotor. The Pemberton Billing proposal (References 37B and 8P) of the helicopter with biplane rotors is an example of this system (Figure 108).

Although the use of such a full system to produce all of the required flight thrust may be questioned, Nemeth (Reference 14N) has suggested the use of smaller tip cycloidal blades to provide a lateral trimming force to balance that originating from the antitorque rotor in a single-rotor helicopter. The Gyrodyne QH-50 coaxial helicopter incorporates small cyclogiro-like blades at the rotor tips to produce differential rotor torque spoiling for yaw control. There exists the possibility that such a secondary cycloidal blade arrangement may have future uses as an ancillary control source in the helicopter rotor.

Proposals and patents have suggested the use of the cycloidal rotor at the tail of the single-rotor helicopter configuration in place of the familiar tail rotor (Figure 109). In one instance, as demonstrated in the patent by Pullin (Reference 52P), the tail-mounted cycloidal rotor rotates about a horizontal axis which is aft and parallel to the centerline of the helicopter. In this case, the cycloidal rotor produces the torque-compensating side thrust. Also in

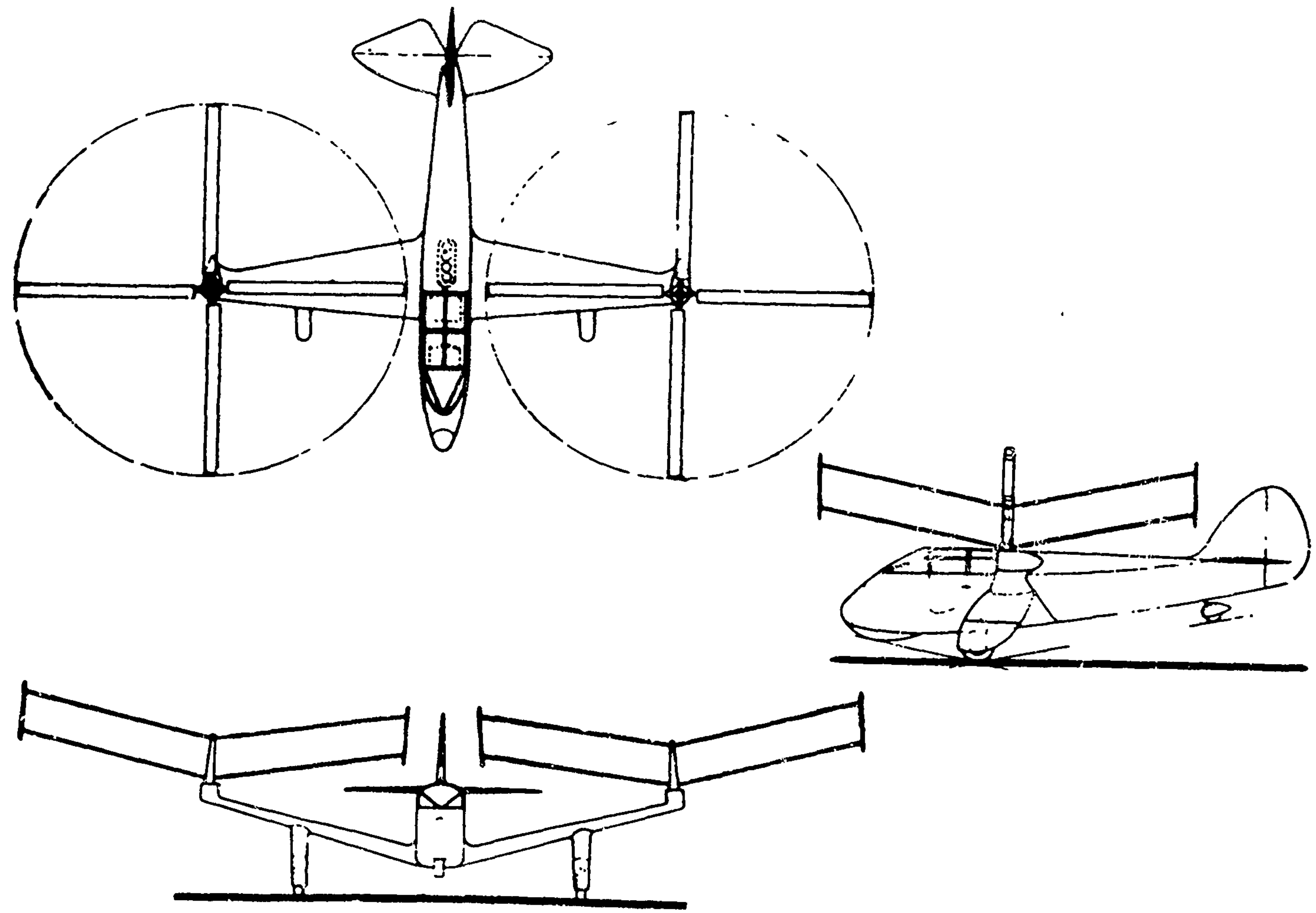


Figure 108. Pemberton Billing Helicopter Project With Tip Rotor Cycloidal Propeller Blades for Azimuthal Thrust (References 37B and 8P).

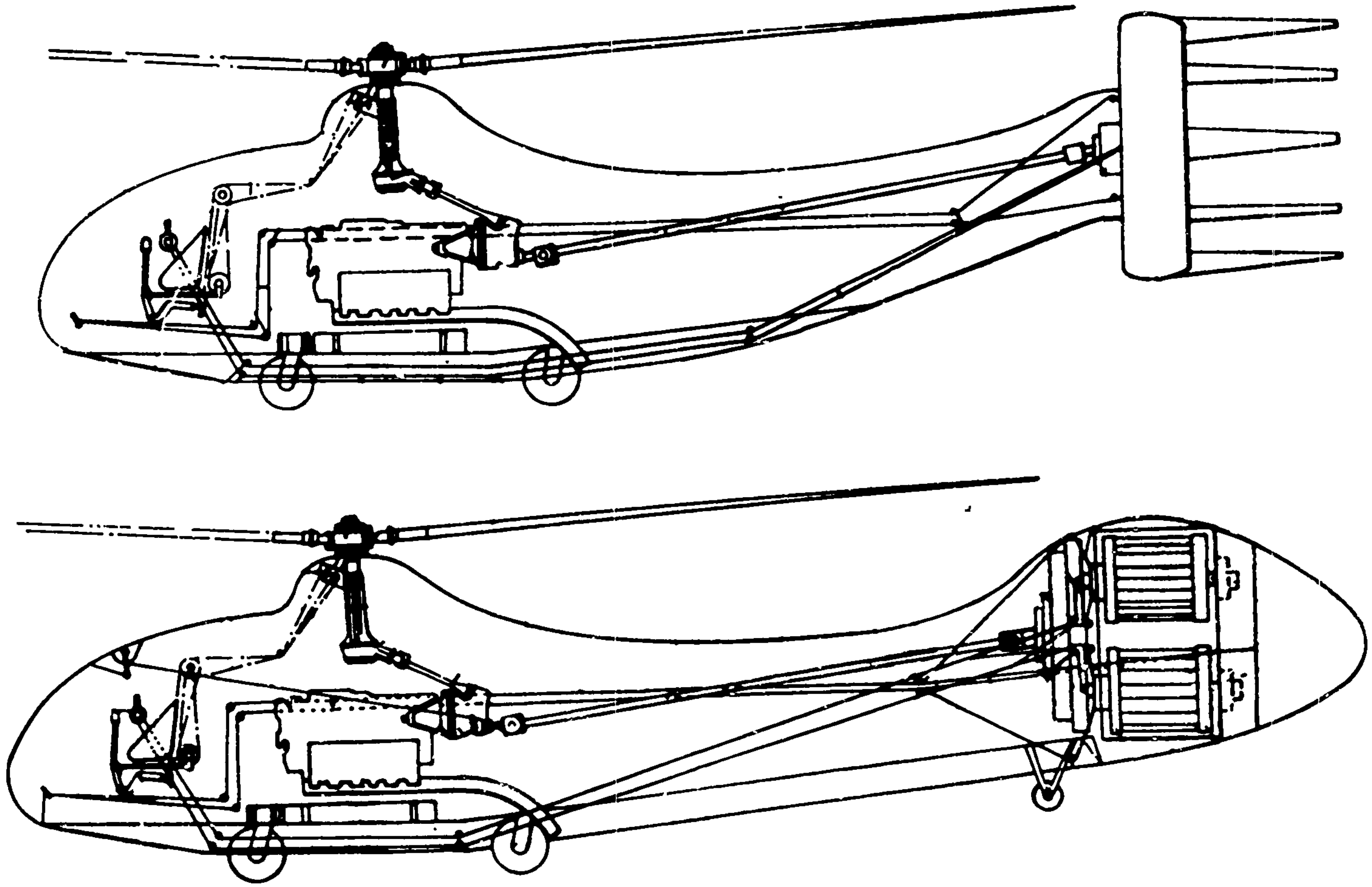


Figure 109. Application of The Cycloidal Rotor for Helicopter Torque Control and Main Rotor Tilt. The Bulk and Drag of The Single Cycloidal Rotor in The Upper Picture is Reduced by The Use of Double Rotors as Shown in The Lower Picture. Design Suggestion by Pullin (Ref. 52P).

this arrangement, this tail rotor may produce a force throughout the azimuth of its rotation by the proper manipulation of its feathering control. It now would become possible to produce a vertically upward tail force that could be used to incline the main helicopter rotor for forward flight.

Of more interest in this respect would be the tail installation of the cycloidal rotor with its axis vertical. In this manner, a combined torque-compensating side force as well as the primary center-line propulsive thrust could be generated. In this latter instance, we could envision a single-rotor compound helicopter with aft cycloidal propulsion.

12. Evaluation of Cyclogiro Aircraft Potential

The potential of the cyclogiro aircraft comes from the fact that it is just about the only known type of aircraft that can combine the high-speed characteristics of the conventional airplane with the low-speed characteristics of the helicopter, without drastic changes in geometry, using the same elements in both flight conditions. This makes the cyclogiro a candidate for the U. S. Army "aircraft composite" mission.

Advances since World War II in propulsion, in materials technology, and in mechanical systems indicate, at least in a preliminary way, that most of the problems identified by Heuver and Eastman can be overcome. Preliminary design of a cyclogiro aircraft for the Army composite mission is presented in the next section.

C. HORIZONTAL-AXIS PROPELLERS WITH CYCLIC PITCH: THE RICHARD HELICOPLANE

1. General Description

In the same way that the cyclogiro rotor can produce lifting as well as propulsive forces by cyclic feathering of its blades, a propeller with a horizontal axis can be made to produce a vertical lift force, as well as a horizontal thrust, by varying in the proper way the pitch of the blade during its circular trajectory.

The concept of articulating conventional propellers can be found in many sources; for example, it was proposed and incorporated by Zimmerman in the XF5U-1 "Flying Pancake" airplane shown in Figure 110. However, the specific concept of incorporating cyclic pitch into a propeller represents the life's work of G. C. Richard, a Frenchman, who first proposed what he called the "helicoplane" in 1932, leading to full-scale tests of a 12-foot rotor by O. N. E. R. A. at the Chalais-Meudon wind tunnel in 1948, as shown in Figure 111.

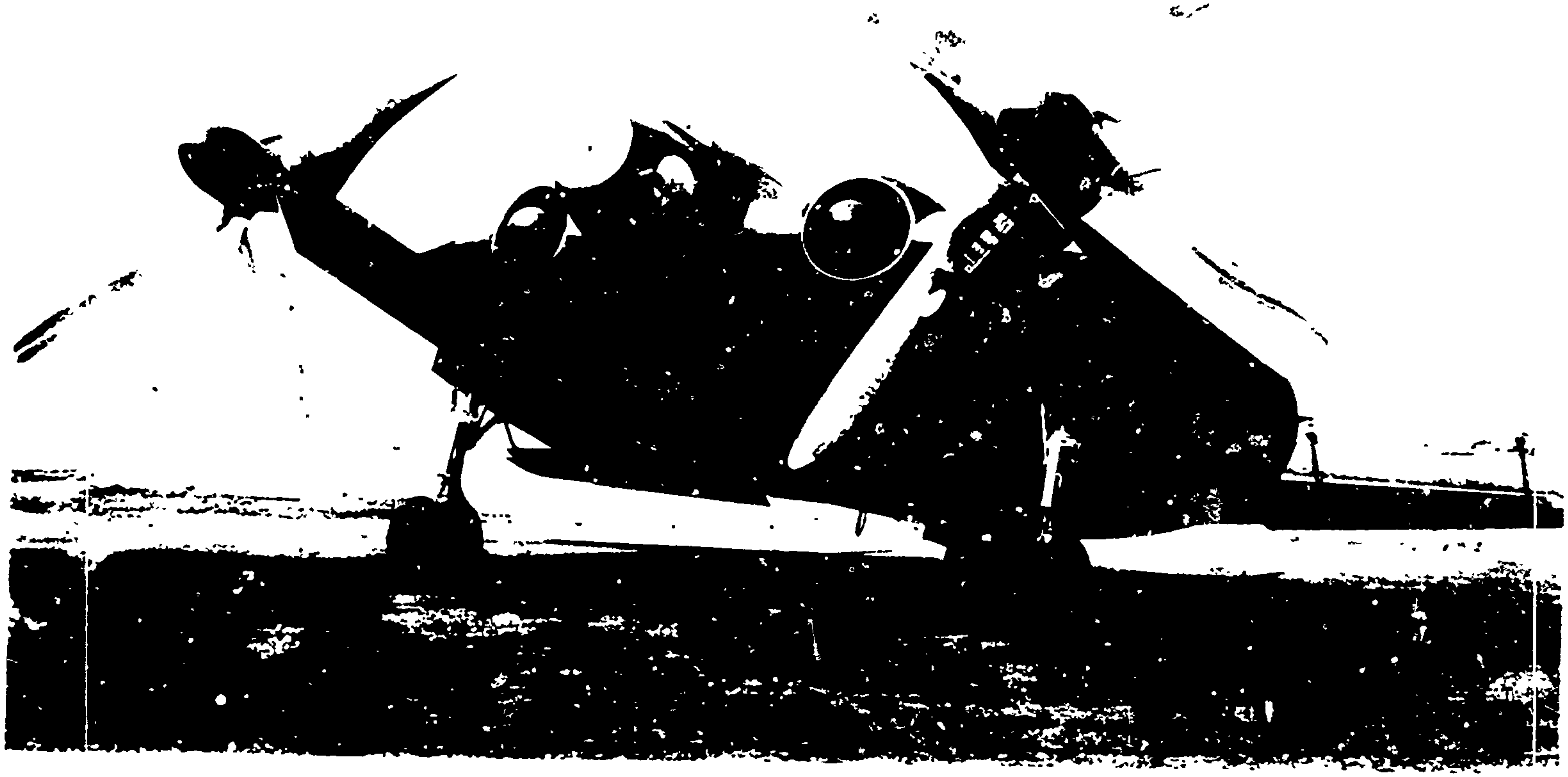


Figure 110. Vought XF5U-1 Aircraft With Potential Performance Range From 0 to 450 Knots. Yawed Propellers Were Subject to Large Vertical Radial-Lift Forces in Forward Flight. See Refs. 66L and 67L.

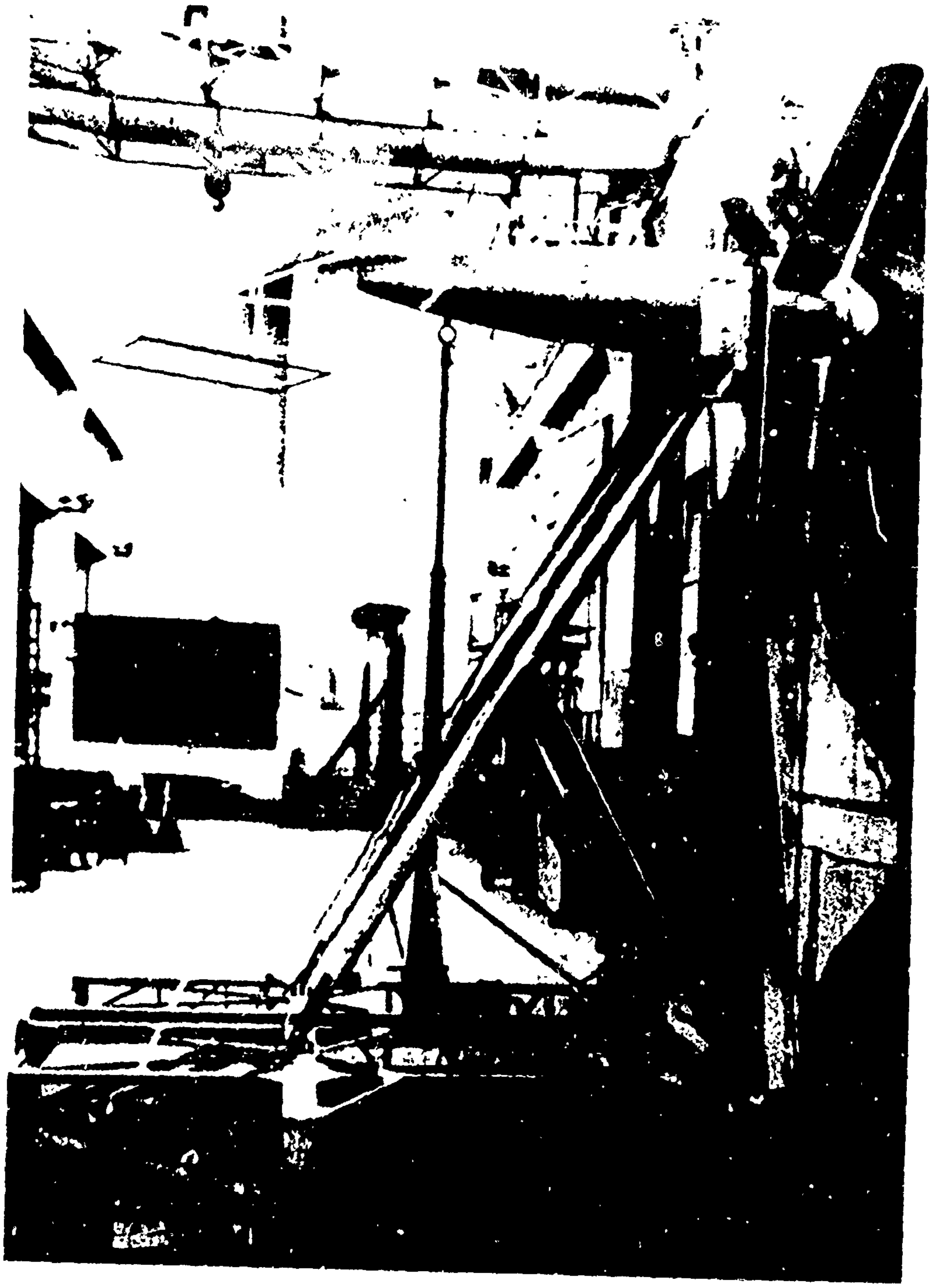


Figure 111. Helicoplane Richard Test Propeller in Chalais-Meudon Wind Tunnel (1948). See Refs. 10H, 31R, 34R-36R, 50-80.

The helicoplane is defined as an aircraft with one or several rotating wings that have a horizontal axis, oriented in the direction of flight. The blades of the rotors are subjected to a cyclic variation of the aerodynamic circulation, which can itself be obtained by a cyclic variation of the pitch of the blades. In contrast to the helicoplane, the helicopter obtains its lift by means of the collective pitch and its forward (or side) propulsion by the cyclic pitch; the helicoplane obtains its thrust (forward propulsion) by the collective pitch and its side force (lift) by the cyclic pitch. Thus, it stands to reason that the helicopter will be more efficient in hover, and the helicoplane will be more efficient in forward flight.

2. Principle of the Helicoplane

The concept can best be described by referring to Figure 112A. Figure 112A shows schematically a conventional propeller, with a fairly large amount of twist, rotating around a horizontal axis and moving with a forward velocity V. Airfoil sections of the two-bladed propeller are shown as they pass through the horizontal plane. The descending blade has a rotational speed v, and the airfoil operates at the angle of attack α, giving rise to a resultant force R, which has components P_1, normal to the propeller disc, and S in the plane of the disc. Since the angle is constant around the azimuth, the resultant force for the ascending blade B is still R, but its components are P_2 and S, respectively. The contribution of the two blades to the propeller thrust is $P_1 + P_2$, parallel to the propeller axis. S and S' are equal and opposite, and therefore their vertical resultant is zero. The forces S and S' contribute additively to the propeller torque.

Consider now Figure 112B, which schematizes a cyclically variable pitch propeller, the cyclic variation taking place around the axis 00', as shown. Assume that the pitch of the blade at A is the same as in Figure 112A, but that a cyclic-pitch mechanism allows the descending blade to pivot around the axis 00' as it describes the arc AMB, so that the change in pitch over the pitch at A is the angle β. Let us assume that the angle β is larger than the original angle α; since the resultant velocity V_r is constant, the angle of attack α' of the ascending blade B with V_r is in the opposite direction of the corresponding angle at B in Figure 11[illegible] Consider then the aerodynamic resultant R_1 at B. It has a compo[illegible]$_1$, parallel to the free-stream velocity, which is a drag, and an upward component S_1, which adds to the lift and acts in the same direction as the rotor torque.

The propeller disc is seen to be divided into four quadrants: descending, propulsion, ascending, and propulsion again. In the descending quadrant, a lift force and a propulsive force are created; in the following propulsion quadrant, a propulsive force is created; in the ascending quadrant, a lift force and a negative propulsive force (drag) are created; finally, the last quadrant is also mostly propulsive.

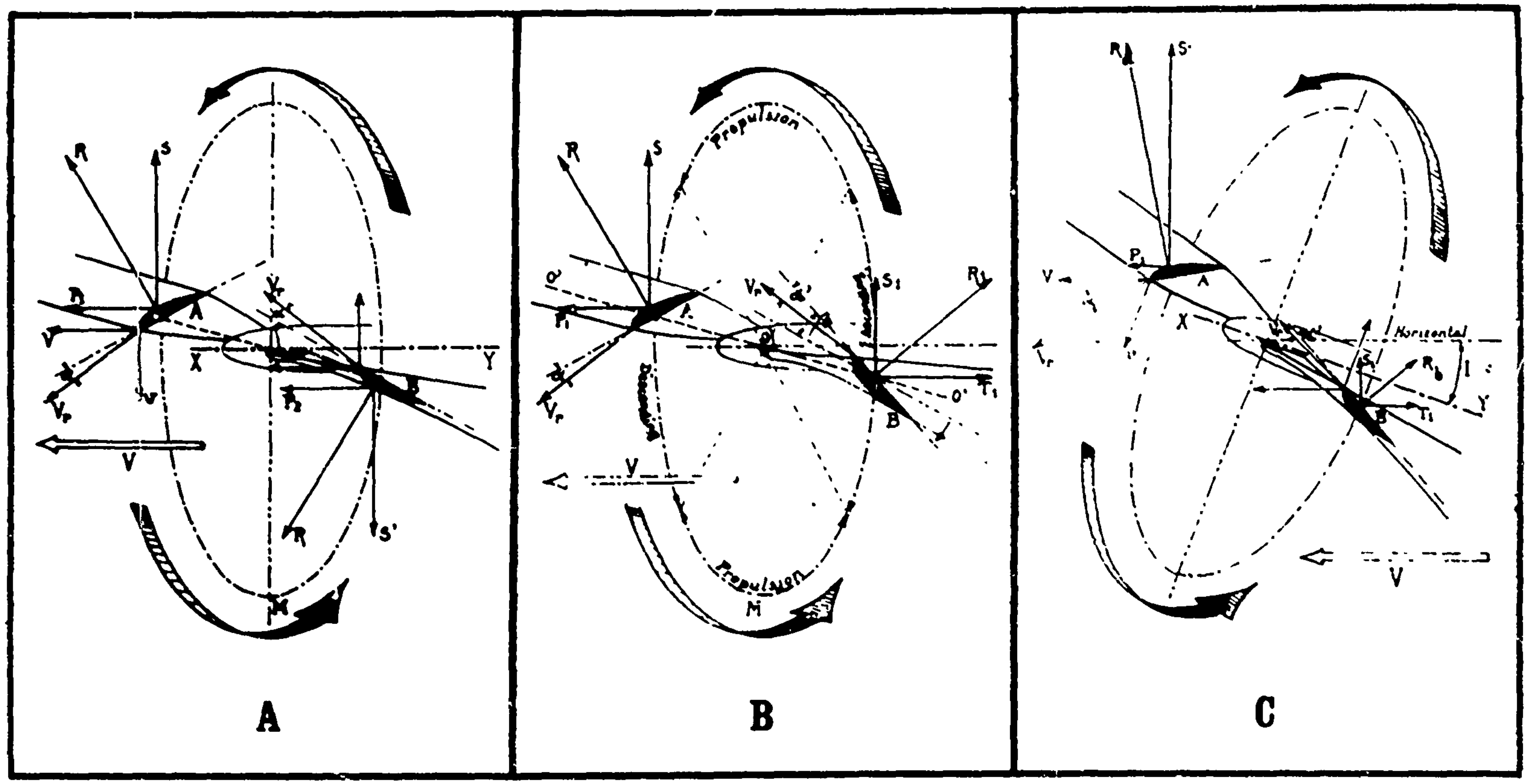


Figure 112. Comparison Between the Operation of the Conventional Propeller (A), Helicoplane (B), and the Propeller With Axis Inclined to the Direction of Flight (C).

3. Wind Tunnel Test Results on the Helicoplane Principle

Richard made the first wind tunnel tests of the helicoplane principle in 1936, under the sponsorship of the French Air Ministry, in the Issy-les-Moulineaux wind tunnel. He used two counterrotating propellers, 1.20 meters in diameter, driven by a 5-HP motor. The test results were reported in Wind Tunnel Report 107/G, dated 30 November 1936, in which it was categorically stated that "the Richard system, which employs a sinusoidal variation of the blade incidence, simultaneously produces lift and thrust ...".

There is no point in reproducing the numerical results of the earlier tests, since they were superseded by those of later tests, which will now be discussed.

In 1948, the French Office d'Etudes et Recherches Aéronautiques (O.N.E.R.A.) sponsored a series of full-scale tests of a helicoplane propeller, consisting of three blades, with a diameter of 4 meters, as shown in Figure 111. A standard variable-pitch propeller hub was used, which was modified by incorporation of a cyclic-pitch mechanism, with tiltable swash plate, covering a wide range of incidences. The rotor was mounted forward of a nacelle, 3.570 meters long and 0.64 meter in diameter, containing also an electric motor, a gearbox, and electrical actuators for the remote control of the pitch mechanism.

A typical rotor blade is shown in Figure 113. These blades were made of wood and were quite heavy (40 kg). They had a trapezoidal shape. The feathering axis was at 38% of the chord. The twist distribution was linear, and the total twist was calculated from standard propeller theory to give maximum efficiency, as a propeller, at cruise velocity, assumed to be 45 meters/second. The resultant total twist is 35°. The blade airfoil was NACA 23015.

The map of test runs actually performed in the Chalais-Meudon wind tunnel in 1948, under the supervision of Richard, is shown in Figure 114. The notation of Figure 114 is as follows:

$\beta = \dfrac{\Theta_1 - \Theta_2}{2}$, defines the amplitude of the cyclic motion. $\beta = 0$ corresponds to the conventional propeller

V = wind tunnel test section velocity

Θ_1 = root chord pitch angle of the descending blade as it crosses the horizontal

Θ_2 = root chord pitch angle of the ascending blade as it crosses the horizontal

Figure 113. Richard Helicoplane Rotor Blade, French O.N.E.R.A. 1948 Wind Tunnel Tests

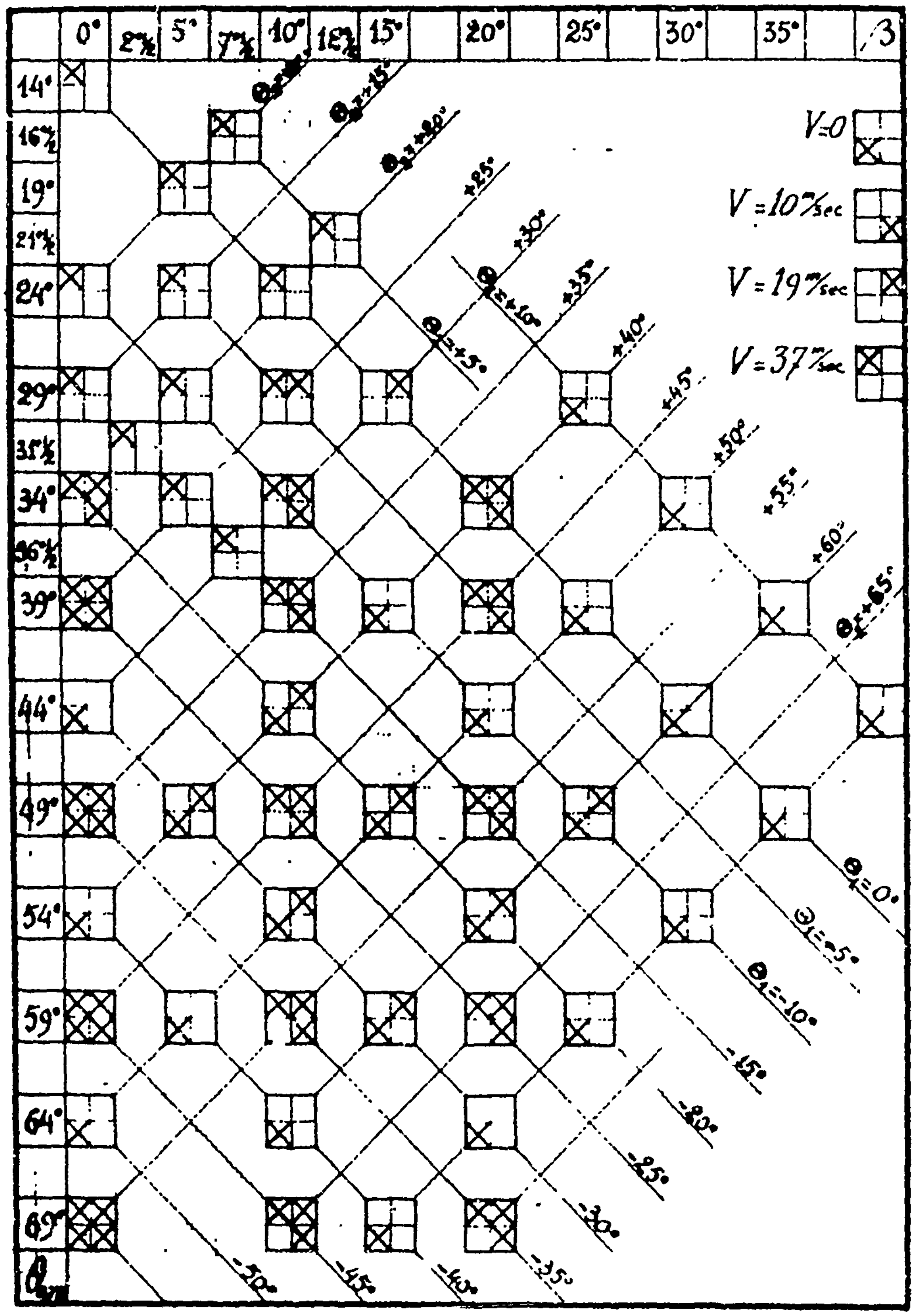


Figure 114. Matrix of Runs Performed, Richard Helicoplane O.N.E.R.A. 1948 Wind Tunnel Tests

$\Theta_{.7R}$ = rotor collective pitch, measured at the 70% radius station

Before the tests were completed, the program was dropped by O. N. E. R. A., and no formal report was ever written by O. N. E. R. A. However, in 1952, Richard wrote a complete book: "The Helicoplane. Principle. Realizations. Tests. Theories.". This book was never published but the manuscript was made available to Aerophysics Company. The comments and figures that follow are extracted from that book.

Tests were first made of the propeller with cyclic pitch and then of the propeller without cyclic pitch but with its axis at an incidence to the free stream. This configuration, which Richard claims to be a special and important case of the helicoplane, will be discussed in section II. Finally, the helicoplane with cyclic pitch was tested for the runs shown in Figure 114.

The helicoplane rotor tests, under static conditions, are summarized in Figure 115. F_z is the vertical force created by the rotor, and P is the applied shaft horsepower.

For one value of the abscissa of Figure 115, corresponding to $\Theta_0 = 59^o$, one shows in Figure 116 a typical polar curve; i. e., F_z as a function of F_x, F_x being the horizontal thrust of the rotor. It is thus seen that though a significant vertical force F_z is generated (for example, a maximum of 22.6 kg at $\Theta_0 = 59^o$), the helicoplane configuration does not lend itself to a vertical takeoff and landing aircraft since there is a corresponding large thrust of about 60 kg. The tests, however, show beyond a shadow of a doubt the ability of the helicoplane to create large vertical-lift forces.

As discussed earlier, tests were made at three forward speeds. Results at the highest test speed only, V = 27 meters/second, will be briefly described here.

A polar-like curve, showing the variation of F_x, propeller thrust, versus F_z, propeller lift (horizontal-axis propeller), for a given shaft power, P = 10 HP, is shown in Figure 117 for given values of the cyclic angle β and for various values of collective pitch Θ_0. Consider, for example, the round point on the curve farthest to the left. It corresponds to F_x = 11.6 kg. For P = 10 CV, at V = 37 meters/second, this corresponds to a propulsive efficiency of 57%. In addition, the lift is 65 kg. Consider now the intersection of the curve with the F_z axis. At this point, F_z/P = 11.1 kg/HP.

Typical results of forward flight performance are presented in Figure 118 for $\Theta_0 = 24^o$ and $\beta = \pm 10^o$. The effect of tilting the propeller axis over the direction of flight (shown by the angle I) is also represented.

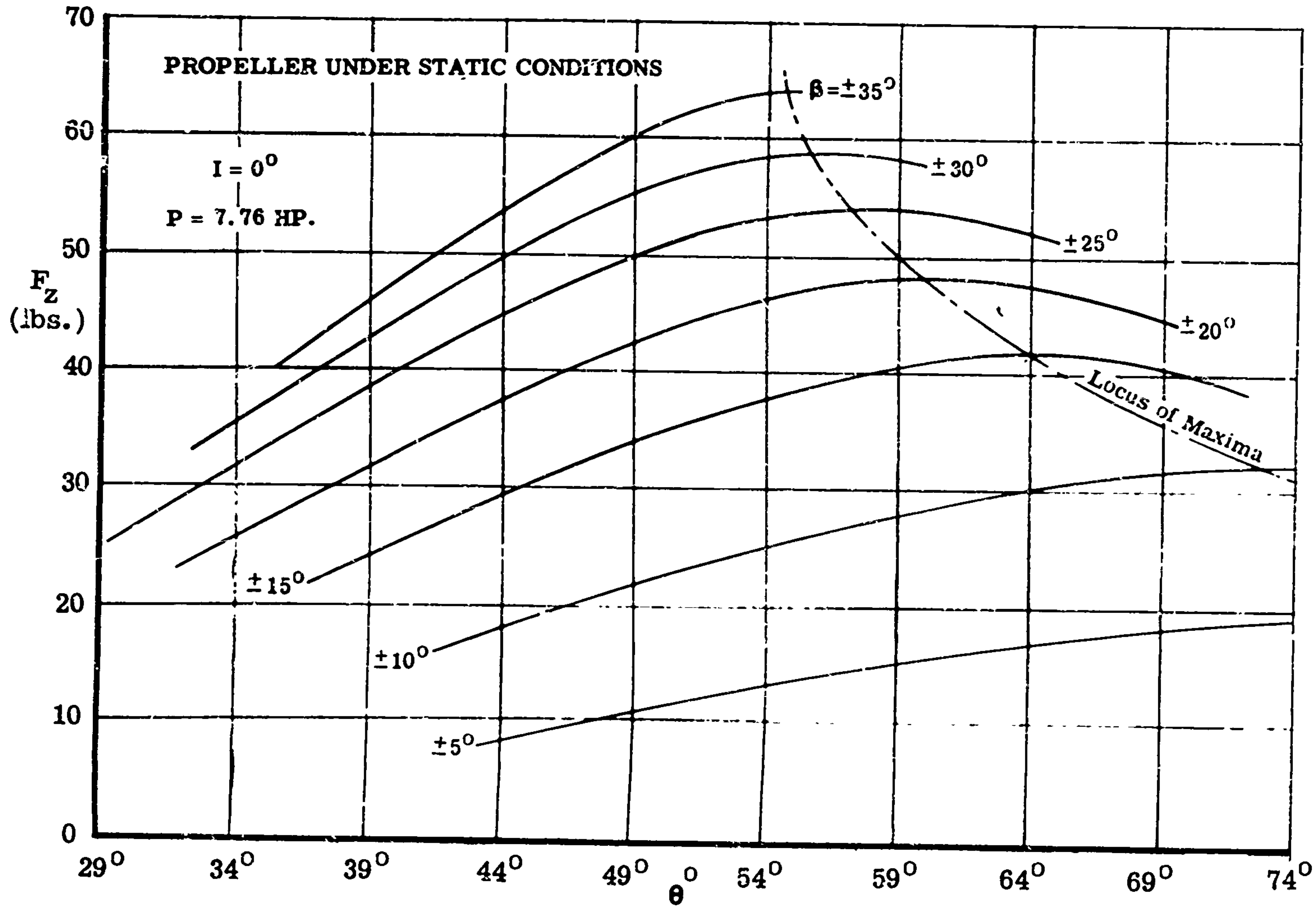


Figure 115. Static Thrust of Horizontal-Axis Richard Helicoplane, O. N. E. R. A. 1948 Tests.

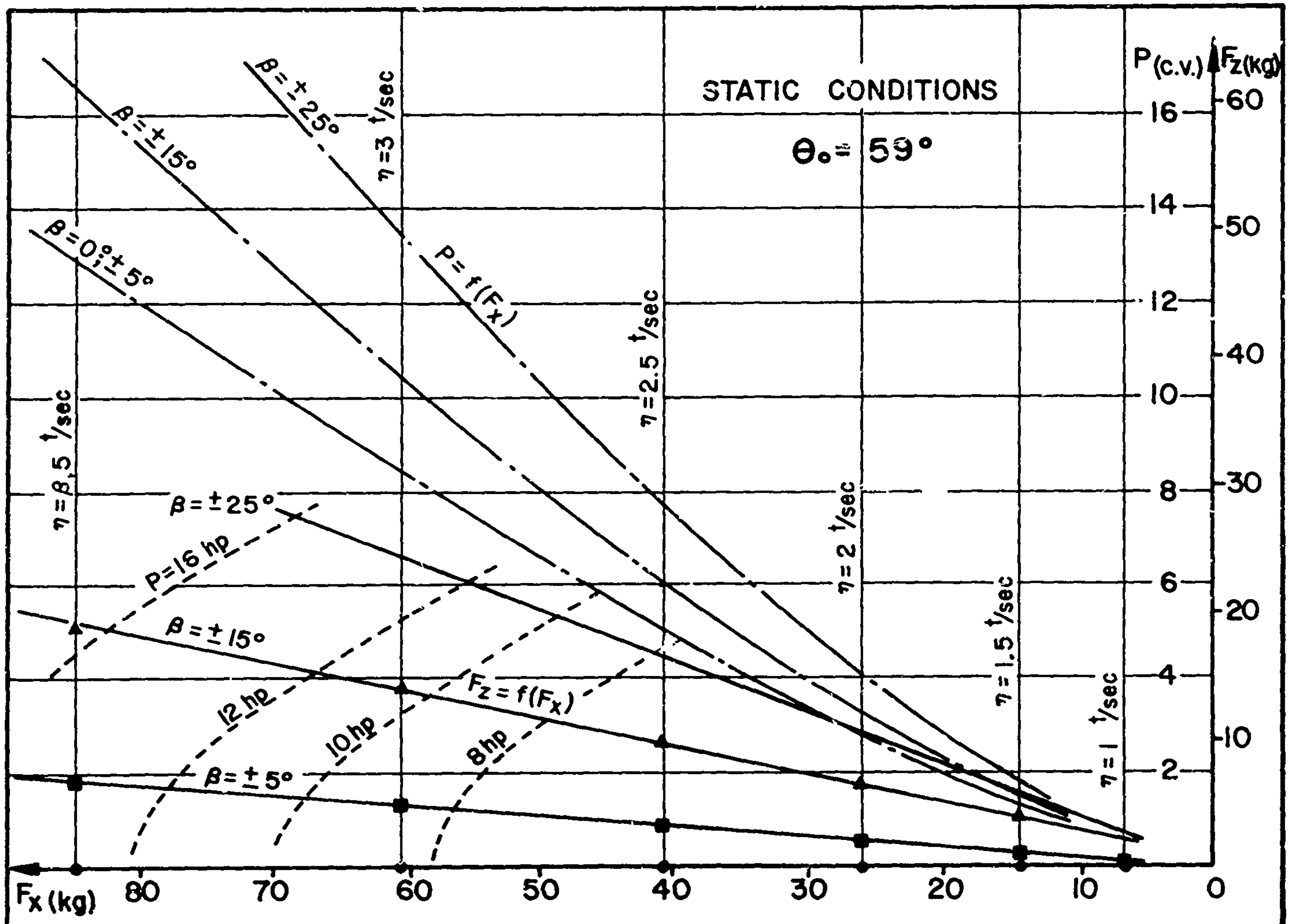


Figure 116. Static Performance, Horizontal-Axis Richard Helicoplane, O.N.E.R.A. 1948 tests, $\theta_0 = 59^o$

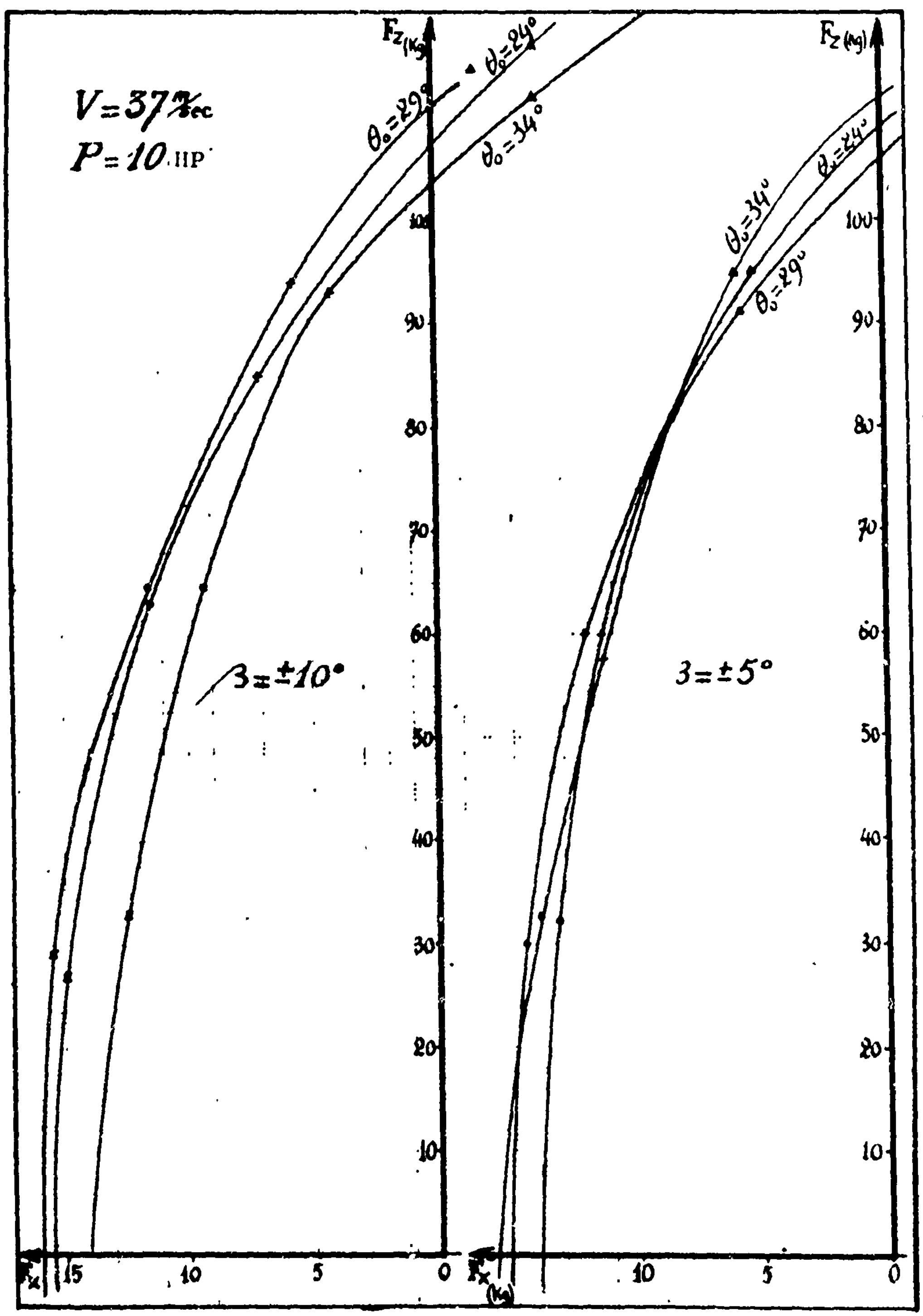


Figure 117. Forward Flight Polar, Horizontal-Axis Richard Helicoplane O. N. E. R. A. 1948 Tests.

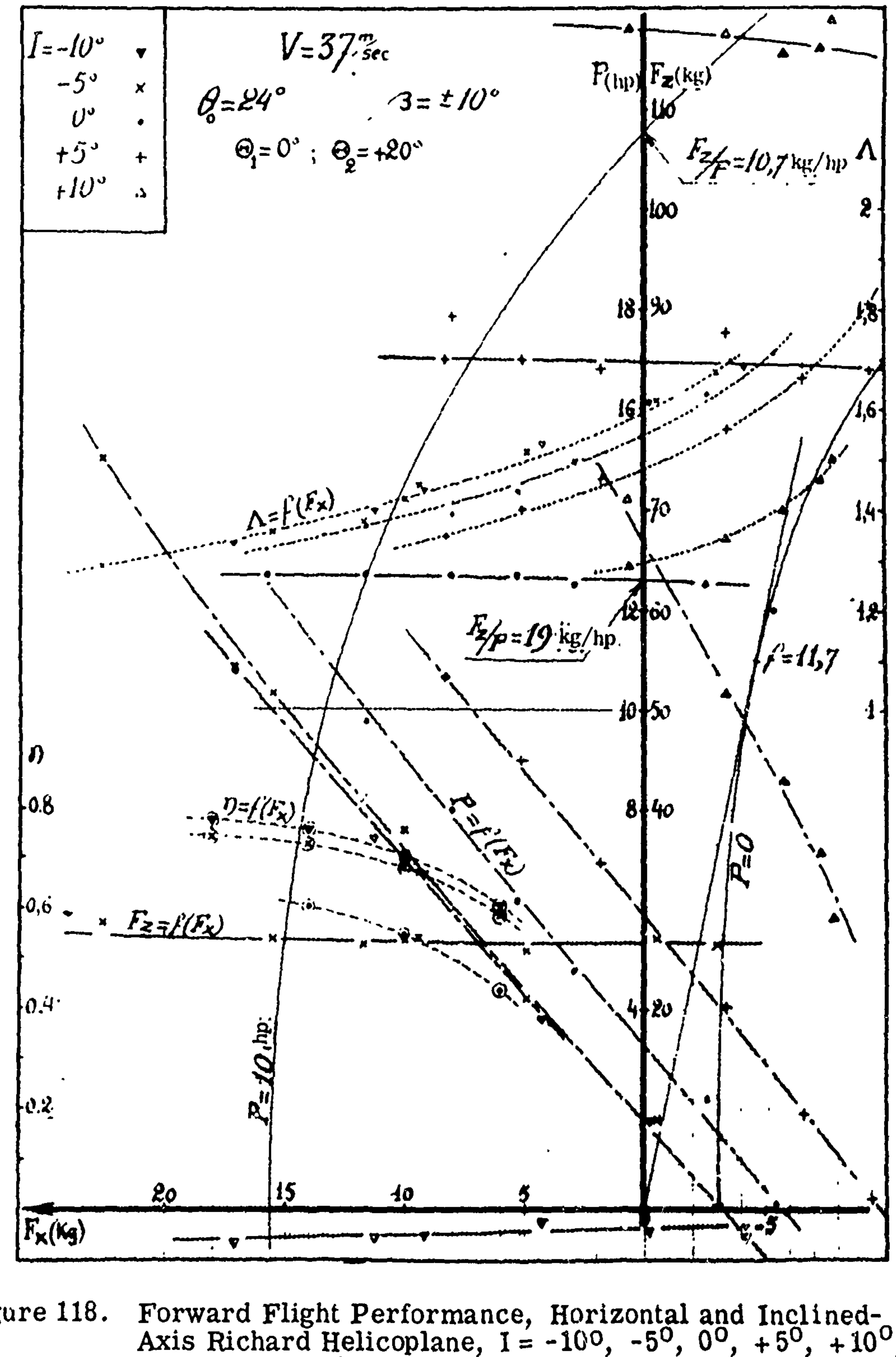


Figure 118. Forward Flight Performance, Horizontal and Inclined-Axis Richard Helicoplane, I = -10°, -5°, 0°, +5°, +10°, O.N.E.R.A. 1948 Tests.

The conclusion of the tests reported here is that a propeller with cyclic pitch, such as the Richard helicoplane, will simultaneously produce thrust and lift, in forward flight as well as in hover. The lift thus created is not negligible and is such that it is possible to consider the use of such a propeller in a wingless aircraft configuration.

Such an aircraft would even be a STOL aircraft with VTOL capabilities under certain conditions; for example, by tilting the propeller somewhat at hover or by deflecting the slipstream by means of flaps. Its maximum speed would be that of any propeller aircraft.

As will be seen in section II, cyclic-pitch propellers and "thrust wing" or "radial-lift" propellers are operating on the same principle. It may prove to be advantageous to combine the two.

The tests further show that the creation of the lift force is achieved at a low power cost. This represents an efficient scheme of integration of lift and propulsion.

4. Potential of the Helicoplane Concept

The O. N. E. R. A. wind tunnel tests demonstrated the correctness of the helicoplane concept, but the performance results obtained are by no means optimum, nor is the mechanical configuration that was realized the only or the best one.

First, the blades, shown in Figure 113, were of solid wood and weighed 40 kg each. Thus, part of the power of the rotor was used to overcome the cyclic inertia forces of the blades.

Second, the rotor blades were not optimized, neither for planform nor for twist distribution. Whenever technology makes it possible, it would be desirable to have blades with variable radial twist distribution (at least two segments adjustable, one with respect to the other), that variation being cyclic, if possible.

Third, it is advantageous to have the highest possible blade lift for the ascending blade; hence, the need for a cyclically actuated high-lift device (flap, slot, or boundary layer suction or blowing) during the ascending quadrant of the rotor disc. Richard also suggests that a means to increase the lift of the helicoplane is by increasing the speed of the descending blade and decreasing that of the ascending blade. This can be achieved mechanically by offsetting the center of rotation of the rotor.

Thus, it appears that improvements in technology (light blades and light, compact, and reliable mechanical devices) would significantly enhance the potential of the helicoplane concept.

Richard proposed an application of the helicoplane concept to a light, cheap private plane. He also suggested the incorporation of helicoplane rotors to the Chance-Vought XF5U-1 "Flying Pancake". Such a configuration, heavily armored, might make a good "Flying Tank". The helicoplane works best with large-diameter propellers, turning at low speed; hence, the noise level is fairly low.

The most likely early use of the helicoplane principle is in conjunction with another principle; for example, in conjunction with the radial-lift propeller, which will be discussed next, or in conjunction with a deflected-slipstream wing, similar to that of Kaman's K-16B VTOL airplane.

II. NEAR-HORIZONTAL AXIS "RADIAL-LIFT" CONCEPTS

A. RADIAL-LIFT PROPELLER OR SELF-PROPELLING WING

The side force of a propeller in yaw is well known to aeronautical engineers as an undesirable phenomenon, since it has a destabilizing effect on the directional stability of a propeller aircraft.

Quite obviously, if the axis of a propeller in forward flight is pitched up to the horizontal, the resultant side force on the propeller is a lift. One would be inclined to think that the magnitude of this vertical force is the projection of the thrust over the vertical: T sin I, where T is the propeller thrust, and I is the inclination of the propeller axis over the horizontal. This is not the case. For the proper propeller, one with a fairly large diameter and low RPM, the lift component can be five to ten times the projection of the thrust vector.

This phenomenon was discovered by Richard in France and von Holst in Germany in the thirties. It was applied to the Curtiss-Wright X-100 and X-19 aircraft in the United States in the early sixties. It is used in a current German project, the VFW VC.400 (manufactured by Vereinigte Flugtechnische Werke, in Bremen). It corresponds to a special case of Richard's helicoplane, that in which the cyclic circulation on the propeller blades is obtained by tilting the propeller axis, rather than by mechanical means, as was described in the previous section. One of the proponents of the radial-lift propeller is Professor Focke. The concept will thus be described as Professor Focke reported it in the Fifth Cierva Memorial Lecture (Reference 15F).

1. Principle of the Radial-Lift Propeller or Self-Propelling Wing

Focke starts from the premise that, if high subsonic forward speeds are desired for a VTOL aircraft, the vertical-axis rotor route becomes hopeless. He then recounts Dr. von Holst's proposal, which comes not from an engineer but from a physiologist who spent part of his life studying bird flight, as follows.

In Figure 119, a bird, of weight W, is just moving its wing downward, holding its body relatively high by its muscles, thus producing W' which is a little larger than W. The lift is L, the resultant R, the drag D, and the forward thrust T. The procedure looks as if the wing, having the angle of incidence α , were in gliding flight with the angle γ. The bird is proceeding horizontally. If the wing has a good lift-drag ratio, T is considerable and so the bird turns the wing to more incidence. Therefore, lift is maintained during the upward movement, but deceleration occurs, partly absorbing the speed gained during the downward movement. This is ornithopter flight, much discussed at the beginning of aviation but soon abandoned, mainly on grounds of the inertia forces. Von Holst knew this and his thoughts went another way: if one wing is down and we could have nother one coming from above, the process could go on. The bird cannot do this, but human technique can, as shown in Figure 120.

Let us take an axis, nearly horizontal, slowly rotating; for instance, 4 wings may be fixed on it, each a distance of 90 degrees from the next. Let wing 1 go down first, doing the same job as the bird's wing; and let wing 3 do the same as the bird's wing does going up. In the meantime, wings 2 and 4 do not idle, but they work as a propeller, providing additional thrust. And so it goes on. Von Holst, as a naturalist, created the self-propelling wing coming from the living creatures but offering to the human engineer exciting possibilities, which von Holst explained in detail in a paper published at Göttingen in 1942. Note that every one of these ideas had been expressed by Richard in 1934 and had met with general incredulity.

Let us further examine the adaptation of natural flight to aeronautics. Why did we take out of use in airplanes the conventional propeller for very high speeds? Because there was the geometrical addition of the peripheral and of the forward speed. Here we are seeing nearly the contrary. The cosine of the angle between the direction of flight and the direction of true speed of the wing is 0.88. The wing receives only 13 percent more speed than the flying speed. Figure 120 shows wing 3 in operation. Its high drag must be compensated for by the three other wings. But its true airspeed is even 2 percent lower than the flying speed. Consider what this means if we are later approaching Mach 1. By the very slow rotation, we will scarcely have more difficulty than an airplane in this region, and the same is happening at higher Mach numbers. Another advantage of von Holst's self-propelling wing is the fact that profile drag exists only from the wing and not again a second time from the propeller.

2. VFW Wind Tunnel Tests

In 1957, the German company Vereinigte Flugtechnische Werke (VFW) began extended research, design studies, and wind tunnel tests in the matter of the self-propelling wing. Figure 121 shows the most important results. The inclinations of the axis at speeds from 0 to 600 km/h are given at the top of the figure. The slightly different running of the curves is caused by different rotational speeds between 700 and 900 RPM. Pure calculation is indicated by dashes. The most interesting item is the maximum Mach number 0.736, at a medium speed, going down again with further increasing speeds.

3. Characteristics of the VFW VC.400 VTOL Aircraft

Following many rumored cancellations, two prototypes of the VC.400 tandem tilt-wing aircraft, shown in Figure 122, are being

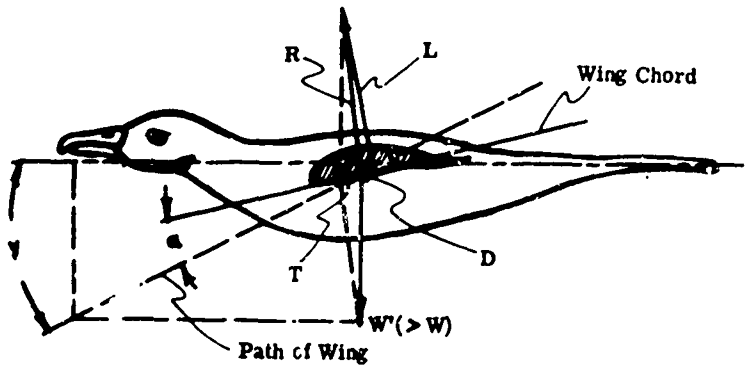


Figure 119. Schematic Representation of Bird Flight After von Holst and Focke. (Ref. 40F).

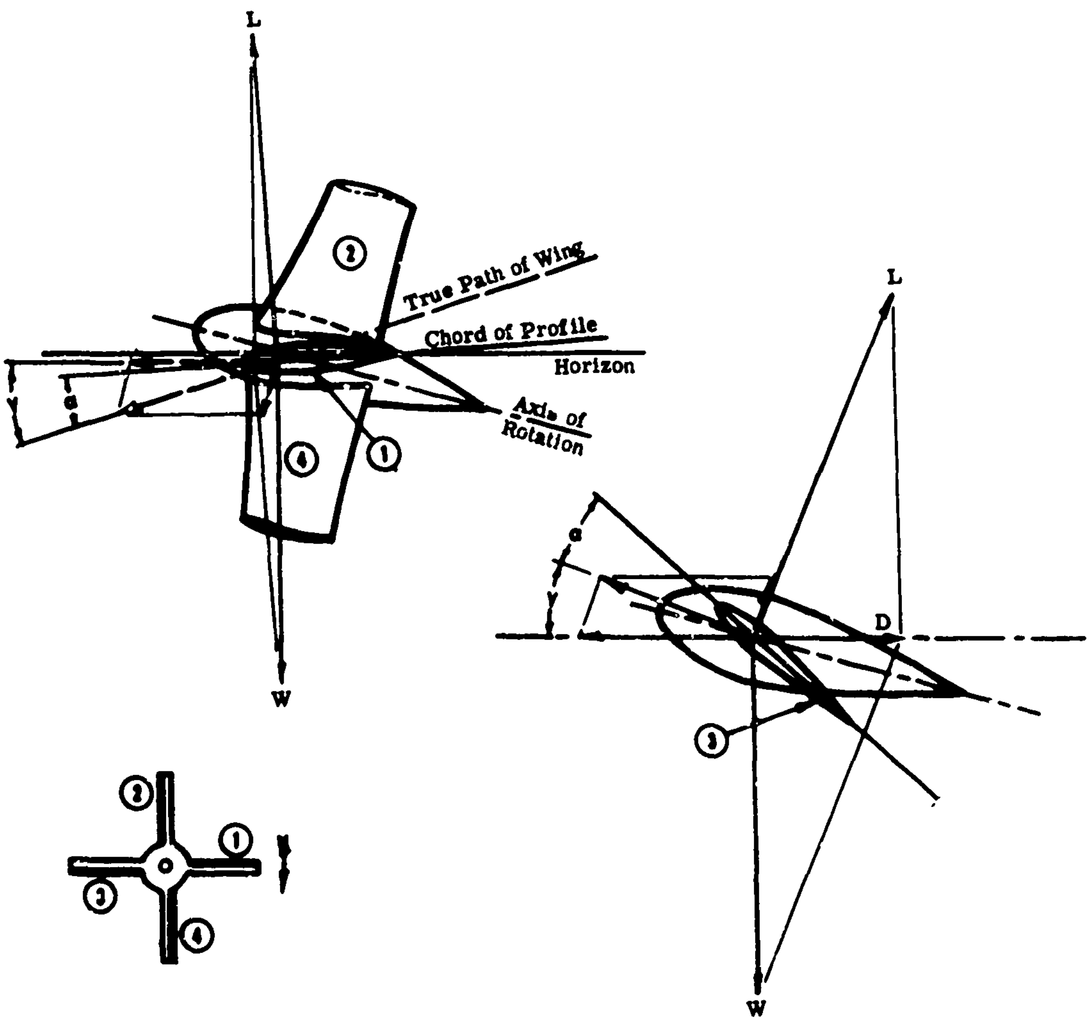


Figure 120. Forces Acting on a Slowly Rotating Inclined-Axis Self-Propelling Wing. Wing (1) Is Descending, (3) Ascending.

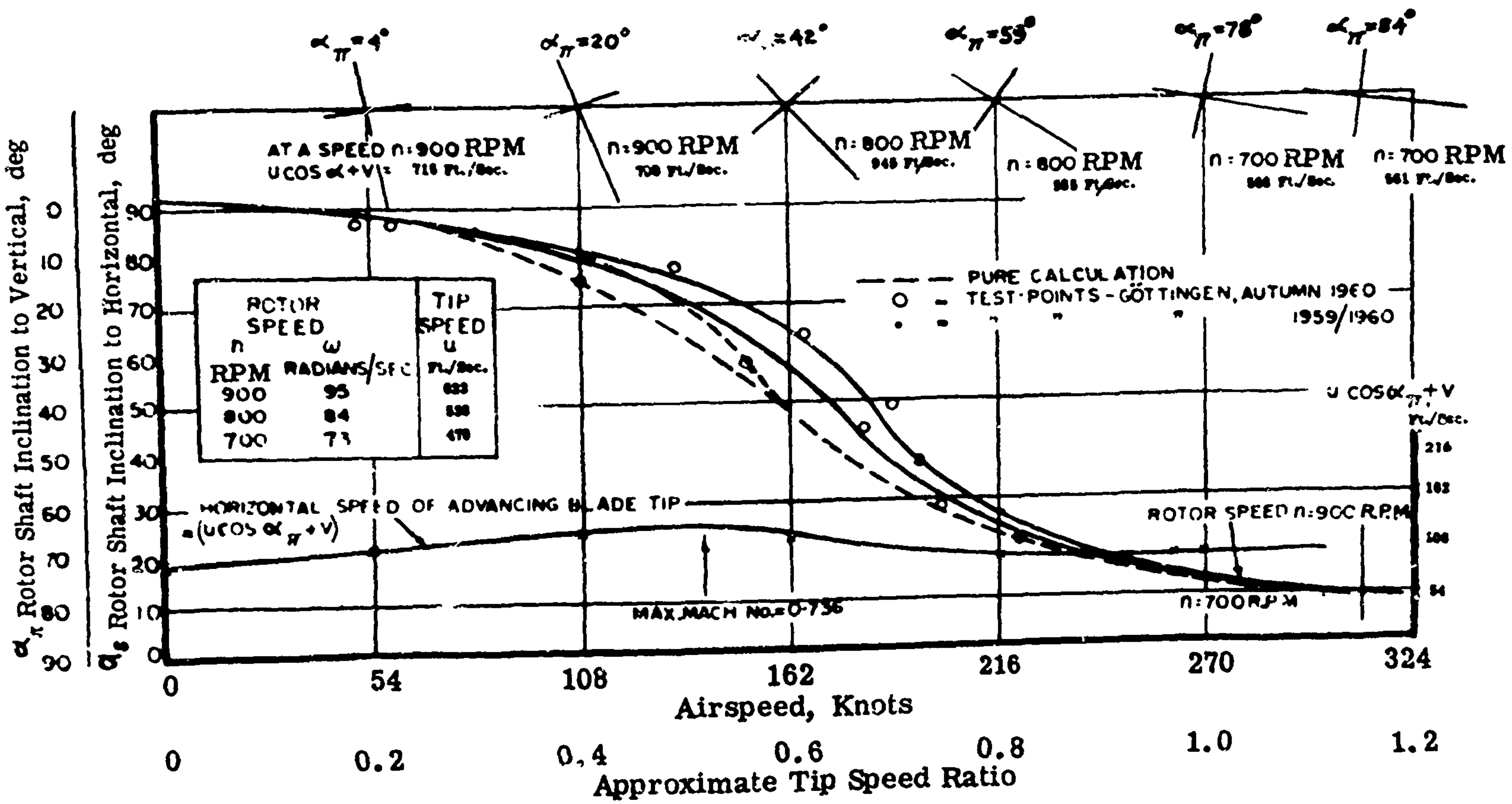


Figure 121. Wind Tunnel Results of the Self-Propelling Wing of Focke and Vereinigte Flugtechnische Werke (VFW) 1959-1960. (Ref. 40F)

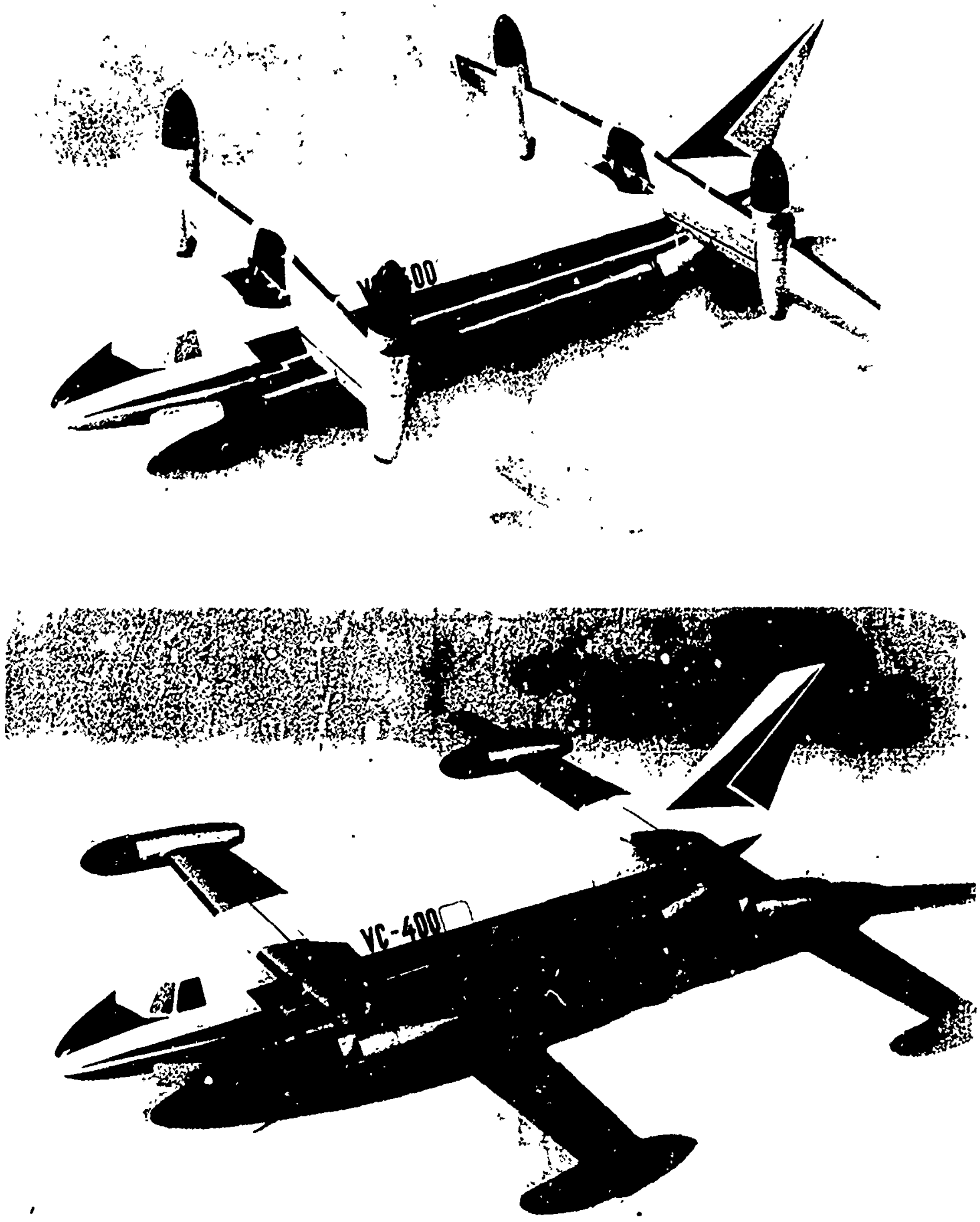


Figure 122. Vereinigte Flugtechnische Werke (VFW) VC. 400 Tilt-Wing VTOL Transport, Shown in Vertical and Horizontal Flight Arrangements.

built for the German Defense Ministry, which is funding the project for possible military transport (Reference: Flight International, 23 May 1968). Component development and testing are well in hand, and three sets of 23-foot propellers and gearboxes have been ordered from Hamilton Standard Division of United Aircraft Corporation. Each of the tandem pairs of propellers is driven by its own 3,960-SHP T64-GE-16 engine, with a common interconnecting transmission. Flight tests of the VC.400-V1 are expected to start in 1970, followed by those of the -V2 in 1971. A civil version with double the number of engines and payload has been projected as the VC.500.

Span: 63 ft. 10 in.

Length: 73 ft. 5 in.

Height: 25 ft. 2.5 in.

Operating Empty Weight: 34,612 lb.

Max. Takeoff (STOL): 63,934 lb.

Max. Speed: 426 knts.

Max. Climb: 6,889 ft./min.

VTOL Radius With 5-Ton Payload: 657 naut. mi.

4. Curtiss-Wright X-100 and X-19 VTOL Aircraft

In the late 1950's and early 1960's, the Curtiss-Wright Corporation engaged in an extensive VTOL program using radial-lift propellers. These efforts are described in Reference 88B. Formulas are given in Reference 56B for the propeller normal force, when the propeller axis is inclined from the horizontal. Curtiss-Wright studies compared the lift-drag ratio obtainable from the inclined propeller with that of a wing. It was concluded that, even at high speed (300 to 400 knots), it was advantageous to have 10 to 20 percent of the aircraft lift carried by the propeller.

The X-100 aircraft, shown in Figure 123, was designed and built to investigate the use of normal force propellers and to determine the flight characteristics of such a vehicle. Thus it was designed using a very heavy wing loading of approximately 170 lb./sq. ft.

The propellers designed for the X-100 aircraft had a hover figure of merit of about 80 percent and a cruise efficiency of 82 percent. By adjusting the blade chord distribution so that the blade was wide inboard and narrow outboard, the normal force produced by the propeller was increased over that of a propeller using conventional blades. This increase in propeller normal force is obtained without a reduction of takeoff or cruise performance. Test results showed that the desired high level of normal force was obtained

Figure 123. Curtiss-Wright X-100 VTOL Aircraft Employing the Radial-Lift Concept.

with the X-100 propeller. It may be noted that the normal force is maximum in the low-speed range, where it becomes expensive in terms of weight to increase lift by increasing wing area.

The characteristics of the X-100 airplane operating in the conversion regime were extremely encouraging, as the aircraft could easily be flown at all speeds through the conversion and back without the necessity of juggling power, attitude, and propeller tilt angle within narrow operating bands. Propellers operating at high values of normal force do not exhibit a sharp stall, and therefore the aircraft can be flown under wide ranges of angle of attack without encountering stalls.

Based on the data obtained during the development of the X-100 airplane, a new, larger, high-speed VTOL aircraft was designed: the X-19 (Figure 124). This aircraft unfortunately suffered from mechanical design limitations that forced early abandonment of the project.

B. THE HELICOPLANE WITH INCLINED PROPELLER AXIS

It is seen, by referring to the helicoplane discussion of section I. C, that an inclined-axis helicoplane, without cyclic pitch, is precisely identical to the radial-lift propeller or self-propelling wing.

In the previous discussion, the self-propelling wing was described using the words of Focke and von Holst. However, in his own publications, Richard used almost identical explanations. To clarify this point further, consider Figure 112. It can be seen that the conventional propeller with its axis inclined to the free stream behaves exactly as the cyclic-pitch propeller.

Richard's results, some of which were shown in Figures 115 through 118, show that, on many occasions, it is possible to get a greater efficiency, i. e., a larger lift-drag ratio, using cyclic pitch than simply inclining the propeller. I is the angle of inclination of the propeller. Actually, a choice should be made in each design case of the optimum configuration. In some cases, both should be used.

C. POTENTIAL OF THE RADIAL-LIFT CONCEPTS

The potential of the radial-lift concepts, based on American (Curtiss-Wright), German (von Holst, Focke-Vereinigte Flugtechnische Werke), and French (Richard) experience, appears to be enormous. In spite of the great recent strides forward (Curtiss-Wright and VFW), extensive research is needed. The general helicoplane principle, which underlies the whole field, clearly indicates that the lift generation phenomena are unsteady; actually, the circulation around the blade changes direction as the blade moves in its circular trajectory. Therefore, theory is

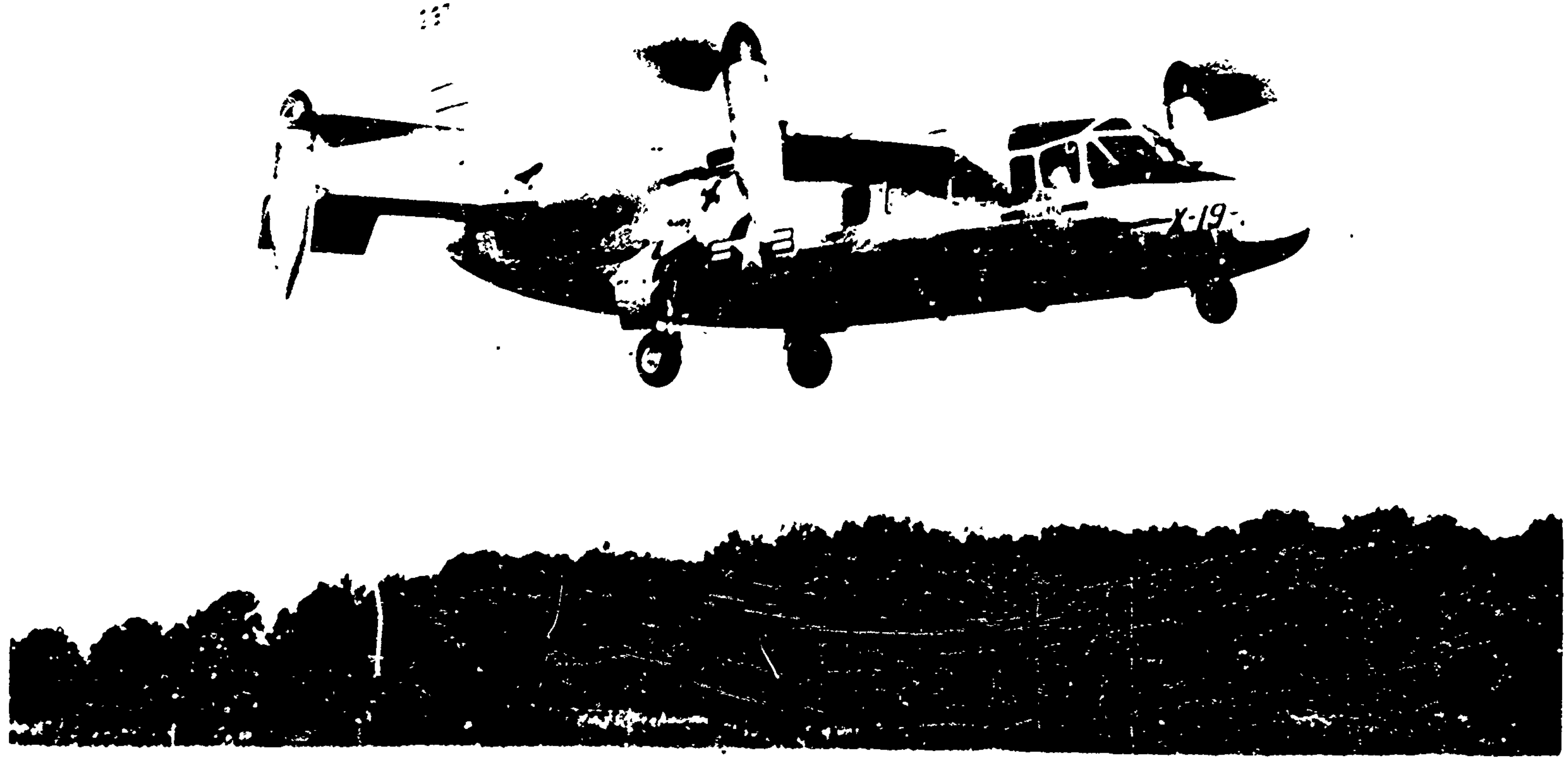


Figure 124. Curtiss-Wright X-19 VTOL Airplane Employing the Radial-Lift Concept.

not adequate to predict radial-lift propeller performance. At best, it can justify some of them a posteriori!

III. NON-AERONAUTICAL APPLICATIONS OF HARWAS

The bibliographical search of material relating to horizontal-axis lifting devices has revealed the existence of a large number of aerodynamic, but non-aeronautical, applications of these devices, related to the use of wind power to generate electricity or to pump water, related to ship propulsion using wind power in a sail-like fashion, or related to underwater cycloidal ship propulsion. These applications are briefly reviewed below.

A. WING ROTOR-TYPE WINDMILLS

Modern use of the conventional propeller-type horizontal-axis windmill is still considerable. The modern windmill is technically very advanced and very efficient, making use, for example, of high-aspect-ratio, laminated-plastic, laminar-flow, variable-pitch blades. It is typically used to drive an electric generator.

Wing rotor-type windmills are paradoxically called "horizontal windmills" (Reference 11B), though they have a singular vertical axis about which a wing rotor profile revolves. A typical windmill that employs a double (Savonius) section is shown in Figure 125.

A wing rotor windmill is designed to optimize torque and power. Bach reported in Reference 3B the results of a systematic investigation of a family of Savonius and similar sections for windmill applications. He plotted not only the torque and power coefficients but also the lift and drag coefficients. These are of interest to the designer to insure the design of a structurally sound windmill tower. Bach's lift and drag results are shown in Figures 126 and 127.

One can obtain an idea of the relative efficiency of the wing-rotor-type and of the conventional propeller-type windmill by plotting their respective power and torque coefficients versus the U/V ratio. This is done in Figure 128.

The power coefficient is defined as

$$C_p = \frac{2P}{\rho F V^3}$$

where

P = measured shaft power

F = largest projected frontal area

ρ = density

V = wind speed

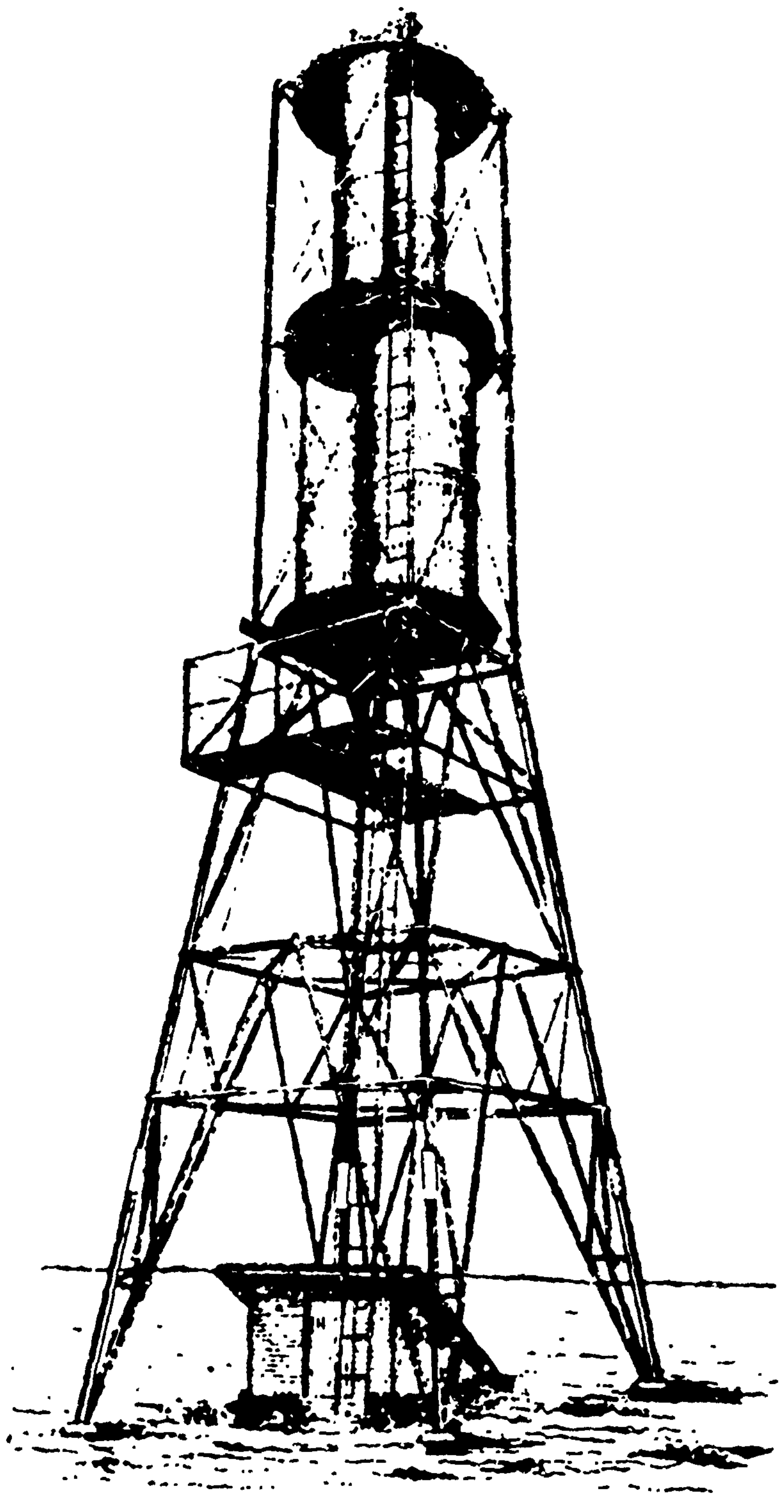


Figure 125. Vertical-Axis Double Savonius Windmill-Type F-13 of the Soviet Wind Energy Institute (Ref. 6K).

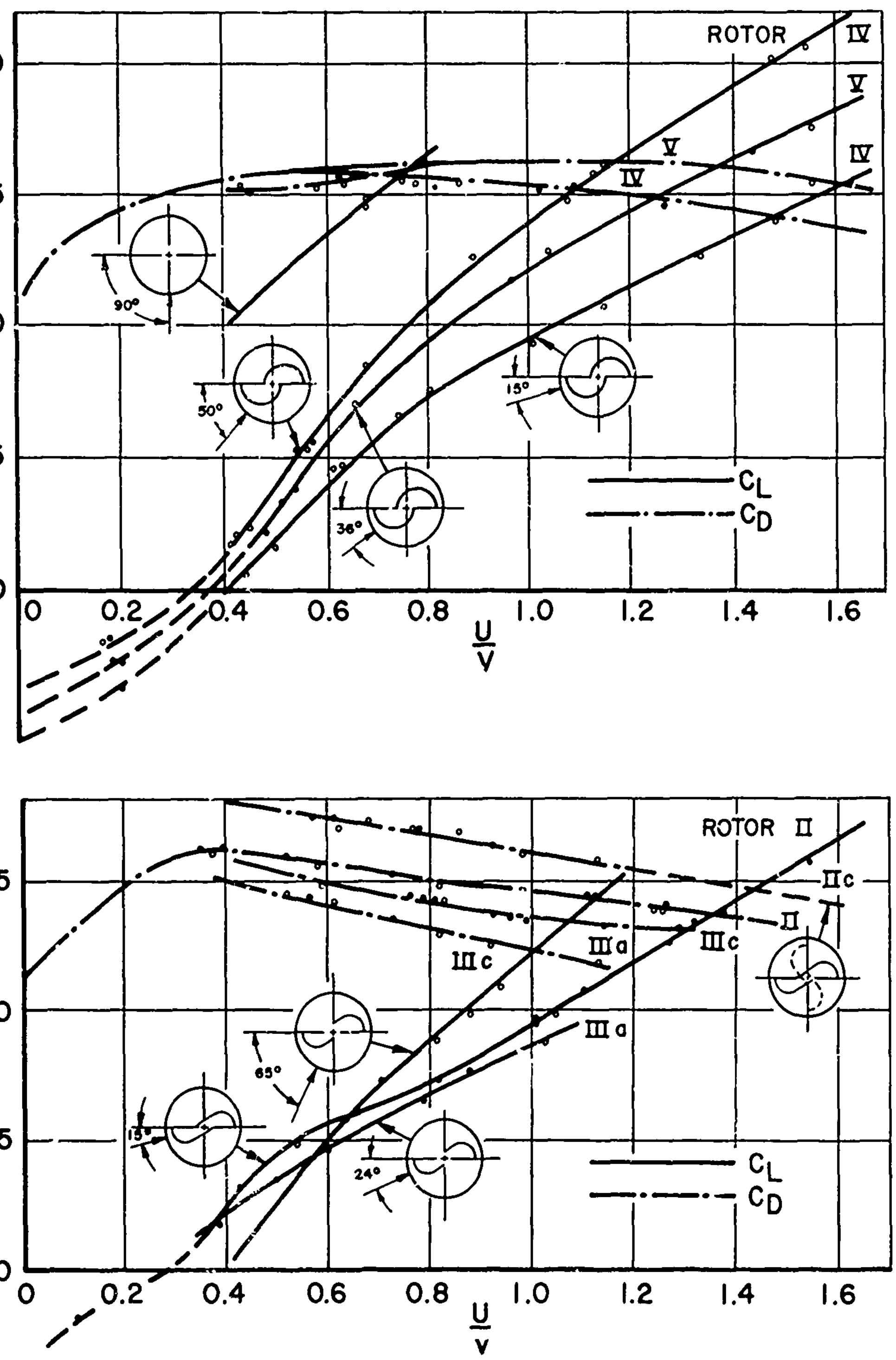


Figure 126. Aerodynamic Performance of a Collection of Basic and Modified Savonius Wing Rotors Through Power Extracting (Braked) U/V Range up to U/V Max. in Free Autorotation. From Ref. 3B.

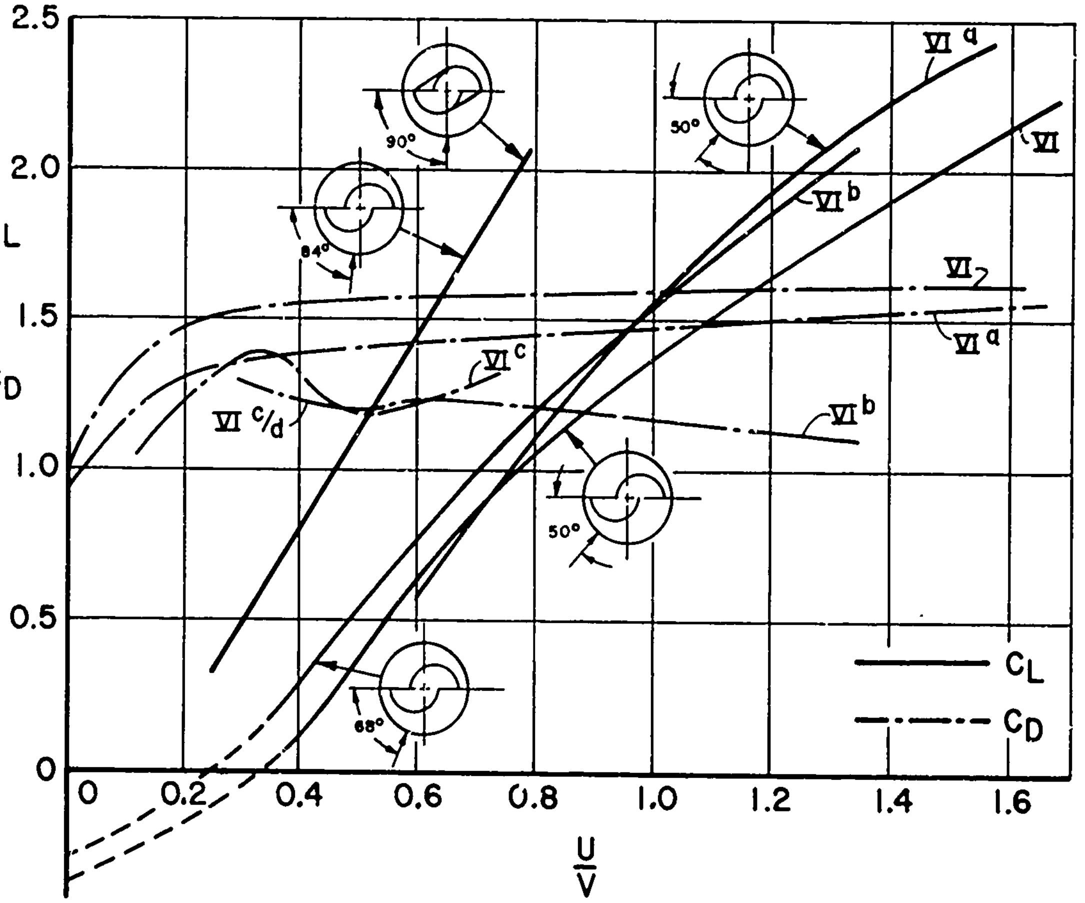


Figure 127. Aerodynamic Performance of a Collection of Basic and Modified Savonius Wing Rotors Through Power Extracting (Braked) U/V Range up to U/V Max. in Free Autorotation. From Ref. 3B. (Rotors: VI, VIa, VIc, IVb) Note: Small Arrows Directed at Rotor Profile Indicate Position of Static Zero or Null Starting Torque Position.

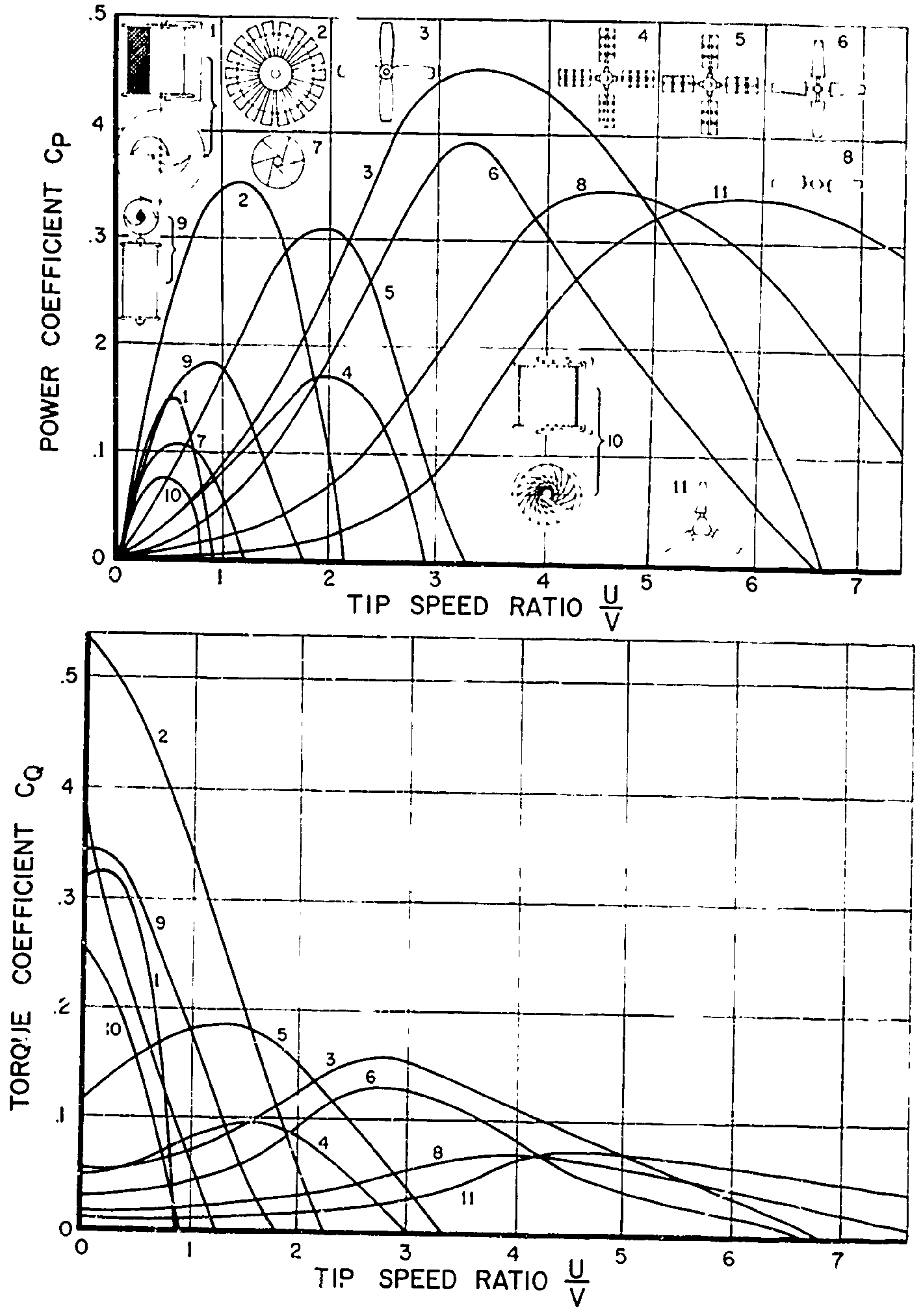


Figure 128. Performance Summary of 11 types of Windmills.

The torque coefficient is defined as

$$C_q = \frac{2Q}{\rho F R V^2}$$

where Q = measured torque.

An inspection of the upper curve of Figure 128 indicates the superiority of the propeller-type windmill (Types 2, 3, 4, 5, 6, 8, and 11) over the wing rotor windmill (Types 1, 7, 9, and 10) in extracting power out of the wind. This comparison is based on identical swept-out rotor disc or projected frontal areas (F).

However, a second look at the torque curves of Figure 128 indicates that the wing rotor windmill shows consistently higher torque coefficients at very low U/V's than the propeller-type windmill (there is one exception, the familiar "American"-type (2) windmill). Usually the wing rotor windmill will have maximum torque at U/V = 0. This is of significant advantage when starting under load, without clutch, is required. Such an arrangement is ideal for the pumping of water, and it is usually for this purpose that the simplicity and directness of the wing rotor or Savonius mills find an application. Conversely, electric generators may have no starting torque, and propeller-type windmills are better adapted to electricity production because of their higher power coefficients.

Figure 125 illustrates the simplicity of the wing rotor mill arrangement. The vertical shaft of the mill is directly connected to a positive-displacement pump which delivers water to a surface reservoir, intermittently, as the wind blows. The mill will turn with the wind approaching from any direction. This arrangement is most useful in remote areas (Reference 48B).

The vertical-axis wing rotor mill has a potential application as an electrical power source, through the proper gearing, for remote, unattended beacons or buoy systems.

B. CYCLOGIRO WINDMILL TURBINE

Like the wing rotor windmill discussed above, the cyclogiro windmill has a vertical, rather than a horizontal, axis. Since the cyclogiro rotor system is capable of autorotation (Figure 100), it is further capable of extracting energy from the wind in the windmill braking state. Many investigators have proposed and patented this type of mill; see, for example, Reference 110S. A typical example is Donaldson's full-size mill, shown in Figure 129.

It is of interest to note that in some of the University of Washington cyclogiro wind tunnel tests, the models were so arranged that the power output from the drive motor running backward as a generator could be

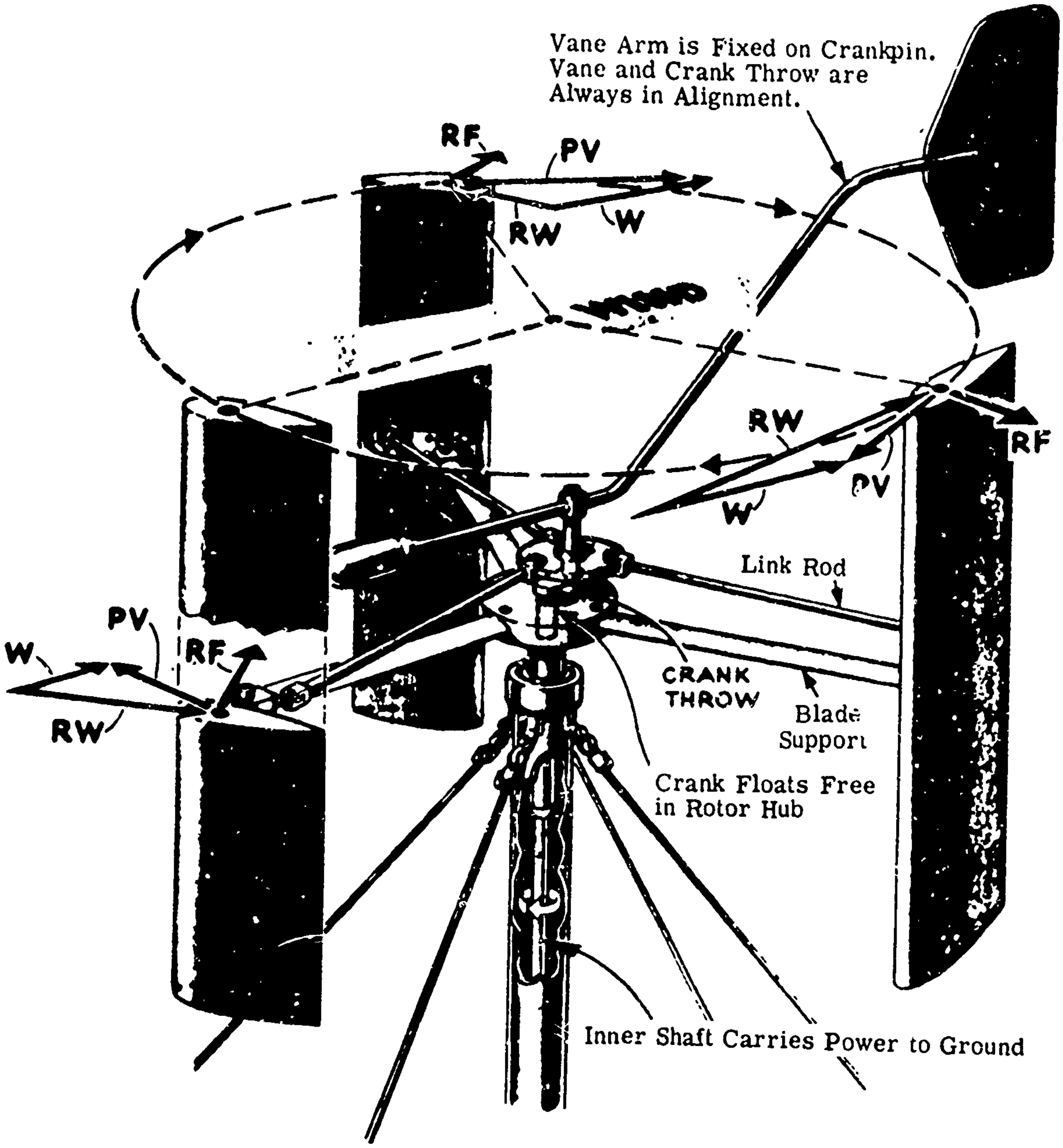


Figure 129. Horizontal Windmill of the Cyclogiro Type by Donaldson (Ref. 19D). Essentially an Autorotating Low-Pitch Cyclogiro Delivering Power Through a Vertical Shaft.

measured under conditions of autorotation or windmilling. This wind generated output is presented as negative values of the power coefficient ($-C_P$) in the data Figures 23 and 24 of Reference 8B and of data Figures 5, 6, 8, and 9 of Reference 2E.

The simple analysis reported in Reference 30P and the preliminary design of Reference 29P suggest that such a mill may be more efficient than the propeller-type windmill. Whether or not this is the case, the vertical-axis cyclogiro mill has one very attractive, unique feature. The success of any wind prime mover depends upon the ability of the designer to spread a given amount of power-extractive structure over a very large "capture" area through which the wind blows. It has been shown that there exist areas of the world where the wind blows with a high degree of constancy and that are close enough to civilization to make industrial use of the power generated. It is therefore always important to make use of the largest swept areas possible. The propeller-type mill's swept blade area seems to be limited by the economics of rotor diameter and of the overall tower height that supports such a piece of equipment. A concept then suggests itself of a cyclogiro-type device that can be made to sweep out large cylindrical areas by running the rotor blades around an immense circular track that could be located on the crown of an air-accelerating hill. This suggestion is embodied in the design of Reference 29P, in which the blades travel on individual wheel systems. The wheels follow a very large diameter circular track, the windmill rotor cylinder describing a right circular cylinder to the approaching wind. Further extensions of this idea suggest the use of the blades travelling in circular moats or on air bearings, etc. Feathering is usually sensed aerodynamically. Through cabling and reduction gearing, a central generator can be driven.

In the Madaras proposal, which was backed by full-scale tests (References 3M through 11M), the rotor blades are replaced by Magnus cylinders running on a large circular railroad track. It has been shown (Reference 110S) that five times as many cylinder rotors would be required, as compared to the airfoil rotor blade system, for an equal extraction of wind power by this means.

C. MAGNUS EFFECT SHIP PROPULSION

A discussion of the practical applications of the Magnus effect would not be complete without mention of its application to ship propulsion. In particular, the full-size experiments in the midtwenties by Flettner (References 19F through 38F) deserve comment. Several Flettner rotor ships were built. Two typical configurations are shown in Figures 130 and 131. The focus of Flettner's experiments was the attempted revival of the sailing merchant ship. It must be remembered that even at that late date the windjammer was still in its last stages of commercial service. Comparative wind tunnel model tests of a windjammer with its full set of sails were made against the same hull driven by two cylindrical Magnus rotors. The results, for that time, were

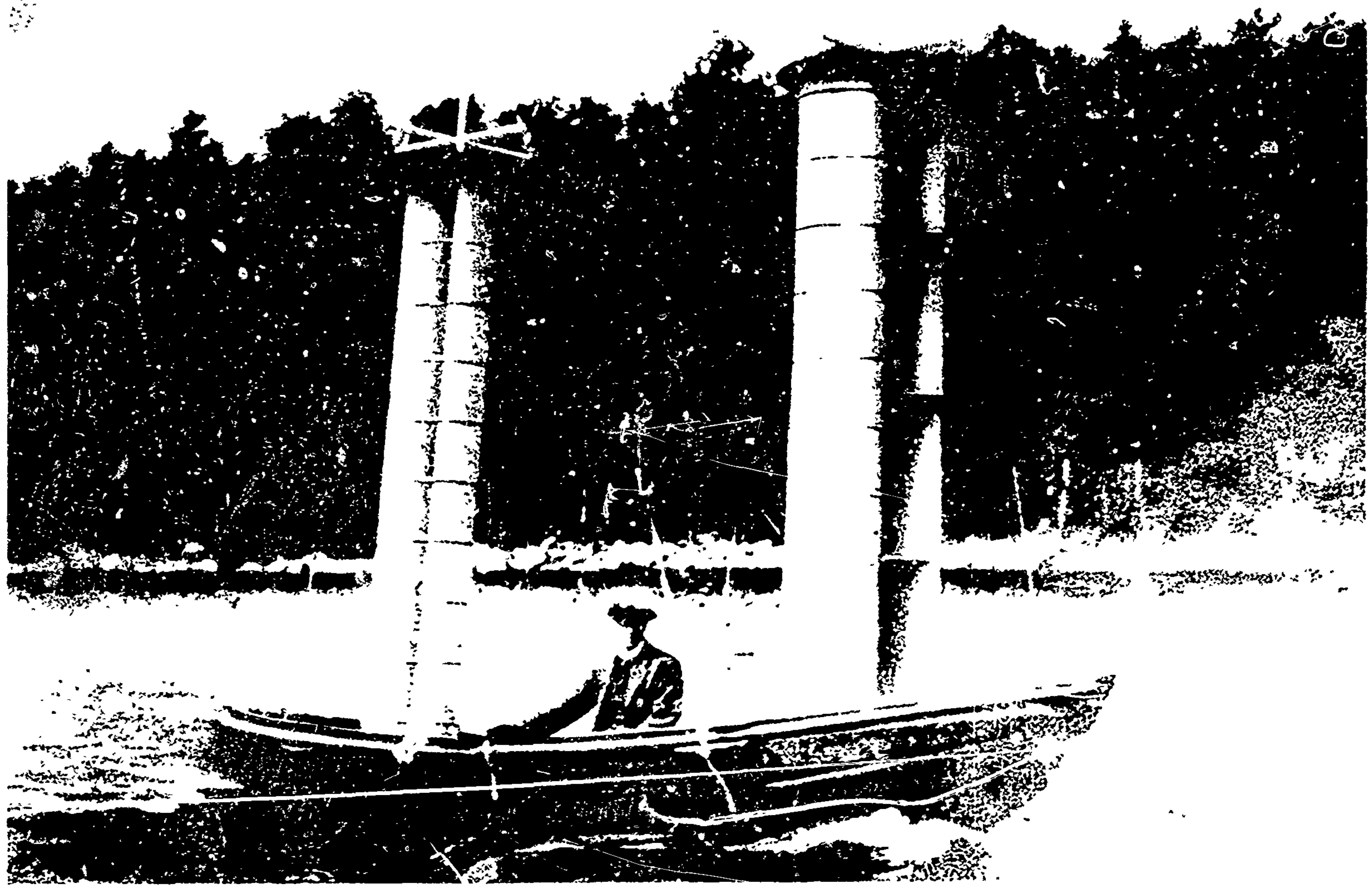


Figure 130. Savonius Autorotating Rotor Sailboat (1925). Semicylindrical Rotor Halves May Be Reversed To Come About on an Opposite Tack.

Figure 131. Powered Cylindrical Flettner Rotor 37-Ft. Racing Yacht Hull (1925). Rotor Must Be Stopped and Reversed for Coming About. Dia., 3.5 Ft.; H, 19.1 Ft.

indeed very encouraging. One must remember the complexity of the multiple-sail system and rigging of the old merchantman to appreciate the vast improvement that was reflected in the aerodynamic and handling performance of the simple two-Magnus-rotor arrangement. Figure 132 is a performance comparison of the applied Flettner rotor system against the full-rigged barkentine, and an isolated, single, rigid airfoil sail. It is important to note that the total projected area of the barkentine is the same for the singular airfoil sail. The barkentine and Flettner rotor curves also included the measured aerodynamic influence of the ship's hull above the waterline. It is most important to note that the Flettner curve is based on the total rotor projected area of only 12.5% that of the barkentine and sail arrangement. Note that the shaded area of the barkentine polar curves indicates the practical area in which sail trim changes may take place and still keep the craft underway. As would be expected, the isolated airfoil sail, without the obstructions of rigging and the optimization of a fixed profile, has greater L/D (ability to point upwind) and C_N (greater sail force) potentials. It is toward this latter arrangement that modern sail design (sail wing, flex wing, wingsail, etc.) is tending. Thus, the potential of Magnus effect to ship propulsion remains only for pleasure craft and the like (Figure 131). It would be interesting to adapt the autorotating wing rotor to such craft (Figure 129, References 46L and 47L) when better aerodynamic sections become available.

D. CYCLOIDAL SHIP PROPULSION

The following areas of marine cycloidal propulsion have been examined in the light of their application to the general cyclogiro requirements:

1. Rotor blade kinematics, controls, and linkages
2. Rotor blade stress analysis and loads
3. Theoretical treatment of cycloidal propeller performance

As a general consideration, the present state-of-the-art use of cycloidal propulsion is in the amplified low- or pi-pitch ranges, and this fact alone limits any usefulness of marine experience. In item 1, the adaptation of marine blade-feathering systems to low-pitch cyclogiro aircraft configurations is, in many cases, schematically adaptable, but the weight and bulk of the marine blade feathering systems restrict their general use to marine craft. Rotor blade stress analysis and blade load distribution (2) were found to be generally adaptable though scant (References 20K, 30K, and 67M).

Although there is no lack of theoretical treatment of the cycloidal propeller, there is not presently a unified theory that could reflect the rotor performance for the proper range of blade aspect ratio, number, shape, twist, advance and pitch ratios, etc. All of the theoretical work

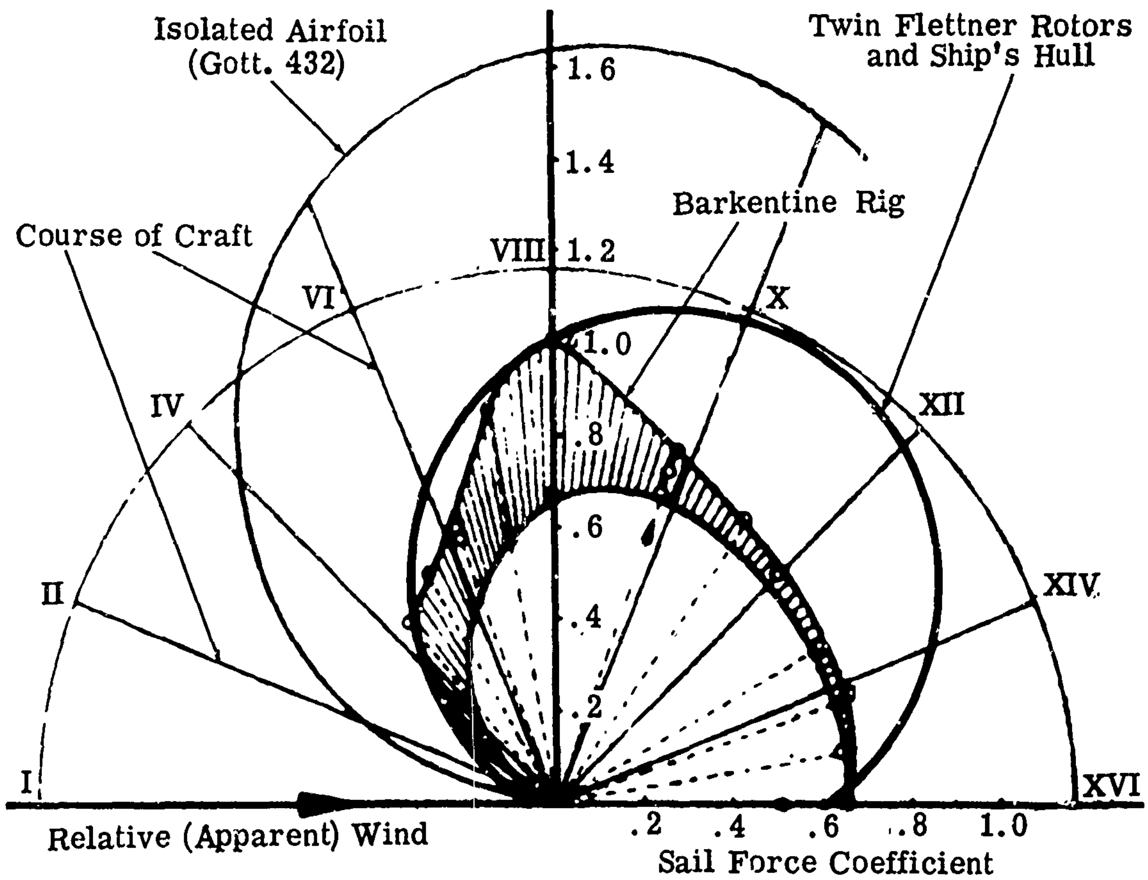


Figure 132. Performance Comparison of a Barkentine Sail and Flettner Rotor. Ship's Hull and Rigging Included.

to date covers the marine requirements (ahead thrust) in the low- or pi-pitch regime. Although the full-feathering cyclogiro could profit from part of this analysis in the area of hover and vertical flight, it is felt that marine theory cannot be of use when forward flight considerations are involved (rotor lift as well as propulsion).

Mueller, in Reference 67M, showed a general performance curve that compares the cycloidal marine propeller with an optimized conventional screw propeller. This plot is reproduced in Figure 133 in the form of the variation with thrust-load coefficient of what Mueller calls the "degree of perfection", also referred to as "real efficiency". The thrust-load coefficient is defined as follows:

$$C_{TL} = \frac{T}{0.5 \; \rho \; A_0 \; V_A^2}$$

where

T = the thrust of the propeller

ρ = the density of water

A_0 = the disc area of the propeller

V_A = the speed of advance of the propeller

The real efficiency is defined as the ratio of the actual efficiency η_0 of a real propeller in unlimited water to the ideal efficiency η_1 of the imaginary actuator-disc propeller of the same disc area A_0 and working at the same thrust-load coefficient C_{TL}.

A comparison of an efficient cycloidal propeller (Voith-Schneider amplified low pitch) with the best screw propeller (controllable propeller) shows a slight performance advantage for the conventional screw. However, at high speeds of advance, the cyclogiro propeller takes over. Thus, the advantage of the cyclogiro propeller does not lie in the fact that it has a higher propulsive efficiency, but in the fact that the efficiency remains constant whatever the direction of motion. In contrast, the performance of a four-blade controllable-pitch screw propeller, in back drive, is also shown in Figure 133. The screw propeller loses nearly one-half of its efficiency in back drive, while the cycloidal propeller loses none. Hence, the logical use of the cycloidal propeller is where flexible control and maneuverability are important: tug boats, floating cranes, fireboats, ferryboats, or for such military applications as minesweeping.

The performance curve for a cycloidal propeller with sinusoidal blade motion, which is a variant of the amplified low-pitch system (Reference 67M), is also shown in Figure 133. There, reduced performance is traded for a very simple control system and mechanical

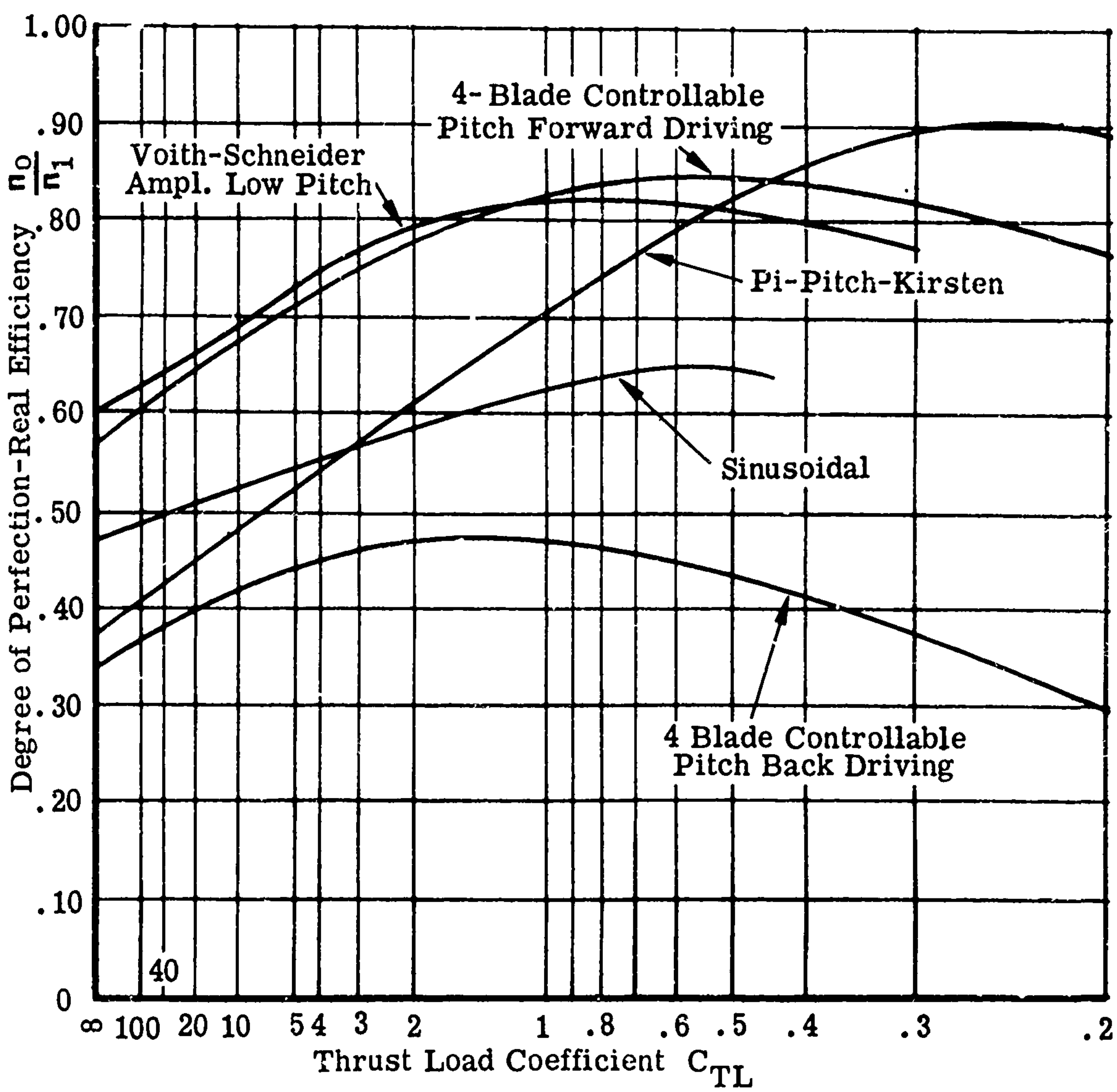


Figure 133. Comparative Performance of Three Types of Marine Vertical Axis Cycloidal Propellers With a Forward and Backward Driving Controllable Pitch Axial Propeller (Ref. 67M).

layout. Only very limited model testing exists for the marine propeller in the high-pitch regimes (Reference 18M).

Mueller (Reference 67M) suggests a means for obtaining a "poor man's" full-feathering cycloidal propeller. In this instance, when the ship is in a harbor or in close quarters, when maneuverability and precise control become desirable, the cycloidal propeller operates strictly in a low or amplified low-pitch regime with the blades normally feathering with respect to the rotor system. Once free of congestion and shipping and in the open sea, the propeller may be momentarily declutched (continuing to rotate without load) or stopped, and the feathering mechanism may be "gear-shifted" over into the high-pitch mode where the blades rock relative to the ship's hull.

The ship may now be accelerated into high pitch and advance ratios of high, forward, unobstructed speeds. This arrangement suggests a high-speed, efficient propeller with the control and maneuvering capability of the vertical-axis propeller. Schematically, this gear-shifting may be represented by rotating the slider blade-feathering link half a turn from the low-pitch to the high-pitch position (when $\psi = 180^{\circ}$), as shown in Figure 93. Thus, a quasi-full-feathering cycloidal propeller becomes feasible for ship propulsion without the intermediate mid-pitch transition and matching mechanism necessary for a comparable arrangement in aircraft. Two such intermittent full-feathering cycloidal marine propellers have been patented by Schneider (Reference 56S) and more recently by Bilke, et al (References 41B and 42B). The latter mechanisms are very ingenious, simple and with much merit.

SUMMARY OF ANALYSIS

A summary of the status of potential applications of horizontal-axis rotating-wing aircraft systems is presented in Table VII. The most remarkable part of this table is that it shows the extraordinary variety of HARWAS; it also shows the status of advancement of those systems: those that have been fully developed, those on which limited research has been done but which show promise, and those which show promise but on which hardly any research at all has been performed.

It is interesting, at the end of this study, to attempt to outline the common features of the very diverse systems that were reviewed. This will be done in the form of two remarks:

1. The operation of almost all HARWAS is fundamentally based on unsteady aerodynamics. For example, wing rotors, cyclogiro systems, helicoplanes, and radial-lift propellers rely fundamentally on time-varying lift and drag forces. This automatically explains why less is known about them than about fixed-wing aerodynamics. The operation of fixed-wing aircraft can, at least in first approximation, be understood in terms of steady or quasi-steady flow. This is not possible for HARWAS. There are today no established engineering rules to explain unsteady lift and drag flow phenomena. It could very well be that serious study in this direction is required before there can be a positive understanding of HARWAS aerodynamics.

2. The other common feature of cyclogiros and radial-lift propellers is that they were evolved in an attempt to copy nature, i.e., bird or insect flight. The paradox of modern aviation is that it has achieved enormous success by separating the functions of lift and of propulsion, which is unknown in nature. As stated in the introduction of this report, all early attempts to copy bird flight in aeronautical devices have been markedly unsuccessful. It is the conclusion of this report that, for VTOL and STOL aircraft at least, one has much to learn from the successful integration of lift and propulsion in animal flight. There again, bird flight is a nonstationary process!

Kirsten in the United States, von Holst in Germany, and Richard in France all suggested different versions of HARWAS as a direct consequence of their interest in, and study of, bird flight. It is suggested that their approaches are worth pursuing.

If one were to select the two most promising HARWAS configurations of those listed in Table VII, and an additional constraint was that these configurations should not be under active study elsewhere at the present time (example: Reference 57W), the two HARWAS systems would be as follows:

1. The rotating airfoil flap (RAF) for application to a STOL aircraft

2. The full-feathering cyclogiro for application to the composite aircraft mission

TABLE VII. SUMMARY AND EVALUATION CHART FOR HORIZONTAL AXIS ROTATING-WING AIRCRAFT SYSTEMS (HARWAS).

		SYSTEM	AIRCRAFT APPLICATION	POTENTIAL	NEEDS FURTHER RESEARCH	NEEDS ADVANCED TECHNOLOGY	FULL SIZE TEST OR DEVELOPMENT	ANALYSIS AVAILABLE	STUDY IN DEPTH	RESTRICTIONS	SIGNIFICANT REFERENCE
HORIZONTAL AXIS LIFTING SYSTEMS	MAGNUS EFFECT AND RELATED SYSTEMS	ROTATING CYLINDER SLAT	Stol	Little					Yes		51W
		ROTATING CYLINDER IN WING	Stol	None							51W
		ROTATING CYLINDER AT TRAILING EDGE	V/Stol[1]	Fair				Yes			42S
		ROTATING CYLINDER FLAP	V/Stol[1]	Excl.	Yes		Done		Yes	Current Patent	56W
		ROTATING CYLINDER WING	Stol	None			Done				4Z
		ROTATING AIRFOIL SLAT	Stol	None ?							50L
		ROTATING AIRFOIL IN WING	Stol	None ?							50L
		ROTATING AIRFOIL FLAP	Stol	Excl.	Yes		Req'd.	Yes	Yes		52C
		ROTATING AIRFOIL IN FLAP LEADING EDGE	V/Stol[1]	Good?							22L
		ROTATING AIRFOIL CONVERTIBLE-FIXED WING	Stol	Fair			Done		Yes		21C
		WING ROTOR ROTATING AIRFOIL DECELERATOR		Very Good	Yes		Req'd.	Yes		Current Patent	52B
		ORBITING AND THRUST FLAP	V/Stol?	Very Possible	Yes		Req'd.			Current Patent	54S
		TRANSVERSE FLOW FAN AND FLAP	V/Stol?	Very Possible	Yes	Yes[2]	Req'd.	Fan Only		Current Patent	12-21L
	CYCLOGIRO SYSTEM	LOW PITCH	Vtol	Near Hover			Done	Yes	Yes		26W
		AMPLIFIED LOW PITCH	Vtol	Near Hover				Yes	Yes		26H
		PI PITCH	Vtol	Fair			Done	Yes	Yes		30K
		AMPLIFIED HIGH PITCH	V/Stol	Excl.	Yes	Yes[3]	Req'd.	Yes	Yes		8B
		HIGH PITCH	Stol	Excl.	Yes			Yes	Yes		1E
		FULL FEATHERING	V/Stol	Excl.	Yes		Req'd.	In Parts	Yes		2E
		OTHER		None			Done				50L
		CONICAL ROTOR		?	Yes						32R
Near Horizontal Axis Lift-Thrust Devices		RADIAL-LIFT PROPELLER	Vtol[1]	Excl.	Yes		Done	Yes	Yes		85B
		CYCLIC LIFTING PROPELLER	Stol?	Very Good?	Yes		Done	Yes	Yes		31-38R
NON-AERONAUTICAL APPLICATIONS OF HARWAS	Turbine Sail	WING ROTOR OR SAVONIUS WINDMILL		Good Limited			Done		Yes		3B
		MAGNUS EFFECT SHIP PROPULSION		Sport Only			Done	Yes	Yes		31F
	Propulsion Turbine	CYCLOIDAL SHIP PROPULSION		Excl. Limited	Yes		Done	Yes	Yes		30K
		CYCLOGIRO WINDMILL TURBINE		Good ?				Yes	Yes		29-30P

NOTES: 1 - As Deflected Slipstream or Tilt Wing. 2 - Fan Wt. Reduction. 3 - Gas Turbine Matching

PRELIMINARY PERFORMANCE AND DESIGN STUDY OF TWO HARWAS CONCEPTS

I. ROTATING AIRFOIL FLAP (RAF) STOL AIRCRAFT

The search for better high-lift devices is more urgent than ever, not only for STOL aircraft but also for conventional high-performance aircraft. Actually, there is no basic difference between the high-lift devices of a conventional airplane and those of such STOL aircraft as the Grumman Mohawk or the De Havilland Caribou. It is a matter of degree: the former type has larger flaps, larger leading-edge slats, a higher power loading, and the maximum favorable interference between the propelling unit and the wing. Recently, the Boeing Aircraft Company advanced the concept of the conventional/short takeoff and landing (C/STOL) aircraft, an airplane with the size and the capacity of the Boeing 737, the favorable economics of conventional takeoff and landing, and the flexibility of STOL performance.

The use of horizontal-axis rotating aerodynamic devices, either autorotating or powered, in conjunction with fixed wings, opens new possibilities for the enhancement of either low-speed lift or low-speed lateral control of CTOL, STOL, or C/STOL aircraft. In the latter mode, the rotating devices could be used as fixed surfaces for the CTOL operation and as rotating surfaces for the STOL operation. Conversion from a fixed to a rotating position is not expected to be a significant problem. As shown in Table VII, at least 10 candidate configurations have been suggested in the past. Out of these, two are of more immediate interest: the rotating cylinder in flap (RCIF) and the rotating airfoil flap (RAF). Extensive research and development are being done at the present time on the RCIF by Alvarez-Calderon and the Ames Research Center of NASA. It is therefore proper here to concentrate on the less-researched RAF.

Aerodynamic test data relating to the RAF are collected, examined, and compared with similar data for other high-lift systems. The results of this analysis are used for a preliminary design exercise in which the present flap system of the DeHavilland DHC-5 Buffalo (shown in Figure 134) is replaced by a rotating airfoil flap system. The fact that all data on the RAF are small scale requires an extrapolation to full scale, which may or may not be valid, but for which similar experience with other high-lift devices is a useful guide. An attempt was made at being conservative, rather than optimistic.

A. AERODYNAMIC CHARACTERISTICS OF THE ROTATING AIRFOIL FLAP (RAF)

As shown in the ANALYSIS section of the report, the Küchemann study (Reference 51K) is the only source of comprehensive data for appli- of the external RAF to aircraft and will therefore be used here for further discussion as well as for sizing. The data will be examined on a

Figure 134. De Havilland DHC-5 "Buffalo" Transport Aircraft With Double Slotted Flaps Extended for Maximum STOL Takeoff.

comparative basis with other related high-lift systems under conditions as similar as possible.

The comparison is shown in Figure 135 in the form of five polar curves for complete aircraft configurations with different high-lift devices, which have the following in common:

- There are no propeller effects ($T_c' = 0$).
- If the flap is fixed, the flap deflection δ_f is 40^o to 45^o.
- The flap chord, C_f, is 20 to 25% of the wing chord C_w.
- Airfoil thickness ratio is 15 to 18%.

The five configurations are as follows:

1 Full-scale airplane, with external fixed flap,

$$\delta_f = 40^o, \quad C_f = .2\ C_w$$

2 Model airplane, Küchemann, with external fixed flap,

$$\delta_f = 45^o, \quad C_f = .25\ C_w$$

3 Model airplane, Küchemann, with rotating flap,

$$U/V = 4.0, \quad C_f = .25\ C_w$$

4 Full-scale STOL airplane, DeHavilland Buffalo, low-C_L end of computed polar curve only,

$$\delta_f = 40^o, \quad C_f = .25\ C_w$$

5 Full-scale airplane model (Ames wind tunnel) of a rotating cylinder flap

$$\delta_f = 40^o, \quad C_f = .46\ C_w \text{ (including rotating cylinder)}$$

$$U/V = 5.1$$

Obviously, the major differences among the five configurations are as follows:

- Scale effect (Reynolds number):

1, 4 and 5 are full scale; 2 and 3 are small scale

- Wing aspect ratio:

  (4) has very large aspect ratio

  (1) has large aspect ratio

  (5) has fairly small aspect ratio

  (2) and (3) are with very small aspect ratio

Thus, the RAF models (2) and (3) have joint disadvantages of model data and small wing aspect ratio.

A comparison of (1) and (2) shows the scale effect and the aspect ratio effect for two airplanes with external fixed flap: the maximum lift coefficient is about the same, but the corresponding drag of (2) is one-third larger than that of (1).

The effect of rotating the flap (RAF) is shown by comparing (2) (U/V = 0) and (3) (U/V = 4.0). There is a significant increase in C_{Lmax}, but there is a correspondingly large increase of C_D. The sudden collapse of C_{Lmax} for (3) shows a very sharp stall, representative of the sudden flow breakaway, at the low test Reynolds number.

A comparison of (1) and (5) shows that at low C_L's the polar curves are much the same. At very low C_L, (1) has a lower drag than (5), but (1) stalls earlier ($C_L \approx 2.1$). Configuration (5) would stall only at $C_L \approx 3.1$.

A comparison of (1), (4), and (5) shows that (4) and (5) have very similar polar curves, which both extend the polar curve of (1) to higher C_L's. Thus, based on this figure (poweroff condition), a good double-slotted flap and the rotating cylinder flap (RCIF) have about the same characteristics. Although not shown here but in Figures 33 and 36, the influence of propeller slipstream is to dramatically increase the C_{Lmax} of the RCIF, configuration (5), from 3.1 to 12. It is to be noted from actual flight tests that the C_{Lmax} of the double-slotted flap only increases to 3.6 with propeller effects.

Finally, a comparison of (3) and (5) shows that, under the conditions of similarity stated above, airplane (3) (the RAF) has a higher C_{Lmax} than airplane (5) (the RCIF). Further, at $C_L = 3$, the drag of airplane (3) is one-third higher than that of airplane (5). It was noted earlier that the one-third factor may correspond to a scale effect. Thus, the lift-drag ratio of configuration (3), full scale, could be about the same as that of configuration (5). It remains that (3) has a C_{Lmax} that is 25% higher than (5). Stall could also be less abrupt than is shown in Figure 135 for configuration (3).

Assuming now that the propeller slipstream effect is as large on configuration (3) (the RAF) as on configuration (5) (the RCIF), one might speculate that the RAF is capable of very high lift coefficients, of the order of 15.

Naturally, all this is speculation, but it indicates the desirability of following the full-scale wind tunnel tests on the RCIF by similar tests on the RAF.

The aerodynamic problems to be investigated in RAF full-scale tests are as follows:

1. Size; i.e., Reynolds number effect on aerodynamic performance.

2. Effect of propeller slipstream on performance.

3. Effect of wing aspect ratio, flap aspect ratio, airfoil shape, airfoil thickness ratio, and flap tip plate shape.

4. Effect of flap-chord-to-wing-chord ratio and of the position of the flap axis with respect to the fixed-wing trailing edge.

5. Effect, if it exists, as hinted in Reference 42S, of the fixed-wing airfoil on the overall geometry of the RAF.

6. Installation arrangement of the RAF as an external airfoil flap. May not be the optimum aerodynamic or mechanical arrangement. Variations have been described by Tino (Figure 76), Lake (Figure 89), and Henter-Käser (Figure 88).

7. Effect of external and locked RAF on cruise lift-drag ratio and environmental (icing) problems.

8. Pitching moment data on the RAF. Should be obtained for all the tests suggested above.

B. THE RAF AS A CONTROL DEVICE

There are no test data that can be used to substantiate the effectiveness of the RAF as a lateral control device (aileron) for the low-speed operation of a STOL aircraft. It is well known that the minimum approach speed of an aircraft is sometimes dictated by control, not by high-lift considerations. The RAF can be broken down into several spanwise sections rotating independently, and the outer section can be used for lateral control. (See Table VIII).

The tests suggested in the preceding paragraph should definitely include a determination of the lateral control effectiveness of the RAF.

C. POWER REQUIRED TO ROTATE THE RAF

There is a great shortage of data on the power required to activate a rotating airfoil flap. The only data available (Wiese, Reference 56W) concern the power required to rotate isolated airfoils (not in conjunction with a fixed wing) about their 50% chord axis. Wiese's data are shown in Figure 136, and they really have more of a qualitative than a quantitative value. On the contrary, the power required to drive the NASA/Ames RCIF system was exactly determined and is also plotted in Figure 136, where it can be used as a lower boundary.

In Figure 136, the power coefficient C_R is plotted versus U/V.

$$C_R = P/(1/2 \rho U^3 S_f)$$

where

P = power required

ρ = density

U = peripheral velocity of flap

S_f = flap area

Certain trends can be observed from Figure 136, as follows:

- Required power decreases with increasing Reynolds numbers.
- Required power decreases with increasing aspect ratio.
- Required power decreases with the addition and shape of tip plates.
- Possibly, profile shape affects the required power.

It is felt that a reasonable estimate of the variation of C_P with U/V is provided by the curve of Figure 136 corresponding to AR = 5 and an elliptical tip plate. The curve is used in the numerical example and design study that follow.

It is of interest to note that the majority of test curves for the lenticular rotating airfoil of Figure 136 (16.7% thickness ratio) do not pass through the origin but tend to originate near U/V = 1, in the autorotational condition. Also shown in Figure 136 is configuration 40 of Table III, which autorotates at a U/V of nearly 2. It is possible that this shape would have reduced power requirements in the driven mode as well.

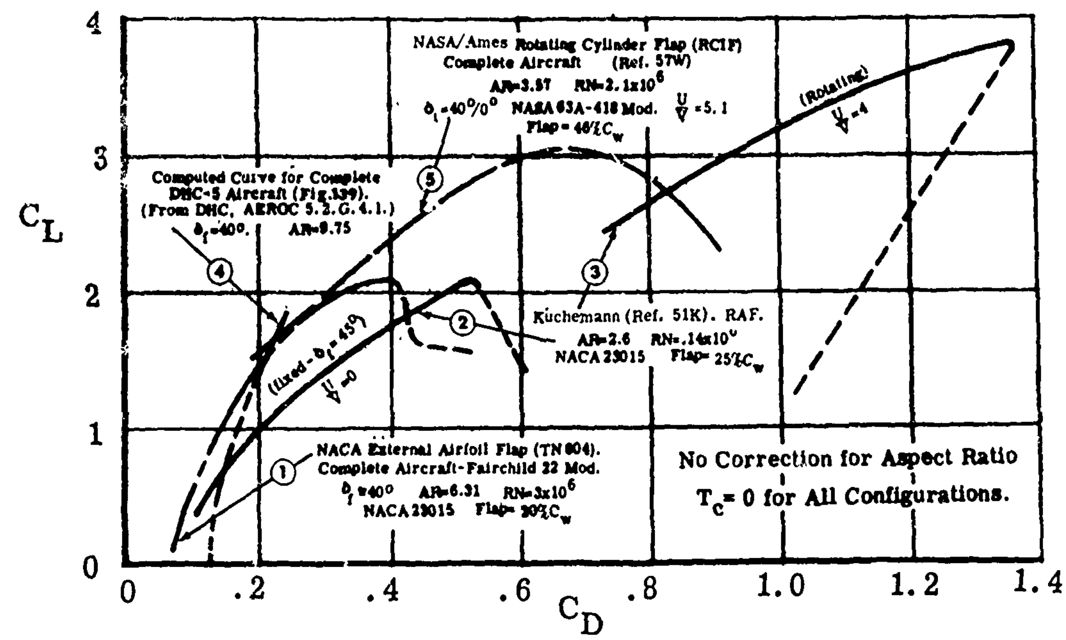


Figure 135. Lift and Drag Polars for Rotating Airfoil Flap and Other Related High-Lift Flap Devices.

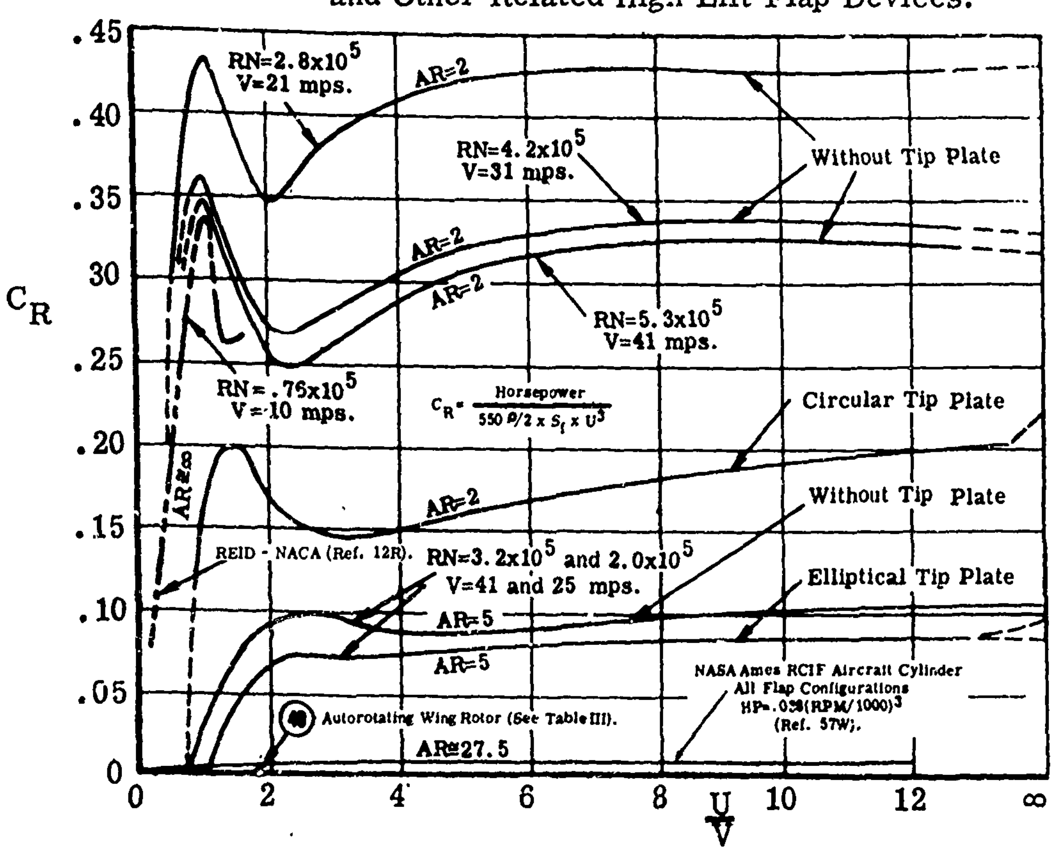


Figure 136. Power Requirements for Rotating an Isolated Lenticular Wing Rotor and RCIF Cylinder Flap.

D. APPLICATION OF THE RAF TO A STOL TRANSPORT AIRCRAFT

To investigate the application of the RAF to aircraft, the following preliminary study was undertaken to understand the problems of RAF adaptation, powering, and practical performance. To this end, it was considered to be desirable to adapt the RAF system, with a minimum of modifications, to an existing STOL transport aircraft. The aircraft selected for this study is the DeHavilland DHC-5 "Buffalo" transport aircraft (Figure 134). The basic characteristics of the RAF-modified version of this aircraft are shown in Figure 137 and are tabulated in Figure 139. For matters of direct comparison, it will be noted that the gross weight (for STOL landing) and the wing area have been kept identical for the RAF-modified and the nonmodified DHC-5. As with other flapwing area conventions, the external nonrotating flap is not included in the total wing area measurement. For the purposes of this discussion, the overall RAF system consists of six flap elements, each with a nominal aspect ratio of five, elliptical tip plates, and a lenticular cross section profile. Thus, the approximate power requirements of each flap section may be determined from the tests by Wiese, Figure 136.

The RAF axis is located in the "optimum" position 2 (Figure 43). The RAF system is further broken down into two inboard rotating flap elements and four outboard rotating flaperons. Referring to Figure 137, the rotating flap element, drive, and control system are represented schematically in plan view. Note that the two outboard flaperons rotate directly together and are split to provide for a midpoint support hanger. In practice, the individual flap elements would be allowed to slide axially on splines or couplings to accommodate wing and flap deflecting during flight. For the same reason, the support bearings would need to be self-aligning. Figure 138 further indicates that the individual port and starboard flap systems acquire their driving power from hydraulic pumps possibly attached to the main flight engine accessory pad. An alternate suggestion would be to drive the flaps from an auxiliary power unit centrally located within the fuselage in the area of the cross-coupling clutch.

The functioning of the "hydraulic mechanical selector mixer system" is tabulated in Table VIII. The effect of various control and power functions in these units is further tabulated to show the flap responses over the full range of flight regimes and for various aircraft missions.

A comparison of the RAF with the existing double-slotted flap of the DHC-5 is of great interest. The existing DHC-5 flap and aileron system is briefly described here. The wing incorporates high lift, full-span, double-slotted flaps along the trailing edge. The outer section of the trailing flap operates as a conventional aileron. The DHC-5 flap system is power-operated via a hydraulic motor; gearboxes, torque tubes, and irreversible screw jacks. The flap system is provided with adequate protection against a malfunction. The flap-aileron system consists of fore sections and trailing sections--inner, mid, and outer on

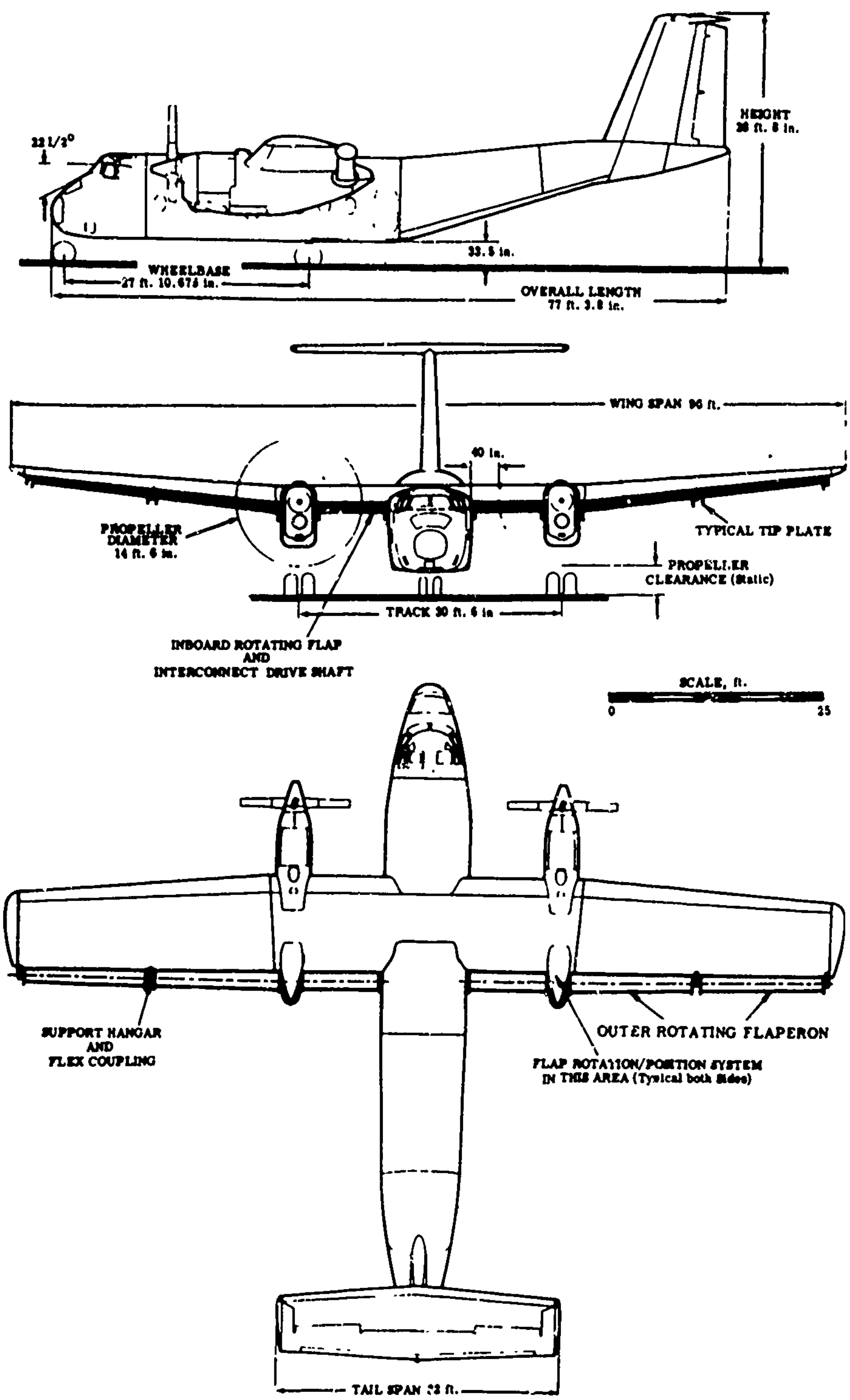


Figure 137. Modification of DeHavilland DHC-5 "Buffalo" Incorporating Full-Span Rotating Airfoil Flaps (RAF) and Aileron (Flaperon) System. Gross Weight and Total Wing Area are Identical.

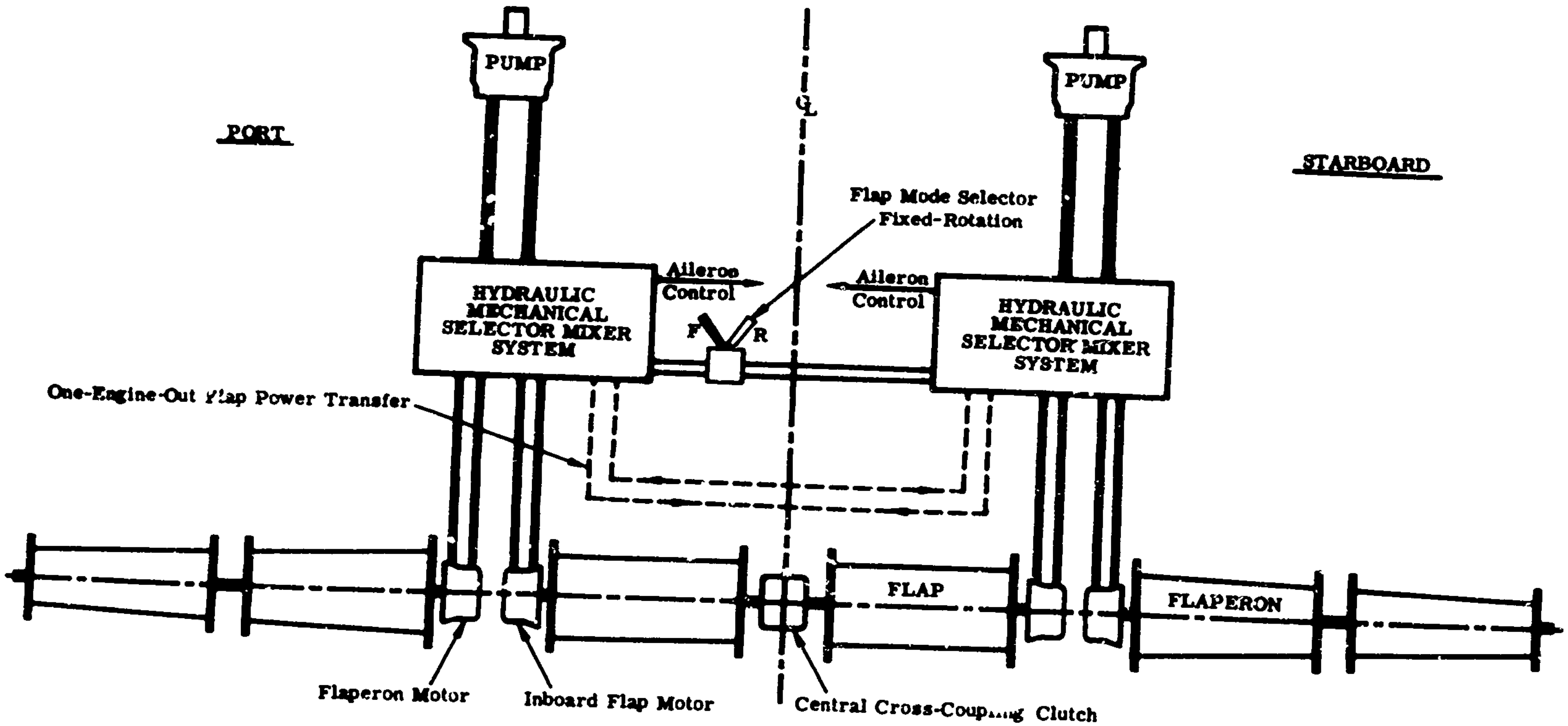


Figure 138. Schematic Representation of the Hydraulic and Mechanical RAF Drive and Control System as Might Apply to Twin-Engine Aircraft. Functioning of the Components Is Described in Table VIII.

TABLE VIII. HYPOTHETICAL ROTATING AIRFOIL FLAP FUNCTION AND FLIGHT PROGRAM ADAPTED TO THE DHC-5 "Buffalo"-TYPE STOL AIRCRAFT

FLIGHT OPERATION →	CONVENTIONAL		STOL - BOTH ENGINES.		STOL - ONE ENGINE OUT.		STOL - BOTH ENGINES OUT.	
MECHANICAL AND HYDRAULIC CONTROL SYSTEM REQUIREMENTS →	Two independent hydraulic systems with accumulators. One pump driven off of each engine (accessory pad). Fixed flaps operated from cockpit by conventional lever. Additional selector - flap: fixed-rotation Two position. Flaperons also hydraulically operated primarily through individual port and starboard motors. Mixed to account for yaw differential and general aileron flight requirements. Mechanical back-up/override also required. For schematic of above, see Fig. 138.		Upon selection of flap and flaperon rotation, hydraulic pump in each engine nacelle drive a corresponding motor (Fig. 138). A selection, mixing and distribution box drive the flaps at selected RPM. Mechanical and/or hydraulic cross-coupling insures uniformity of port and starboard inboard flap rotation. Outboard flaperon motor controlled by proportional mixing valving in interconnected distribution boxes. Responds to normal aileron movement and may override fixed flap system.		One engine remains effectively furnishing hydraulic power for reduced rotation of flap and flaperon. If flight situation is such the cockpit control (flap: fixed-rotation selector) may be put to fixed mode to conserve power for propeller thrust as req'd. Interconnected distribution boxes shut off "dead" hydraulic plumbing and flap continues rotation by motor or mechanical cross-shaft.		All flap/flaperon systems may be converted to operate as fixed adjustable flaps and mechanically controlled ailerons. Alternate hydraulic power for non rotation functions may be sought from accumulator or the like. Autorotation of inboard flaps may be desirable for lift enhancement during landing approach.	
Flight Regime	Inboard Flap	Outboard Flaperon	Inboard Flap	Outboard Flaperon	Inboard Flap	Outboard Flaperon	Inboard Flap	Outboard Flaperon
TAKE OFF RUN	δ_f - Fixed Deflected Less Than for Take Off	Combining Fixed Flap Settings with Allowances for Further Aileron Deflection	Powered Rotation to Max. U/V and C_{d_f} Req'd. for Take Off →	Ditto Also Allowances for Differential RPM Modulation	Abort Take Off →	Ditto	——	——
LIFT-OFF	Ditto	Ditto Rigged to Avoid Adverse Yaw	Rotating at Optimum U/V and C_l for Lift-Off	Ditto Used as Full External Aileron	Abort Take Off →	Ditto	——	——
CLIMB OUT	Ditto	Fixed Ditto	Rotation Decreasing	Ditto	Abort Take Off or Continue with Flap in Cross-Coupled Rotation →	Ditto	——	——
CLIMB TO ALTITUDE	Fixed δ_f Reduced Further	Ditto	Flap Braking and Fixing at Climb δ_f →	Ditto →	Ditto →	Ditto	——	——
CRUISE	Fixed δ_f = Min. Drag	Ditto (Used as Full External Aileron)	Fixed δ_f = Min. Drag	Ditto (Used as Full External Aileron) Fixed	Fixed δ_f = Min. Drag	Ditto (Used as Full External Aileron) Fixed →	Fixed →	Ditto (Used as Full External Aileron) Fixed
DESCENT	Fixed δ_f Some	Ditto	Ditto or Reverse Rotation for Neg. C_l	Ditto	Fixed δ_f = Some	Ditto	Fixed δ_f = Some	Ditto
APPROACH	Fixed δ_f = at High C_l Comensurate with C_l Avail.	Ditto	Rotating up to C_l max.	Ditto →	Rotating Ditto →	Rotating	Flaps Fixed to High Avail. C_l or Put into Autorotation as Req'd.	Ditto
FLARE	Ditto	Ditto	Ditto →	Ditto →	Ditto →	Ditto	Ditto	Ditto
LANDING RUN	Ditto	Ditto	Ditto Braked to Stop or Set Fixed δ_f = 90° →	Ditto →	Ditto →	Ditto	Ditto	Ditto

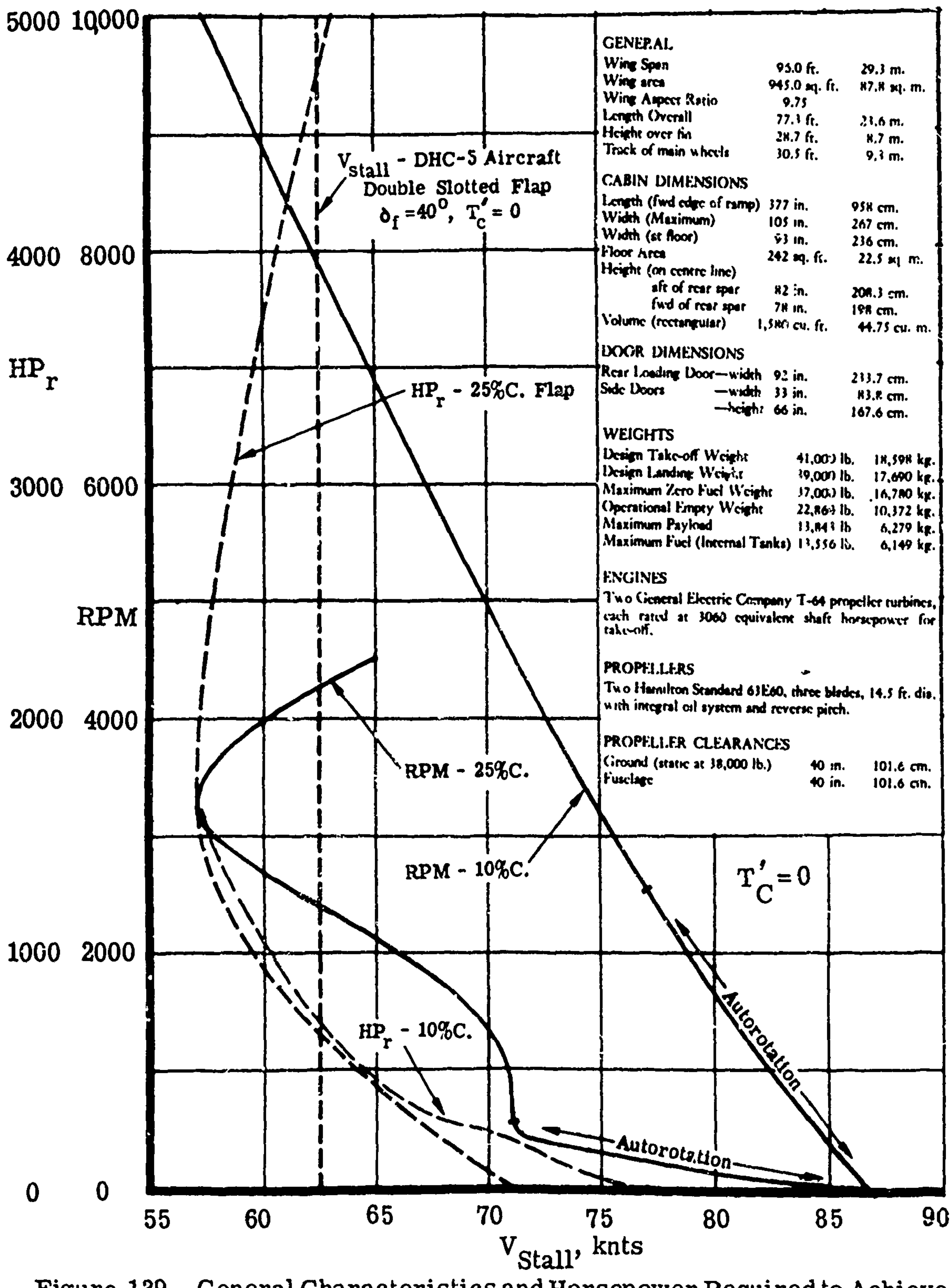


Figure 139. General Characteristics and Horsepower Required to Achieve $C_{L_{max}}$ (V_{Stall}) With RAF on DHC-5 STOL-Type Aircraft.

each wing. The fore and trailing sections are separated from the wing shroud and each other to provide the slotted-flap characteristic for greater aerodynamic efficiency. The relative motion of the two sections is defined by mechanical linkages hinged from, and carried by, the rear wing spar. The outer trailing sections function as ailerons, superimposed on their travel as part of the flap system. To provide additional lateral control of the DHC-5, the aileron system is coupled to the spoilers. The spoilers are coupled to operate asymmetrically in proportion to aileron control commands. The spoilers extend "up" in proportion to "up" commands to the associated aileron. The conventional cable/rod aileron control circuit is coupled to the servo control valves of the hydraulic actuators that function the spoilers. The system is designed such that a failure or seizure of the spoiler actuator cannot impair normal aileron operation. Various safety and gust locks are located throughout the flap system.

The RAF flap mechanism is understood from the representation of Figure 138 and Table VIII. Not indicated are the safety and duplication arrangements required to insure fail-safe flap function in response to hydraulic or mechanical failure.

An aerodynamic performance comparison of the RAF concept with a conventional STOL aircraft is limited by the test data of Küchemann (Reference 51K). The restriction is such that only during a power-off landing ($T_c' = 0$) situation could an equitable comparison be made of these data with the actual DHC-5 flight test data. Thus, the comparative stall speeds of the gliding standard DHC-5 with double-slotted flaps and two RAF systems have been graphically presented in Figure 139. In this situation, standard sea level conditions, equal wing areas (945 $ft.^2$), and equal gross weights (39,100 lbs.) are considered.

An attempt at a performance comparison of the RAF modified "Buffalo" and the original Buffalo is shown in Figure 139. The comparison is made in terms of the stalling speed of the aircraft in the approach condition with power off. The stall speed of the Caribou with flaps retracted is 87 knots. The corresponding stall speed, with fixed double-slotted flap $\delta_f = 40^o$, is 63 knots (corresponding to $C_{L_{max}} = 3.10$). Two RAF configurations are considered, one with a 10% chord flap and the other with a 25% chord flap. The basis for the performance estimate is Küchemann's data (Reference 51K and Figures 41 and 43). The plots of Figure 139--flap RPM is shown as the solid curves and flap required horsepower as the dashed curves--were established as follows. Values of U/V between 0 and 5.20 are assumed. The corresponding $C_{L_{max}}$, for each flap chord, are determined from test data. To each $C_{L_{max}}$, there corresponds a stall speed which is calculated. The corresponding U is then calculated, hence the flap RPM; the coefficient C_R corresponding to the assumed U/V is determined from Figure 136, and the corresponding horsepower is calculated.

It can be seen that the RAF in autorotation will permit the lowering of the stall speed to 77 knots for the 10% flap and to 71 knots for the

25% flap. At U/V's above autorotation, the flap power required rises rapidly. There is a slight power advantage to have a 25% flap rather than a 10% flap.

The power expenditure corresponding to a stall speed equal to that of the basic Buffalo aircraft--63 knots--is about 650 HP. Above that point, power expenditure is out of proportion to potential gains, as 1000 HP is required to lower the stall speed by 10 knots. Note that the hump of the 25% flap RPM curve comes from the apparent sudden stall of the position 2 airfoil.

The above discussion and the data of Figure 139 must, however, be considered unrealistic for two related reasons.

First, the data of Figure 139 are for $T_c' = 0$, and it was shown in the discussion of Figure 135 that there was at least a suspicion that T_c' had a powerful influence on the maximum attainable lift coefficient. Thus, the calculated values of $C_{L_{max}}$ used to establish Figure 139 may, in actuality, be pessimistic by a factor of 2 or 3.

Second, because of the lack of meaningful data, it was assumed that the RAF-modified and the original Buffalo had the same gross weight. This fails to account for the weight of the auxiliary motors needed to drive the rotating flaps. It would be interesting to determine the one point for which this is true: the RAF system is simpler than the basic double-flap arrangement, hence a potential weight saving, which can be used in motors to drive the rotating flaps. It is impossible to determine at this time whether this "break-even" point corresponds to a V_{stall} greater or smaller than the 63 knots of the basic Caribou.

All of this indicates that large-scale test data are needed before a meaningful assessment of the RAF system can be made.

E. ADDITIONAL APPLICATIONS OF THE RAF CONCEPT

The RAF concept is ideally suited for application to the COIN aircraft configuration. A conceptual study is shown in Figure 140. The COIN aircraft requires both STOL performance and good control at low speeds. It uses large propellers which immerse the wing nearly totally in their slipstream. The RAF is considered to be a prime means to deflect the propeller slipstream and to prevent wing stall at low speeds.

The outboard RAF unit is independently modulated to provide the strong, effective low-speed control at and near hovering flight. With both engines out, the RAF continues to autorotate and provide substantial lift for power-off emergency landings. The rotating flaps may be programmed and controlled to operate in the manner previously outlined in Table VIII. The compactness of this COIN aircraft may reduce the flap area with a subsequent saving in the flap power required.

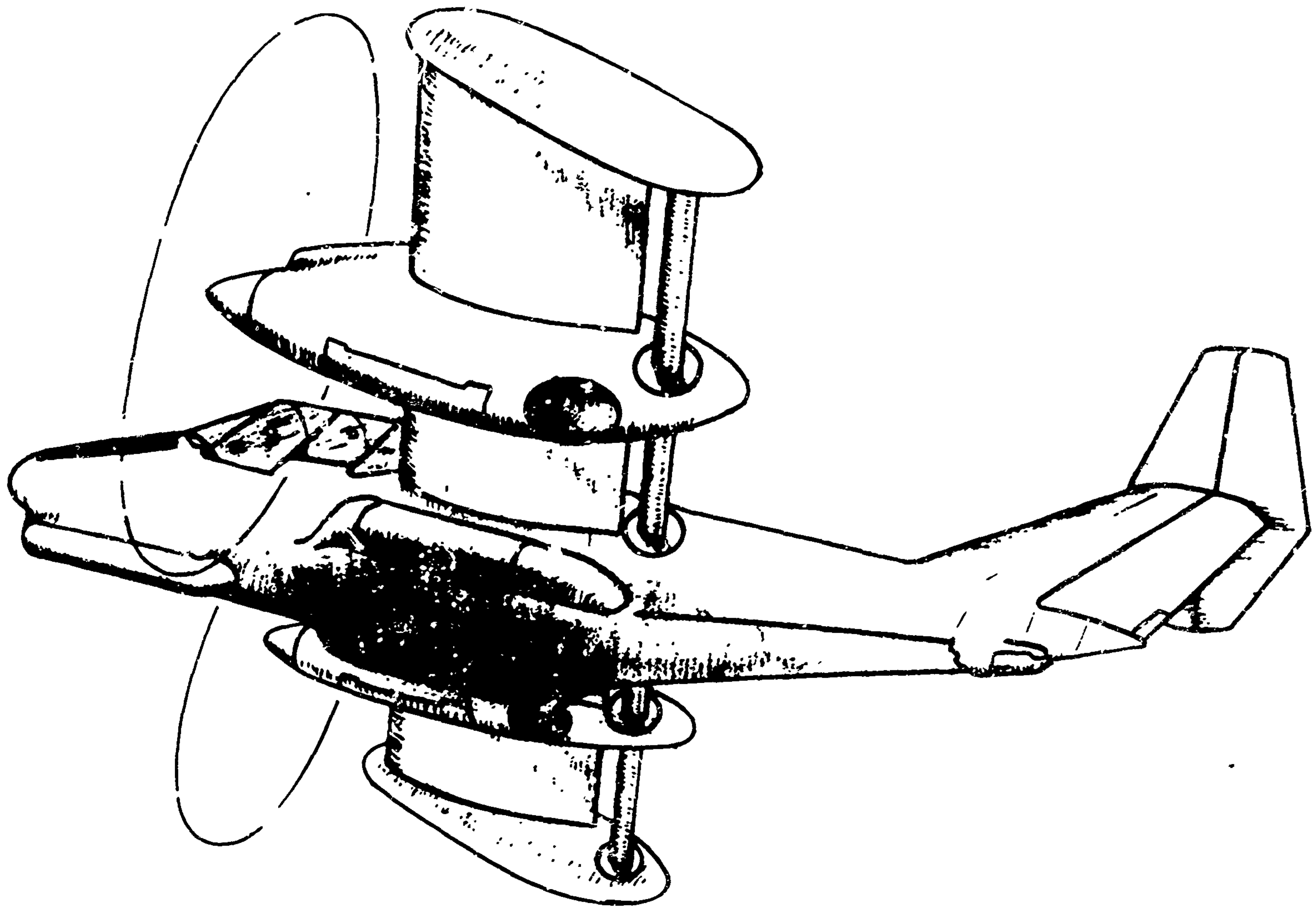


Figure 140. Deflected Slipstream V/STOL Aircraft Utilizing Rotating Airfoil Flap (RAF) for Slipstream and Lateral Control.

II. VTOL CYCLOGIRO TRANSPORT FOR THE COMPOSITE AIRCRAFT MISSION

A. DESIGN PHILOSOPHY

USAAVLABS has conducted much research in the last few years in the areas of the high-performance helicopter, the compound helicopter, and the composite aircraft to provide further increases in Army mobility (References 61C and 68L). The most advanced concept, the composite aircraft, is aimed at combining into one aircraft the hover efficiency and downwash velocities of the helicopter and the high-speed efficiency of fixed-wing-type aircraft, in the speed range of 30 to 350 knots. The cyclogiro aircraft is the only known nonrotary-wing aircraft that has full hover capability with relatively low disc loadings, as demonstrated in the ANALYSIS section of this report. It was therefore reasonable that a preliminary design of a cyclogiro composite aircraft should be compared to other proposed composite aircraft. In view of the newness of the application of the cyclogiro concept to the composite aircraft mission and of the total lack of research in this area for the last twenty years, one is constrained to a conceptual study, rather than a detailed, quantitative one.

The assumptions used in References 61C and 68L for the design objectives are those also used here. They are briefly summarized below:

Payload	3000 lbs
Fuel	3000 lbs
Useful Load	6450 lbs
Hover O.G.E. at 95° F	6000 ft pressure altitude
Disc Loading	10 lb/ft^2 or less (except for tilt wing or cyclogiro which have 35 lb/ft^2)
Maximum Speed	300-350 knts
Internal Cargo Compartment	5.5 ft wide x 6 ft high x 14.3 ft long
Power Plant	Current-or-advanced-technology gas turbine sized to meet the concept's power requirements (rubber engines)

The disc loading is chosen at 35 lb/ft^2 as a compromise between a lighter loading that would give less hover power required but would present rotor structural problems, and a higher loading that would present the opposite situation: good structural efficiency, poor hover efficiency, and higher rotor parasite area. The disc loading is based on the projected area of the cylinder described by the rotor blades, including the fuselage blanketed area. Like all other parameters of this study, the disc loading is not optimized. Only a detailed aerodynamic and weight study would make it possible to ascertain whether the assumed value is close to optimum or not.

The preliminary design study mainly consists of three elements: a configuration study showing the approximate sizing of the aircraft, a performance study, and a control study showing specific means to achieve control with a cyclogiro rotor. The overall purpose of the study is to indicate that the considerations described in the ANALYSIS section of the report can be meaningfully applied to the design of a cyclogiro transport.

B. GENERAL CHARACTERISTICS OF THE CONFIGURATION

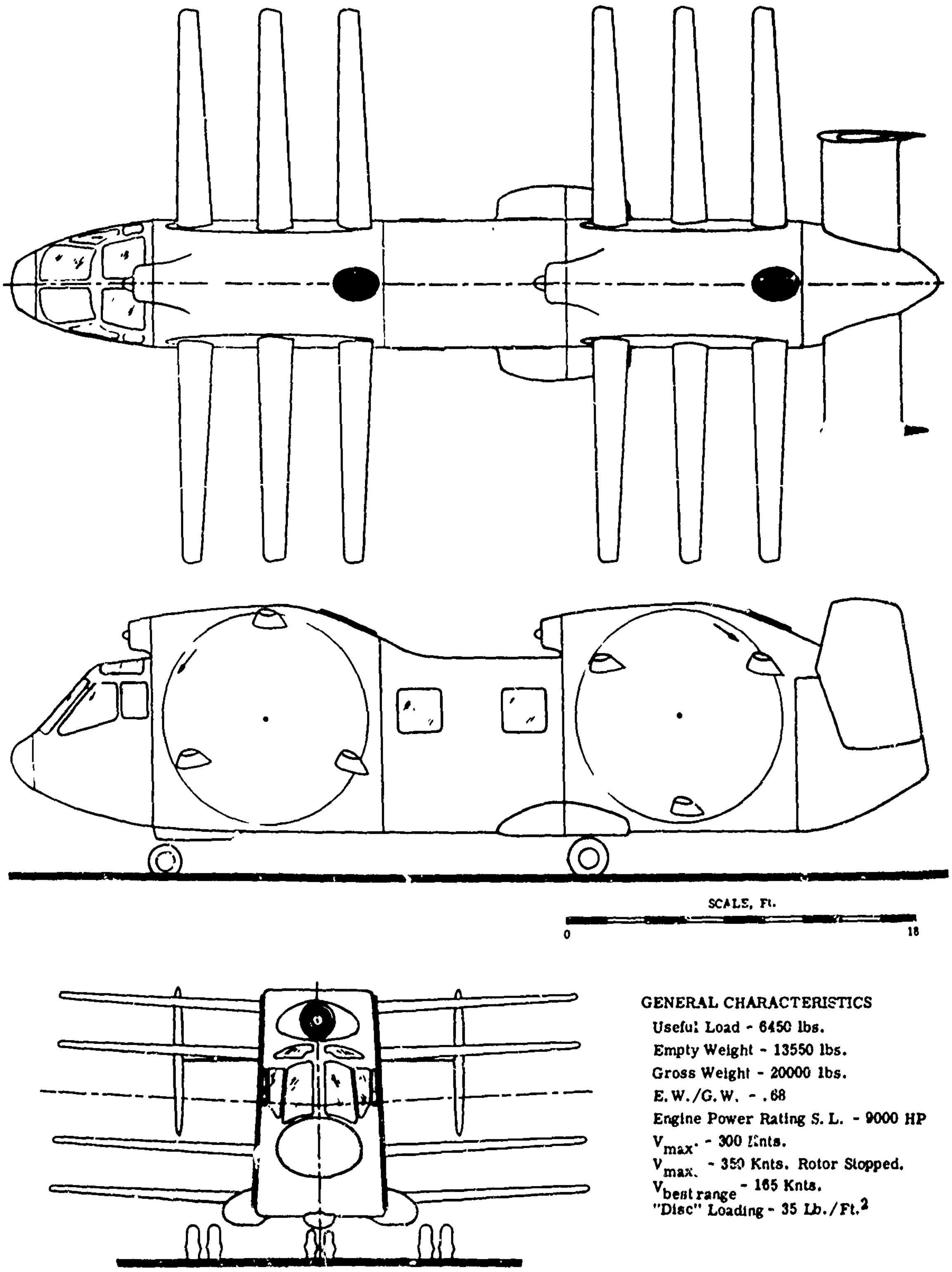
A three-view preliminary drawing of the configuration is shown in Figure 141. A tandem-rotor configuration was chosen, with front and aft rotors rotating in opposite directions. Each rotor consists of three blades. Details of rotor geometry resemble closely those of a configuration that was thoroughly tested by Baker in the University of Washington wind tunnel (Reference 8B, Figures 76 and 77), except that a reduced solidity is used.

Each rotor is basically driven by a gas turbine engine mounted on top of the fuselage, along the centerline. In case of failure, the engines are mechanically interconnected, and a system of overriding clutches permits autorotation in case of total power failure.

Detailed studies made twenty years ago concluded that the weight of a complete cyclogiro rotor-propulsion system including the powerplant was of the same order of magnitude as the weight of the corresponding helicopter rotor powerplant system. Technical advances have considerably reduced the weight of the rotor system, of the transmission, and of the gas turbine powerplant; it is assumed that corresponding advances in cyclogiro rotor technology, the transmission, and the blade-rocking system may make possible a corresponding reduction of the weight of the cyclogiro rotor-propulsion system.

It is assumed that the cyclogiro mechanical loss is 7% of the total horsepower.

The cyclogiro rotor type used here is of the combined high-pitch and amplified high-pitch type, to be described later in some detail. At high speed, it is a high-pitch type; at lower speeds and hover, it is of the amplified high-pitch type. A full-feathering rotor system would result in a higher aerodynamic efficiency; however, it would present



GENERAL CHARACTERISTICS

Useful Load - 6450 lbs.
Empty Weight - 13550 lbs.
Gross Weight - 20000 lbs.
E.W./G.W. - .68
Engine Power Rating S. L. - 9000 HP
V_{max} - 300 Knts.
V_{max} - 350 Knts. Rotor Stopped.
$V_{best\ range}$ - 165 Knts.
"Disc" Loading - 35 Lb./Ft.^{2}

Figure 141. High-Speed Amplified High-Pitch VTOL Cyclogiro Project.

additional and unknown development and mechanical difficulties at this time.

The gross weight of the configuration is assumed to be 20,000 pounds, which may be slightly optimistic in view of the high installed horsepower (9000 SHP). It is assumed to be distributed equally between the two rotors, to the effect that rotor aerodynamic interference between the front and rear rotors is ignored.

A parasite drag area of 15 ft.^{2} is assumed, which is conservative if the landing gear is assumed to be retractable (not shown in the figure).

Any configuration such as that of Figure 141 will look different from that of a fixed-wing aircraft or of a conventional VTOL aircraft, and will have a high fuselage. However, it does not show any unacceptable aerodynamic or structural compromises: the fuselage is hardly larger and heavier than that of a conventional aircraft; the integration of lift and propulsion into the cyclogiro rotors and the absence of antitorque rotors and of any control system external to the rotors tend to make up for the complexity of the rotors themselves. Should be necessary, the aspect ratio (i.e., span) of the cyclogiro rotors could be increased without the configuration looking misshapen.

C. PERFORMANCE CHARACTERISTICS OF THE CONFIGURATION

One possible way to look at performance is as follows. Based on the results of the ANALYSIS section (Figure 99, for example), one can expect, for a properly designed cyclogiro, a hovering figure of merit of 0.8. This gives an HP/W figure of the order of 0.20 for a disc loading of 35 p.s.f.

As far as forward flight is concerned, it was shown that a propulsive efficiency of the order of 0.8 (or even higher) could be achieved. One could thus calculate forward-flight performance or at least estimate maximum speed, based on that figure.

It was decided to follow another approach for this study. In order to avoid giving grounds to extreme and uncritical optimism, the performance of the aircraft was calculated, based on Baker's actual wind tunnel test data (Reference 8B) of a small nonoptimized model. The only deviation from Baker's rotor geometry was to reduce the rotor solidity by a factor of 2. A comparison of Baker's data with theory shows that the results come very short of the theory. Hence, use of Baker's results should correspond to a most pessimistic use of the cyclogiro.

Out of the results of Reference 8B, two curves are reproduced here: Figure 142 shows a polar curve, C_L versus C_D, for various values of J (the symbols are the same as those defined in the ANALYSIS section); Figure 143 shows a lift-power curve, C_L versus C_P, for the same advance ratios. The design points on these curves correspond to

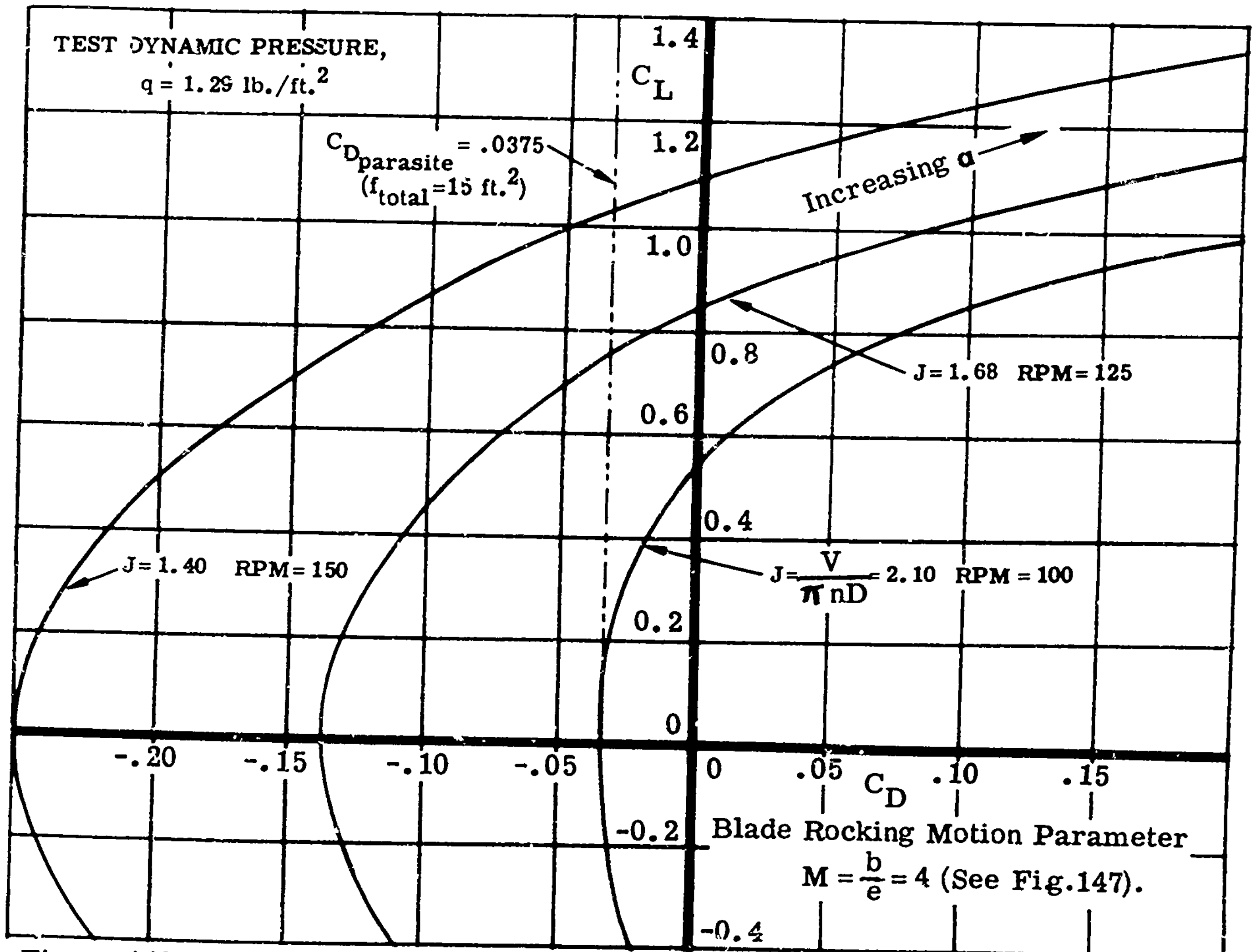


Figure 142. University of Washington High-Pitch Cyclogiro Wind Tunnel Results (Ref. 8B) in Area of Design Interest. Lift (C_L) is Plotted Against Thrust ($-C_D$) at Three Advance Ratios.

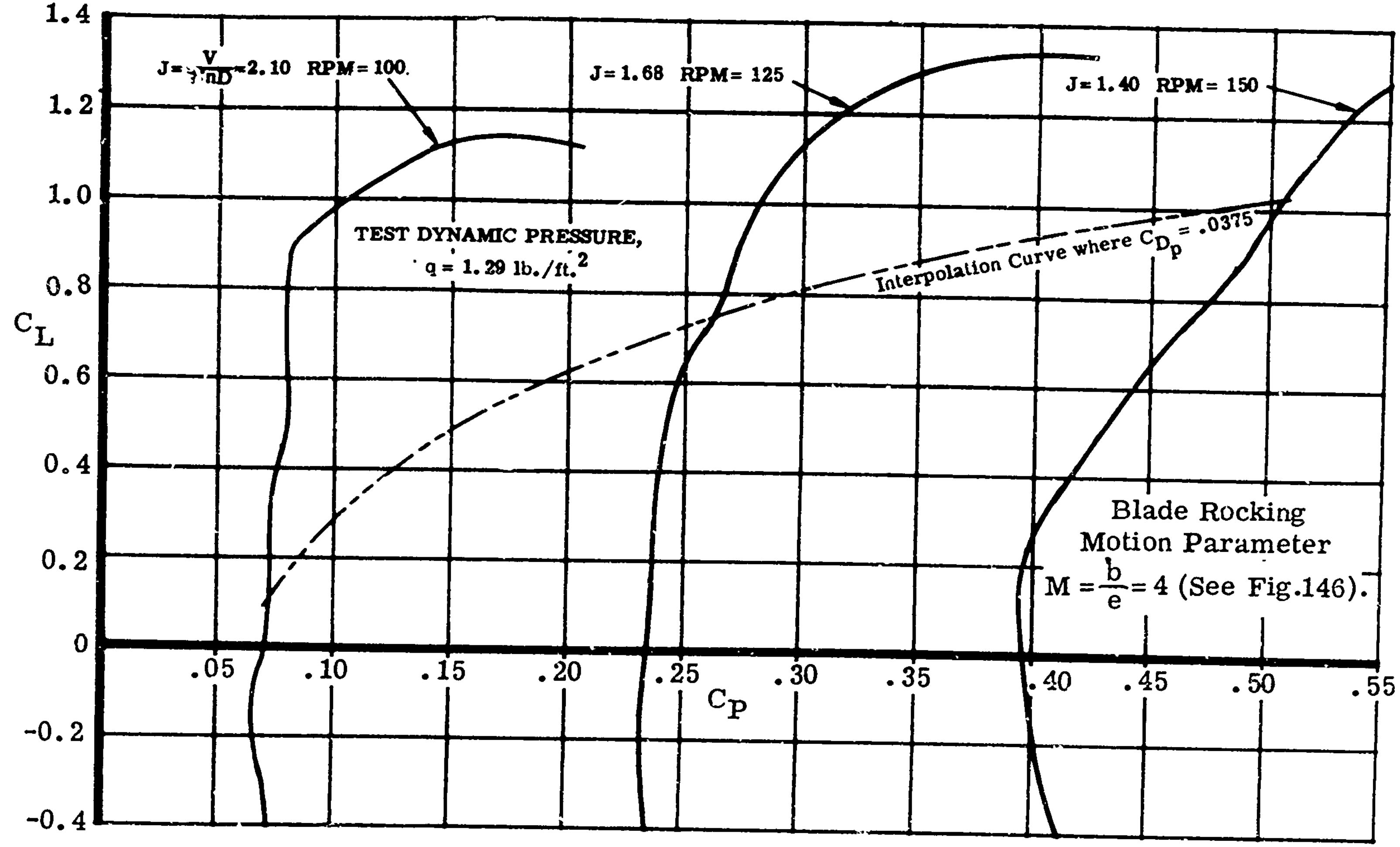


Figure 143. University of Washington Amplified High-Pitch Cyclogiro Wind Tunnel Results (Ref. 8B) in the Area of Design Interest. Vertical Lift (C_L) is Plotted Against the Power Required (C_P) at Three Advance Ratios.

a thrust coefficient equal to minus the drag coefficient, itself corresponding to a parasite drag area of 7.5 ft.^{2} per rotor; i.e., a C_{D_f} = .0375.

Comparative concept characteristics and calculated performance are shown in Figure 144 for the helicopter, the compound helicopter, the slowed-rotor compound, the composites, the tilt wing, and two cyclogiros (a high-pitch and a stopped-rotor configuration).

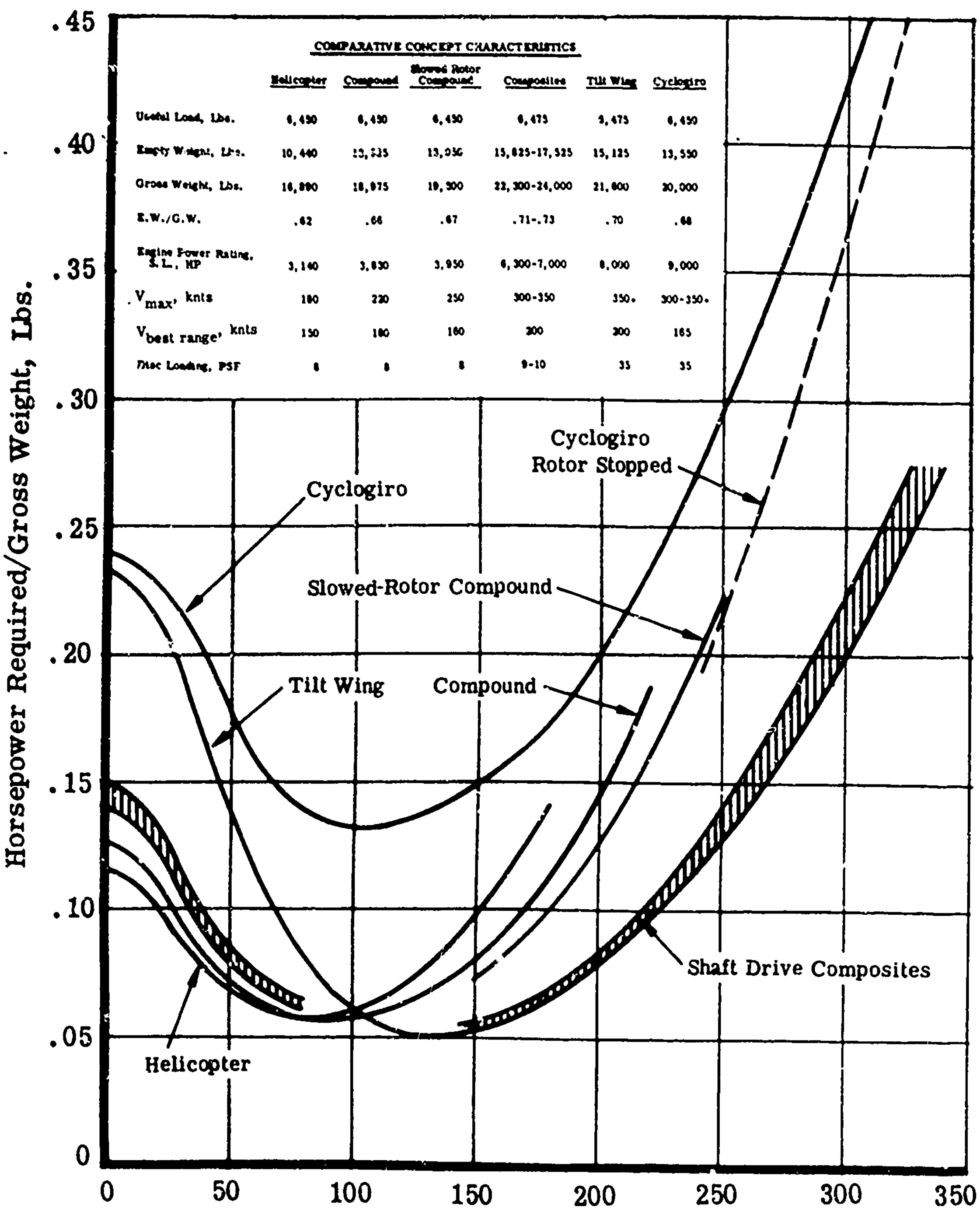
It can be seen that the cyclogiro performance is not spectacular, because of the pessimistic assumptions made, but that at least it extends the area of operation of the other configurations toward higher speeds. It could be shown that use of the assumptions first discussed in this paragraph would lead to a drastically improved picture. The limitations of the test results that were used for the performance curves will be discussed at the end of this section.

D. REVIEW OF HIGH-PITCH AND AMPLIFIED HIGH-PITCH BLADE MOTIONS

Cyclogiro blade-rocking motion was discussed in some detail in the ANALYSIS section. However, it is useful to elaborate here on the specific details of a cyclogiro blade motion that will be the basis for the proposed cyclogiro aircraft control system. The geometrical description of the blade-rocking motion that leads to the aerodynamic generation of thrust and lift forces on the cyclogiro rotor, either separately or simultaneously, will be discussed in this section. Application to cyclogiro control will be made in the next paragraph. The cases of the high-pitch cyclogiro (Figure 145) and the amplified high-pitch cyclogiro (Figure 146) will also be discussed.

Consider first, for example, the ideal basic motion of the forward port rotor of the proposed cyclogiro of Figure 141 moving at a constant translational velocity V_T, which corresponds to the velocity V of the ANALYSIS section of the report. This motion is described in Figure 145A, in which the blade chord line is shown at six equidistant stations about the periphery of the rotor orbit. The rotor blade axes revolve geometrically about an instantaneous center o on the mechanical axis of symmetry, which is a line determined by the point o and the center A_p of the orbit circle. One can define also an instantaneous aerodynamic or directional center o', which is the point of intersection of the normals to the resultant velocity vectors V_r at the six stations, as shown in Figure 145A. Note that the velocity vectors carry subscripts corresponding to their respective stations, 1 through 6.

One may recall here (see Figure 88) that when the point o' is outside the orbit circle, one has a high-pitch arrangement. If o' is on the circle, one has a pi-pitch arrangement; if o' is inside the circle, one has a low-pitch arrangement. Only the high-pitch arrangement will be considered further here.



COMPARATIVE CONCEPT CHARACTERISTICS

	Helicopter	Compound	Slowed Rotor Compound	Composites	Tilt Wing	Cyclogiro
Useful Load, Lbs.	6,450	6,450	6,450	6,475	6,475	6,450
Empty Weight, Lbs.	10,440	12,525	13,050	15,825-17,525	15,125	13,550
Gross Weight, Lbs.	16,890	18,975	19,500	22,300-24,000	21,600	20,000
E.W./G.W.	.62	.66	.67	.71-.73	.70	.68
Engine Power Rating, S.L., HP	3,140	3,830	3,950	6,300-7,000	8,000	9,000
V_{max}, knts	180	220	250	300-350	350+	300-350+
$V_{best\ range}$, knts	150	180	160	200	300	165
Disc Loading, PSF	8	8	8	9-10	35	35

Figure 144. Comparative VTOL Aircraft Concept Characteristics and Forward-Flight Performance.

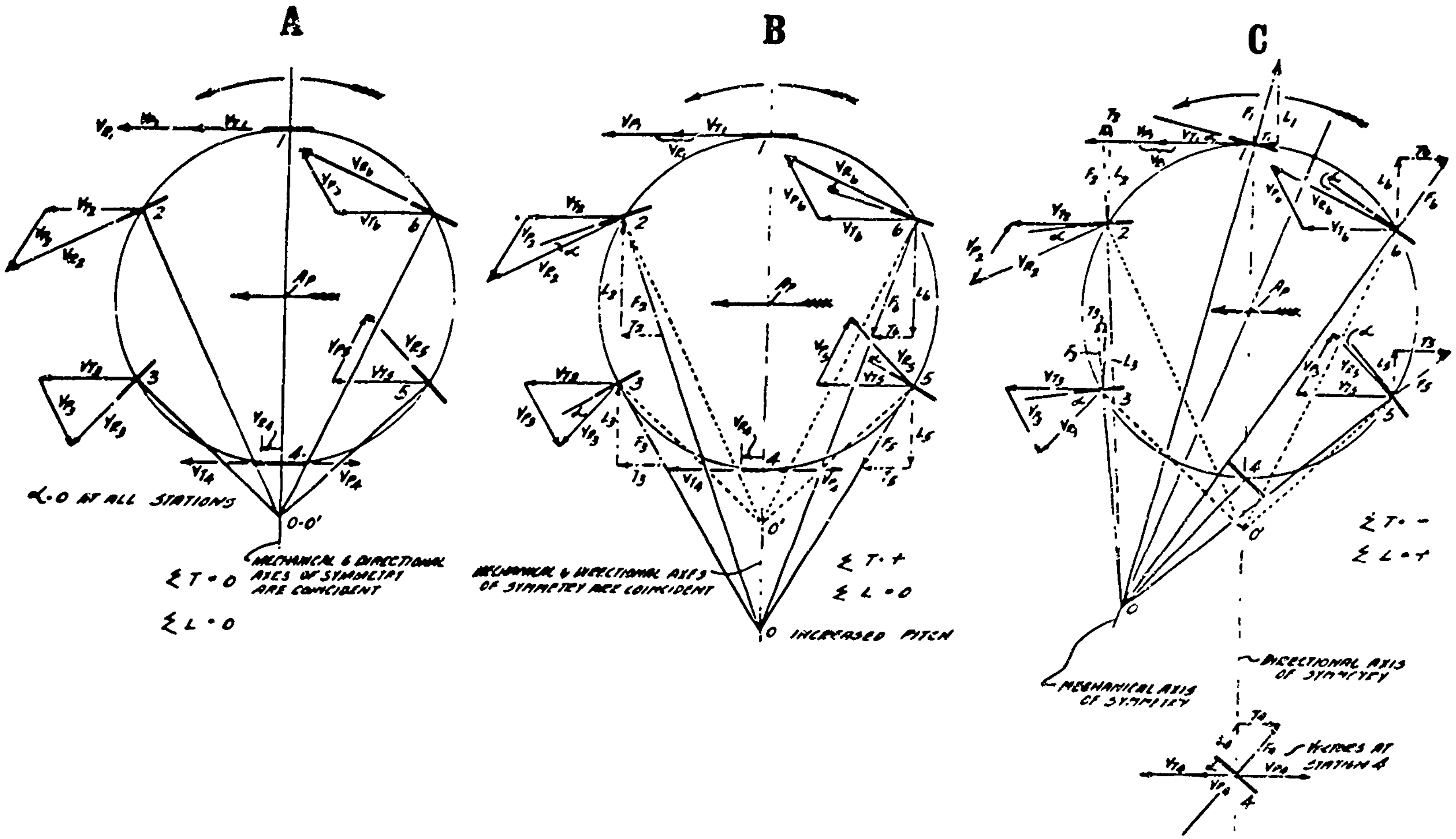


Figure 145. Schematic Diagrams Explaining Geometrically the Blade Rocking Motion for a High-Pitch Cyclogiro Rotor.

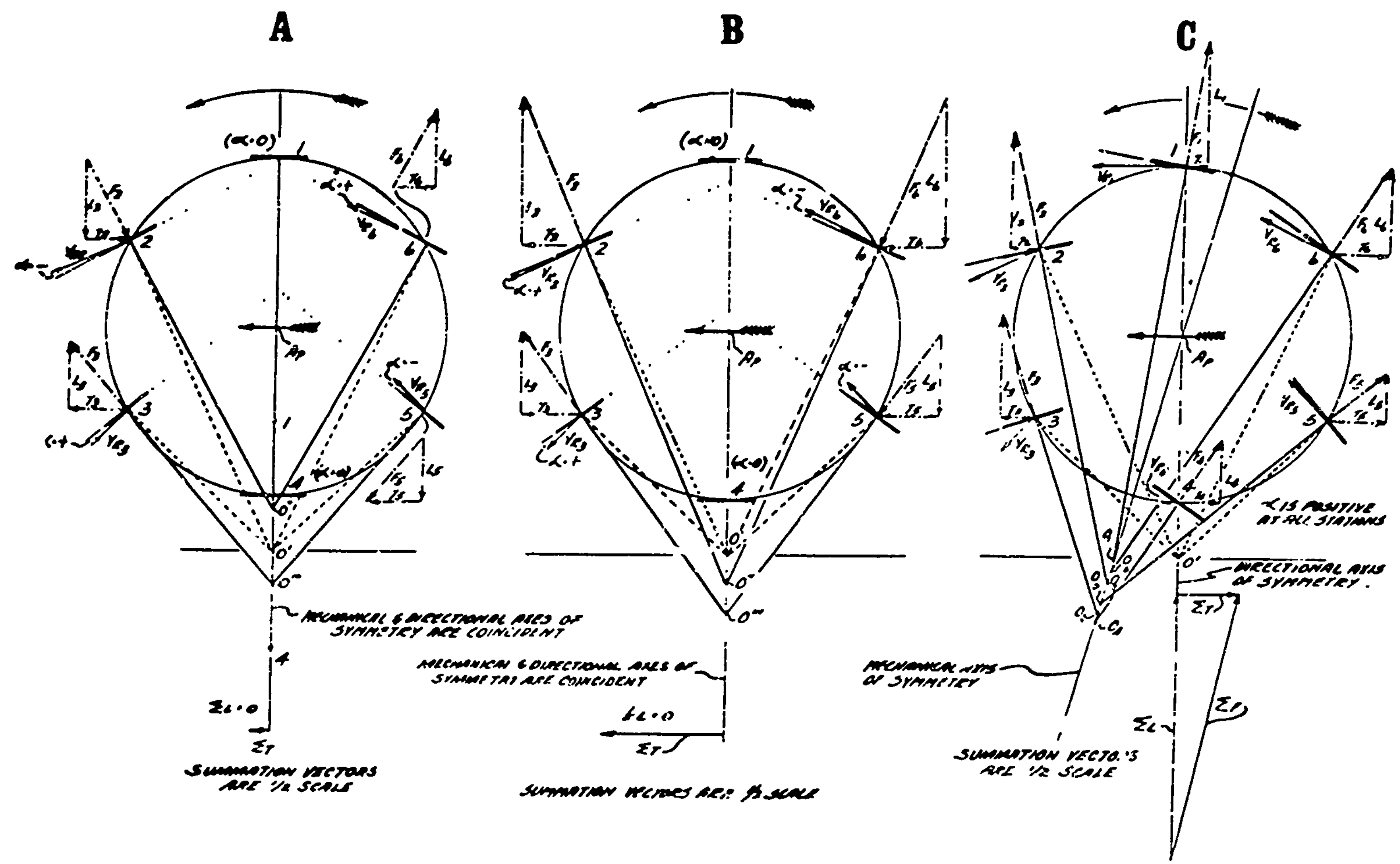


Figure 146. Schematic Diagrams Explaining Geometrically the Blade Rocking Motion for an Amplified High-Pitch Cyclogiro Rotor.

Note that, for the motions of interest here, the instantaneous aerodynamic center o' remains fixed through a blade revolution and is also an "overall" center.

Returning to Figure 145A, it can be seen that the two centers o and o' coincide and that the sum of thrust forces and of lift forces is equal to zero. The resultant net force on the rotor is zero.

Consider now Figure 145B, in which the instantaneous blade mechanical center o is displaced vertically downward along the axis A_p - o'. Rotational and translational velocity of the rotor remains the same. The change in feathering at stations 2, 3, 5, and 6 causes the corresponding blades to have an increased angle of attack α_T with respect to the local resultant air velocity V_R. The forces thus generated at the six stations are shown in Figure 145B. In this instance, the vertical-lift components cancel out, but there is an overall net thrust, directed to the left. Thus, mechanically, thrust control of the rotor can be achieved by the mechanical displacement of the mechanical intersection point o away from the aerodynamic intersection point o'.

Consider now Figure 145C, in which point o is not only moved downward from o' but is also moved to the left of the axis A_p - o', the basic local velocities remaining unchanged. In this case, the summation of the lift forces becomes positive. Thus, lift control of the rotor can be produced by moving the mechanical intersection point o to the left. The effect is analogous to that resulting from a change of angle of attack of a fixed wing. Note that the lateral position of o in Figure 145C is extreme and corresponds to a negative thrust. In practice, point o is moved just enough to the left to provide the necessary lift, while retaining enough thrust to overcome the aircraft parasite drag.

A mechanism such as that described in Figure 145 was embodied in the Baker wind tunnel model (Reference 8B) and is shown schematically in Figure 147. The result of the wind tunnel tests was shown in Figure 142. A complete polar curve can be covered by going through a complete range of the "angle-of-attack" parameter α of Figure 145C. For a given advance ratio J (corresponding to the j of the ANALYSIS section), one clearly sees in Figure 142 the passage from a "thrusting" to a "dragging" rotor as the point o of Figure 145C moves to the left.

As discussed in the ANALYSIS section, an ideal rocking motion is undesirable, at least at low pitch, because of excessive accelerations. The scheme of Figure 145 is therefore acceptable for high-speed cyclogiro operation, but an amplified pitch system must be devised for operation at lower speeds and at hover. Specifically, operation becomes impossible when the point o' approaches the orbit circle too closely.

Consider then the amplified high-pitch motion schematically described in Figure 146. The basic difference is that the instantaneous mechanical center o' moves during each blade revolution in its orbit.

Specifically, looking first at Figure 146A for stations 2 and 6, o' is at point o'', whereas for stations 3 and 5 it is at point o'''. For station 1, o' lies at the position on the axis shown as "1", above point o''; for station 4, o' lies somewhat below point o''', in the position shown as "4".

This device may be construed as superimposing a "higher control harmonic" to the basic cycloidal mechanism. In practice, this harmonic can be introduced by means of an eccentric, as shown in Figure 94, or by the two oscillating sections A and C in the mechanism of Figure 147.

A detailed consideration of the force diagrams of Figure 146A shows that the asymmetry created by the amplified motion only creates a negligible horizontal thrust; its main effect is, as intended, to reduce the maximum blade accelerations, hence blade stresses, in the bottom part of the orbit ($\psi = 180^{\circ}$).

The steps taken in Figures 146B and 146C are similar to those that were taken in Figures 145B and 145C, with corresponding results; i.e., the generation of a net horizontal thrust force in Figure 146B, and of both a thrust and a vertical-lift force in Figure 146C. The difference is that, instead of just one mechanical center, one has six mechanical centers, o_1 to o_6, spread as shown in Figure 146C.

Note that low-pitch and amplified low-pitch motion characteristics can be explained, as was done for the high-pitch motion in Figures 145 and 146, by drawing corresponding figures with the instantaneous center o' located inside the rotor orbit.

In summary, basic features of cyclogiro control are as follows:

1. High-pitch motion control is satisfactory for high flight speeds; amplified high-pitch motion control is required for low speeds and hover flight.

2. Horizontal thrust is modulated by a vertical displacement of the mechanical instantaneous center o along the mechanical axis.

3. Vertical lift is modulated by a horizontal displacement of point o away from the mechanical axis.

4. Lift and thrust forces are generated simultaneously by a combined mechanical (angular) horizontal and vertical displacement of point o away from the mechanical axis.

5. Lift and thrust, alone or in combination, can be further modulated by overall rotor RPM changes consistent with structural limitations of the rotor and its blades. Weight and structural considerations dictate that the rotor RPM be as low as possible and that the advance ratio j as high as possible.

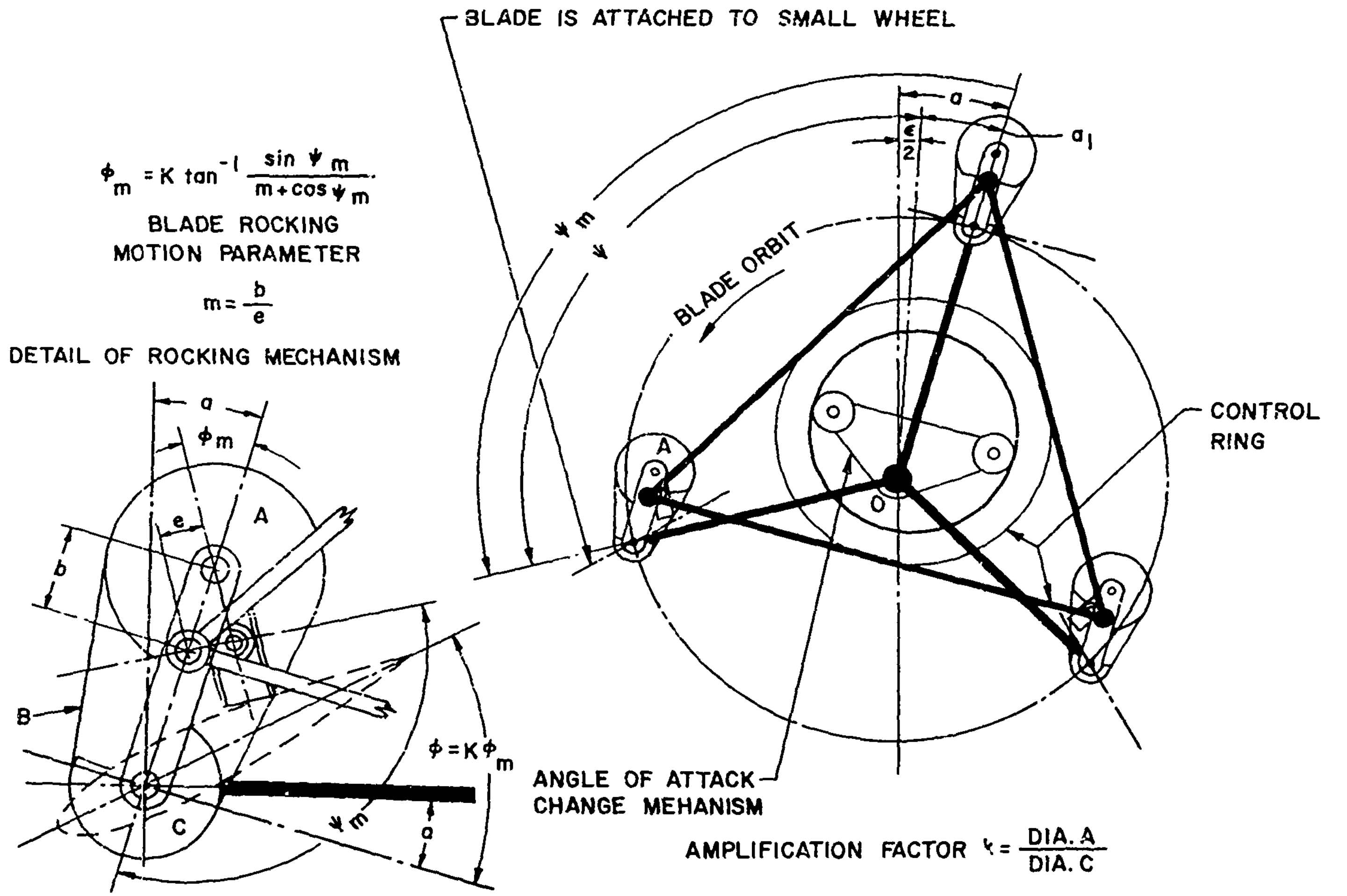


Figure 147. Lightweight Amplified High-Pitch Cyclogiro Mechanism from University of Washington Wind Tunnel Tests (Ref. 8B). Three Radial Torque Arms Drive Blades and Feathering Mechanism About Rotor Orbit.

E. CONTROL SYSTEM OF THE CYCLOGIRO PROPOSED DESIGN

Forward motion of the control column will cause a simultaneous vertical displacement of all instantaneous mechanical intersection points o'' and o''' (Figure 146B) in both fore and aft rotors of the tandem cyclogiro project. Forward motion of this column produces forward horizontal translation of the cyclogiro; rearward column motion will cause the craft to move backward.

Lateral displacement of this main control column produces a direct rolling couple about the aircraft centerline, simultaneously increasing the net rotor lift on one side of the aircraft and decreasing it on the other; that is, this lateral movement of the control stick produces an opposite horizontal displacement of the instantaneous mechanical center point o (Figure 145C). From hover, as will be seen, this control motion will produce a roll and lateral crabbing translation by the opposite horizontal displacement of the instantaneous mechanical centers (o_1 - o_6) on each side of the aircraft.

The use of the rudder pedals will produce yawing of the aircraft fuselage. At forward speed, the required yawing couple is generated by a fore-and-aft horizontal thrust differential between rotors on the opposite sides of the aircraft. This involves a differential fore-and-aft and side-to-side vertical displacement of the mechanical center point o (Figure 145B). In hover, of course, the use of the rudder pedal produces a turn about the aircraft's vertical z-axis.

Vertical and hovering flight are controlled by the side-mounted "collective pitch" lift stick. At normal and high forward speeds, this stick is full down. Upon slowing down to hover, this stick is manually pulled up, thereby making the necessary adjustment in the horizontal displacement in all of the rotor lift controls. The first function, when this control is moved up, is to introduce the amplified blade motion into the four rotor systems. Further movement upward of this control horizontally displaces the instantaneous mechanical intersection centers (o_1 - o_6), in Figure 146C, and consequently increases the collective lift of all four rotor systems. The other components of the control system continue to introduce overriding control motions into the rotor system, insuring direct and positive maneuvering responses about all of the flight axes at very low speeds and in hovering flight.

In all instances, engine output power is modulated by the control system to insure the proper balance between the rotor power required for each flight maneuver and the optimum power available from the engines.

Should a total engine failure occur, the engines would disconnect and the rotors would enter the autorotational state, as follows. The overriding reatures of the transmission system would:

1. Mechanically effect conversion to amplified blade motion, if the blades were not already in that mode.

2. Displace the instantaneous mechanical intersection points o_1 - o_6 to the extreme position shown in Figure 146C. This is the case where the lift capability is the largest (to be paid for by a drag, which is of no consequence in this instance).

Autorotational data are shown in Reference 8B, Figures 23 and 24. It can be shown that there is considerable autorotational lift available for power-off flight. The glide angle can be estimated from Figure 145C as

$$\Theta_g = \tan^{-1} \frac{\Sigma T}{\Sigma L}$$

CONCLUSIONS

From Table VII, one might identify several interesting avenues for future research and development:

1. Wing rotors present promise as aerial delivery devices, as they present today the best-known combination of high lift-to-drag ratio and of high maximum lift coefficient. The study of their aerodynamics is very incomplete. Surprisingly, the study of their dynamics has made great progress in the last three years because of military interest in bomblets.

2. Immediate full-scale research and development of a powered rotating airfoil flap, such as the one discussed in this report, to be used also for lateral and directional control, including possibly a rotating rudder, are strongly recommended.

3. Cyclogiros for high-subsonic transport show promise. The development of such aircraft will be hampered by many difficult structural, aerodynamic, and aero-elastic problems. Much engine and power train development directed toward other VTOL systems will be directly usable for the advanced cyclogiro.

4. The Curtiss-Wright X-19 aircraft and the VFW VC.400 airplane are fascinating projects. The fact that the latter is being pushed actively today in Germany means that this configuration has current interest compared to many concepts cited which are dormant. What is of interest is the fact that the VFW VC.400 operates essentially on the same principle and has some of the same problems as the cyclogiro, in forward flight. At hover, the situation is completely different, the cyclogiro operating as a helicopter and the VC.400 requiring significant rotation of the propeller axis in order to achieve significant vertical lift. Richard teaches us that the optimum configuration may be a combination of the radial-lift propeller and the helicoplane.

5. Several other configurations appear worthy of future research; for example, the rotating airfoil convertible to fixed wing, the orbiting flap and undulating propeller, and the transverse-fan VTOL.

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A

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CONCLUSIONS

From Table VII, one might identify several interesting avenues for future research and development:

1. Wing rotors present promise as aerial delivery devices, as they present today the best-known combination of high lift-to-drag ratio and of high maximum lift coefficient. The study of their aerodynamics is very incomplete. Surprisingly, the study of their dynamics has made great progress in the last three years because of military interest in bomblets.

2. Immediate full-scale research and development of a powered rotating airfoil flap, such as the one discussed in this report, to be used also for lateral and directional control, including possibly a rotating rudder, are strongly recommended.

3. Cyclogiros for high-subsonic transport show promise. The development of such aircraft will be hampered by many difficult structural, aerodynamic, and aero-elastic problems. Much engine and power train development directed toward other VTOL systems will be directly usable for the advanced cyclogiro.

4. The Curtiss-Wright X-19 aircraft and the VFW VC. 400 airplane are fascinating projects. The fact that the latter is being pushed actively today in Germany means that this configuration has current interest compared to many concepts cited which are dormant. What is of interest is the fact that the VFW VC. 400 operates essentially on the same principle and has some of the same problems as the cyclogiro, in forward flight. At hover, the situation is completely different, the cyclogiro operating as a helicopter and the VC. 400 requiring significant rotation of the propeller axis in order to achieve significant vertical lift. Richard teaches us that the optimum configuration may be a combination of the radial-lift propeller and the helicoplane.

5. Several other configurations appear worthy of future research; for example, the rotating airfoil convertible to fixed wing, the orbiting flap and undulating propeller, and the transverse-fan VTOL.

APPENDIX I. BIBLIOGRAPHICAL LISTING

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APPENDIX II. CROSS INDEX TABLES

A		REFERENCE Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X			X										X													X	X				X	X	
	2	WING ROTOR		X					X	X	X				X	X			X								X										
	3	MAGNUS CYLINDER			X	X						X	X	X					X	X	X	X	X	X	X	X		X				X	X				
	4	TRANSVERSE FLOW FAN																																			
	5	OTHER						X											X															X			
GENERAL	6	THEORETICAL EXPOSITION			X						X	X																			X						
	7	PERFORMANCE			X	X			X											X				X			X	X			X						
	8	STABILITY							X																		X										
	9	CONTROL or MANEUVERABILITY			X				X						X	X											X										
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION									X		X														X										
	12	REVIEW			X			X				X	X				X																				
	13	COMMENT of INTEREST																										X					X				
APPLICATION	14	AIRCRAFT SUSTENTATION	X				X		X						X	X	X		X	X	X	X	X	X	X	X	X	X		X			X	X		X	
	15	AIRCRAFT PROPULSION	X				X										X		X			X												X		X	
	16	MARINE PROPULSION			X	X																															
	17	COMPLETE AIRCRAFT					X		X						X	X	X					X				X	X	X				X					
	18	COMPLETE SHIP			X																																
	19	ROTATING FLAP or SLAT																		X	X	X		X		X							X				
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR		X																																	
	22	DEVICE OTHER THAN AIRCRAFT		M	X					B				M	K	K											K			M							
GEOMETRY	23	FEATHERING PITCH SYSTEM	4	8			4																							2	1'				4		
	24	ROTOR SYSTEMS per INSTAL.	2		2		4		3		1			M	2	2			6	1		2		1		2	2					4		4			
	25	NUMBER of BLADES per ROTOR	3	3			6		1						2	2			1/2								4			6		1		M		B	
	26	BLADE or ROTOR PROFILE	F	S	C	C	B		R		F	C	C	C	S	S			Sc	C		C		C		C	F			F		C		F		F	
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILARY to FIXED WING	X																	X		X		X		X											
TEST	29	WIND TUNNEL				X			X											X				X													
	30	FLIGHT or DROP TEST									X																X	X									
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL										X								X				X													
	33	THREE DIMENSIONAL			X	X			X		X	X																									
	34	FLOW PATTERN STUDY			X							X	X																								
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY				X			X				X																								
	37	ROTATION				X					X		X							X				X													
	38	POWER												X																							
	39	BLADE ANGLE																		X				X													
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS							X																												
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO											X																								
	45	TIP PLATE DIA. or SHAPE				X							X																								
	46	MOMENT of INERTIA																																			
QUANITIES MEASURED	47	LIFT				X			X				X							X																	
	48	DRAG				X			X				X																								
	49	THRUST																																			
	50	TORQUE				X																															
	51	ROTATION							X					X																							
	52	TIP SPEED or ADVANCE RATIO				X			X				X							X																	
	53	POWER																		X																	
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED									X																X										
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P	P	B	R	P	R	K	K	B	R	R	S	'	P	'		P	B	P	P	P	S	P	P	P	S	P	P	S	S	S	P	P	P	
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY								X																											
	61	NOT GENERALLY AVAILABLE							X	X																											
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION										X																									
	64	NOT SEARCHED																						X				X					X		

B		REFERENCE NO ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X							X	X						X		X	X	X		X		X											X	
	2	WING ROTOR			X	X		X	X				X	X	X									X		X				X			X				X
	3	MAGNUS CYLINDER		X			X						X									X					X							X	X		
	4	CROSS-FLOW FAN																																			
	5	OTHER										X		X																					X		
GENERAL	6	THEORETICAL EXPOSITION						X																												X	
	7	PERFORMANCE			X					X					X				X								X							X			
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																																			
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION						X	X																												
	12	REVIEW											X									X												X			
	13	COMMENT of INTEREST		X					X															X			X						X				X
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X			X			X		X		X			X			X	X		X	X	X					X					X		
	15	AIRCRAFT PROPULSION	X							X		X		X			X			X	X																
	16	MARINE PROPULSION					X												X			X					X							X	X		
	17	COMPLETE AIRCRAFT		X								X		X			X			X				X						X							
	18	COMPLETE SHIP																				X															
	19	ROTATING FLAP or SLAT																							X												
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT			W						W		W		W								W										D				W
GEOMETRY	23	FEATHERING PITCH SYSTEM	4							3	2						1		1	8	8															1	
	24	ROTOR SYSTEMS per INSTAL.		1				1		2	1			2	1		2		1	2			2						1	1							1
	25	NUMBER of BLADES per ROTOR	6	1	2			1		3	3			1	M		3		6	4			4						1	1			1				1
	26	BLADE or ROTOR PROFILE		C	S			F		A	F			F			A		F	A	~		F							F			F	C			S
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING																								X				X							
TEST	29	WIND TUNNEL	4		X					X																								X			
	30	FLIGHT or DROP TEST						X																													
	31	TOWING TANK or in WATER																	X																		
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL			X					X									X															X			
	34	FLOW PATTERN STUDY			X			X																										X			
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY			X					X					X																			X			
	37	ROTATION			X					X									X															X			
	38	POWER			X																																
	39	BLADE ANGLE								X																											
	40	ORBIT ANGLE								X																											
	41	ECCENTRICITY								X									X																		
	42	PROFILE SHAPE or THICKNESS			X																																
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																X			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT			X					X									X															X			
	48	DRAG			X					X																								X			
	49	THRUST								X									X																		
	50	TORQUE			X					X			X																								
	51	ROTATION			X			X		X			X																								
	52	TIP SPEED or ADVANCE RATIO			X					X																											
	53	POWER			X					X			X																								
	54	FORCE DISTRIBUTION			X					X																											
	55	TORQUE DISTRIBUTION			X																																
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P	S	R	R	S	S	S	R	P	P	B	P	S	P	P	P	R	P	P	R	P	S	R	P	S	P	P	P		P	B	R	P	B	B
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED				X																															
	63	ENGLISH TRANSLATION			X																													X		/	
	64	NOT SEARCHED	X			X	X					X				X		X							X			X	X			X					

B		REFERENCE NO	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X			X		X	X							X					X				X		X		X	X	X	X			X		X
	2	WING ROTOR			X										X		X	X	X						X	X		X			X			X			
	3	MAGNUS CYLINDER					X			X	X	X								X		X		X									X			X	
	4	CROSS-FLOW FAN																																			
	5	OTHER											X	X									X		X			X			X						
GENERAL	6	THEORETICAL EXPOSITION				X											X							X							X						
	7	PERFORMANCE				X									X							X	X	X							X		X				X
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																	X			X											X	X			X
	10	LOADS and STRESS ANALYSIS				X																															
	11	PHENOMENON DEMONSTRATION																								X											
	12	REVIEW											X	X		X										X											
	13	COMMENT of INTEREST			X		X																					X									
APPLICATON	14	AIRCRAFT SUSTENTATION	X							X	X	X								X	X	X	X				X	X		X		X	X	X		X	
	15	AIRCRAFT PROPULSION								X	X									X	X		X				X		X			X					
	16	MARINE PROPULSION						X								X											X						X		X		X
	17	COMPLETE AIRCRAFT										X									X	X						X		X						X	
	18	COMPLETE SHIP																																			X
	19	ROTATING FLAP or SLAT																															X				
	20	CONVERTIBLE ROTOR to WING																		X																X	
	21	ROTOR-ROTOR																		X																	
	22	DEVICE OTHER THAN AIRCRAFT			K										W		B	D	D						W												
GEOMETRY	23	FEATHERING PITCH SYSTEM	4			3		1	1							1					2						2		4								1'
	24	ROTOR SYSTEMS per INSTAL.	2		2					6	6	2			1				1	1		2			1	1			2	2	1			2		2	2
	25	NUMBER of BLADES per ROTOR	4		1			4	4	M	M	1			2				1	2		1			9	F			4		1		1	1		1	
	26	BLADE or ROTOR PROFILE	F		F			A	A	C	C	C			S				R	C		C					F			C	-		C	X	A	C	A
	27	TIP PATH other than CIRCULAR																									X										
	28	AUXILIARY to FIXED WING								X	X																			X							
TEST	29	WIND TUNNEL																																		X	
	30	FLIGHT or DROP TEST																																		X	
	31	TOWING TANK or in WATER																															X				X
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL																															X				
	34	FLOW PATTERN STUDY																				X															
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY													X																		X				X
	37	ROTATION																															X				X
	38	POWER																																			X
	39	BLADE ANGLE																													X						X
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																															X				
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																															X				
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT				X																											X				
	48	DRAG				X																											X				
	49	THRUST				X																															X
	50	TORQUE				X																															X
	51	ROTATION																																			X
	52	TIP SPEED or ADVANCE RATIO				X																											X				
	53	POWER													X																		X				X
	54	FORCE DISTRIBUTION				X																									X						
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED			X																					X					X						
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P		S	R	S	P	P	P	P	S	K	A	A	S	R	R	P	P	P	S	S	S	P	B	P	S	P	P	S	S	K	P	P	S	R
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY															X	X																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED						X	X							X																X					

B		REFERENCE Nº ➡	71	72	73	74	75	76	77	78	79	80	81	82	83	84
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.					X	X					X	X		
	2	WING ROTOR			X											X
	3	MAGNUS CYLINDER	X	X		X			X	X	X	X			X	
	4	CROSS-FLOW FAN														
	5	OTHER	X	X							X					
GENERAL	6	THEORETICAL EXPOSITION	X	X		X				X						
	7	PERFORMANCE	X	X					X	X					X	
	8	STABILITY	X	X												
	9	CONTROL or MANEUVERABILITY														
	10	LOADS and STRESS ANALYSIS														
	11	PHENOMENON DEMONSTRATION														
	12	REVIEW								X						
	13	COMMENT of INTEREST											X			
APPLICATION	14	AIRCRAFT SUSTENTATION					X				X	X				X
	15	AIRCRAFT PROPULSION					X				X					
	16	MARINE PROPULSION						X	X							
	17	COMPLETE AIRCRAFT									X					X
	18	COMPLETE SHIP						X	X							
	19	ROTATING FLAP or SLAT										X				X
	20	CONVERTIBLE ROTOR to WING														
	21	ROTOR-ROTOR														
	22	DEVICE OTHER THAN AIRCRAFT	D	D	D	D							W			
GEOMETRY	23	FEATHERING PITCH SYSTEM					4									
	24	ROTOR SYSTEMS per INSTAL.			3						4					4
	25	NUMBER of BLADES per ROTOR	1	1	1,2		3				2	1				1,2
	26	BLADE or ROTOR PROFILE	C	C	[illegible]		F				C	C				[illegible]
	27	TIP PATH other than CIRCULAR														
	28	AUXILIARY to FIXED WING										X				X
TEST	29	WIND TUNNEL								X					X	
	30	FLIGHT or DROP TEST	X	X												
	31	TOWING TANK or in WATER							X							
	32	TWO DIMENSIONAL								X						
	33	THREE DIMENSIONAL								X						
	34	FLOW PATTERN STUDY								X					X	
	35	CAVITATION STUDY														
PARAMETERS VARIED	36	STREAM VELOCITY	X	X						X						
	37	ROTATION	X	X						X					X	
	38	POWER	X							X						
	39	BLADE ANGLE		X												
	40	ORBIT ANGLE														
	41	ECCENTRICITY														
	42	PROFILE SHAPE or THICKNESS		X												
	43	NUMBER of BLADES														
	44	ASPECT RATIO								X					X	
	45	TIP PLATE DIA. or SHAPE								X					X	
	46	MOMENT of INERTIA														
QUANTITIES MEASURED	47	LIFT	X	X						X					X	
	48	DRAG	X	X						X					X	
	49	THRUST														
	50	TORQUE														
	51	ROTATION								X						
	52	TIP SPEED or ADVANCE RATIO								X					X	
	53	POWER														
	54	FORCE DISTRIBUTION														
	55	TORQUE DISTRIBUTION														
	56	FLIGHT PATH PLOTTED	X	X												
	57	STABILITY DERIVATIVES	X	X												
	58	PRESENTATION	R	R	P	R	P	R	S	R	S	P	S	P	S	P
AVAILABILITY	59	CLASSIFIED														
	60	COMPANY PROPRIETARY														
	61	NOT GENERALLY AVAILABLE														
	62	UNPUBLISHED														
	63	ENGLISH TRANSLATION														
	64	NOT SEARCHED														

C		REFERENCE No ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X		X	X		X	X			X	X			X	X																				
	2	WING ROTOR		X						X	X															X					X	X	X		X	X	X
	3	MAGNUS CYLINDER													X		X	X	X	X	X	X	X	X	X		X	X	X	X							
	4	CROSS-FLOW FAN					X							X	X														X								
	5	OTHER			X		X	X									X																				
GENERAL	6	THEORETICAL EXPOSITION								X																					X						
	7	PERFORMANCE								X					X											X					X						
	8	STABILITY	X							X				X	X		X					X	X	X	X	X					X						
	9	CONTROL or MANEUVERABILITY	X				X																X		X						X						
	10	LOADS and STRESS ANALYSIS									X									X	X							X			X				X		
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW																																			
	13	COMMENT of INTEREST															X																				
APPLICATION	14	AIRCRAFT SUSTENTATION	X		X			X	X			X															X		X							X	X
	15	AIRCRAFT PROPULSION	X		X			X	X			X		X	X	X			X	X	X	X	X	X	X		X	X	X	X	X	X			X		
	16	MARINE PROPULSION														X															X						
	17	COMPLETE AIRCRAFT	X				X					X			X																		X				
	18	COMPLETE SHIP													X							X	X	X	X		X	X	X	X	X	X			X		
	19	ROTATING FLAP or SLAT												X																			X				
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																		X	X		X	X			X	X									
	22	DEVICE OTHER THAN AIRCRAFT									K		W				W	D												K							
GEOMETRY	23	FEATHERING PITCH SYSTEM	6		1	8			2			2	1			4	4														1	2	1		1	1	1
	24	ROTOR SYSTEMS per INSTAL.	2	2				4			1	2	1					2	2	2	2	2	2	2	2		2	2			4	2			1	1	1
	25	NUMBER of BLADES per ROTOR	4	1	M			1	6		2	4	6		1	4	M	1	1	1	1	1	1	1	1		1	1			[illegible]	4		4	8	4	4
	26	BLADE or ROTOR PROFILE		~	A			~	F		S	F	A		C	^		~	~	A	A	A	R	R	R		R	R			A	F		P	A	L	L
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING																																			
TEST	29	WIND TUNNEL																		X	X		X	X													
	30	FLIGHT or DROP TEST													X								X		X												
	31	TOWING TANK or in WATER																												X							
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL																																			
	34	FLOW PATTERN STUDY													X								X		X												
	35	CAVITATION STUDY													X																						
PARAMETERS VARIED	36	STREAM VELOCITY																																			
	37	ROTATION												X	X		X						X		X												
	38	POWER												X	X								X		X												
	39	BLADE ANGLE													X													X									
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																					X		X												
	44	ASPECT RATIO												X			X																				
	45	TIP PLATE DIA. or SHAPE													X		X																				
	46	MOMENT of INERTIA													X																						
QUANTITIES MEASURED	47	LIFT												X	X																						
	48	DRAG												X	X								X		X												
	49	THRUST												X	X								X		X												
	50	TORQUE					X								X																						
	51	ROTATION															X																				
	52	TIP SPEED or ADVANCE RATIO													X										X												
	53	POWER												X	X								X		X												
	54	FORCE DISTRIBUTION													X																						
	55	TORQUE DISTRIBUTION															X																				
	56	FLIGHT PATH PLOTTED													X																						
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P	P	P	P	P	P	P	B	P	P	P	S	B	P	S	P	P	P	P	S	S	S	S	R	S	P	S	S	R	P	S	P	P	S	S
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																							X												

C		REFERENCE Nº	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X			X			X	X		X	X									X	X		X	
	2	WING ROTOR			X	X	X								X	X		X	X		X	X					
	3	MAGNUS CYLINDER						X	X			X							X						X		
	4	CROSS-FLOW FAN																									
	5	OTHER															X			X							
GENERAL	6	THEORETICAL EXPOSITION							X		X			X													
	7	PERFORMANCE		X					X		X	X		X			X	X	X	X							
	8	STABILITY															X	X	X								
	9	CONTROL or MANEUVERABILITY		X							X						X									X	
	10	LOADS and STRESS ANALYSIS												X													
	11	PHENOMENON DEMONSTRATION																									
	12	REVIEW																	X								
	13	COMMENT of INTEREST			X											X								X			
APPLICATION	14	AIRCRAFT SUSTENTATION				X	X				X		X	X			X		X		X	X	X		X	X	
	15	AIRCRAFT PROPULSION	X				X			X	X		X	X			X						X			X	
	16	MARINE PROPULSION	X	X				X				X															
	17	COMPLETE AIRCRAFT				X					X			X			X		X		X	X					
	18	COMPLETE SHIP		X								X	X														
	19	ROTATING FLAP or SLAT																	X						X		
	20	CONVERTIBLE ROTOR to WING																			X	X					
	21	ROTOR-ROTOR																									
	22	DEVICE OTHER THAN AIRCRAFT						X							W			[illegible]									
GEOMETRY	23	FEATHERING PITCH SYSTEM	2	1			1			7	6		1	1									1	1		1	
	24	ROTOR SYSTEMS per INSTAL.	1		2	2		3		1	2		2	4	1	1	4				2					2	
	25	NUMBER of BLADES per ROTOR	4		1	2	2			4	4		M	3	3	1	2				1		B		1	2	
	26	BLADE or ROTOR PROFILE	⌒		~	S	~	C		F	F			A	~	F	A	F			~		F		C	F	
	27	TIP PATH other than CIRCULAR																									
	28	AUXILIARY to FIXED WING				X													X		X						
TEST	29	WIND TUNNEL												X				X	X	X							
	30	FLIGHT or DROP TEST																X									
	31	TOWING TANK or in WATER																									
	32	TWO DIMENSIONAL																		X							
	33	THREE DIMENSIONAL																X	X								
	34	FLOW PATTERN STUDY						X																			
	35	CAVITATION STUDY																									
PARAMETERS VARIED	36	STREAM VELOCITY																X	X								
	37	ROTATION																X	X								
	38	POWER																	X								
	39	BLADE ANGLE																X	X								
	40	ORBIT ANGLE																									
	41	ECCENTRICITY																									
	42	PROFILE SHAPE or THICKNESS																	X								
	43	NUMBER of BLADES																									
	44	ASPECT RATIO																	X								
	45	TIP PLATE DIA. or SHAPE																	X								
	46	MOMENT of INERTIA																X									
QUANTITIES MEASURED	47	LIFT							X			X							X	X							
	48	DRAG										X						X	X	X							
	49	THRUST																									
	50	TORQUE																									
	51	ROTATION																X									
	52	TIP SPEED or ADVANCE RATIO										X						X	X								
	53	POWER																	X								
	54	FORCE DISTRIBUTION										X								X							
	55	TORQUE DISTRIBUTION																									
	56	FLIGHT PATH PLOTTED																									
	57	STABILITY DERIVATIVES																X									
	58	PRESENTATION	P	S	S	S	P	S	E	P	S	S	S	R	P	P	K	R	R	R	P	P	P	S	P	P	
AVAILABILITY	59	CLASSIFIED																									
	60	COMPANY PROPRIETARY												X													
	61	NOT GENERALLY AVAILABLE												X													
	62	UNPUBLISHED												X			X										
	63	ENGLISH TRANSLATION																									
	64	NOT SEARCHED																									

D		REFERENCE NO ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X			X	X	X					X	X	X	X	X	X		X	X							X	X	X					X		X	
	2	WING ROTOR			X							X							X			X	X				X				X	X	X			X		
	3	MAGNUS CYLINDER		X					X	X	X																								X			
	4	CROSS-FLOW FAN																						X	X	X												
	5	OTHER																																				
GENERAL	6	THEORETICAL EXPOSITION																																				
	7	PERFORMANCE							X	X	X	X			X	X	X	X																		X	X	
	8	STABILITY								X		X						X									X											
	9	CONTROL or MANEUVERABILITY									X									X																		
	10	LOADS and STRESS ANALYSIS																																				
	11	PHENOMENON DEMONSTRATION			X				X		X																									X		
	12	REVIEW			X						X																											
	13	COMMENT of INTEREST			X					X												X					X						X					
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X		X			X			X	X										X	X	X	X	X	X	X	X	X			X		X	
	15	AIRCRAFT PROPULSION	X				X																	X	X	X	X	X	X	X					X		X	
	16	MARINE PROPULSION									X				X	X	X	X								X												
	17	COMPLETE AIRCRAFT		X	X		X			X														X	X	X			X	X		X			X			
	18	COMPLETE SHIP									X				X	X	X																					
	19	ROTATING FLAP or SLAT								X																												
	20	CONVERTIBLE ROTOR to WING																																				
	21	ROTOR-ROTOR									X																											
	22	DEVICE OTHER THAN AIRCRAFT				W		W				B							K	W	W	K	K										K					
GEOMETRY	23	FEATHERING PITCH SYSTEM	8			2	6	1					2	1	1	1	1	1		2	1								8	8							6	
	24	ROTOR SYSTEMS per INSTAL.		2		1	2	1		1		1			2	2	2			1	1	1	1	2	2		1		2	2	2	2	2		1	1	2	
	25	NUMBER of BLADES per ROTOR	2	1		4	3	2		1		1	4	6	4	4	4	6		2	3	1	1	M	M		1	4	3	3	1	1	2		4	1	3	
	26	BLADE or ROTOR PROFILE		C		F	F	A		C		R	F	A	A	A	A	A		F	A	R	~				F	L			~	~	3		F	F	A	
	27	TIP PATH other than CIRCULAR																																				
	28	AUXILIARY to FIXED WING	X																					X	X						X	X			X			
TEST	29	WIND TUNNEL										X																									X	
	30	FLIGHT or DROP TEST			X																						X									X		
	31	TOWING TANK or in WATER													X	X	X																			X		
	32	TWO DIMENSIONAL									X																									X		
	33	THREE DIMENSIONAL									X	X									X															X	X	
	34	FLOW PATTERN STUDY									X				X	X	X				X															X		
	35	CAVITATION STUDY																																				
PARAMETERS VARIED	36	STREAM VELOCITY									X	X			X			X			X															X	X	
	37	ROTATION							X		X				X																					X	X	
	38	POWER															X	X			X															X	X	
	39	BLADE ANGLE						X																														
	40	ORBIT ANGLE																																			X	
	41	ECCENTRICITY																																				
	42	PROFILE SHAPE or THICKNESS							X			X																								X	X	
	43	NUMBER of BLADES																																		X		
	44	ASPECT RATIO										X																								X		
	45	TIP PLATE DIA. or SHAPE									X	X																										
	46	MOMENT of INERTIA																																		X		
QUANTITIES MEASURED	47	LIFT							X		X	X																								X	X	
	48	DRAG							X		X	X			X																					X	X	
	49	THRUST													X	X	X	X																			X	
	50	TORQUE										X			X	X	X	X																			X	
	51	ROTATION							X			X																									X	
	52	TIP SPEED or ADVANCE RATIO										X			X																					X		
	53	POWER														X	X																			X		
	54	FORCE DISTRIBUTION									X							X																			X	
	55	TORQUE DISTRIBUTION																																				
	56	FLIGHT PATH PLOTTED							X																		X									X		
	57	STABILITY DERIVATIVES										X																										
	58	PRESENTATION	P	P	S	P	P	P	S	S	S	R	P	P	R	R	R	R	P	P	S	S	P	P	P	P	S	P	P	S	P	P	S	P	P	P	R	R
AVAILABILITY	59	CLASSIFIED																																				
	60	COMPANY PROPRIETARY																																				
	61	NOT GENERALLY AVAILABLE										X																										
	62	UNPUBLISHED																																				
	63	ENGLISH TRANSLATION																																				
	64	NOT SEARCHED															X		X									X						X				

E		REFERENCE Nº ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X											X				X	
	2	WING ROTOR			X		X			X		X	X	X						X
	3	MAGNUS CYLINDER							X		X	X				X				
	4	CROSS-FLOW FAN				X														
	5	OTHER																X		
GENERAL	6	THEORETICAL EXPOSITION		X		X					X	X	X			X				
	7	PERFORMANCE	X	X		X										X			X	
	8	STABILITY								X									X	
	9	CONTROL or MANEUVERABILITY																	X	
	10	LOADS and STRESS ANALYSIS																		
	11	PHENOMENON DEMONSTRATION				X						X	X	X						
	12	REVIEW		X		X														
	13	COMMENT of INTEREST			X				X											
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X			X		X							X			X	
	15	AIRCRAFT PROPULSION	X	X			X								X				X	
	16	MARINE PROPULSION							X		X									
	17	COMPLETE AIRCRAFT					X									X			X	
	18	COMPLETE SHIP																		
	19	ROTATING FLAP or SLAT														X				
	20	CONVERTIBLE ROTOR to WING																		
	21	ROTOR-ROTOR																		
	22	DEVICE OTHER THAN AIRCRAFT			W	F				K										K
GEOMETRY	23	FEATHERING PITCH SYSTEM	S	S											O				I	
	24	ROTOR SYSTEMS per INSTAL.	2	2	1		4			1				1	1	2			2	2
	25	NUMBER of BLADES per ROTOR	3	X	2	M	1			1	C			1	B	1			3	1
	26	BLADE or ROTOR PROFILE	A	A	S		L			W				E	L	C			A	W
	27	TIP PATH other than CIRCULAR																		
	28	AUXILIARY to FIXED WING																		
TEST	29	WIND TUNNEL	X	X												X		X		
	30	FLIGHT or DROP TEST																		
	31	TOWING TANK or in WATER																		
	32	TWO DIMENSIONAL																		
	33	THREE DIMENSIONAL	X	X	X											X				
	34	FLOW PATTERN STUDY				X						X				X				
	35	CAVITATION STUDY																		
PARAMETERS VARIED	36	STREAM VELOCITY	X	X												X				
	37	ROTATION	X	X		X						X	X			X				
	38	POWER		X		X										X				
	39	BLADE ANGLE	X	X												X		X		
	40	ORBIT ANGLE																X		
	41	ECCENTRICITY	X	X														X		
	42	PROFILE SHAPE or THICKNESS				X										X				
	43	NUMBER of BLADES		X		X														
	44	ASPECT RATIO														X				
	45	TIP PLATE DIA. or SHAPE														X				
	46	MOMENT of INERTIA																		
QUANTITIES MEASURED	47	LIFT	X	X												X		X	X	
	48	DRAG	X	X												X		X		
	49	THRUST	X	X																
	50	TORQUE	X	X																
	51	ROTATION																		
	52	TIP SPEED or ADVANCE RATIO														X				
	53	POWER	X	X												X				
	54	FORCE DISTRIBUTION											X					X	X	
	55	TORQUE DISTRIBUTION																		
	56	FLIGHT PATH PLOTTED											X							
	57	STABILITY DERIVATIVES																		
	58	PRESENTATION	R	R	B	R	P	P	S	P	R	S	S	S	P	R	P	R	S	P
AVAILABILITY	59	CLASSIFIED																		
	60	COMPANY PROPRIETARY																		
	61	NOT GENERALLY AVAILABLE																		
	62	UNPUBLISHED																		
	63	ENGLISH TRANSLATION																		
	64	NOT SEARCHED						X									X			

Category	No.	REFERENCE Nº
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OTHER THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL.
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMENSIONAL
	33	THREE DIMENSIONAL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

F		REFERENCE №
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OTHER THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL.
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMENSIONAL
	33	THREE DIMENSIONAL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

		REFERENCE No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X	X		X	X	X		X							X					X	X			X	X	X	X	X	X	X	X	X	X	X
	2	WING ROTOR				X				X		X					X								X					X	X	X					
	3	MAGNUS CYLINDER											X	X	X	X	X		X	X	X	X										X					
	4	CROSS-FLOW FAN																																			
	5	OTHER										X																									
GENERAL	6	THEORETICAL EXPOSITION												X			X	X	X	X	X																
	7	PERFORMANCE											X	X			X	X			X																
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																																			
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW												X																		X					
	13	COMMENT of INTEREST				X				X												X															
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X	X	X	X	X		X		X	X	X	X						X		X			X	X	X				X	X			
	15	AIRCRAFT PROPULSION	X	X	X		X	X	X																												
	16	MARINE PROPULSION										X																							X	X	X
	17	COMPLETE AIRCRAFT	X	X	X	X		X	X				X	X	X	X		X										X	X								
	18	COMPLETE SHIP										X																							X	X	X
	19	ROTATING FLAP or SLAT																				X															
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT																							W	W				W	W	W					
GEOMETRY	23	FEATHERING PITCH SYSTEM	8	8			1	1	1		1							1						A			8	2	2	2	2	4	2	8	1	1	1
	24	ROTOR SYSTEMS per INSTAL.	U		1		2	1	4	1	1	1		1	2	2								A	1		4	2	2	1	1	1	5	2			
	25	NUMBER of BLADES per ROTOR	[illegible]		M		N	4	4	1	6	4		1	1	1								3	M		3	2	2	1	1	N	F	G			
	26	BLADE or ROTOR PROFILE	F		F		A	A	A	F	L			C	C	C						C		F	[illegible]			L	L	L	L			F			
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING					X				X											X															
TEST	29	WIND TUNNEL				X																															
	30	FLIGHT or DROP TEST				X																															
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL				X																															
	34	FLOW PATTERN STUDY																																			
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY																																			
	37	ROTATION																																			
	38	POWER																																			
	39	BLADE ANGLE				X																															
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT																																			
	48	DRAG																																			
	49	THRUST																																			
	50	TORQUE																																			
	51	ROTATION				X																															
	52	TIP SPEED or ADVANCE RATIO																																			
	53	POWER																																			
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	P	P	P	P	P	P	P	P	P	F	D	P	P	S	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																	X	X			X			X										X	X

G		REFERENCE Nº ➡	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X	X				X		X	X			X											X			
	2	WING ROTOR					X	X								X											X	X	
	3	MAGNUS CYLINDER				X				X				X			X	X	X	X	X	X	X	X	X				X
	4	CROSS-FLOW FAN																											
	5	OTHER																											
GENERAL	6	THEORETICAL EXPOSITION								X																			X
	7	PERFORMANCE						X								X													X
	8	STABILITY														X													
	9	CONTROL or MANEUVERABILITY																											
	10	LOADS and STRESS ANALYSIS																											
	11	PHENOMENON DEMONSTRATION				X				X																			
	12	REVIEW																											
	13	COMMENT of INTEREST																X				X	X	X	X				
APPLICATION	14	AIRCRAFT SUSTENTATION			X	X			X		X			X	X		X	X	X	X	X	X	X	X	X	X			
	15	AIRCRAFT PROPULSION			X				X		X	X																	
	16	MARINE PROPULSION	X																									X	
	17	COMPLETE AIRCRAFT				X					X							X	X	X	X	X	X	X	X				
	18	COMPLETE SHIP	X																									X	
	19	ROTATING FLAP or SLAT															X												
	20	CONVERTIBLE ROTOR to WING																											
	21	ROTOR-ROTOR															X				X								
	22	DEVICE OTHER THAN AIRCRAFT						X		X						B	X		K								P	W	
GEOMETRY	23	FEATHERING PITCH SYSTEM	1		7				4		2				7														
	24	ROTOR SYSTEMS per INSTAL.				1					2				4	M		2	2	4	2	4	4	4	4	R	1		
	25	NUMBER of BLADES per ROTOR			4	1			4		4				2	M	1	1	1	1	1	1	1	1	1	M	2	2	
	26	BLADE or ROTOR PROFILE	A		F	C			L		L				F	C	C	C	C	C	C	C	C	C	C	F	S	S	C
	27	TIP PATH other than CIRCULAR																											
	28	AUXILIARY to FIXED WING																											
TEST	29	WIND TUNNEL						X								X												X	
	30	FLIGHT or DROP TEST				X																							
	31	TOWING TANK or in WATER																											
	32	TWO DIMENSIONAL																											X
	33	THREE DIMENSIONAL														X												X	X
	34	FLOW PATTERN STUDY						X																				X	X
	35	CAVITATION STUDY																											
PARAMETERS VARIED	36	STREAM VELOCITY						X								X												X	X
	37	ROTATION						X																					X
	38	POWER																											
	39	BLADE ANGLE						X								X											X		
	40	ORBIT ANGLE														X													
	41	ECCENTRICITY																											
	42	PROFILE SHAPE or THICKNESS						X								X											X		
	43	NUMBER of BLADES														X													
	44	ASPECT RATIO						X								X													X
	45	TIP PLATE DIA. or SHAPE														X													X
	46	MOMENT of INERTIA																											
QUANTITIES MEASURED	47	LIFT														X												X	X
	48	DRAG														X												X	X
	49	THRUST																											
	50	TORQUE																										X	
	51	ROTATION						X								X											X	X	
	52	TIP SPEED or ADVANCE RATIO						X								X												X	X
	53	POWER																										X	
	54	FORCE DISTRIBUTION						X																					
	55	TORQUE DISTRIBUTION						X																				X	
	56	FLIGHT PATH PLOTTED																											
	57	STABILITY DERIVATIVES																											
	58	PRESENTATION	S	S	P	S	R	R	P	S	P	P	P	P	P	R	P	S	P	P	P	S	S	S	S	P	P	S	R
AVAILABILITY	59	CLASSIFIED																											
	60	COMPANY PROPRIETARY																											
	61	NOT GENERALLY AVAILABLE																											
	62	UNPUBLISHED					X																						
	63	ENGLISH TRANSLATION																											
	64	NOT SEARCHED		X			X					X	X	X															

H		REFERENCE NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X		X	X		X	X	X	X	X		X	X	X	X				X	X	X	X	X				X	X	X	X	X		X	X
	2	WING ROTOR			X														X									X	X								
	3	MAGNUS CYLINDER												X						X							X							X	X		
	4	CROSS-FLOW FAN																																			
	5	OTHER						X							X	X																			X		
GENERAL	6	THEORETICAL EXPOSITION	X	X												X			X								X			X	X						
	7	PERFORMANCE	X	X												X							X							X	X		X	X	X		X
	8	STABILITY																												X							
	9	CONTROL or MANEUVERABILITY														X														X				X			
	10	LOADS and STRESS ANALYSIS																												X							
	11	PHENOMENON DEMONSTRATION																	X			X					X										
	12	REVIEW				X																													X		
	13	COMMENT of INTEREST					X																														
APPLICATION	14	AIRCRAFT SUSTENTATION				X			X	X	X	X		X	X		X	X				X	X	X	X			X	X	X	X		X			X	X
	15	AIRCRAFT PROPULSION				X			X		X	X			X		X	X						X		X				X	X		X	X		X	X
	16	MARINE PROPULSION	X	X			X																				X					X		X			
	17	COMPLETE AIRCRAFT									X	X						X				X	X							X	X		X	X		X	X
	18	COMPLETE SHIP					X																				X					X		X			
	19	ROTATING FLAP or SLAT																										X	X					X			
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT			W								W			C			X																		
GEOMETRY	23	FEATHERING PITCH SYSTEM	1	1.		3	1		6	6	3	3	2		8		6	1				1	1	4	2							3	3'			5	1
	24	ROTOR SYSTEMS per INSTAL.		1	1		2		2	2	2	2			2		2	4				1	2	4	4	2	2			4	4		16			4	14
	25	NUMBER of BLADES per ROTOR		6	6		6		3	3		3		1	4		4	1		1		4	3	4	2	2	1	1	1	3	3		6			3	6
	26	BLADE or ROTOR PROFILE		~	M		A	A	~	F	A	A	F	C	~			L		C		A	A	F	F	F	C	R	R	A	A					L	
	27	TIP PATH other than CIRCULAR									X	X						X																			
	28	AUXILIARY to FIXED WING																																			
TEST	29	WIND TUNNEL																												X							
	30	FLIGHT or DROP TEST																				X															
	31	TOWING TANK or in WATER		X			X																				X										
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL																				X								X			X				X
	34	FLOW PATTERN STUDY																	X															X			
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY	X	X																										X			X				X
	37	ROTATION	X	X																										X			X	X			X
	38	POWER	X	X																																	
	39	BLADE ANGLE	X	X																										X	X						
	40	ORBIT ANGLE	X																												X						
	41	ECCENTRICITY																													X						
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	[illegible] SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT																												X			X				X
	48	DRAG																												X							
	49	THRUST	X	X																																	
	50	TORQUE	X	X																										X							
	51	ROTATION	X																																		
	52	TIP SPEED or ADVANCE RATIO	X																																		
	53	POWER																												X			X				X
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	R	S	P	R	S	P	P	P	P	P	P	P	P	P	P	P	B	R	P	B	S	P	P	P	S	P	P	R	P	R	B	P	B	P	B
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																		X	X																

H		REFERENCE NO	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X		X	X		X			X		X			X													X	
	2	WING ROTOR						X		X	X				X				X	X	X	X	X	X	X	X	X				
	3	MAGNUS CYLINDER	X		X	X		X			X				X																
	4	CROSS-FLOW FAN																													
	5	OTHER														X															
GENERAL	6	THEORETICAL EXPOSITION														X															
	7	PERFORMANCE	X		X			X	X						X	X							X	X							
	8	STABILITY																													
	9	CONTROL or MANEUVERABILITY	X						X																						
	10	LOADS and STRESS ANALYSIS																													
	11	PHENOMENON DEMONSTRATION			X																										
	12	REVIEW													X																
	13	COMMENT of INTEREST									X	X			C						X				X	X					
APPLICATION	14	AIRCRAFT SUSTENTATION		X		X	X	X			X	X		X	X	X	X		X	X	X	X	X	X	X	X				X	
	15	AIRCRAFT PROPULSION	X	X		X					X					X														X	
	16	MARINE PROPULSION	X						X																						
	17	COMPLETE AIRCRAFT	X			X	X												X	X	X	X	X	X	X	X				X	
	18	COMPLETE SHIP	X						X																						
	19	ROTATING FLAP or SLAT	X								X				X																
	20	CONVERTIBLE ROTOR to WING									X											X									
	21	ROTOR-ROTOR																													
	22	DEVICE OTHER THAN AIRCRAFT								W																	F				
GEOMETRY	23	FEATHERING PITCH SYSTEM	1	2		2	4		1					B			2													4	
	24	ROTOR SYSTEMS per INSTAL.		2	1	2	2			1							1				2	2	2	2	2	2	3			2	
	25	NUMBER of BLADES per ROTOR		8	1	4	3			3			2	2			3				1	1	1	1	1	1	2			2	
	26	BLADE or ROTOR PROFILE		F	C	A	F			S			⌒				⌒				~	~	~	~	~	~	S			⌒	
	27	TIP PATH other than CIRCULAR																												X	
	28	AUXILIARY to FIXED WING				X					X																				
TEST	29	WIND TUNNEL			X			X							X																
	30	FLIGHT or DROP TEST																				X	X	X	X	X					
	31	TOWING TANK or in WATER							X						X												X				
	32	TWO DIMENSIONAL																													
	33	THREE DIMENSIONAL			X																		X	X	X		X				
	34	FLOW PATTERN STUDY	X												X																
	35	CAVITATION STUDY																													
PARAMETERS VARIED	36	STREAM VELOCITY			X			X							X																
	37	ROTATION	X		X			X							X																
	38	POWER																													
	39	BLADE ANGLE													X																
	40	ORBIT ANGLE																													
	41	ECCENTRICITY						X																							
	42	PROFILE SHAPE or THICKNESS																													
	43	NUMBER of BLADES													X																
	44	ASPECT RATIO													X																
	45	TIP PLATE DIA. or SHAPE						X							X																
	46	MOMENT of INERTIA																													
QUANTITIES MEASURED	47	LIFT			X			X							X																
	48	DRAG						X							X																
	49	THRUST																													
	50	TORQUE																													
	51	ROTATION													X												X				
	52	TIP SPEED or ADVANCE RATIO													X																
	53	POWER																									X				
	54	FORCE DISTRIBUTION																													
	55	TORQUE DISTRIBUTION																													
	56	FLIGHT PATH PLOTTED																													
	57	STABILITY DERIVATIVES																													
	58	PRESENTATION	P	P	S	P	P	B	S	P	S	S	P	F	A	R	P	P	S	S	S	S	S	S	S	S	S	P	P	P	
AVAILABILITY	59	CLASSIFIED						1																							
	60	COMPANY PROPRIETARY																													
	61	NOT GENERALLY AVAILABLE																													
	62	UNPUBLISHED																													
	63	ENGLISH TRANSLATION														X															
	64	NOT SEARCHED																X	X	X								X	X		

I		REFERENCE № ➡	1	2	3	4	5	6	7	8	9	10	11	12
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X		X	X	X	X	X	X	X	X	
	2	WING ROTOR												X
	3	MAGNUS CYLINDER			X									
	4	CROSS-FLOW FAN												
	5	OTHER												
GENERAL	6	THEORETICAL EXPOSITION	X	X					X	X	X	X	X	
	7	PERFORMANCE	X	X	X				X	X	X	X	X	
	8	STABILITY												
	9	CONTROL or MANEUVERABILITY												
	10	LOADS and STRESS ANALYSIS												
	11	PHENOMENON DEMONSTRATION												
	12	REVIEW												
	13	COMMENT of INTEREST			X	X	X	X						
APPLICATION	14	AIRCRAFT SUSTENTATION				X	X	X						
	15	AIRCRAFT PROPULSION												
	16	MARINE PROPULSION			X				X	X	X	X	X	
	17	COMPLETE AIRCRAFT				X	X	X						
	18	COMPLETE SHIP			X									
	19	ROTATING FLAP or SLAT												
	20	CONVERTIBLE ROTOR to WING												
	21	ROTOR-ROTOR												
	22	DEVICE OTHER THAN AIRCRAFT												K
GEOMETRY	23	FEATHERING PITCH SYSTEM	1	1		2	2	2	1	1	1	1	1	
	24	ROTOR SYSTEMS per INSTAL			2	1	1	1						2
	25	NUMBER of BLADES per ROTOR			1	4	4	4	4	4	4	4		2
	26	BLADE or ROTOR PROFILE			C	F	F	F	⌒	⌒	⌒	⌒		S
	27	TIP PATH other than CIRCULAR												
	28	AUXILIARY to FIXED WING												
TEST	29	WIND TUNNEL												
	30	FLIGHT or DROP TEST												
	31	TOWING TANK or in WATER			X									
	32	TWO DIMENSIONAL						X	X	X	X	X	X	
	33	THREE DIMENSIONAL												
	34	FLOW PATTERN STUDY												
	35	CAVITATION STUDY												
PARAMETERS VARIED	36	STREAM VELOCITY												
	37	ROTATION												
	38	POWER												
	39	BLADE ANGLE												
	40	ORBIT ANGLE												
	41	ECCENTRICITY												
	42	PROFILE SHAPE or THICKNESS												
	43	NUMBER of BLADES												
	44	ASPECT RATIO												
	45	TIP PLATE DIA or SHAPE												
	46	MOMENT of INERTIA												
QUANTITIES MEASURED	47	LIFT												
	48	DRAG												
	49	THRUST												
	50	TORQUE												
	51	ROTATION												
	52	TIP SPEED or ADVANCE RATIO												
	53	POWER												
	54	FORCE DISTRIBUTION												
	55	TORQUE DISTRIBUTION												
	56	FLIGHT PATH PLOTTED												
	57	STABILITY DERIVATIVES												
	58	PRESENTATION	S	S	S	S	S	S	S	S	S	S	B	P
AVAILABILITY	59	CLASSIFIED												
	60	COMPANY PROPRIETARY												
	61	NOT GENERALLY AVAILABLE												
	62	UNPUBLISHED												
	63	ENGLISH TRANSLATION	X	X										
	64	NOT SEARCHED												

J		REFERENCE NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.					X		X				X				X		X					X				X	X
	2	WING ROTOR				X		X		X		X									X	X			X		X		
	3	MAGNUS CYLINDER			X																X								
	4	CROSS-FLOW FAN																											
	5	OTHER																											
GENERAL	6	THEORETICAL EXPOSITION						X				X													X			X	X
	7	PERFORMANCE						X					X								X				X		X	X	X
	8	STABILITY																			X						X		
	9	CONTROL or MANEUVERABILITY															X												
	10	LOADS and STRESS ANALYSIS																											
	11	PHENOMENON DEMONSTRATION						X																					
	12	REVIEW																			X						X		
	13	COMMENT of INTEREST			X																								
APPLICATION	14	AIRCRAFT SUSTENTATION							X				X								X	X		X					
	15	AIRCRAFT PROPULSION																						X					
	16	MARINE PROPULSION															X												X
	17	COMPLETE AIRCRAFT																			X								
	18	COMPLETE SHIP																											
	19	ROTATING FLAP or SLAT																			X								
	20	CONVERTIBLE ROTOR to WING																			X								
	21	ROTOR-ROTOR			X					X																			
	22	DEVICE OTHER THAN AIRCRAFT				K	W			K									W								B		
GEOMETRY	23	FEATHERING PITCH SYSTEM					1										13		2					3				1	1
	24	ROTOR SYSTEMS per INSTAL.					1	1		2		1	1						1		1	2		2	1				
	25	NUMBER of BLADES per ROTOR				2	3	1	4	1		1	6						13		1	1		1	1				
	26	BLADE or ROTOR PROFILE				S	A	F	F	[illegible]		F	~						F		L	~		A	F			A	
	27	TIP PATH other than CIRCULAR																						X					
	28	AUXILIARY to FIXED WING																											
TEST	29	WIND TUNNEL						X													X				X		X		
	30	FLIGHT or DROP TEST										X															X		
	31	TOWING TANK or in WATER																											
	32	TWO DIMENSIONAL																											
	33	THREE DIMENSIONAL						X					X								X				X		X		
	34	FLOW PATTERN STUDY						X																	X				
	35	CAVITATION STUDY																											
PARAMETERS VARIED	36	STREAM VELOCITY						X													X				X		X		
	37	ROTATION						X					X								X						X		
	38	POWER																											
	39	BLADE ANGLE											X								X								
	40	ORBIT ANGLE																											
	41	ECCENTRICITY											X																
	42	PROFILE SHAPE or THICKNESS																			X						X		
	43	NUMBER of BLADES																											
	44	ASPECT RATIO						X																	X		X		
	45	TIP PLATE DIA. or SHAPE																									X		
	46	MOMENT of INERTIA						X																			X		
QUANTITIES MEASURED	47	LIFT						X					X								X				X		X		
	48	DRAG						X													X				X		X		
	49	THRUST			X																								X
	50	TORQUE						X																					
	51	ROTATION						X					X												X				
	52	TIP SPEED or ADVANCE RATIO																			X				X				
	53	POWER											X																
	54	FORCE DISTRIBUTION																											
	55	TORQUE DISTRIBUTION						X																					
	56	FLIGHT PATH PLOTTED										X															X		
	57	STABILITY DERIVATIVES																									X		
	58	PRESENTATION	P		S	B	P	R	P	P	P	S	S			P	P	P	P	P	S	P	P	P	R		R	R	S
AVAILABILITY	59	CLASSIFIED																											
	60	COMPANY PROPRIETARY																											
	61	NOT GENERALLY AVAILABLE																										X	
	62	UNPUBLISHED																											
	63	ENGLISH TRANSLATION																										X	
	64	NOT SEARCHED	X			X					X					X		X		X			X						

K		REFERENCE NO ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYST.	1	CYCLOGIRO or CYCLOIDAL PRO.	X	X	X	X	X		X	X		X	X	X					X		X	X	X	X	X	X	X	X	X	X	X	X	X				X
	2	WING ROTOR						X								X																			X		
	3	MAGNUS CYLINDER									X							X																X		X	
	4	CROSS-FLOW FAN																																			
	5	OTHER					X									X																					
GENERAL	6	THEORETICAL EXPOSITION	X								X								X			X											X				
	7	PERFORMANCE	X								X											X	X	X			X					X	X		X		
	8	STABILITY																						X			X										
	9	CONTROL or MANEUVERABILITY																				X	X	X		X	X	X	X				X				
	10	LOADS and STRESS ANALYSIS																				X				X							X				
	11	PHENOMENON DEMONSTRATION														X																		X			
	12	REVIEW						X																						X			X	X			X
	13	COMMENT of INTEREST				X	X									X									X					X	X			X			X
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X					X								X	X		X	X	X		X	X	X	X	X	X				X		X	X
	15	AIRCRAFT PROPULSION	X	X	X				X	X											X	X	X			X				X							X
	16	MARINE PROPULSION					X		X				X						X												X	X	X		X		
	17	COMPLETE AIRCRAFT	X															X				X	X		X	X		X	X					X			
	18	COMPLETE SHIP					X						X																		X	X	X		X		
	19	ROTATING FLAP or SLAT																																			
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT						W				W																							W		
GEOMETRY	23	FEATHERING PITCH SYSTEM	3	3	3	3			6			4	1	7					2		2	2	2	2	2	2	2	3	2	2	2	3	1'				1
	24	ROTOR SYSTEMS per INSTAL.	4	4								1		2				2				6	5		4				4	4							
	25	NUMBER of BLADES per ROTOR	1	1	1			2	3			3		4				1	1						6			4	6	6					2	2	
	26	BLADE or ROTOR PROFILE	A	A	A			S	F			P						C	A			A	A		A	A		A	A	A			A		S	S	
	27	TIP PATH other than CIRCULAR	X	X	X																																
	28	AUXILIARY to FIXED WING																																			
TEST	29	WIND TUNNEL																				X			X	X								X			
	30	FLIGHT or DROP TEST																																	X		
	31	TOWING TANK or in WATER																				X				X							X		X		
	32	TWO DIMENSIONAL																																X			
	33	THREE DIMENSIONAL																				X				X							X		X		
	34	FLOW PATTERN STUDY																															X		X		
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY																								X							X	X			
	37	ROTATION																								X							X	X	X		
	38	POWER																								X							X				
	39	BLADE ANGLE																															X				
	40	ORBIT ANGLE																															X				
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																								X							X				
	43	NUMBER of BLADES																								X							X				
	44	ASPECT RATIO																								X							X				
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT																								X								X			
	48	DRAG																																X			
	49	THRUST																								X							X				
	50	TORQUE																															X				
	51	ROTATION																															X				
	52	TIP SPEED or ADVANCE RATIO																															X		X		
	53	POWER																															X	X			
	54	FORCE DISTRIBUTION																															X		X		
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	B	P	P	R	S	B	P	[illegible]	R	P	S	P		P	P	S	P		S	S	S	R	S	R	S	P	P	S	S	S	R	S	S	S	S
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED								X	X		X				X				X			X													

K		REFERENCE Nº ➡	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	X	X		X	X	X	X	X	X				X	X				X
	2	WING ROTOR				X							X					X	X		
	3	MAGNUS CYLINDER												X	X				X		
	4	CROSS-FLOW FAN																			
	5	OTHER				X															
GENERAL	6	THEORETICAL EXPOSITION					X	X	X	X	X	X	X			X					
	7	PERFORMANCE			X				X				X			X			X		
	8	STABILITY							X												
	9	CONTROL or MANEUVERABILITY			X				X							X					
	10	LOADS and STRESS ANALYSIS																			
	11	PHENOMENON DEMONSTRATION											X								
	12	REVIEW	X																		
	13	COMMENT of INTEREST	X	X							X				X						
APPLICATION	14	AIRCRAFT SUSTENTATION	X				X	X	X	X	X	X			X			X			X
	15	AIRCRAFT PROPULSION	X				X	X	X	X	X	X					X				X
	16	MARINE PROPULSION			X											X					
	17	COMPLETE AIRCRAFT	X				X	X	X						X						X
	18	COMPLETE SHIP			X																
	19	ROTATING FLAP or SLAT																X			
	20	CONVERTIBLE ROTOR to WING																			
	21	ROTOR-ROTOR																			
	22	DEVICE OTHER THAN AIRCRAFT																			
GEOMETRY	23	FEATHERING PITCH SYSTEM	1	1	P		2	2	2	2	2	2				1	B				
	24	ROTOR SYSTEMS per INSTAL.		2	2			2	2				1				2	1	1		2
	25	NUMBER of BLADES per ROTOR		4	7	1		8	8				1				M	1	1		2
	26	BLADE or ROTOR PROFILE	A	A	A	A		~					F			A	r	L	L		A
	27	TIP PATH other than CIRCULAR																			
	28	AUXILIARY to FIXED WING													X						
TEST	29	WIND TUNNEL				X												X	X		
	30	FLIGHT or DROP TEST											X								
	31	TOWING TANK or in WATER			X											X					
	32	TWO DIMENSIONAL																			
	33	THREE DIMENSIONAL				X							X					X	X		
	34	FLOW PATTERN STUDY																			
	35	CAVITATION STUDY																			
PARAMETERS VARIED	36	STREAM VELOCITY			X											X		X	X		
	37	ROTATION			X														X		
	38	POWER																			
	39	BLADE ANGLE			X	X												X			
	40	ORBIT ANGLE																			
	41	ECCENTRICITY																			
	42	PROFILE SHAPE or THICKNESS																			
	43	NUMBER of BLADES																			
	44	ASPECT RATIO											X						X		
	45	TIP PLATE DIA. or SHAPE																	X		
	46	MOMENT of INERTIA																			
QUANTITIES MEASURED	47	LIFT				X												X	X		
	48	DRAG				X										X		X	X		
	49	THRUST			X																
	50	TORQUE																			
	51	ROTATION																			
	52	TIP SPEED or ADVANCE RATIO																	X		
	53	POWER			X																
	54	FORCE DISTRIBUTION														X					
	55	TORQUE DISTRIBUTION																			
	56	FLIGHT PATH PLOTTED											X								
	57	STABILITY DERIVATIVES																			
	58	PRESENTATION	S	S	R	R	R	B	S	S	B	S	S	R	S	S	P	R	R	P	S
AVAILABILITY	59	CLASSIFIED																			
	60	COMPANY PROPRIETARY																			
	61	NOT GENERALLY AVAILABLE																			
	62	UNPUBLISHED																			
	63	ENGLISH TRANSLATION																			
	64	NOT SEARCHED																		X	X

L		REFERENCE NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.		X		X																					X	X	X	X	X			X	X		X	X
	2	WING ROTOR	X		X				X	X			X																			X					
	3	MAGNUS CYLINDER			X		X	X			X	X																				X					
	4	CROSS-FLOW FAN												X	X	X	X	X	X	X	X	X	X														
	5	OTHER																													X	X			X		
GENERAL	6	THEORETICAL EXPOSITION		X		X	X	X			X	X	X																								
	7	PERFORMANCE		X	X	X						X																						X			
	8	STABILITY		X																																X	
	9	CONTROL or MANEUVERABILITY		X		X																X															
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION								X			X																								
	12	REVIEW		X	X																					X											
	13	COMMENT of INTEREST					X		X																					X	X						
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X									X	X	X	X	X	X	X			X			/	X	X	X		X		X	X	X		X
	15	AIRCRAFT PROPULSION		X										X	X	X	X	X	X	X	X						X	X	X		X		X				X
	16	MARINE PROPULSION				X														X		X								X							
	17	COMPLETE AIRCRAFT		X	X									X	X	X	X	X	X	X	X						X	X	X		X		X				
	18	COMPLETE SHIP				X														X																	
	19	ROTATING FLAP or SLAT			X									X	X	X	X	X	X				X														
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT																																			
GEOMETRY	23	FEATHERING PITCH SYSTEM		14																							6	2	2				1.3	/		1	2
	24	ROTOR SYSTEMS per INSTAL.	2		2					1		1	/														4	1	1		2		2	1	2		
	25	NUMBER of BLADES per ROTOR	M		1					1		1	1	M	M	M	M	M	M	M	M	M	M				6	4	6		2		3	4	1		2
	26	BLADE or ROTOR PROFILE	X		R					F		C	F														A	F	F		A		A	A	P		[illegible]
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING	X											X	X	X	X	X	X																		
TEST	29	WIND TUNNEL		X	X			X	X	X	X	X	X																			X		X			
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL			X							X																						X			
	34	FLOW PATTERN STUDY							X	X		X	X																								
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY		X	X	X						X																									
	37	ROTATION		X	X	X		X				X																						X			
	38	POWER																																			
	39	BLADE ANGLE		X	X	X																															
	40	ORBIT ANGLE				X																															
	41	ECCENTRICITY				X																												X			
	42	PROFILE SHAPE or THICKNESS			X																																
	43	NUMBER of BLADES																																X			
	44	ASPECT RATIO																																X			
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT		X	X			X				X														X								X			
	48	DRAG		X	X																																
	49	THRUST				X																															
	50	TORQUE																																			
	51	ROTATION																																			
	52	TIP SPEED or ADVANCE RATIO			X	X																															
	53	POWER				X																				X								X			
	54	FORCE DISTRIBUTION										X																				X					
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P	S	S	R	S	S	S	S	S	R	S	/	P	P	P	P	P	P	P	P	P			B	P	P	P	M	S	R	P	S	P	R	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																																		X	

L		REFERENCE Nº	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X				X	X	X	X					X		X		X	X	X			X	X							X				X
	2	WING ROTOR		X					X		X	X	X	X			X	X																		
	3	MAGNUS CYLINDER				X					X						X									X	X									
	4	CROSS-FLOW FAN																				X						X	X	X	X					
	5	OTHER			X						X					X		X								X					X		X	X	X	
GENERAL	6	THEORETICAL EXPOSITION	X		X																															
	7	PERFORMANCE	X		X	X					X											X								X	X					
	8	STABILITY														X	X					X				X						X			X	
	9	CONTROL or MANEUVERABILITY							X							X			X	X													X			
	10	LOADS and STRESS ANALYSIS																									X					X				
	11	PHENOMENON DEMONSTRATION																																		
	12	REVIEW				X															X										X					
	13	COMMENT of INTEREST								X							X							X							X	X			X	X
APPLICATION	14	AIRCRAFT SUSTENTATION				X	X	X		X							X	X																		
	15	AIRCRAFT PROPULSION		X				X		X					X		X	X	X	X	X			X	X		X		X				X	X		
	16	MARINE PROPULSION	X														X							X	X								X	X		
	17	COMPLETE AIRCRAFT											X	X			X		X	X	X															
	18	COMPLETE SHIP						X							X		X	X						X					X				X	X		
	19	ROTATING FLAP or SLAT											X	X			X																			
	20	CONVERTIBLE ROTOR to WING																									X									
	21	ROTOR-ROTOR																																		
	22	DEVICE OTHER THAN AIRCRAFT							W			P										K														
GEOMETRY	23	FEATHERING PITCH SYSTEM	1				2		2	1					7				6	4	1			1	1							1				
	24	ROTOR SYSTEMS per INSTAL.					2	7	1		1	1	3	3	M				1	1	1	1			1								2	2		
	25	NUMBER of BLADES per ROTOR		M		1	6	2	4		2	1	1	1	2				1	1	4	1			5				1	1			4	4		
	26	BLADE or ROTOR PROFILE				C	F	A	L		~	~	L	L	F				F	F	A	C		A	A	A	L		C	C			A	A		
	27	TIP PATH other than CIRCULAR																																		
	28	AUXILIARY to FIXED WING																																		
TEST	29	WIND TUNNEL				X					X																X						X	A		
	30	FLIGHT or DROP TEST																							X	X							X	X		
	31	TOWING TANK or in WATER										X										X														
	32	TWO DIMENSIONAL											X	X																						
	33	THREE DIMENSIONAL																													X					
	34	FLOW PATTERN STUDY				X					X		X	X							X					X							X	X		
	35	CAVITATION STUDY																											X	X	X					
PARAMETERS VARIED	36	STREAM VELOCITY				X					X																						X			
	37	ROTATION				X					X																									
	38	POWER																			X										X					
	39	BLADE ANGLE																															X			
	40	ORBIT ANGLE																								X										
	41	ECCENTRICITY																																		
	42	PROFILE SHAPE or THICKNESS																																		
	43	NUMBER of BLADES																																		
	44	ASPECT RATIO																																		
	45	TIP PLATE DIA. or SHAPE				X																														
	46	MOMENT of INERTIA																																		
QUANTITIES MEASURED	47	LIFT				X					X															X			X				X	X		
	48	DRAG				X					X															X			X				X	X		
	49	THRUST																																		
	50	TORQUE																																		
	51	ROTATION																																		
	52	TIP SPEED or ADVANCE RATIO									X																									
	53	POWER				X																														
	54	FORCE DISTRIBUTION																															X			
	55	TORQUE DISTRIBUTION																								X										
	56	FLIGHT PATH PLOTTED																																		
	57	STABILITY DERIVATIVES																																		
	58	PRESENTATION	R	P	S	S	P	P	F	S	S	S	S	S	P	F	K	R	P	F	S	R		S	S	R	F	R	S	S	R	R	R	R	S	R
AVAILABILITY	59	CLASSIFIED																																		
	60	COMPANY PROPRIETARY																																		
	61	NOT GENERALLY AVAILABLE																																		
	62	UNPUBLISHED																																		
	63	ENGLISH TRANSLATION																																		
	64	NOT SEARCHED																																		X

Mc		REFERENCE № ➡
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OTHER THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMENSIONAL
	33	THREE DIMENSIONAL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

M		REFERENCE NO
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OT[illegible]R THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL.
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMEN[illegible]L
	33	THREE DIME[illegible]AL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

M		REFERENCE NO →	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.					X										X			X	X	X	X		X		X		X	X	X	X	X	X	X	X	
	2	WING ROTOR				X		X	X				X	X	X				X					X				X									X
	3	MAGNUS CYLINDER	X		X					X								X																			
	4	CROSS-FLOW FAN																																			
	5	OTHER																																			
GENERAL	6	THEORETICAL EXPOSITION						X																						X				X			
	7	PERFORMANCE			X		X															X						X	X	X	X	X	X	X			
	8	STABILITY											X																								
	9	CONTROL or MANEUVERABILITY																		X			X								X	X					X
	10	LOADS and STRESS ANALYSIS																															X				
	11	PHENOMENON DEMONSTRATION																	X									X									
	12	REVIEW																															X				
	13	COMMENT of INTEREST											X	X																							
APPLICATION	14	AIRCRAFT SUSTENTATION				X	X		X	X			X				X	X	X	X	X	X	X	X	X												
	15	AIRCRAFT PROPULSION															X		X	X	X		X		X												
	16	MARINE PROPULSION																X											X		X	X	X	X		X	
	17	COMPLETE AIRCRAFT											X					X		X			X		X												
	18	COMPLETE SHIP																X													X	X	X				
	19	ROTATING FLAP or SLAT							X	X														X													
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT												W					D																		K
GEOMETRY	23	FEATHERING PITCH SYSTEM					2										1			1	1		1	1	1		1			1	1	1	1	1	1	1'	
	24	ROTOR SYSTEMS per INSTAL.			1		1	1	6	2							1	4	1	1	1		1		1					1							1
	25	NUMBER of BLADES per ROTOR			1	1	3	1	2	1							M	1	1	3	3		3	2	4											8	1
	26	BLADE or ROTOR PROFILE			C	C	F	F	S	C			A				A	C	F	A	A		A	3	F			F		A	A		A			A	R
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING				X				X														X													
TEST	29	WIND TUNNEL			X																	X															
	30	FLIGHT or DROP TEST						X											X			X						X									
	31	TOWING TANK or in WATER																											X	X		X	X				
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL					X																						X	X							
	34	FLOW PATTERN STUDY																											X			X					
	35	CAVITATION STUDY																												X							
PARAMETERS VARIED	36	STREAM VELOCITY			X																	X								X			X				
	37	ROTATION			X		X															X								X							
	38	POWER																																			
	39	BLADE ANGLE			X																	X															
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																				X															
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT			X		X															X															
	48	DRAG			X																	X															
	49	THRUST																															X				
	50	TORQUE																																			
	51	ROTATION																																			
	52	TIP SPEED or ADVANCE RATIO			X																																
	53	POWER					X																										X				
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED						X																				X									
	57	STABILITY DERIVATIVES													X																						
	58	PRESENTATION	P		S	P	S	S	P	P	P	P	S	B	R	P	P	S	B	P	P	S	P	P	P	P	P	B	S	R	S	S	S	S	P	P	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																										X									
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																												X							
	64	NOT SEARCHED	X								X	X			X	X										X	X								X		

M

	No.	REFERENCE Nº ➡	71	72
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.		
	2	WING ROTOR	X	X
	3	MAGNUS CYLINDER		
	4	CROSS-FLOW FAN		
	5	OTHER		
GENERAL	6	THEORETICAL EXPOSITION		
	7	PERFORMANCE		
	8	STABILITY		
	9	CONTROL or MANEUVERABILITY	X	X
	10	LOADS and STRESS ANALYSIS		
	11	PHENOMENON DEMONSTRATION		
	12	REVIEW		
	13	COMMENT of INTEREST		
APPLICATION	14	AIRCRAFT SUSTENTATION		
	15	AIRCRAFT PROPULSION		
	16	MARINE PROPULSION		
	17	COMPLETE AIRCRAFT		
	18	COMPLETE SHIP		
	19	ROTATING FLAP or SLAT		
	20	CONVERTIBLE ROTOR to WING		
	21	ROTOR-ROTOR		
	22	DEVICE OTHER THAN AIRCRAFT	K	K
GEOMETRY	23	FEATHERING PITCH SYSTEM		
	24	ROTOR SYSTEMS per INSTAL.	I	I
	25	NUMBER of BLADES per ROTOR	I	I
	26	BLADE or ROTOR PROFILE	R	R
	27	TIP PATH other than CIRCULAR		
	28	AUXILIARY to FIXED WING		
TEST	29	WIND TUNNEL		
	30	FLIGHT or DROP TEST		
	31	TOWING TANK or in WATER		
	32	TWO DIMENSIONAL		
	33	THREE DIMENSIONAL		
	34	FLOW PATTERN STUDY		
	35	CAVITATION STUDY		
PARAMETERS VARIED	36	STREAM VELOCITY		
	37	ROTATION		
	38	POWER		
	39	BLADE ANGLE		
	40	ORBIT ANGLE		
	41	ECCENTRICITY		
	42	PROFILE SHAPE or THICKNESS		
	43	NUMBER of BLADES		
	44	ASPECT RATIO		
	45	TIP PLATE DIA. or SHAPE		
	46	MOMENT of INERTIA		
QUANTITIES MEASURED	47	LIFT		
	48	DRAG		
	49	THRUST		
	50	TORQUE		
	51	ROTATION		
	52	TIP SPEED or ADVANCE RATIO		
	53	POWER		
	54	FORCE DISTRIBUTION		
	55	TORQUE DISTRIBUTION		
	56	FLIGHT PATH PLOTTED		
	57	STABILITY DERIVATIVES		
	58	PRESENTATION	P	P
AVAILABILITY	59	CLASSIFIED		
	60	COMPANY PROPRIETARY		
	61	NOT GENERALLY AVAILABLE		
	62	UNPUBLISHED		
	63	ENGLISH TRANSLATION		
	64	NOT SEARCHED		

N		REFERENCE No. →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.		X	X				X	X				X	X	X		X	X	X														X	X	
	2	WING ROTOR						X				X	X								X	X	X	X					X				X			
	3	MAGNUS CYLINDER	X			X	X				X		X									X			X	X	X				X	X				X
	4	CROSS-FLOW FAN																																		
	5	OTHER				X																														
GENERAL	6	THEORETICAL EXPOSITION							X												X	X														
	7	PERFORMANCE							X		X										X	X									X					
	8	STABILITY																																		
	9	CONTROL or MANEUVERABILITY				X	X																								X					
	10	LOADS and STRESS ANALYSIS																																		
	11	PHENOMENON DEMONSTRATION																																		
	12	REVIEW																			X	X														
	13	COMMENT of INTEREST								X					X	X								X									X			
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X					X	X	X	X	X		X		X	X	X	X	X		X					X			X			X	
	15	AIRCRAFT PROPULSION		X	X			X			X		X	X		X		X	X	X															X	
	16	MARINE PROPULSION						X	X																						X	X		X		
	17	COMPLETE AIRCRAFT		X						X	X	X	X	X	X	X																				
	18	COMPLETE SHIP							X																						X					
	19	ROTATING FLAP or SLAT	X								X										X	X							X			X				
	20	CONVERTIBLE ROTOR to WING										X																								
	21	ROTOR-ROTOR						X					X			X																				
	22	DEVICE OTHER THAN AIRCRAFT															F						W	K									W			
GEOMETRY	23	FEATHERING PITCH SYSTEM		8	B				1					1		2		7	7	7															4	
	24	ROTOR SYSTEMS per INSTAL.		2	2	1	1	1			2		2	4	2			2	2	2				2							2		1		2	
	25	NUMBER of BLADES per ROTOR		4	4	1	1	1			1		1	2	3			2	2	2				1					1		1		M			
	26	BLADE or ROTOR PROFILE	C	A	A	C	C	N			C			A	A			F	F	F	L	L		F					A		C	C			F	
	27	TIP PATH other than CIRCULAR																																		
	28	AUXILIARY to FIXED WING	X									X	X								X	X							X			X				
TEST	29	WIND TUNNEL																			X	X														
	30	FLIGHT or DROP TEST								X			X																							
	31	TOWING TANK or in WATER							X																											
	32	TWO DIMENSIONAL																				X														
	33	THREE DIMENSIONAL																			X	X														
	34	FLOW PATTERN STUDY																				X														
	35	CAVITATION STUDY																																		
PARAMETERS VARIED	36	STREAM VELOCITY																			X	X														
	37	ROTATION																			X	X														
	38	POWER																			X	X														
	39	BLADE ANGLE																																		
	40	ORBIT ANGLE																																		
	41	ECCENTRICITY																																		
	42	PROFILE SHAPE or THICKNESS																																		
	43	NUMBER of BLADES																																		
	44	ASPECT RATIO																			X	X														
	45	TIP PLATE DIA. or SHAPE																			X	X														
	46	MOMENT of INERTIA																																		
QUANTITIES MEASURED	47	LIFT																			X	X														
	48	DRAG																			X	X														
	49	THRUST																																		
	50	TORQUE																																		
	51	ROTATION																																		
	52	TIP SPEED or ADVANCE RATIO																																		
	53	POWER																																		
	54	FORCE DISTRIBUTION																																		
	55	TORQUE DISTRIBUTION																																		
	56	FLIGHT PATH PLOTTED																																		
	57	STABILITY DERIVATIVES																																		
	58	PRESENTATION	P	P	P	P	P	P	R	S	S	P	S	P	S	P	P	P	P	P	R	S	S	S	R	R	R	P	P	S	S	P	S	K	P	S
AVAILABILITY	59	CLASSIFIED																																		
	60	COMPANY PROPRIETARY																																		
	61	NOT GENERALLY AVAILABLE																																		
	62	UNPUBLISHED																																		
	63	ENGLISH TRANSLATION									X																							X		
	64	NOT SEARCHED															X						X		X	X	X	X		X				X		X

0		REFERENCE Nº ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X		X										X	X	
	2	WING ROTOR		X							X	X	X	X			
	3	MAGNUS CYLINDER															
	4	CROSS-FLOW FAN															
	5	OTHER					X	X	X	X							
GENERAL	6	THEORETICAL EXPOSITION	X														
	7	PERFORMANCE	X				X	X	X	X							
	8	STABILITY															
	9	CONTROL or MANEUVERABILITY									X	X		X			
	10	LOADS and STRESS ANALYSIS															
	11	PHENOMENON DEMONSTRATION															
	12	REVIEW															
	13	COMMENT of INTEREST															
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X					X	X	X	X	X	X	X	X	
	15	AIRCRAFT PROPULSION	X													X	
	16	MARINE PROPULSION															
	17	COMPLETE AIRCRAFT									X	X				X	
	18	COMPLETE SHIP															
	19	ROTATING FLAP or SLAT												X			
	20	CONVERTIBLE ROTOR to WING															
	21	ROTOR-ROTOR									X						
	22	DEVICE OTHER THAN AIRCRAFT		K													
GEOMETRY	23	FEATHERING PITCH SYSTEM	2												1	4	
	24	ROTOR SYSTEMS per INSTAL.		2							2	2		2	10	2	
	25	NUMBER of BLADES per ROTOR	3	1			3	3	3	3	1	1		1	10	M	
	26	BLADE or ROTOR PROFILE	F	~							A	A		A	P	F	
	27	TIP PATH other than CIRCULAR															
	28	AUXILIARY to FIXED WING									X						
TEST	29	WIND TUNNEL					X	X	X	X							
	30	FLIGHT or DROP TEST															
	31	TOWING TANK or in WATER															
	32	TWO DIMENSIONAL															
	33	THREE DIMENSIONAL					X	X									
	34	FLOW PATTERN STUDY															
	35	CAVITATION STUDY															
PARAMETERS VARIED	36	STREAM VELOCITY					X	X	X	X							
	37	ROTATION					X	X	X	X							
	38	POWER															
	39	BLADE ANGLE					X	X									
	40	ORBIT ANGLE															
	41	ECCENTRICITY															
	42	PROFILE SHAPE or THICKNESS															
	43	NUMBER of BLADES															
	44	ASPECT RATIO															
	45	TIP PLATE DIA. or SHAPE															
	46	MOMENT of INERTIA															
QUANTITIES MEASURED	47	LIFT					X	X	X	X							
	48	DRAG					X	X	X	X							
	49	THRUST															
	50	TORQUE															
	51	ROTATION															
	52	TIP SPEED or ADVANCE RATIO					X	X	X	X							
	53	POWER															
	54	FORCE DISTRIBUTION	X														
	55	TORQUE DISTRIBUTION															
	56	FLIGHT PATH PLOTTED															
	57	STABILITY DERIVATIVES															
	58	PRESENTATION	S	P	P	P	R	R	R	R	P	P	P	P	P	P	P
AVAILABILITY	59	CLASSIFIED															
	60	COMPANY PROPRIETARY															
	61	NOT GENERALLY AVAILABLE					X	X	X	X							
	62	UNPUBLISHED															
	63	ENGLISH TRANSLATION															
	64	NOT SEARCHED			X	X							X				X

D		REFERENCE № ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP	X			X		X	X	X		X	X	X	X	X	X	X	X	X	X					X	X	X	X	X	X	X					
	2	WING ROTOR									X											X	X		X								X	X	X	X	X
	3	MAGNUS CYLINDER		X			X																	X	X												
	4	CROSS-FLOW FAN																																			
	5	OTHER								X	X					X																					
GENERAL	6	THEORETICAL EXPOSITION																					X									X		X			
	7	PERFORMANCE	X	X			X				X	X			X														X		X	X					
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY		X																							X			X	X						
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW																																			
	13	COMMENT of INTEREST												X			Y			X		X															
APPLICATION	14	AIRCRAFT SUSTENTATION		X		X		X	X	X	X	X	X	X	X	X										X	X	X	X	X			X	X			
	15	AIRCRAFT PROPULSION		X				X		X			X			X										X	X	X		X							
	16	MARINE PROPULSION	X				X																														
	17	COMPLETE AIRCRAFT		X				X		X			X													X	X	X	X	X			X	X			
	18	COMPLETE SHIP					X																														
	19	ROTATING FLAP or SLAT																																			
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR								X																								X			
	22	DEVICE OTHER THAN AIRCRAFT																						X	X						W	W	K	D	F	F	F
GEOMETRY	23	FEATHERING PITCH SYSTEM	1			4		7	7	1		2	2	2	2	8		5	8	6	6					1	1	1	1	1	1	1					
	24	ROTOR SYSTEMS per INSTAL	1	2		4	2	2	2	2		1	4		1	M	1	2		2	2	1				2	2	2	2	2	1		2			2	1
	25	NUMBER of BLADES per ROTOR	1	1			1	4	2	3		3	2		3	M	3	3	8	3	3	2				A	A	4	4	4	16		1			1	1
	26	BLADE or ROTOR PROFILE	E	C		F	C	F	F	A		F	F		F	F	A	A	A	A	A	S				A	A	A	A	A	A		~		L	L	X
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING																																			
TEST	29	WIND TUNNEL									X													X	X												
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER	X																																		
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL	X								X																										
	34	FLOW PATTERN STUDY																													X						
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY	X																										X								
	37	ROTATION										X			X																						
	38	POWER																																			
	39	BLADE ANGLE	X								X																										
	40	ORBIT ANGLE	X																																		
	41	ECCENTRICITY										X																									
	42	PROFILE SHAPE or THICKNESS																																			X
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			X
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT									X	X			X								X														
	48	DRAG									X												X														
	49	THRUST	X																																		
	50	TORQUE	X																																		
	51	ROTATION													X																						
	52	TIP SPEED or ADVANCE RATIO	X									X			X																						
	53	POWER	X									X																									
	54	FORCE DISTRIBUTION																											X		X						
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	R	S		P	S	P	P	R	S	S	S	S	S	P	P	S	S	S	S	S	S	R	R	P	P	P	S	P	S	S	P	P	P	P	F
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED					X																	X	X												

P		REFERENCE NO ➡	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X		X		X				X			X			X	X	X	X		X		
	2	WING ROTOR		X																	X		X	
	3	MAGNUS CYLINDER						X	X	X		X			X	X					X			
	4	CROSS-FLOW FAN				X																		
	5	OTHER		X		X																		
GENERAL	6	THEORETICAL EXPOSITION								X					X	X								
	7	PERFORMANCE		X					X	X					X	X								
	8	STABILITY																						
	9	CONTROL or MANEUVERABILITY																	X					
	10	LOADS and STRESS ANALYSIS								X														
	11	PHENOMENON DEMONSTRATION							X															
	12	REVIEW							X					X							X			
	13	COMMENT of INTEREST									X	X												
APPLICATION	14	AIRCRAFT SUSTENTATION	X				X	X	X						X		X			X		X		
	15	AIRCRAFT PROPULSION	X		X	X	X										X			X		X		
	16	MARINE PROPULSION							X	X						X								
	17	COMPLETE AIRCRAFT					X	X									X		X	X				
	18	COMPLETE SHIP								X														
	19	ROTATING FLAP or SLAT																						
	20	CONVERTIBLE ROTOR to WING																						
	21	ROTOR-ROTOR																						
	22	DEVICE OTHER THAN AIRCRAFT																			W		W	
GEOMETRY	23	FEATHERING PITCH SYSTEM	9		8		3				1						1		1	1				
	24	ROTOR SYSTEMS per INSTAL.	2		4		1	M									4		1	2			1	
	25	NUMBER of BLADES per ROTOR	4		2	M	6	1		1					1		3		8	4		6	1	
	26	BLADE or ROTOR PROFILE	F	A		A	A	C		C					C		F		A			A		
	27	TIP PATH other than CIRCULAR																						
	28	AUXILIARY to FIXED WING						X																
TEST	29	WIND TUNNEL		X						X														
	30	FLIGHT or DROP TEST																						
	31	TOWING TANK or in WATER																						
	32	TWO DIMENSIONAL																						
	33	THREE DIMENSIONAL		X						X														
	34	FLOW PATTERN STUDY								X														
	35	CAVITATION STUDY																						
PARAMETERS VARIED	36	STREAM VELOCITY								X					X	X								
	37	ROTATION								X					X	X								
	38	POWER																						
	39	BLADE ANGLE		X																				
	40	ORBIT ANGLE																						
	41	ECCENTRICITY																						
	42	PROFILE SHAPE or THICKNESS																						
	43	NUMBER of BLADES																						
	44	ASPECT RATIO																						
	45	TIP PLATE DIA. or SHAPE								X						X								
	46	MOMENT of INERTIA																						
QUANTITIES MEASURED	47	LIFT		X						X					X	X								
	48	DRAG		X						X					X	X								
	49	THRUST																						
	50	TORQUE																						
	51	ROTATION								X					X									
	52	TIP SPEED or ADVANCE RATIO													X	X								
	53	POWER													X									
	54	FORCE DISTRIBUTION								X														
	55	TORQUE DISTRIBUTION																						
	56	FLIGHT PATH PLOTTED																						
	57	STABILITY DERIVATIVES																						
	58	PRESENTATION	P	R	P	P	P	P	R	B	B	S	P	R	S	S	P	P	P	P	B	P	S	
AVAILABILITY	59	CLASSIFIED																						
	60	COMPANY PROPRIETARY																						
	61	NOT GENERALLY AVAILABLE																						
	62	UNPUBLISHED																						
	63	ENGLISH TRANSLATION																						
	64	NOT SEARCHED		X									X					X						

		R REFERENCE Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP	X	X	X	X							X					X														X		X	X		
	2	WING ROTOR			X	X	X			X				X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X						
	3	MAGNUS CYLINDER							X		X	X		X	X	X			X									X	X								
	4	CROSS-FLOW FAN																																			
	5	OTHER					X	X	X								X																X			X	
GENERAL	6	THEORETICAL EXPOSITION						X	X	X								X																X	X		
	7	PERFORMANCE						X	X	X		X		X	X	X		X	X		X				X			X	X	X			X			X	X
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY		X																																	
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																				X	X	X		X		X									
	12	REVIEW																										X									
	13	COMMENT of INTEREST					X			X	X									X			X	X													
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X	X	X					X	X															X	X	X	X	X	X	X		X	X
	15	AIRCRAFT PROPULSION	X	X	X	X							X																			X	X	X		X	X
	16	MARINE PROPULSION																	X										X		X						
	17	COMPLETE AIRCRAFT	X		X	X																												X		X	
	18	COMPLETE SHIP																	X										X								
	19	ROTATING FLAP or SLAT										X																X	X	X							
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																													X						
	22	DEVICE OTHER THAN AIRCRAFT																W					X			X											
GEOMETRY	23	FEATHERING PITCH SYSTEM	7	7	4	4	2						2																			3		3	3		
	24	ROTOR SYSTEMS per INSTAL	8	2	2	2	2					1		1	1	1			2		1	1			1	1				2			2	2	2	2	1
	25	NUMBER of BLADES per ROTOR	2	M	2	2	1					1		1	1	1			1		X	1			X	1				1	3		3			4	3
	26	BLADE or ROTOR PROFILE	F		~	~	A					C		ξ	ξ	ξ	A		C		F	F			F	M		F	X	A	S		A	A	A	A	A
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING										X	X	X	X	X													X								
TEST	29	WIND TUNNEL									X	X		X	X	X	X				X		X		X		X	X	X	X							X
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER																				X						X		X							
	32	TWO DIMENSIONAL												X	X	X																					
	33	THREE DIMENSIONAL										X									X	X			X			X	X	X							X
	34	FLOW PATTERN STUDY												X	X	X												X	X	X							
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY										X		X	X	X					X				X			X	X				X			X	X
	37	ROTATION										X		X	X	X					X				X		X	X								X	X
	38	POWER																																		X	X
	39	BLADE ANGLE						X				X					X												X	X			X				X
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS										X		X	X	X					X				X	X			X								
	43	NUMBER of BLADES																			X				X			X									
	44	ASPECT RATIO						X																				X	X	X							
	45	TIP PLATE DIA or SHAPE																										X									
	46	MOMENT of INERTIA																				X						X									
QUANTITIES MEASURED	47	LIFT						X				X		X	X	X	X				X				X			X	X	X			X				X
	48	DRAG						X				X		X	X	X	X				X				X				X								X
	49	THRUST																																			X
	50	TORQUE																																			X
	51	ROTATION																			X	X			X			X	X								X
	52	TIP SPEED or ADVANCE RATIO										X		X	X	X											X		X								X
	53	POWER												X	X	X																					X
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	F	P	P	S	P	S	S	B	S	R	P	R	S	S	R	B	S	P	R	R	R	R	R	P	S	S	R	S	P	S	S	R	R	R	R
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																X			X
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																																			

Q		REFERENCE NO ⇨	1	2
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	
	2	WING ROTOR		X
	3	MAGNUS CYLINDER		
	4	CROSS-FLOW FAN		
	5	OTHER		
GENERAL	6	THEORETICAL EXPOSITION		
	7	PERFORMANCE	X	
	8	STABILITY		
	9	CONTROL or MANEUVERABILITY		
	10	LOADS and STRESS ANALYSIS		
	11	PHENOMENON DEMONSTRATION		
	12	REVIEW	X	
	13	COMMENT of INTEREST		X
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X
	15	AIRCRAFT PROPULSION	X	
	16	MARINE PROPULSION		
	17	COMPLETE AIRCRAFT	X	X
	18	COMPLETE SHIP		
	19	ROTATING FLAP or SLAT		
	20	CONVERTIBLE ROTOR to WING		
	21	ROTOR-ROTOR		
	22	DEVICE OTHER THAN AIRCRAFT		
GEOMETRY	23	FEATHERING PITCH SYSTEM	1	
	24	ROTOR SYSTEMS per INSTAL		2
	25	NUMBER of BLADES per ROTOR		1
	26	BLADE or ROTOR PROFILE		~
	27	TIP PATH other than CIRCULAR		
	28	AUXILIARY to FIXED WING		
TEST	29	WIND TUNNEL		
	30	FLIGHT or DROP TEST	X	
	31	TOWING TANK or in WATER		
	32	TWO DIMENSIONAL		
	33	THREE DIMENSIONAL		
	34	FLOW PATTERN STUDY		
	35	CAVITATION STUDY		
PARAMETERS VARIED	36	STREAM VELOCITY		
	37	ROTATION	X	
	38	POWER		
	39	BLADE ANGLE		
	40	ORBIT ANGLE		
	41	ECCENTRICITY		
	42	PROFILE SHAPE or THICKNESS		
	43	NUMBER of BLADES		
	44	ASPECT RATIO		
	45	TIP PLATE DIA. or SHAPE		
	46	MOMENT of INERTIA		
QUANTITIES MEASURED	47	LIFT	X	
	48	DRAG		
	49	THRUST		
	50	TORQUE		
	51	ROTATION		
	52	TIP SPEED or ADVANCE RATIO		
	53	POWER	X	
	54	FORCE DISTRIBUTION		
	55	TORQUE DISTRIBUTION		
	56	FLIGHT PATH PLOTTED		
	57	STABILITY DERIVATIVES		
	58	PRESENTATION	S	S
AVAILABILITY	59	CLASSIFIED		
	60	COMPANY PROPRIETARY		
	61	NOT GENERALLY AVAILABLE		
	62	UNPUBLISHED		
	63	ENGLISH TRANSLATION		
	64	NOT SEARCHED		

R		REFERENCE Nº	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.													X	X	X	X	X	X	X	X	X	X	X	X		X			X				X		X
	2	WING ROTOR				X		X																					X							X	
	3	MAGNUS CYLINDER					X	X		X		X		X													X			X	X		X	X			
	4	CROSS-FLOW FAN																																			
	5	OTHER	X	X	X																																
GENERAL	6	THEORETICAL EXPOSITION		X	X		X					X													X												
	7	PERFORMANCE		X	X	X		X				X					X				X	X	X														
	8	STABILITY																											X								
	9	CONTROL or MANEUVERABILITY								X												X	X		X	X											
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW						X																	X												
	13	COMMENT of INTEREST												X	X	X	X	X	X	X				X			X	X	X		X				X	X	
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X					X		X									X	X	X		X	X	X	X	X	X	X		X				X
	15	AIRCRAFT PROPULSION	X	X	X																X	X	X		X	X		X			X						
	16	MARINE PROPULSION										X		X																X				X	X		
	17	COMPLETE AIRCRAFT																			X	X	X		X	X	X	X	X		X						
	18	COMPLETE SHIP										X		X																							
	19	ROTATING FLAP or SLAT								X																							X				
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																X			
	22	DEVICE OTHER THAN AIRCRAFT				F																												W		K	
GEOMETRY	23	FEATHERING PITCH SYSTEM													1	1	1	1	1	1	1	1	1	1	3			1			1				1		2
	24	ROTOR SYSTEMS per INSTAL				2				2				2					2			2	2	2	2	2							2	4		1	
	25	NUMBER of BLADES per ROTOR				3				1				1					3			3	3	3		1			1				1	1		2	4
	26	BLADE or ROTOR PROFILE								C		C		C					A			A	A	A	A	C			A				C	C		S	F
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING										X																					X				
TEST	29	WIND TUNNEL						X				X																									
	30	FLIGHT or DROP TEST																				X	X						X							X	
	31	TOWING TANK or in WATER				X																															
	32	TWO DIMENSIONAL						X																													
	33	THREE DIMENSIONAL						X				X																									
	34	FLOW PATTERN STUDY					X					X																									
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY				X						X									X				X												
	37	ROTATION										X													X												
	38	POWER																			X																
	39	BLADE ANGLE																							X												
	40	ORBIT ANGLE																							X												
	41	ECCENTRICITY																							X												
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT						X				X																									
	48	DRAG						X				X																									
	49	THRUST																																			
	50	TORQUE																																			
	51	ROTATION																																			
	52	TIP SPEED or ADVANCE RATIO										X																									
	53	POWER				X																															
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																					X	X													
	58	PRESENTATION	S	R	R	S	R	B	P	P	P	R	P	B	B	S	B	S	S	S	S	S	S	S	P	P	S	S	B	S	B	P	P	P	S	S	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED	X	X																																	
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED							X		X		X																			X					

R		REFERENCE Nº	71	72	73
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X		
	2	WING ROTOR			
	3	MAGNUS CYLINDER		X	X
	4	CROSS-FLOW FAN			
	5	OTHER			
GENERAL	6	THEORETICAL EXPOSITION			
	7	PERFORMANCE		X	
	8	STABILITY			
	9	CONTROL or MANEUVERABILITY			
	10	LOADS and STRESS ANALYSIS			
	11	PHENOMENON DEMONSTRATION		X	
	12	REVIEW			
	13	COMMENT of INTEREST			
APPLICATION	14	AIRCRAFT SUSTENTATION	X		
	15	AIRCRAFT PROPULSION	X		
	16	MARINE PROPULSION			
	17	COMPLETE AIRCRAFT	X		
	18	COMPLETE SHIP			
	19	ROTATING FLAP or SLAT			
	20	CONVERTIBLE ROTOR to WING			
	21	ROTOR-ROTOR			
	22	DEVICE OTHER THAN AIRCRAFT		X	
GEOMETRY	23	FEATHERING PITCH SYSTEM	A		
	24	ROTOR SYSTEMS per INSTAL.	2		
	25	NUMBER of BLADES per ROTOR	6		
	26	BLADE or ROTOR PROFILE	F	C	
	27	TIP PATH other than CIRCULAR			
	28	AUXILIARY to FIXED WING			
TEST	29	WIND TUNNEL			
	30	FLIGHT or DROP TEST			
	31	TOWING TANK or in WATER			
	32	TWO DIMENSIONAL			
	33	THREE DIMENSIONAL		X	
	34	FLOW PATTERN STUDY			
	35	CAVITATION STUDY			
PARAMETERS VARIED	36	STREAM VELOCITY			
	37	ROTATION		X	
	38	POWER			
	39	BLADE ANGLE			
	40	ORBIT ANGLE			
	41	ECCENTRICITY			
	42	PROFILE SHAPE or THICKNESS		X	
	43	NUMBER of BLADES			
	44	ASPECT RATIO			
	45	TIP PLATE DIA. or SHAPE			
	46	MOMENT of INERTIA			
QUANTITIES MEASURED	47	LIFT		X	
	48	DRAG			
	49	THRUST			
	50	TORQUE			
	51	ROTATION		X	
	52	TIP SPEED or ADVANCE RATIO			
	53	POWER			
	54	FORCE DISTRIBUTION			
	55	TORQUE DISTRIBUTION			
	56	FLIGHT PATH PLOTTED			
	57	STABILITY DERIVATIVES			
	58	PRESENTATION	P	S	R
AVAILABILITY	59	CLASSIFIED			
	60	COMPANY PROPRIETARY			
	61	NOT GENERALLY AVAILABLE			
	62	UNPUBLISHED			
	63	ENGLISH TRANSLATION			
	64	NOT SEARCHED			X

S		REFERENCE Nº ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.					X	X																													
	2	WING ROTOR	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	3	MAGNUS CYLINDER	X		X	X			X																												
	4	CROSS-FLOW FAN																																			
	5	OTHER	X																																		
GENERAL	6	THEORETICAL EXPOSITION				X																															
	7	PERFORMANCE	X		X							X								X		X											X				
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																																			
	10	LOADS and STRESS ANALYSIS																									X										
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW	X		X		X	X				X																					X				
	13	COMMENT of INTEREST												X	X	X	X	X		X			X	X				X			X			X	X	X	X
APPLICATION	14	AIRCRAFT SUSTENTATION							X			X									X																X
	15	AIRCRAFT PROPULSION																																			
	16	MARINE PROPULSION			X		X	X								X	X		X		X			X			X						X				
	17	COMPLETE AIRCRAFT																																			X
	18	COMPLETE SHIP			X		X	X				X				X	X							X			X										
	19	ROTATING FLAP or SLAT							X																												
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR										X							X							X											
	22	DEVICE OTHER THAN AIRCRAFT	W	K	W					K	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	E	W	K	K	W	W	W	W	W
GEOMETRY	23	FEATHERING PITCH SYSTEM					1'	1'																													
	24	ROTOR SYSTEMS per INSTAL.		1					2													1	1								1	1					1
	25	NUMBER of BLADES per ROTOR		1	2				1	2	2	2	2					2	2		1-3	2	2		2	2	2		2	2	2	2		2			2
	26	BLADE or ROTOR PROFILE		F	S				C	S	S	S	S					S	S		S	S	S		S	S	S		S	S	S	S		S			S
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING							X																												
TEST	29	WIND TUNNEL			X							X										X															
	30	FLIGHT or DROP TEST			X																											X					
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL			X							X										X															
	34	FLOW PATTERN STUDY			X	X																															
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY			X							X										X											X				
	37	ROTATION			X							X										X											X				
	38	POWER																																			
	39	BLADE ANGLE										X																									
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS										X										X															
	43	NUMBER of BLADES										X										X															
	44	ASPECT RATIO										X																									
	45	TIP PLATE DIA. or SHAPE										X																									
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT										X																									
	48	DRAG										X																									
	49	THRUST										X																									
	50	TORQUE										X										X															
	51	ROTATION										X										X															
	52	TIP SPEED or ADVANCE RATIO			X							X										X											X				
	53	POWER			X							X										X											X				
	54	FORCE DISTRIBUTION																															X				
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																																			
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	[illegible]	P	S	S	B	B	P	P	P	B	P	S	S	S	S	S	P	S	P	S	S	S	P	P	P	S	S	P	S	S	S	S	S	S	S
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																											X								

S		REFERENCE Nº ➡	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP			X																			X	X	X		X		X			X		X				
	2	WING ROTOR	X	X		X																							X							X	X
	3	MAGNUS CYLINDER					X		X																		X			X				X			
	4	CROSS-FLOW FAN																																			
	5	OTHER						X		X	X	X	X	X	X	X	X	X	X	X	X					X						X			X		
GENERAL	6	THEORETICAL EXPOSITION					X		X		X		X											X		X											
	7	PERFORMANCE		X	X		X		X		X		X													X	X										
	8	STABILITY			X																																
	9	CONTROL or MANEUVERABILITY			X																																
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW			X																			X													
	13	COMMENT of INTEREST				X																								X							
APPLICATION	14	AIRCRAFT SUSTENTATION	X		X				X																	X						X	X	X	X	X	X
	15	AIRCRAFT PROPULSION			X			X		X	X	X	X	X	X	X	X	X	X	X	X										X	X	X		X		
	16	MARINE PROPULSION																		X		X	X	X						X							
	17	COMPLETE AIRCRAFT	X		X																										X				X	X	
	18	COMPLETE SHIP																												X							
	19	ROTATING FLAP or SLAT										X	X	X	X	X	X	X	X	X	X													X			
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR																																		X	X
	22	DEVICE OTHER THAN AIRCRAFT	W	W		W																				X			W								
GEOMETRY	23	FEATHERING PITCH SYSTEM			1																	1	13	1		5		2									
	24	ROTOR SYSTEMS per INSTAL	1	1	2																							2	1		2		2		2		
	25	NUMBER of BLADES per ROTOR	2	2	3				1																		1	4	M	1	2		1	1	2	1	1
	26	BLADE or ROTOR PROFILE	S	S	A		C		C																	A	C	F	~	C	A			C	A	~	W
	27	TIP PATH other than CIRCULAR																								X											
	28	AUXILIARY to FIXED WING										X	X	X	X	X	X	X	X	X	X										X			X			
TEST	29	WIND TUNNEL		X	X																						X										
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL							X																												
	33	THREE DIMENSIONAL		X																							X										
	34	FLOW PATTERN STUDY																																			
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY		X					X				X											X			X										
	37	ROTATION							X															X			X										
	38	POWER																																			
		BLADE ANGLE											X											X													
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																						X													
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																									X										
	45	TIP PLATE DIA or SHAPE																									X										
	16	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT			X				X																		X										
	48	DRAG																									X										
	49	THRUST		X									X																								
	50	TORQUE		X																																	
	51	ROTATION		X																																	
	52	TIP SPEED or ADVANCE RATIO		X					X																		X										
	53	POWER		X	X																						X										
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																						X													
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	S	R	S	B	R	P	R	S	S	S	R	P	P	P	P	S	P	P	S	P	P	R	P	S	R	P	P	S	B	P	P	P	S	P	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																						X													
	64	NOT SEARCHED				X	X																X		X												

	S	REFERENCE Nº ➡	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP				X	X	X	X		X	X						X			X		X					X		X			X	X	X	X	
	2	WING ROTOR	X	X	X										X	X				X		X		X	X		X		X			X					
	3	MAGNUS CYLINDER		X										X			X		X							X											
	4	CROSS-FLOW FAN																																			
	5	OTHER											X			X												X									
GENERAL	6	THEORETICAL EXPOSITION				X									X										X												
	7	PERFORMANCE				X					X				X	X				X		X			X				X				X				
	8	STABILITY									X														X												
	9	CONTROL or MANEUVERABILITY									X														X			X									
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION			X																																
	12	REVIEW									X		X												X											X	
	13	COMMENT of INTEREST	X		X							X		X							X								X								
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X				X	X		X	X					X			X	X		X	X					X			X	X	X			
	15	AIRCRAFT PROPULSION					X	X	X		X	X																					X	X			
	16	MARINE PROPULSION									X																			X						X	
	17	COMPLETE AIRCRAFT	X	X				X			X	X								X					X								X	X			
	18	COMPLETE SHIP							X		X																									X	
	19	ROTATING FLAP or SLAT															X															X					
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR					X																														
	22	DEVICE OTHER THAN AIRCRAFT																				W		W			K										
GEOMETRY	23	FEATHERING PITCH SYSTEM					1	1	6		1	1											2					1		2			1	6		1	
	24	ROTOR SYSTEMS per INSTAL	2				3	4	2			2								2		1	4	1	1		1	1	2	1/2			6	2			
	25	NUMBER of BLADES per ROTOR	1	1	1		P		2			2		1						1		2	1	2	1		1	3	1	4		1	X	4			
	26	BLADE or ROTOR PROFILE	~	E	F		A	A	~		A	A		C			c			R		S	F	A	A		~	A	^	F		L	A	A			
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING															X															X					
TEST	29	WIND TUNNEL									X				X	X				X					X												
	30	FLIGHT or DROP TEST			X															X					X												
	31	TOWING TANK or in WATER												X															X								
	32	TWO DIMENSIONAL													X																						
	33	THREE DIMENSIONAL													X	X						X			X				X								
	34	FLOW PATTERN STUDY												X																							
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY													X							X			X				X								
	37	ROTATION																				X			X												
	38	POWER																																			
	39	BLADE ANGLE														X									X												
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE													X																						
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT														X									X				X								
	48	DRAG														X																					
	49	THRUST																																			
	50	TORQUE																				X															
	51	ROTATION													X							X			X												
	52	TIP SPEED or ADVANCE RATIO																				X															
	53	POWER																				X															
	54	FORCE DISTRIBUTION													X																						
	55	TORQUE DISTRIBUTION													X																						
	56	FLIGHT PATH PLOTTED																							X												
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	S	P	B	S	P	P	S		S	S	R	N	R	R	P	S	R	S	S	R	P	P	S	P	P	P	S	P	P	F	S	P	R	S	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED																X	X							X					X				X		X

S		REFERENCE Nº	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	142
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP	X		X	X	X									X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	
SYSTEM	2	WING ROTOR		X					X		X	X	X	X	X																						X
SYSTEM	3	MAGNUS CYLINDER					X	X																										X			
SYSTEM	4	CROSS-FLOW FAN																																			
SYSTEM	5	OTHER																														X					
GENERAL	6	THEORETICAL EXPOSITION	X				X																				X		X								
GENERAL	7	PERFORMANCE	X				X							X	X												X		X								
GENERAL	8	STABILITY												X	X														X								
GENERAL	9	CONTROL or MANEUVERABILITY												X	X	X	X				X	X							X								
GENERAL	10	LOADS and STRESS ANALYSIS																																			
GENERAL	11	PHENOMENON DEMONSTRATION		X								X																									
GENERAL	12	REVIEW	X																					X			X										
GENERAL	13	COMMENT of INTEREST		X																						X		X			X					X	
APPLICATION	14	AIRCRAFT SUSTENTATION			X	X					X					X	X	X	X	X	X		X	X	X	X	X		X		X	X	X	X			
APPLICATION	15	AIRCRAFT PROPULSION			X	X										X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X				
APPLICATION	16	MARINE PROPULSION	X																			X								X							
APPLICATION	17	COMPLETE AIRCRAFT												X	X			X						X	X	X	X				X	X					
APPLICATION	18	COMPLETE SHIP			X	X																								X							
APPLICATION	19	ROTATING FLAP or SLAT																																X			
APPLICATION	20	CONVERTIBLE ROTOR to WING																																			
APPLICATION	21	ROTOR-ROTOR																																			
APPLICATION	22	DEVICE OTHER THAN AIRCRAFT					W		F		K	P																						X	W		
GEOMETRY	23	FEATHERING PITCH SYSTEM			8	8		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
GEOMETRY	24	ROTOR SYSTEMS per INSTAL			2	2			1		2	1		1	1			2			2	1	2		2	2				2	2	2			1		1
GEOMETRY	25	NUMBER of BLADES per ROTOR			6	6			2		1	1		1	1	5		3	3	5	5	5	M		10	10				10	10		5		3		2
GEOMETRY	26	BLADE or ROTOR PROFILE			⌢	^			S		~			A	A	A	A	A	A	A	A	A	A		A	A	A		A	A	A		A		⌢		S
GEOMETRY	27	TIP PATH other than CIRCULAR																																			
GEOMETRY	28	AUXILIARY to FIXED WING																																X	X		X
TEST	29	WIND TUNNEL												X	X												X		X								
TEST	30	FLIGHT or DROP TEST												X	X																						
TEST	31	TOWING TANK or in WATER																																			
TEST	32	TWO DIMENSIONAL																																			
TEST	33	THREE DIMENSIONAL												X	X												X		X								
TEST	34	FLOW PATTERN STUDY																																			
TEST	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY												X	X												X										
PARAMETERS VARIED	37	ROTATION												X	X																						
PARAMETERS VARIED	38	POWER																											X								
PARAMETERS VARIED	39	BLADE ANGLE												X	X																						
PARAMETERS VARIED	40	ORBIT ANGLE																																			
PARAMETERS VARIED	41	ECCENTRICITY																																			
PARAMETERS VARIED	42	PROFILE SHAPE or THICKNESS																																			
PARAMETERS VARIED	43	NUMBER of BLADES																																			
PARAMETERS VARIED	44	ASPECT RATIO																																			
PARAMETERS VARIED	45	TIP PLATE DIA or SHAPE																																			
PARAMETERS VARIED	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT																									X		X								
QUANTITIES MEASURED	48	DRAG																																			
QUANTITIES MEASURED	49	THRUST																																			
QUANTITIES MEASURED	50	TORQUE																																			
QUANTITIES MEASURED	51	ROTATION																																			
QUANTITIES MEASURED	52	TIP SPEED or ADVANCE RATIO																																			
QUANTITIES MEASURED	53	POWER																									X										
QUANTITIES MEASURED	54	FORCE DISTRIBUTION																																			
QUANTITIES MEASURED	55	TORQUE DISTRIBUTION																																			
QUANTITIES MEASURED	56	FLIGHT PATH PLOTTED												X	X												X		X								
QUANTITIES MEASURED	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	S	S	P	P	S	R	S	P	P	R	R	R	R	P	P	P	P	P	P	P	P	S	S	S	R	S	S	P	S	P	P	P	P	S	P
AVAILABILITY	59	CLASSIFIED																																			
AVAILABILITY	60	COMPANY PROPRIETARY																																			
AVAILABILITY	61	NOT GENERALLY AVAILABLE																																			
AVAILABILITY	62	UNPUBLISHED											X																								
AVAILABILITY	63	ENGLISH TRANSLATION																																			
AVAILABILITY	64	NOT SEARCHED							X		X			X																							

S		REFERENCE Nº ➡	141	142	143	144
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X			X
	2	WING ROTOR				
	3	MAGNUS CYLINDER		X	X	
	4	CROSS-FLOW FAN				
	5	OTHER				
GENERAL	6	THEORETICAL EXPOSITION			X	
	7	PERFORMANCE			X	
	8	STABILITY				
	9	CONTROL or MANEUVERABILITY				
	10	LOADS and STRESS ANALYSIS				
	11	PHENOMENON DEMONSTRATION				
	12	REVIEW			X	
	13	COMMENT of INTEREST				
APPLICATION	14	AIRCRAFT SUSTENTATION				X
	15	AIRCRAFT PROPULSION	X			X
	16	MARINE PROPULSION				
	17	COMPLETE AIRCRAFT	X			
	18	COMPLETE SHIP				
	19	ROTATING FLAP or SLAT				
	20	CONVERTIBLE ROTOR to WING				
	21	ROTOR-ROTOR				
	22	DEVICE OTHER THAN AIRCRAFT				
GEOMETRY	23	FEATHERING PITCH SYSTEM	8			
	24	ROTOR SYSTEMS per INSTAL.	2			
	25	NUMBER of BLADES per ROTOR	4		1	
	26	BLADE or ROTOR PROFILE	F		C	
	27	TIP PATH other than CIRCULAR				
	28	AUXILIARY to FIXED WING				
TEST	29	WIND TUNNEL		X	X	
	30	FLIGHT or DROP TEST				
	31	TOWING TANK or in WATER				
	32	TWO DIMENSIONAL			X	
	33	THREE DIMENSIONAL			X	
	34	FLOW PATTERN STUDY			X	
	35	CAVITATION STUDY				
PARAMETERS VARIED	36	STREAM VELOCITY			X	
	37	ROTATION			X	
	38	POWER				
	39	BLADE ANGLE				
	40	ORBIT ANGLE				
	41	ECCENTRICITY				
	42	PROFILE SHAPE or THICKNESS				
	43	NUMBER of BLADES				
	44	ASPECT RATIO			X	
	45	TIP PLATE DIA. or SHAPE			X	
	46	MOMENT of INERTIA				
QUANTITIES MEASURED	47	LIFT			X	
	48	DRAG			X	
	49	THRUST				
	50	TORQUE				
	51	ROTATION				
	52	TIP SPEED or ADVANCE RATIO			X	
	53	POWER				
	54	FORCE DISTRIBUTION				
	55	TORQUE DISTRIBUTION				
	56	FLIGHT PATH PLOTTED				
	57	STABILITY DERIVATIVES				
	58	PRESENTATION	P	R	S	P
AVAILABILITY	59	CLASSIFIED				
	60	COMPANY PROPRIETARY				
	61	NOT GENERALLY AVAILABLE				
	62	UNPUBLISHED				
	63	ENGLISH TRANSLATION				
	64	NOT SEARCHED	X			

T		REFERENCE Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.		X		X	X	X	X	X					X	X												X					X				
	2	WING ROTOR	X								X		X	X					X	X														X			
	3	MAGNUS CYLINDER			X												X	X			X	X	X	X	X	X			X		X	X			X		
	4	CROSS-FLOW FAN																																			
	5	OTHER									X																X					X					
GENERAL	6	THEORETICAL EXPOSITION					X	X	X																												
	7	PERFORMANCE			X		X	X	X	X					X			X			X	X		X	X	X											
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																		X																	
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW		X	X								X		X		X																				
	13	COMMENT of INTEREST	X								X					X												X	X		X	X		X			
APPLICATION	14	AIRCRAFT SUSTENTATION									X			X			X		X	X							X		X		X			X	X		
	15	AIRCRAFT PROPULSION									X																X						X				
	16	MARINE PROPULSION		X	X	X				X																											
	17	COMPLETE AIRCRAFT																	X										X						X		
	18	COMPLETE SHIP			X					X																											
	19	ROTATING FLAP or SLAT												X						X														X	X		
	20	CONVERTIBLE ROTOR to WING																	X	X																	
	21	ROTOR-ROTOR			X						X																										
	22	DEVICE OTHER THAN AIRCRAFT	W										W															W								W	
GEOMETRY	23	FEATHERING PITCH SYSTEM		1		1	1	1	1	1					1	1												1					8				
	24	ROTOR SYSTEMS per INSTAL.				1					2		1	4	1				2					1	1	1		M							2		
	25	NUMBER of BLADES per ROTOR	2			6					2		2	1	M		1		1	1	1			1	1	1		4					4		1		
	26	BLADE or ROTOR PROFILE	3			F					S		S	F	A		C		A	A	C			C	C	C		F					F		C		
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING												X						X											X				X		
TEST	29	WIND TUNNEL			X																X	X	X	X	X	X											
	30	FLIGHT or DROP TEST															X																				
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL																			X		X														
	34	FLOW PATTERN STUDY																						X	X	X											
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY			X																X	X		X		X											
	37	ROTATION			X																X	X		X		X											
	38	POWER																																			
	39	BLADE ANGLE			X																																
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																			X					X											
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																			X					X											
	45	TIP PLATE DIA. or SHAPE																			X					X											
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT			X																X	X				X											
	48	DRAG			X																X	X				X											
	49	THRUST																																			
	50	TORQUE																						X		X											
	51	ROTATION																																			
	52	TIP SPEED or ADVANCE RATIO			X																X																
	53	POWER																					X														
	54	FORCE DISTRIBUTION																					X	X													
	55	TORQUE DISTRIBUTION																							X												
	56	FLIGHT PATH PLOTTED																														X					
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	S	R	R	P	R	R	R	R	S	P	S	P	R	B	S	R	P	P	R	R	R	R	R	R	P	S	S	P	S	S	P	S	P	P	P
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED					X	X	X	X		X						X				X								X						X	X

T		REFERENCE NO ➡	36	37	38	39	40	41	42	43	44	45	46	47
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.										X		
	2	WING ROTOR				X							X	X
	3	MAGNUS CYLINDER	X	X	X		X							
	4	CROSS-FLOW FAN												
	5	OTHER						X						
GENERAL	6	THEORETICAL EXPOSITION												
	7	PERFORMANCE		X	X									X
	8	STABILITY												
	9	CONTROL or MANEUVERABILITY					X							
	10	LOADS and STRESS ANALYSIS												
	11	PHENOMENON DEMONSTRATION												
	12	REVIEW												
	13	COMMENT of INTEREST				X						X	X	
APPLICATION	14	AIRCRAFT SUSTENTATION	X			X		X	X	X				X
	15	AIRCRAFT PROPULSION												
	16	MARINE PROPULSION			X		X							
	17	COMPLETE AIRCRAFT												X
	18	COMPLETE SHIP			X									
	19	ROTATING FLAP or SLAT												
	20	CONVERTIBLE ROTOR to WING												X
	21	ROTOR-ROTOR												
	22	DEVICE OTHER THAN AIRCRAFT				D					W		K	
GEOMETRY	23	FEATHERING PITCH SYSTEM												
	24	ROTOR SYSTEMS per INSTAL.				1							1	2
	25	NUMBER of BLADES per ROTOR		1		1		4					2	1
	26	BLADE or ROTOR PROFILE		C		F		~					S	R
	27	TIP PATH other than CIRCULAR												
	28	AUXILIARY to FIXED WING												
TEST	29	WIND TUNNEL		X										X
	30	FLIGHT or DROP TEST				X							X	
	31	TOWING TANK or in WATER												
	32	TWO DIMENSIONAL												
	33	THREE DIMENSIONAL		X										X
	34	FLOW PATTERN STUDY												
	35	CAVITATION STUDY												
PARAMETERS VARIED	36	STREAM VELOCITY												X
	37	ROTATION												
	38	POWER												X
	39	BLADE ANGLE												
	40	ORBIT ANGLE												
	41	ECCENTRICITY												
	42	PROFILE SHAPE or THICKNESS												X
	43	NUMBER of BLADES												
	44	ASPECT RATIO		X										
	45	TIP PLATE DIA. or SHAPE		X										
	46	MOMENT of INERTIA												
QUANTITIES MEASURED	47	LIFT		X										X
	48	DRAG		X										X
	49	THRUST												
	50	TORQUE												
	51	ROTATION												
	52	TIP SPEED or ADVANCE RATIO												
	53	POWER												
	54	FORCE DISTRIBUTION												
	55	TORQUE DISTRIBUTION												
	56	FLIGHT PATH PLOTTED				X								
	57	STABILITY DERIVATIVES												
	58	PRESENTATION	P	B	S	S	S	P	P	P	F	R	S	S
AVAILABILITY	59	CLASSIFIED												
	60	COMPANY PROPRIETARY												
	61	NOT GENERALLY AVAILABLE												
	62	UNPUBLISHED												
	63	ENGLISH TRANSLATION												
	64	NOT SEARCHED	X						X	X	X			

U		REFERENCE NO ➡
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OTHER THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL.
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMENSIONAL
	33	THREE DIMENSIONAL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

V		REFERENCE Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	2	WING ROTOR						X																													
	3	MAGNUS CYLINDER																																			
	4	CROSS-FLOW FAN																																			
	5	OTHER								X																											
GENERAL	6	THEORETICAL EXPOSITION																																			
	7	PERFORMANCE															X							X			X	X				X	X				
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY															X								X						X						
	10	LOADS and STRESS ANALYSIS																																			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW											X				X													X	X		X			X	
	13	COMMENT of INTEREST	X																																		
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X		X	X		X																	X											
	15	AIRCRAFT PROPULSION	X			X																				X											
	16	MARINE PROPULSION										X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	17	COMPLETE AIRCRAFT	X	X																						X											
	18	COMPLETE SHIP											X				X							X	X		X	X		X							
	19	ROTATING FLAP or SLAT																													X			X		X	X
	20	CONVERTIBLE ROTOR to WING		X																																	
	21	ROTOR-ROTOR																																			
	22	DEVICE OTHER THAN AIRCRAFT			W			W			W																										
GEOMETRY	23	FEATHERING PITCH SYSTEM		1	2	4			7	2		1	1	1	1	1	1	1'	1	1	1	1'	1	1	1	1	1	1		1	1	1	1	1	1	1	
	24	ROTOR SYSTEMS per INSTAL.		2						2																2			1								
	25	NUMBER of BLADES per ROTOR		3		8				6									4							3			1								
	26	BLADE or ROTOR PROFILE		A	F	F				7								A	A							A			A								
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING																																			
TEST	29	WIND TUNNEL																																			
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER															X							X			X	X				X					
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL																																			
	34	FLOW PATTERN STUDY																																			
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY																																			
	37	ROTATION																																			
	38	POWER																																			
	39	BLADE ANGLE																																			
	40	ORBIT ANGLE																																			
	41	ECCENTRICITY																																			
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																			
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT																																			
	48	DRAG																																			
	49	THRUST																						X			X	X									
	50	TORQUE																																			
	51	ROTATION																																			
	52	TIP SPEED or ADVANCE RATIO																																			
	53	POWER																																			
	54	FORCE DISTRIBUTION																																			
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED															X																				
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	S	P	P	P	P	R	S	P	P	P	R	P	P	P	R	P	P	P	P	P	S	R	S	S	R	R	R	S	S	R	R	R	R	S	R
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																						X			X	X				X	X	X	X		X
	64	NOT SEARCHED					X	X	X		X																					X	X	X	X		X

V		REFERENCE NO ➡	[illegible]	[illegible]
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.	X	
	2	WING ROTOR		X
	3	MAGNUS CYLINDER		
	4	CROSS-FLOW FAN		
	5	OTHER	X	
GENERAL	6	THEORETICAL EXPOSITION		
	7	PERFORMANCE		
	8	STABILITY		
	9	CONTROL or MANEUVERABILITY		
	10	LOADS and STRESS ANALYSIS		
	11	PHENOMENON DEMONSTRATION		
	12	REVIEW		
	13	COMMENT of INTEREST		X
APPLICATION	14	AIRCRAFT SUSTENTATION	X	
	15	AIRCRAFT PROPULSION	X	
	16	MARINE PROPULSION		
	17	COMPLETE AIRCRAFT	X	
	18	COMPLETE SHIP		
	19	ROTATING FLAP or SLAT		
	20	CONVERTIBLE ROTOR to WING		
	21	ROTOR-ROTOR	X	
	22	DEVICE OTHER THAN AIRCRAFT		W
GEOMETRY	23	FEATHERING PITCH SYSTEM		
	24	ROTOR SYSTEMS per INSTAL.		
	25	NUMBER of BLADES per ROTOR		
	26	BLADE or ROTOR PROFILE		
	27	TIP PATH other than CIRCULAR		
	28	AUXILIARY to FIXED WING		
TEST	29	WIND TUNNEL		
	30	FLIGHT or DROP TEST		
	31	TOWING TANK or in WATER		
	32	TWO DIMENSIONAL		
	33	THREE DIMENSIONAL		
	34	FLOW PATTERN STUDY		
	35	CAVITATION STUDY		
PARAMETERS VARIED	36	STREAM VELOCITY		
	37	ROTATION		
	38	POWER		
	39	BLADE ANGLE		
	40	ORBIT ANGLE		
	41	ECCENTRICITY		
	42	PROFILE SHAPE or THICKNESS		
	43	NUMBER of BLADES		
	44	ASPECT RATIO		
	45	TIP PLATE DIA or SHAPE		
	46	MOMENT of INERTIA		
QUANTITIES MEASURED	47	LIFT		
	48	DRAG		
	49	THRUST		
	50	TORQUE		
	51	ROTATION		
	52	TIP SPEED or ADVANCE RATIO		
	53	POWER		
	54	FORCE DISTRIBUTION		
	55	TORQUE DISTRIBUTION		
	56	FLIGHT PATH PLOTTED		
	57	STABILITY DERIVATIVES		
	58	PRESENTATION	P	S
AVAILABILITY	59	CLASSIFIED		
	60	COMPANY PROPRIETARY		
	61	NOT GENERALLY AVAILABLE		
	62	UNPUBLISHED		
	63	ENGLISH TRANSLATION		
	64	NOT SEARCHED		

W		REFERENCE Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP		X							X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	
	2	WING ROTOR	X		X	X	X	X	X	X			X																								
	3	MAGNUS CYLINDER																								X											X
	4	CROSS-FLOW FAN																								X											X
	5	OTHER		X																								X	X								
GENERAL	6	THEORETICAL EXPOSITION																		X			X		X		X					X					
	7	PERFORMANCE													X	X				X	X		X		X		X	X	X	X		X					X
	8	STABILITY																																			
	9	CONTROL or MANEUVERABILITY																																			
	10	LOADS and STRESS ANALYSIS																															X	X			
	11	PHENOMENON DEMONSTRATION																																			
	12	REVIEW													X																						X
	13	COMMENT of INTEREST												X										X		X		X	X		X	X					
APPLICATION	14	AIRCRAFT SUSTENTATION		X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X				X			X			X	X	X	X	
	15	AIRCRAFT PROPULSION						X				X				X	X	X	X	X	X	X	X				X			X			X	X		X	
	16	MARINE PROPULSION																																			X
	17	COMPLETE AIRCRAFT			X	X	X	X	X	X		X						X		X	X												X	X		X	
	18	COMPLETE SHIP																																			X
	19	ROTATING FLAP or SLAT			X																					X											
	20	CONVERTIBLE ROTOR to WING																																			
	21	ROTOR-ROTOR				X	X	X																									X	X			
	22	DEVICE OTHER THAN AIRCRAFT	K											W																							W
GEOMETRY	23	FEATHERING PITCH SYSTEM									7	8				1	1	1	1	1	1	1	1	1	3	1	1	1	1	!	1	1	1	1	8	6	
	24	ROTOR SYSTEMS per INSTAL.	1	2	2	4					4	2		1		1	1	6	1	6	6									1			2	2	2	2	
	25	NUMBER of BLADES per ROTOR	1	4	1	2	1	2			3	6		6		4	8	8	6	8	8									4			3	3	3	3	
	26	BLADE or ROTOR PROFILE	R	^	~	3	~	S			F	F		F			^	L	^	A	A									A			L	L	A	^	
	27	TIP PATH other than CIRCULAR																																			
	28	AUXILIARY to FIXED WING			X	X																				X											
TEST	29	WIND TUNNEL																												X							X
	30	FLIGHT or DROP TEST																																			
	31	TOWING TANK or in WATER																																			
	32	TWO DIMENSIONAL																																			
	33	THREE DIMENSIONAL														X														X							X
	34	FLOW PATTERN STUDY																							X												
	35	CAVITATION STUDY																																			
PARAMETERS VARIED	36	STREAM VELOCITY																												X							X
	37	ROTATION														X														X							X
	38	POWER																																			
	39	BLADE ANGLE														X														X							
	40	ORBIT ANGLE																												X							
	41	ECCENTRICITY														X																					
	42	PROFILE SHAPE or THICKNESS																																			
	43	NUMBER of BLADES																																			
	44	ASPECT RATIO																																			
	45	TIP PLATE DIA. or SHAPE																																			X
	46	MOMENT of INERTIA																																			
QUANTITIES MEASURED	47	LIFT														X														X							X
	48	DRAG																												X							X
	49	THRUST																																			
	50	TORQUE																												X							
	51	ROTATION														X														X							
	52	TIP SPEED or ADVANCE RATIO																												X							
	53	POWER														X																					
	54	FORCE DISTRIBUTION																																			X
	55	TORQUE DISTRIBUTION																																			
	56	FLIGHT PATH PLOTTED																							X												
	57	STABILITY DERIVATIVES																																			
	58	PRESENTATION	P	P	P	P	P	P	P	P	P	P	P	S	S	S	P	S	S	S	S	S	S	S	S	S	R	S	S	R	S	S	P	P	P	P	S
AVAILABILITY	59	CLASSIFIED																																			
	60	COMPANY PROPRIETARY																																			
	61	NOT GENERALLY AVAILABLE																																			
	62	UNPUBLISHED																																			
	63	ENGLISH TRANSLATION																																			
	64	NOT SEARCHED											X																								

W		REFERENCE Nº ➡	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.			X					X	X	X	X	X							X	X		
	2	WING ROTOR				X	X	X	X						X					X				
	3	MAGNUS CYLINDER	X														X		X					
	4	CROSS-FLOW FAN																						
	5	OTHER																						
GENERAL	6	THEORETICAL EXPOSITION																						
	7	PERFORMANCE			X	X	X	X	X								X		X					
	8	STABILITY																						
	9	CONTROL or MANEUVERABILITY												X										
	10	LOADS and STRESS ANALYSIS																						
	11	PHENOMENON DEMONSTRATION																						
	12	REVIEW																						
	13	COMMENT of INTEREST																						
APPLICATION	14	AIRCRAFT SUSTENTATION	X							X	X	X	X	X			X		X		X	X		
	15	AIRCRAFT PROPULSION		X						X	X	X	X	X								X		
	16	MARINE PROPULSION			X																			
	17	COMPLETE AIRCRAFT									X	X	X								X	X		
	18	COMPLETE SHIP			X																			
	19	ROTATING FLAP or SLAT																						
	20	CONVERTIBLE ROTOR to WING																						
	21	ROTOR-ROTOR																						
	22	DEVICE OTHER THAN AIRCRAFT				B	B	B	B						K					K				
GEOMETRY	23	FEATHERING PITCH SYSTEM			2						2	2	2	2							2	2		
	24	ROTOR SYSTEMS per INSTAL.			2	1	1	1	1		2	2	2		1'					1	2	1		
	25	NUMBER of BLADES per ROTOR	1'			1	1	1	1	2	2	2	2	2	2		1		1	1	4	M		
	26	BLADE or ROTOR PROFILE	C'		A	C	C	C	C	A	A	A	A	A	S		C		C	R	F	F		
	27	TIP PATH other than CIRCULAR																						
	28	AUXILIARY to FIXED WING	X																					
TEST	29	WIND TUNNEL				X	X	X	X								X		X					
	30	FLIGHT or DROP TEST			X																			
	31	TOWING TANK or in WATER																						
	32	TWO DIMENSIONAL																						
	33	THREE DIMENSIONAL				X	X	X	X								X		X					
	34	FLOW PATTERN STUDY																						
	35	CAVITATION STUDY																						
PARAMETERS VARIED	36	STREAM VELOCITY				X	X	X	X								X		X					
	37	ROTATION				X	X	X	X								X		X					
	38	POWER																						
	39	BLADE ANGLE															X							
	40	ORBIT ANGLE																						
	41	ECCENTRICITY																						
	42	PROFILE SHAPE or THICKNESS					X	X	X															
	43	NUMBER of BLADES																						
	44	ASPECT RATIO																						
	45	TIP PLATE DIA. or SHAPE																						
	46	MOMENT of INERTIA																						
QUANTITIES MEASURED	47	LIFT				X	X	X	X								X		X					
	48	DRAG				X	X	X	X															
	49	THRUST																						
	50	TORQUE																						
	51	ROTATION																						
	52	TIP SPEED or ADVANCE RATIO				X	X	X	X															
	53	POWER																						
	54	FORCE DISTRIBUTION																						
	55	TORQUE DISTRIBUTION																						
	56	FLIGHT PATH PLOTTED																						
	57	STABILITY DERIVATIVES																						
	58	PRESENTATION	P	P	R	R	R	R	R	P	P	P	P	P	P		R		R	P	P	S		
AVAILABILITY	59	CLASSIFIED																						
	60	COMPANY PROPRIETARY																						
	61	NOT GENERALLY AVAILABLE																						
	62	UNPUBLISHED																						
	63	ENGLISH TRANSLATION																						
	64	NOT SEARCHED		X	X																X			

X		REFERENCE NO ➡
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.
	2	WING ROTOR
	3	MAGNUS CYLINDER
	4	CROSS-FLOW FAN
	5	OTHER
GENERAL	6	THEORETICAL EXPOSITION
	7	PERFORMANCE
	8	STABILITY
	9	CONTROL or MANEUVERABILITY
	10	LOADS and STRESS ANALYSIS
	11	PHENOMENON DEMONSTRATION
	12	REVIEW
	13	COMMENT of INTEREST
APPLICATION	14	AIRCRAFT SUSTENTATION
	15	AIRCRAFT PROPULSION
	16	MARINE PROPULSION
	17	COMPLETE AIRCRAFT
	18	COMPLETE SHIP
	19	ROTATING FLAP or SLAT
	20	CONVERTIBLE ROTOR to WING
	21	ROTOR-ROTOR
	22	DEVICE OTHER THAN AIRCRAFT
GEOMETRY	23	FEATHERING PITCH SYSTEM
	24	ROTOR SYSTEMS per INSTAL.
	25	NUMBER of BLADES per ROTOR
	26	BLADE or ROTOR PROFILE
	27	TIP PATH other than CIRCULAR
	28	AUXILIARY to FIXED WING
TEST	29	WIND TUNNEL
	30	FLIGHT or DROP TEST
	31	TOWING TANK or in WATER
	32	TWO DIMENSIONAL
	33	THREE DIMENSIONAL
	34	FLOW PATTERN STUDY
	35	CAVITATION STUDY
PARAMETERS VARIED	36	STREAM VELOCITY
	37	ROTATION
	38	POWER
	39	BLADE ANGLE
	40	ORBIT ANGLE
	41	ECCENTRICITY
	42	PROFILE SHAPE or THICKNESS
	43	NUMBER of BLADES
	44	ASPECT RATIO
	45	TIP PLATE DIA. or SHAPE
	46	MOMENT of INERTIA
QUANTITIES MEASURED	47	LIFT
	48	DRAG
	49	THRUST
	50	TORQUE
	51	ROTATION
	52	TIP SPEED or ADVANCE RATIO
	53	POWER
	54	FORCE DISTRIBUTION
	55	TORQUE DISTRIBUTION
	56	FLIGHT PATH PLOTTED
	57	STABILITY DERIVATIVES
	58	PRESENTATION
AVAILABILITY	59	CLASSIFIED
	60	COMPANY PROPRIETARY
	61	NOT GENERALLY AVAILABLE
	62	UNPUBLISHED
	63	ENGLISH TRANSLATION
	64	NOT SEARCHED

Y		REFERENCE NO	1	2	3
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.			
	2	WING ROTOR		X	
	3	MAGNUS CYLINDER			
	4	CROSS-FLOW FAN			
	5	OTHER	X		
GENERAL	6	THEORETICAL EXPOSITION			
	7	PERFORMANCE	X		
	8	STABILITY			
	9	CONTROL or MANEUVERABILITY			
	10	LOADS and STRESS ANALYSIS			
	11	PHENOMENON DEMONSTRATION			
	12	REVIEW			
	13	COMMENT of INTEREST			
APPLICATION	14	AIRCRAFT SUSTENTATION	X		
	15	AIRCRAFT PROPULSION	X		
	16	MARINE PROPULSION			
	17	COMPLETE AIRCRAFT			
	18	COMPLETE SHIP			
	19	ROTATING FLAP or SLAT			
	20	CONVERTIBLE ROTOR to WING			
	21	ROTOR-ROTOR			
	22	DEVICE OTHER THAN AIRCRAFT			
GEOMETRY	23	FEATHERING PITCH SYSTEM			
	24	ROTOR SYSTEMS per INSTAL.			
	25	NUMBER of BLADES per ROTOR			
	26	BLADE or ROTOR PROFILE			
	27	TIP PATH other than CIRCULAR			
	28	AUXILIARY to FIXED WING			
TEST	29	WIND TUNNEL	X		
	30	FLIGHT or DROP TEST			
	31	TOWING TANK or in [illegible]			
	32	TWO DIMENSIONAL			
	33	THREE DIMENSIONAL	X		
	34	FLOW PATTERN STUDY			
	35	CAVITATION STUDY			
PARAMETERS VARIED	36	STREAM VELOCITY	X		
	37	ROTATION	X		
	38	POWER			
	39	BLADE ANGLE	X		
	40	ORBIT ANGLE			
	41	ECCENTRICITY			
	42	PROFILE SHAPE or THICKNESS			
	43	NUMBER of BLADES			
	44	ASPECT RATIO			
	45	TIP PLATE DIA. or SHAPE			
	46	MOMENT of INERTIA			
QUANTITIES MEASURED	47	LIFT	X		
	48	DRAG	X		
	49	THRUST	X		
	50	TORQUE	X		
	51	ROTATION	X		
	52	TIP SPEED or ADVANCE RATIO	X		
	53	POWER	X		
	54	FORCE DISTRIBUTION			
	55	TORQUE DISTRIBUTION			
	56	FLIGHT PATH PLOTTED			
	57	STABILITY DERIVATIVES			
	58	PRESENTATION	R	P	P
AVAILABILITY	59	CLASSIFIED			
	60	COMPANY PROPRIETARY			
	61	NOT GENERALLY AVAILABLE			
	62	UNPUBLISHED			
	63	ENGLISH TRANSLATION			
	64	NOT SEARCHED		X	X

Z		REFERENCE No ➡	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SYSTEM	1	CYCLOGIRO or CYCLOIDAL PROP.													X	X			X	
	2	WING ROTOR	X							X	X	X	X					X		
	3	MAGNUS CYLINDER		X	X	X	X	X	X	X	X	X	X	X			X			
	4	CROSS-FLOW FAN																		
	5	OTHER																		
GENERAL	6	THEORETICAL EXPOSITION																		
	7	PERFORMANCE																		
	8	STABILITY															X			
	9	CONTROL or MANEUVERABILITY																		
	10	LOADS and STRESS ANALYSIS																		
	11	PHENOMENON DEMONSTRATION																		
	12	REVIEW																		
	13	COMMENT of INTEREST		X	X	X	X	X	X						X				X	
APPLICATION	14	AIRCRAFT SUSTENTATION	X	X	X	X	X	X	X	X	X	X	X	X						
	15	AIRCRAFT PROPULSION																X		
	16	MARINE PROPULSION						X					X			X				
	17	COMPLETE AIRCRAFT	X											X						
	18	COMPLETE SHIP																		
	19	ROTATING FLAP or SLAT																		
	20	CONVERTIBLE ROTOR to WING																X		
	21	ROTOR-ROTOR																		
	22	DEVICE OTHER THAN AIRCRAFT																		
GEOMETRY	23	FEATHERING PITCH SYSTEM														1			1	
	24	ROTOR SYSTEMS per INSTAL.	2	3	3	3	3	3	3								1	M	2	
	25	NUMBER of BLADES per ROTOR	1	1	1	1	1	1	1	1	1	1	1	1			1	1	3	
	26	BLADE or ROTOR PROFILE	~	C	C	C	C	C	C	C	C	C	C	C			C	~	A	
	27	TIP PATH other than CIRCULAR																		
	28	AUXILIARY to FIXED WING								X	X	X	X	X				X		
TEST	29	WIND TUNNEL															X			
	30	FLIGHT or DROP TEST	X	X	X	X														
	31	TOWING TANK or in WATER																		
	32	TWO DIMENSIONAL															X			
	33	THREE DIMENSIONAL																		
	34	FLOW PATTERN STUDY																		
	35	CAVITATION STUDY																		
PARAMETERS VARIED	36	STREAM VELOCITY															X			
	37	ROTATION																		
	38	POWER																		
	39	BLADE ANGLE																		
	40	ORBIT ANGLE																		
	41	ECCENTRICITY																		
	42	PROFILE SHAPE or THICKNESS																		
	43	NUMBER of BLADES																		
	44	ASPECT RATIO										X								
	45	TIP PLATE DIA or SHAPE																		
	46	MOMENT of INERTIA																		
QUANTITIES MEASURED	47	LIFT																		
	48	DRAG																		
	49	THRUST																		
	50	TORQUE																		
	51	ROTATION																		
	52	TIP SPEED or ADVANCE RATIO																		
	53	POWER																		
	54	FORCE DISTRIBUTION																		
	55	TORQUE DISTRIBUTION																		
	56	FLIGHT PATH PLOTTED																		
	57	STABILITY DERIVATIVES																		
	58	PRESENTATION	B	S	S	S	S	S	S	P	P	P	P	P	B	B	R	P	B	
AVAILABILITY	59	CLASSIFIED																		
	60	COMPANY PROPRIETARY																		
	61	NOT GENERALLY AVAILABLE																		
	62	UNPUBLISHED																		
	63	ENGLISH TRANSLATION																		
	64	NOT SEARCHED												X		X				

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Security Classification

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3 REPORT TITLE

REVIEW AND PRELIMINARY EVALUATION OF LIFTING HORIZONTAL-AXIS ROTATING-WING AERONAUTICAL SYSTEMS (HARWAS)

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5 AUTHOR(S) *(First name, middle initial, last name)*

Foshag, William F. and Boehler, Gabriel D.

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13 ABSTRACT

The results of a Review and Preliminary Evaluation of Lifting Horizontal-Axis Rotating-Wing Aeronautical Systems (HARWAS) are presented.

Among the purely aeronautical applications, near-horizontal axis as well as horizontal axis devices are considered. The former cover the radial-lift propeller or "self-propelling" wing; the latter cover Magnus effect and related systems; cyclogiro systems and horizontal-axis propeller systems with cyclic pitch. A limited investigation of non-aeronautical applications of HARWAS is also made, which covers wing-rotor type windmills, cyclogiro windmill turbines, Magnus effect ship propulsion and cycloidal ship propulsion.

Approximately 1200 references are listed. A series of cross-index tables is also included to provide a quick means for the reader to determine the content and availability of the references.

An analysis of the various lift systems pertinent to the HARWAS field is made with a view to potential air vehicle applications. Over 20 original aeronautical applications are identified and evaluated in the light of recent advances in power plants, transmissions and lightweight structural techniques. This analysis points out the extraordinary variety of HARWAS and identifies promising new aeronautical systems. A preliminary performance and design study of two promising HARWAS concepts is also reported. The two concepts are the STOL logistics aircraft using a rotating airfoil flap and the amplified high-pitch cyclogiro for application to the composite aircraft mission.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aerodynamic Characteristics						
Performance (Engineering)						
Rotary Wing						
Vertical Take-off Planes						
Short Take-off Planes						
Airfoils						
Magnus Forces						
Wing Rotors						
Bomblets						
Savonius Rotors						
Flettner Rotors						
Rotating Cylinders						
Autorotation						
Gliders						
Flaps						
Slats						
Rotating Cylinder Flaps						
Rotating Airfoil Flaps						
Orbiting and Undulating Flaps						
Cyclogiros						
Cycloidal Propellers						
Propellers (Aerial)						
Radial-Lift Propellers						
Sails						
Windmills						

Unclassified
Security Classification

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