Performance Analysis of the Slowed-Rotor Compound Helicopter Configuration



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The calculated performance of a slowed-rotor compound aircraft, particularly at high flight speeds, is examined. Correlation of calculated and measured performance is presented for a NASA Langley high advance ratio test to establish the capability to model rotors in such flight conditions. The predicted performance of an isolated rotor and a wing and rotor combination are examined in detail. Three tip speeds and a range of collective pitch settings are investigated. A tip speed of 230 ft/s and zero collective pitch are found to be the best condition to minimize rotor drag over a wide speed range. Detailed rotor and wing performance is examined for both sea level and cruise altitude conditions. Rotor and wing power are found to be primarily from profile drag, except at low speed where the wing is near stall. Increased altitude offloads lift from the rotor to the wing, reducing total power required.

Nomenclature

C_H	longitudinal	inplane	force	coefficient	

 C_Q torque coefficient thrust coefficient

D drag L lift

 $M_{\rm TIP}$ blade tip Mach number in hover

P power

dynamic pressure

V velocity

 μ

 V_T , V_{TIP} blade tip speed in hover shaft angle, positive aft

 β rotor flapping angle, positive forward

 δ_3 rotor blade pitch-flap coupling angle, positive flap up,

pitch down advance ratio

ψ rotor azimuth angle rotor solidity

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Introduction

There has been a recent increased interest in expanding the envelope of vertical lift vehicles, particularly in terms of speed, altitude, and range. Increased range allows attack, scout, and rescue vehicles to reach farther from their bases. Additional speed and altitude capability increases the survivability of military vehicles and cost efficiency of civilian aircraft. Long loiter times improve the effectiveness of scout aircraft, with particular applications of interest being unmanned aerial vehicles (UAVs) and homeland security surveillance aircraft.

Much work has been focused on tilt rotor aircraft; both military and civilian tilt rotors are currently in development. But other configurations may provide comparable benefits to tilt rotors in terms of range and speed. Two such configurations are the compound helicopter and the autogyro. These configurations provide short or vertical takeoff and landing capability but are capable of higher speeds than a conventional helicopter, because the rotor does not provide the propulsive force and is offloaded in forward flight. A drawback is that the rotor must be slowed at high speed to alleviate compressibility and drag divergence effects on the advancing tip. Another drawback is that redundant lift and/or propulsion add weight and drag that can reduce efficiency or payload unless mitigated

One of the first compound helicopters was the McDonnell XV-1 "Convertiplane," built and tested in the early 1950s. There were many novel design features in this remarkable aircraft (Refs. 1–4), which was tested in the NACA 40- by 80-Foot Wind Tunnel at the Ames Aeronautical Laboratory (Ref. 5) and flight tested near McDonnell's St. Louis, Missouri facilities (Ref. 6). The aircraft successfully flew in its three distinct operating modes, helicopter, autogyro, and airplane and could transition smoothly between them.

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One of the features of the XV-1 was the variable-speed rotor. In airplane mode, the rotor would be slowed to a significantly lower speed to reduce its drag in forward flight. The combination of high forward speed and low rotor speed produced an advance ratio near unity, which is far above what is typical for conventional edgewise rotors.

Other prototype compound helicopters since the XV-1 include the Fairey Rotodyne and the Lockheed Cheyenne. Prototypes of both aircraft were built and flown, but never entered production. More recently, a slowed-rotor compound tandem helicopter was evaluated as a candidate for heavy lift (Ref. 7).

The Aeroflightdynamics Directorate, U.S. Army Aviation and Missile Research, Development and Engineering Center, initiated the current effort to explore performance, stability, and control of slowed-rotor compound aircraft, particularly at high flight speeds. The results of the stability and control investigation are found in Ref. 8. In this paper, performance was calculated using the comprehensive analysis CAMRAD II (Ref. 9). Correlation with historical high advance ratio test data is presented to establish the capability to model rotors in such flight conditions. Then the predicted performance of a slowed-rotor vehicle model based on the CarterCopter Technology Demonstrator (CCTD) is examined in detail.

High Advance Ratio Correlation

The data for the correlation were obtained from a high advance ratio test program at NASA Langley by Jenkins and coworkers (Refs. 10,11). The test model used the NACA 0012 airfoil, for which 360-deg airfoil tables are available, making it convenient for high advance ratio correlation. The test was a teetering rotor, which was shown analytically in Ref. 8 to be stable at advance ratios up to three for rigid blades.

Additional correlation from XV-1 wind tunnel data in Refs. 5 and 12 was presented in Ref. 13. Although the analysis matched the test data very closely, the available data suitable for correlation did not represent high advance ratios. Furthermore, the XV-1 rotor is complex and is thus less desirable for correlation as part of this study.

The data from the NASA Langley test was reported in Ref. 11. The teetering rotor was tested in the 30×60 tunnel (Langley Full Scale Tunnel) at advance ratios ranging from 0.65 to 1.45. The variables measured were thrust, drag, power, and flapping angle at shaft angles of 0.5 deg and 5.5 deg (tilted backward relative to the oncoming wind). For the 0.5 deg shaft angle case, four advance ratios were tested; five were tested at 5.5 deg shaft angle.

The rotor properties are shown in Table 1. The rotor's simplicity makes it a good test article for correlation with analysis. The CAMRAD II model was set up to match the wind tunnel test conditions as closely as possible. Distributed properties for the rotor are not available, so it was modeled using rigid blades. Rotor blades for aerodynamic tests are normally very stiff to minimize the effects of elasticity, so a rigid blade assumption is reasonable.

Table 1. Properties of the NASA Langley high advance ratio test rotor (Ref. 11)

Number of blades	2
Radius	7.25 ft
Chord	1.16 ft
Solidity	0.0968
Lock number	5.05
Twist	0 deg
Tip speed	110 ft/s
Airfoil	NACA 0012
δ_3	0 deg

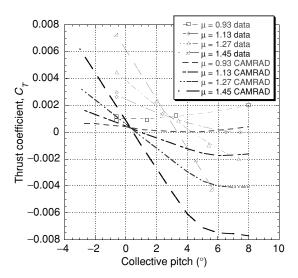


Fig. 1. Thrust correlation with high advance ratio data from Ref. 11 showing bias offset between analysis and test data; $\alpha_s = 0.5$ deg.

The shaft angle was fixed and the rotor was trimmed to zero flapping. Like the wind tunnel test, rotor speed was also fixed, hence advance ratio was set by the free-stream velocity. A rigid wake model was used to calculate the rotor inflow. No precone, undersling, or δ_3 were mentioned in Ref. 11, so these properties were assumed to be zero. As stated earlier, the NACA 0012 airfoil used in the test was particularly convenient because accurate 360-deg airfoil tables are publicly available.

A plot of thrust with collective pitch at 0.5 deg shaft angle is shown in Fig. 1. Since the data are relatively sparse, linear or quadratic lines were fit to the data to improve their readability. An interesting trend is evident. As the advance ratio is increased above approximately 0.9–1.0, the trend of thrust with collective pitch reverses. At $\mu=0.93$, there is almost no change in thrust with collective pitch, and as advance ratio increases, the thrust becomes more negative as collective pitch is increased. This control reversal is captured by CAMRAD II and the slopes of the calculated results match the curve fits very closely. There is, however, an offset in thrust between the predictions and the test data.

The source of the thrust offset in Fig. 1 is unknown. It cannot be corrected by incrementing collective pitch because the thrust at $\mu=0.93$ is nearly constant with collective pitch. Perturbations in shaft angle and (fixed) blade twist did not change the calculated thrust sufficiently to account for the offset. The offsets are thought to be measurement offsets rather than analysis errors given the intersection of the test data lines for the 0.5 deg plot. At zero collective and zero shaft angle, the untwisted rotor should produce zero thrust if trimmed to zero flapping. The shaft angle tested was small, 0.5 deg, so the lines should all cross near the intersection of zero collective and zero thrust. When CAMRAD II was run with zero shaft angle, the curves did cross at zero collective and zero thrust. The test data trend lines cross at about 2.5 deg collective and about C_T of 0.001.

When comparing a nonlinear analysis like CAMRAD II to test data, results exhibiting excellent correlation of slope with a constant offset is strongly suggestive of a bias offset in the measurement. The quality of the slope correlation with CAMRAD II suggests that the data are high quality other than the bias. If a -2.5 deg offset in collective is applied to Fig. 1 and subsequent results, the analysis and test data line up horizontally. That the same offset is present across multiple variables, advance ratios, collective pitch settings, and so on is further evidence suggesting a bias offset in the measurement.

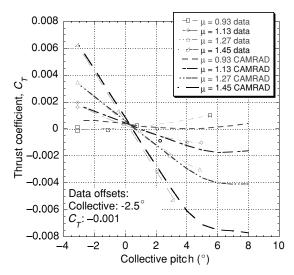


Fig. 2. Thrust correlation with high advance ratio data from Ref. 11 with bias offset removed; $\alpha_s = 0.5$ deg.

By also applying a C_T offset of -0.001 from the test data, the analysis and test data correlate extremely well, see Fig. 2. Reference 11 estimates the measurement error in C_T at 0.0008, so a 0.0010 offset is not unreasonable. Like the collective pitch angle, the same C_T correction also corrects the thrust at $\alpha_s = 5.5$ deg to match analysis; see Fig. 3.

Figure 3 has an additional advance ratio of 0.65, making the reversal in the slope of the thrust curve even more apparent. A detailed exploration of the thrust reversal phenomenon is beyond the scope of this paper, but a brief explanation is warranted. At high advance ratio, much of the retreating blade is in reverse flow. In reverse flow, increased collective pitch reduces the reversed-airfoil angle of attack and decreases the local lift. Moment balance must exist with the advancing side, so with increased speed, the lift on the advancing side must also be reduced (by application of cyclic pitch) as more of the retreating side is in reverse flow. If lift must be decreasing on both advancing and retreating sides of the disk, the total thrust decreases with increased collective pitch and a thrust reversal has occurred. The advance ratio at which the thrust is independent of collective depends on the blade airfoils and twist.

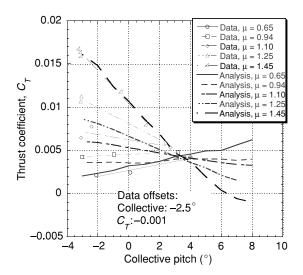


Fig. 3. Thrust correlation with high advance ratio data from Ref. 11 with bias offset removed; $\alpha_s = 5.5$ deg.

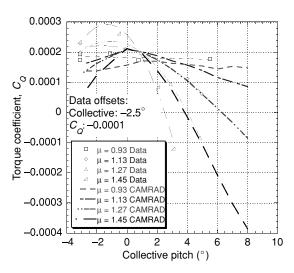


Fig. 4. Torque correlation with high advance ratio data from Ref. 11 with bias offset removed; $\alpha_s = 0.5$ deg.

The flattening of the analysis curves above 5 or 6 deg collective pitch was not specifically investigated but is believed to be the airfoil stalling in reverse flow. The performance of the airfoil, including the maximum lift coefficient should be degraded in reverse flow relative flow approaching the leading edge.

Data for the 5.5 deg shaft angle for variables other than C_T contain significant scatter. This, when combined with the sparseness of data points, makes it difficult to identify any trends in the data or even qualitatively assess the correlation with analysis. Therefore, only results from the 0.5 deg shaft angle are presented.

Torque is shown in Fig. 4. The trends are relatively well captured by the analysis, though not as well as the thrust data. The slope of the curves are more negative for the test data than analysis. The general trend of flattening with negative collective pitch and decreasing with positive collective pitch is reproduced by the analysis. In the range from -3 to +3, the agreement is acceptable. Torque is dominated by drag and is normally more difficult to correlate with analysis. A boundary layer trip strip was applied to the test blades to fix the transition point. This should cause some deviation from the airfoil tables used in the analysis. Also, because of the low maximum tunnel speed in the Langley Full Scale Tunnel, the rotor must be spun quite slowly (110 ft/s tip speed). This makes data collection challenging because small forces must be measured for a 15-ft rotor. A C_Q offset of 0.0001 is equivalent to less than 3.5 ft lb dimensionally.

Correlation of inplane force was less clear, but also encouraging. Figure 5 shows an approximately parabolic shape. The local minima predicted by CAMRAD II all occur at zero collective. The test data are sparse, but at least the $\mu=1.13$ and $\mu=1.27$ lines seem to have minima near zero collective also. The expected trend of inplane force increasing with advance ratio is evident in both the test data and the analysis with the exception of $\mu=1.45$. For some reason, the inplane force for $\mu=1.45$ is lower than $\mu=1.27$ for the test data. The slopes of the CAMRAD II predictions at higher collective pitch settings approximate the slope of the data, though not as closely as the C_T data. For reference, $C_H=0.001$ corresponds to about 4.5 lb of lateral force, so it is challenging to obtain clean data with such small forces.

The conclusions from these results suggest that CAMRAD II can predict performance trends relatively well at high advance ratio using a rigid blade model. The correlation for thrust was clearly better than for torque and inplane force, but these were reasonably good also and

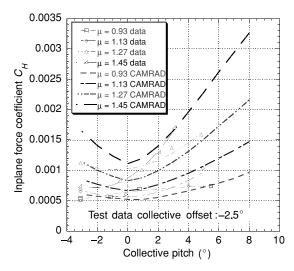


Fig. 5. Inplane force correlation with high advance ratio data from Ref. 11 with bias offset removed; $\alpha_s = 0.5$ deg.

do not suggest any serious deficiencies in the analysis. The rigid blade assumption is accurate to the extent that the test hardware is stiff. Blade elasticity would more likely affect C_T than C_Q or C_H , and C_T correlated very well. A vortex wake model is needed for performance calculations, but a rigid wake geometry is adequate at these high advance ratios.

Slowed-Rotor Compound

A slowed-rotor vehicle model based on the CCTD (Ref. 14) was developed to examine the performance of such a concept. The CCTD is a convenient focal point for the study, because it is in current development and features a teetering rotor. The flapping stability investigation in Ref. 8 indicated that a teetering rotor was the best choice for high advance ratio flight. The analytical model, shown in Fig. 6, replicates the basic geometry and control of the CCTD rotor and wing, as a convenient alternative to inventing a notional aircraft. It should not be considered an attempt to model the CCTD in detail, but rather a focal point for an exploratory study. The analytical model is intentionally simplified to capture broad trends of the performance of the rotor and wing combination in the absence of complications like lateral trim, fuselage drag, or blade elasticity.

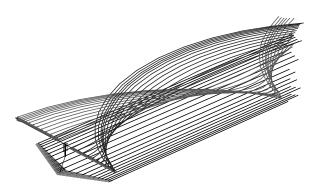


Fig. 6. Illustration of rotor and wing wake models for CCTD: rigid wake geometry at $\mu = 1.0$, $\psi = 90$ deg.

Description of analytical model

The rigid-blade analysis did not allow for elastic bending or torsion, so the effects of many details of the mass and stiffness distributions and aero-dynamic center offsets in the prototype blades would have been obscured by the analysis even if they were available and included. Two models were used for analysis, a model with only a rotor and a model with a rotor and wing. The properties of the rotor and wing are shown in Table 2.

The CCTD is controlled only with collective pitch and spindle tilt. Some mechanism to change the rotor shaft angle relative to the fuselage is necessary to control the revolutions per minute (RPM) of an autorotating rotor, especially over a large speed range. The XV-1 featured direct tilting of the rotor shaft as opposed to a smaller tilting spindle. For the calculations, spindle tilt was modeled by changing the rotor shaft angle in CAMRAD II. All calculations were made with zero cyclic pitch. An implicit trim condition for a teetering rotor is also that the hub moment must be zero. This condition is accommodated by flapping about the teeter hinge.

The prototype rotor has an extremely low Lock number caused by the presence of 65-lb masses at the blade tips. The tip masses provide rotational inertia to store enough energy in the rotor for a jump takeoff. They are located forward-slung in a triangular shape extending from the leading edge of each blade tip. Figure 6 shows the rotor and wing planforms with trailed vortices at an advance ratio of 1.0. Though the trim response features a single degree of freedom, namely the flapping about the teeter hinge $\beta(\psi)$, calculation of the aerodynamics is challenging. Although a rigid wake does not distort, the blade section lift influences the strength of the vortex trailers, which then induce velocity back on the blade sections. With such a large reverse flow region, the trailed vortices overlap the blade on much of the retreating side, making wake convergence challenging.

Note that the chordwise location of the tip masses is of no consequence structurally for the purposes of this study. The rigid blade model does not allow for elastic torsion and is hence insensitive to the chordwise mass distribution. For the purposes of this study, the sweep of the quarter chord due to the masses was also ignored and only the chord width variation at the tip was modeled. This reduced the computation time and

Table 2. Properties of the CarterCopter rotor and wing

Rotor				
Number of blades	2			
Hub type	Teetering			
Radius	22 ft			
Root chord	17 inches			
Tip chord	7 inches			
Solidity	0.032			
Lock number	2.3			
Twist	0 deg			
Airfoils	Variable NACA 65-series			
δ_3	10 deg			
Wing				
Span	32 ft			
Root chord	45 inches			
Tip chord	12.5 inches			
Aspect ratio	13.4			
Sweep angle	18 deg			
Incidence angle	5.2 deg			
Dihedral	6 deg			
Wash out	none			
Airfoil	NACA 65 ₃ 618			
Rel. position	(8.9, 2.63) ft below, forward of rotor			

improved convergence behavior by eliminating direction changes in the bound vortices and aerodynamic panels that interact with trailed vortices in the wake model.

For the actual aircraft, the blade airfoil changes from an NACA 65_4021 at the root to an NACA 65006 at the tip. Airfoil tables were not available for either of these sections, so the NACA 23012 was used as a replacement. Besides availability, for this exploratory study, a more generic blade is preferable to one designed for a specific flight regime. A blade designed (well or poorly) for a specific purpose may have idiosyncrasies that skew results in a nonintuitive way for off-design conditions.

The wing model is straightforward. The wing is swept, tapered, and untwisted, with an aspect ratio of 13.4. The aerodynamic model of the wing in CAMRAD II is identical to the aerodynamic model of the rotor blades, including a rigid vortex wake. The only modeling detail to note at present is again the use of the NACA 23012 airfoil as a replacement for the NACA 65₃618 used on the prototype. Details of trim with the rotor and wing are discussed in the results section following.

Isolated rotor

To trim an autorotating rotor, the procedure was different than that used for the high advance ratio correlation results. In autorotation a rotor is unpowered, so the rotor speed is controlled by the free-stream wind velocity and the angle of attack of the rotor. Two possibilities exist for trim in the analysis. First, the rotor orientation can be fixed and the rotor trimmed by adjusting RPM until a zero torque condition is achieved. Alternatively, the RPM can be set and the shaft tilt adjusted to achieve zero torque. The latter was selected, because it is the more probable method of trim control for a production aircraft. Tilting the shaft manually would significantly increase pilot workload, so in a real application, an automatic control system would likely be used to maintain the desired RPM by tilting the shaft. The XV-1 employed a flyball governor to maintain rotor speed in airplane mode.

The performance metrics of interest are drag and power, with power defined as the product of drag and velocity. This power is supplied by the thrust of the propeller and the DV product would be divided by propeller efficiency to obtain the required engine power. For the purposes of the present work, the engine is not being modeled, so the P = DV power value is used, not adjusted for a propeller efficiency.

Trim variables were collective pitch, rotor speed, and airspeed. The latter two can be specified as either the dimensional rotor speed and velocity, or nondimensional parameters hover tip Mach number and advance ratio. These quantities were varied to examine drag and power under a variety of conditions. Hover tip Mach numbers of $M_{\rm TIP}=0.2$, 0.3, and 0.4 correspond approximately to rotor speeds of 100, 150, and 200 RPM and tip speeds of 230, 345, and 460 ft/s at sea level. Most of the results are at sea level, and the $M_{\rm TIP}$ numbers can be used interchangeably. For the analysis, rotor speed was specified with $V_{\rm TIP}$, so the exact RPM and hover tip Mach numbers were calculated from tip speed.

Power required at several collective pitch settings, forward speeds, and rotor speeds is shown in Fig. 7. Here, the rotor power is plotted at the three tip Mach numbers and at three different forward speeds for each tip Mach number. This shows the effects of changing rotor speed, airspeed, and collective pitch setting on the same plot. Note that the airspeed was specified in knots; the common dimensional airspeeds shown represent different advance ratios for each tip speed.

Figure 7 shows that the minimum power occurs at the minimum rotor speed for all aircraft speeds. It also quantifies the power penalty incurred if the rotor must be operated at a higher speed because of stability or loads considerations. For example, at a flight speed of 246 kt, approximately 60 additional horsepower would be required to spin the rotor at 460 ft/s

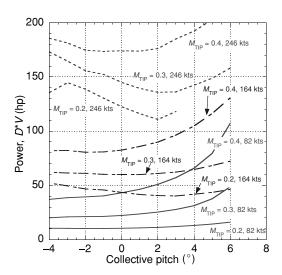


Fig. 7. Isolated rotor power with collective pitch at hover tip Mach numbers of 0.2, 0.3, and 0.4 and 82, 164, and 204 kt forward speed.

rather than 230 ft/s. At 82 kt, approximately 30 additional horsepower would be required.

Figure 7 also suggests that the most efficient collective pitch angle is near zero. The minimum power for nearly every condition is between -2 and 2 deg. The character of the power with collective pitch changes with airspeed. At low airspeed, the power monotonically increases with collective pitch. At the higher airspeeds, a more clearly defined minimum starts to emerge.

The thrust behavior with collective pitch is shown for $V_T = 230$ ft/s in Fig. 8. A thrust reversal similar to that shown in Figs. 2 and 3 occurs for this rotor at about $\mu = 0.85$, where all of the lines converge to a single point. At this point, the thrust coefficient is independent of collective pitch and at higher speeds, thrust decreases with the increasing collective pitch. A collective pitch angle of 2 deg produces nearly constant thrust with the increasing airspeed.

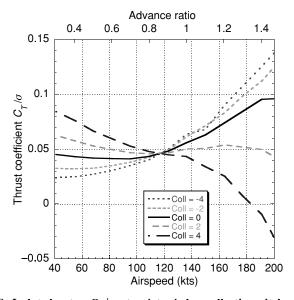


Fig. 8. Isolated rotor C_T/ρ at -4 to 4 deg collective pitch; $V_T = 230$ ft/s.

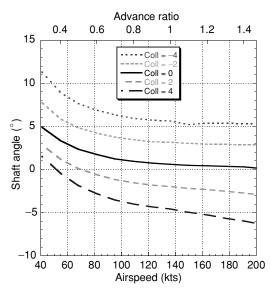


Fig. 9. Isolated rotor shaft angle at -4 to 4 deg collective pitch; $V_T = 230$ ft/s.

The variation in shaft angle required for trim is shown in Fig. 9. For each collective pitch setting, the trend of shaft angle with airspeed is approximately the same. At low speed, the shaft angle increases more rapidly because the dynamic pressure rapidly decreases with the decreased airspeed. At high speed, where there is ample energy to spin the rotor, the shaft angle changes more slowly.

Reference 8 showed an interesting phenomenon regarding shaft angle. In the early development of rotary-wing aircraft, autogyro rotors normally had significant aft tilt to maintain autorotation. But there exists a second orientation of the shaft, with tilt several degrees forward of that shown in Fig. 9, where stable autorotation can be maintained. This second shaft angle has the undesirable characteristic of negative lift on the rotor.

Autorotation is maintained by forward tilt of the elemental lift vector in certain areas of the rotor, producing a positive torque about the hub to balance the drag in other areas. This forward tilt is required to balance drag, but can be relative to positive or negative lift on the airfoil. So one can imagine that in addition to the conventional autorotation state where the rotor is producing positive aircraft lift, there is a second stable state, where the rotor is thrusting downward.

Although it is not practical to trim an aircraft with negative lift on the rotor, a gradient-based trim procedure such as that in CAMRAD II might converge to either of the two possible conditions depending on initial conditions. Over large sweeps of collective pitch, forward speed, and rotor speed, a constant initial condition of zero shaft angle results in trim to the negative lift state for some cases. For this paper, care was taken to ensure that the data were trimmed consistently. If the analysis converged on the undesired trim state from one case to the next, a sudden change in shaft angle, thrust, or some other trim parameter normally reveals the problem.

Rotor and wing

The purpose of modeling the rotor and wing together was to investigate how the two sources of vehicle lift interact with each other and share the vehicle weight, and how this, in turn, affects their individual performance. For the rotor and wing model, the trailed wake models of the wing and rotor are allowed to interact and influence each other.

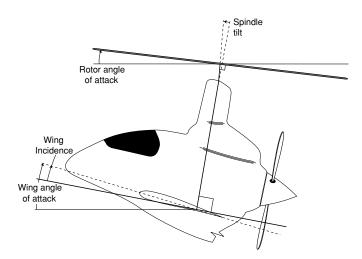


Fig. 10. Diagram of CarterCopter Technology Demonstrator showing vehicle orientation and associated control angles for analysis and prototype.

Because performance was the focus of the present work rather than control, a simple trim condition was specified rather than a full 6-degree of freedom vehicle trim. The only requirements for trim were that the wing and rotor together lift the vehicle weight and that the rotor be autorotating (i.e., shaft torque is zero). As in the isolated rotor analysis, for the purposes of CAMRAD II, the rotor RPM was specified and the shaft angle was a variable calculated by the analysis. The other variable was the incidence of the fuselage, which in turn specified the incidence of the wing. These two variables represent the fuselage angle of attack and spindle tilt of the CCTD. The relationships between and positive directions for these angles are shown in Fig. 10. The vehicle gross weight was chosen to be 4200 lb, which is the maximum vertical takeoff weight of the CCTD.

The distributions of rotor and wing lift are shown in Fig. 11 for the three different rotor speeds. The airspeed scale on the horizontal axis is the same for the three plots. The different rotor speeds result in different advance ratios, indicated on the top of each plot. The collective pitch range has been narrowed to ± 2 deg, but the airspeed range has been expanded to 400 kt. The low end of airspeed range is governed by the minimum speed where the rotor and wing combination can produce 4200 lb of lift.

Looking at these three plots, the best choice for collective pitch seems to be near 0 deg, as seen in the isolated rotor case. For positive pitch, the lift distributions diverge at high speed for $V_T = 230$ ft/s, whereas for negative pitch they diverge at $V_T = 345$ ft/s. So over this speed range, flat pitch is least variable with airspeed.

At $V_T = 230$ ft/s (Fig. 11a), the rotor lift increases slowly with speed; at $V_T = 345$ ft/s (Fig. 11b), the increase is greater and exceeds that of the wing at 360 kt. For $V_T = 460$ ft/s (Fig. 11c), the rotor lift exceeds the wing lift above 310 kt and is relatively independent of collective pitch.

These trends provide guidance for selecting rotor speed and collective. The highest rotor speed, $V_T = 460$ ft/s, is not a good candidate for high-speed flight. Above 310 kt, the rotor must carry more than half of the vehicle weight. If the rotor is to carry a large percentage of the weight, it makes less sense to have a wing in the first place. At the other two rotor speeds, flat pitch is the best choice, especially at $V_T = 230$ ft/s, where the rotor and wing lift are nearly constant with speed. For $V_T = 345$ ft/s, increasing the collective pitch to 1 or 2 deg will keep the rotor lift lower, but if the RPM decreases significantly, the dramatically

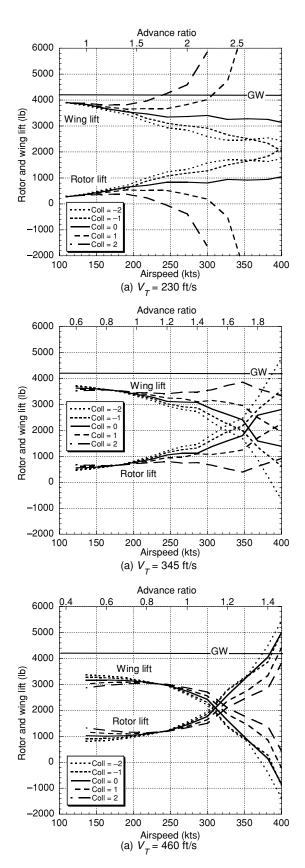


Fig. 11. Lift of rotor and wing vs. airspeed from -2 to 2 deg collective pitch, $230 \le V_T \le 460$ ft/s.

different lift trend at high speed in Fig. 11a shows that a large change in lift may be required to recover rotor speed.

The challenge for a slowed rotor is to make the rotor disappear aerodynamically. Ideally, the drag should be minimized and the rotor should interfere as little as possible with the flight dynamics. The focus of this work is only on the rotor drag, specifically its influence on power required. Total and induced rotor power for the rotor are shown in Fig. 12. Interestingly, the total power changes very little with collective pitch changes. For each of the plots, it is clear that profile power dominates the rotor power. Induced power is comparatively small except for the highest rotor speed (Fig. 12c), where the lift is large. At that rotor speed, compressibility has a significant effect on the blade drag, which results in more rotor lift to maintain autorotation, and in turn, higher induced power. A more judicious selection of airfoil may improve the total power considerably.

Regardless of the airfoil, from a performance standpoint, the lowest rotor speed is the best choice. From Fig. 12, the benefit of slowing the rotor is clear. At 350 kt, for example, the power is approximately 300 hp at the slowest rotor speed, 400 hp for $V_T = 345$ ft/s, and well over 500 hp for $V_T = 460$ ft/s. A more detailed discussion of rotor power at that speed is provided later.

The rotor angle of attack is shown in Fig. 13. This is the angle of the hub relative to the oncoming wind, similar to the isolated rotor shaft angle in Fig. 9, not the tip path plane angle. Since there is no cyclic pitch, the hub plane is also the plane of no feathering. Note that the results for Fig. 9 are for relatively low speed, such that the data from the two plots have little overlap.

For the lowest rotor speed, as the lift diverges for positive collective pitch (Fig. 11a), the shaft angle diverges as well. The shaft angles for zero and negative pitch are relatively unchanged with airspeed, with only a degree or so variation. For the higher tip speeds, Figs. 13b and 13c, the shaft angles do not show any erratic behavior.

The preceding discussion has demonstrated that lower rotor speed improves performance and that zero deg collective pitch is a good setting at virtually any rotor speed and airspeed. More detailed information for the rotor and wing is presented for this collective pitch angle to more fully characterize the performance of the rotor and wing.

Figure 14 shows rotor power at flat pitch for the three tip speeds. This more clearly shows the effect of rotor speed than Fig. 12. The power increases with increasing rotor speed, and the difference widens as the vehicle speed increases. Three factors are at work increasing power required with tip speed. The profile power is increasing, both from increased dynamic pressure and compressibility effects on the section drag coefficient of the blade. Induced power increases also because more thrust is required to overcome profile drag to maintain autorotation.

The effects of compressibility are illustrated in Figs. 15 and 16. Here, the rotor power and lift are compared with dimensional tip speeds of 230 and 460 ft/s and tip Mach numbers of 0.2 and 0.4. To separate the effects of advance ratio and Mach number, a third line is added where the speed of sound was artificially increased by a factor of two such that the tip Mach number of the 460 ft/s rotor speed matched that of the 230 ft/s rotor speed.

In Fig. 15, the difference between the two $M_{\rm TIP} = 0.2$ lines indicates that the profile power increase is resulting from rotor speed. The difference between the two 460 ft/s lines illustrates the effect of compressibility, specifically the drag coefficient of the blade increasing with Mach number. The lines are the same below about 275 kt. Note that the profile drag increase caused by Mach number produces both a direct increase in profile power and an indirect increase in induced power in the same way that an increase in rotor speed does.

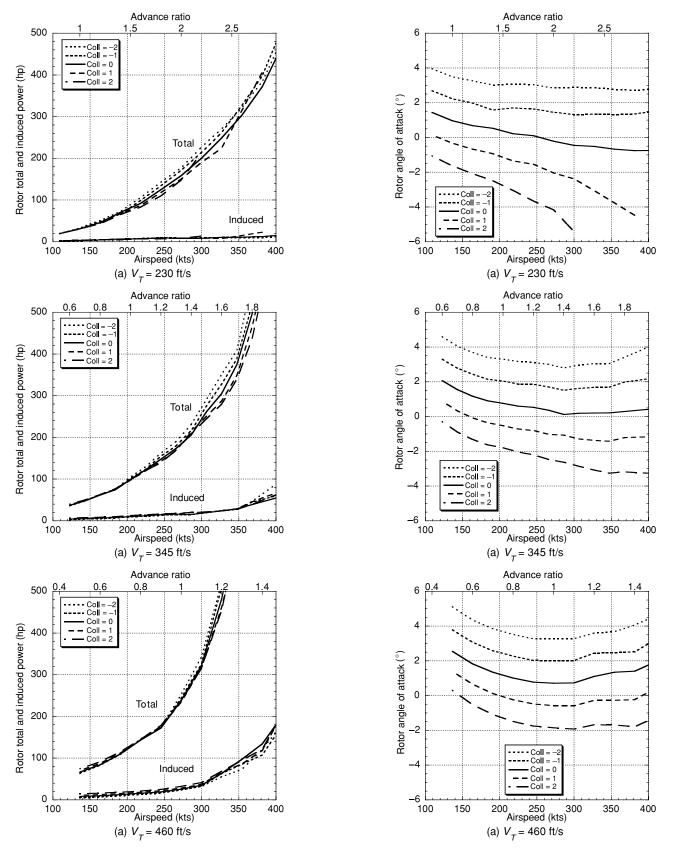


Fig. 12. Total and induced rotor power vs. airspeed from -2 to 2 deg collective pitch; $230 \le V_T \le 460$ ft/s.

Fig. 13. Rotor shaft angle vs. airspeed from -2 to 2 deg collective pitch; $230 \le V_T \le 460$ ft/s.

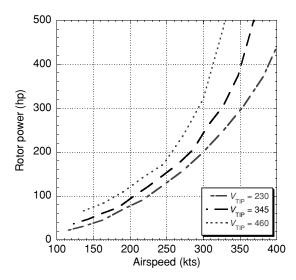


Fig. 14. Rotor power at tip speeds of 230–460 ft/s, 0 deg collective pitch.

Figure 16 shows the influence of compressibility on the rotor lift. Like rotor power, the tip speed has greater influence than the Mach number. For the 460 ft/s cases, the rotor lift exceeds the wing lift at the highest speeds. Suppressing Mach effects only delays the crossing from 310 to about 340 kt.

The wing is largely unaffected by the rotor speed. The total lift is constant, so the wing lift and power required change only to the extent that the rotor lift changes. In Fig. 17, the wing power is almost exactly the same for the three rotor speeds.

The wing angle of attack, also shown in Fig. 17, changes very little with rotor speed, except at very low airspeed. At the lowest speeds, below 150 kt, the wing is operating near stall and requires a fairly large angle of attack. At moderate and high airspeed, even small changes in the wing angle of attack produce substantial changes in the wing lift. Between 200 and 300 kt, there is little change in wing angle of attack with rotor speed. But at the highest speeds, above 300 kt the decreasing (or increasing negative) lift with tip speed becomes evident, consistent with the lift distributions shown in Fig. 11.

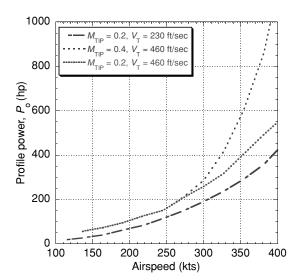


Fig. 15. Effect of compressibility on rotor profile power, 0 deg collective pitch, $M_{\rm TIP} = 0.2$, 0.4, and $V_T = 230$ and 460 ft/s.

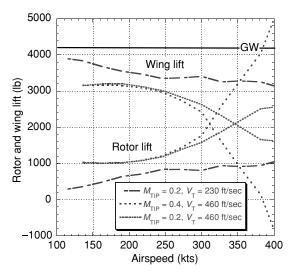


Fig. 16. Effect of compressibility on wing and rotor lift, 0 deg collective pitch, $M_{\rm TIP} = 0.2$, 0.4, and $V_T = 230$ and 460 ft/s.

The total vehicle power is shown in Fig. 18. Because the wing power is nearly insensitive to the rotor speed, the vehicle power looks similar to the rotor power in Fig. 14. The scale is different, but the gradually widening increase in power required with the increasing rotor speed is still clear.

Also notable in Figs. 14, 17, and 18 is that the power required by the rotor is the same level as that of the efficient, high aspect ratio wing, at least at the low rotor speeds. At $V_T = 460$ ft/s, the power curves are very steep, so it is more difficult to compare them to the wing. For the lowest rotor speed, the rotor requires about 450 hp at the highest speed and the wing requires just more than 500 hp. Noting that the wing is carrying more than a 75% of the lift (Fig. 11), this is substantial power increase over a fixed wing, and quantifies the trade-off between vertical takeoff capability and cruise efficiency for this configuration. This is highly dependent on the relative sizing of the rotor and wing as well as the airfoils and could potentially be improved significantly.

The interference power is also shown in Fig. 18. Interference power is similar in concept to induced power. The action of generating lift

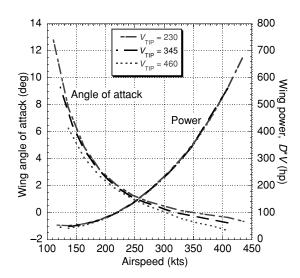


Fig. 17. Wing angle of attack and power at tip speeds of 230–460 ft/s, 0 deg collective pitch.

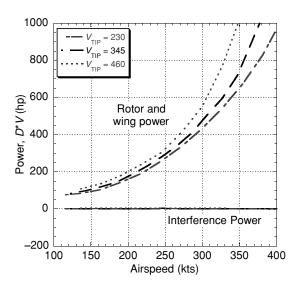


Fig. 18. Total and interference power of rotor and wing at tip speeds of 230–460 ft/s, 0 deg collective pitch.

imparts momentum to the air, and induced drag and induced power can be calculated from the resulting velocities. Interference power is the same as induced power except it is calculated based on velocities resulting from other lifting devices in a wing set. In this case, the flow around the rotor has induced velocity due to the wing and vice versa.

The extremely low interference power indicates that the wing and rotor are separated by a sufficient distance that they are essentially isolated from each other. The advance ratio scales on Figs. 11–13 illustrate that the lowest advance ratio for the rotor is 0.5, which is very high for a helicopter. Not only is the induced power low but also the wake is swept back far behind the vehicle before it interacts with the wing.

The relative importance of profile and induced power for both the wing and the rotor is difficult to ascertain from the preceding discussion. A buildup of power for the lowest tip speed is shown in Fig. 19. The grouping of the lines indicates that induced power is a minor contributor

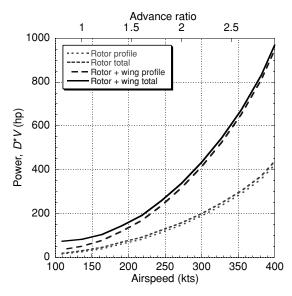


Fig. 19. Relative magnitudes of profile and induced power of wing and rotor, 0 deg collective pitch, $V_T = 230$ ft/s.

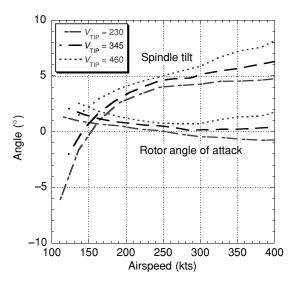


Fig. 20. Rotor hub angle and spindle angle at tip speeds of 230–460 ft/s, 0 deg collective pitch.

for both the rotor and the wing. The lines "profile" and "total" (including profile, induced, interference power) are nearly indistinguishable. The sharing of power between the rotor and the wing is also more clear, as the distance from the *x*-axis to the rotor lines is about the same as that from the rotor lines to the rotor and wing lines.

The rotor incidence information is shown in Fig. 20. The tip path plane angle is the sum of the rotor angle of attack and longitudinal flapping. The data shown are the angle of attack of the hub plane, not including flapping. Spindle tilt is a control parameter and does not provide additional performance information but is included for completeness. The spindle tilt is necessary to independently control the angles of attack of the wing and rotor, as shown in Fig. 10. Additional details on flapping and control are discussed in Ref. 8.

The angle of attack is relatively constant with rotor speed. There is some variation with tip Mach number, but it only amounts to a degree or two. The comparatively large change in spindle tilt is accounting for the change in the wing angle of attack as speed increases. It negates the vehicle attitude change to keep the rotor at a nearly constant angle relative to the oncoming wind (Fig. 20).

Having examined the rotor and wing performance in detail, consideration of the wing and rotor system performance is appropriate. Vehicle efficiency is commonly expressed in terms of lift-to-drag ratio, L/D. The L/D of the rotor, wing, and the combination of the two are shown in Fig. 21. At low rotor speed and low airspeed, the lifting system L/D is as high as 20. The efficient, high aspect ratio wing exceeds an L/D of 30. The rotor has low L/D throughout the airspeed range because it carries very little lift. As the speed increases, the rotor carries slightly more lift and the wing less. Profile drag increases for both, so the L/D of the wing/rotor combination decreases. It is important to note that these calculations do not include any sort of fuselage, so the drag and power calculations are not indicative of what the vehicle performance might be.

Another performance metric is D/q, the drag divided by the dynamic pressure. This indicates an equivalent flat plate area and is most useful for the fuselage but is also useful to compare drag of lifting surfaces. The D/q of the wing and rotor system is shown in Fig. 22. It shows that the power at high speed results primarily from the large dynamic pressure. When the dynamic pressure is divided out, the equivalent flat plate drag is only about 1.5 ft² for the lowest rotor speed. Also, interestingly, the effect of compressibility is evident in the $V_T = 460$ ft/s case. D/q at

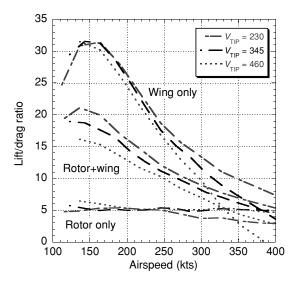


Fig. 21. Combined rotor and wing L/D at tip speeds of 230–460 ft/s, 0 deg collective pitch.

the lowest rotor speed asymptotically approaches horizontal as speed increases, but at the higher rotor speeds, it increases above 300 kt.

One of the drivers for going from a conventional helicopter to a compound helicopter or another vertical lift configuration is that of high altitude performance. A pure helicopter normally stalls at high altitude, but the lifting wing considerably increases the service ceiling. Up to this point, calculations were made for sea level conditions. These will now be compared to high altitude to show the effect on the compound helicopter. The performance was calculated for standard conditions at sea level, 10,000 ft, and 20,000 ft altitude. For a tip speed of 230 ft/s, the corresponding tip Mach numbers for these altitudes are 0.206, 0.214, and 0.222.

Sharing of lift, shown in Fig. 23, is moderately affected. At high speed, an additional 250 lb per 10,000 ft is offloaded from the rotor to the wing. As the profile drag on the rotor blades decreases, less thrust is required to maintain autorotation.

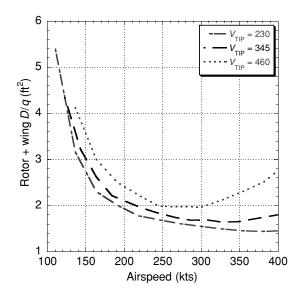


Fig. 22. D/q of rotor and wing at tip speeds of 230–460 ft/s, 0 deg collective pitch.

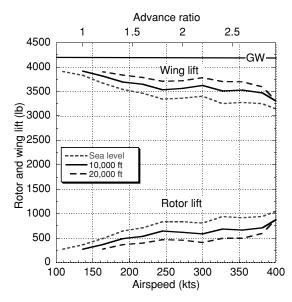


Fig. 23. Lift of rotor and wing from sea level to 20,000 feet, 0 deg collective pitch, $V_T = 230$ ft/s.

The combination of lift redistribution and the reduced air density at high altitude has a strong influence on the rotor and wing power. A breakdown of power, shown in Fig. 24, indicates the total power is reduced by more than 40% from sea level to 20,000 ft at 400 kt. The reduction in power of the wing and rotor combined is slightly more than for the wing alone. The reduction in thrust on the rotor reduces induced power on the rotor but increases induced power on the wing. At low speed, the higher induced power obscures effects of altitude on profile power.

The L/D ratios for the rotor, wing, and the rotor–wing combination are shown in Fig. 25. For the wing alone, the peak L/D is about 32 and is independent of altitude. Though the maximum value does not change, the maximum L/D occurs at a higher speed at higher altitude. For the rotor, the lift is small, so the L/D is small as well. For the rotor and wing

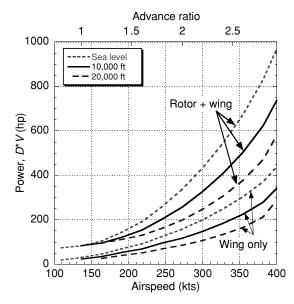


Fig. 24. Wing and total power from sea level to 20,000 feet, 0 deg collective pitch, $V_T = 230$ ft/s.

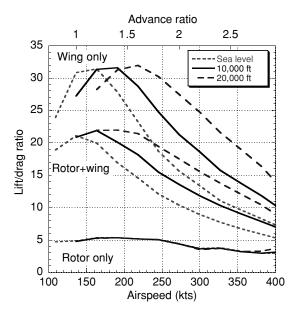


Fig. 25. L/D of rotor and wing from sea level to 20,000 feet, 0 deg collective pitch, $V_T = 230$ ft/s.

together, the maximum L/D increases slightly as altitude increases. The small increase is likely caused by lift shifting to the efficient wing from the less efficient rotor. The difference between the wing only and the rotor and wing narrows with airspeed for every altitude, but narrows less as altitude increases.

These results not only show that high altitude improves the performance of the wing and rotor independently but also that a transfer of lift from the rotor to the wing occurs. This transfer of lift to the efficient wing increases L/D performance, and thus reduces power required.

Conclusions

The performance of slowed-rotor compound aircraft was calculated using the comprehensive analysis CAMRAD II. Correlation with historical high advance ratio test data demonstrated the applicability of CAMRAD II to rotors in such flight conditions. Detailed performance of a rotor similar to that used on the CCTD was presented. The rotor was analyzed as an isolated rotor and with a fixed wing. Specific conclusions follow.

- 1) CAMRAD II with a rigid wake model is able to capture performance trends of high-speed rotors to at least an advance ratio of 1.45. Although some offsets with the Jenkins data existed which could not be accounted for, correlation of the slopes or trends of the calculated data with the NASA Langley high advance ratio rotor test data was good over a wide speed range, particularly for thrust coefficient.
- 2) For an autorotating rotor at high speed, slowing the rotor reduces the power required, whether the rotor is in isolation or in combination with a fixed wing.
- 3) The optimum collective for a high-speed autorotating rotor is that which produces a small amount of positive thrust on the rotor.
- 4) Where there was beneficial sharing of lift between the rotor and the wing, the wing carried most of the lift, and hence rotor power was dominated by profile power. Induced power was generally small unless the wing and the rotor produced opposite lift. Wing power was

also dominated by profile power except at low speed where it was near stall.

- 5) The drag and power of the rotor for $V_T \le 345$ ft/s were about the same as the wing. For $V_T = 460$ ft/s, compressibility effects caused the rotor profile power to increase rapidly above 300 kt.
- 6) The separation between the wing and the rotor for the model in this investigation was sufficient that there was negligible interference between the two at high speed.
- 7) High altitude resulted in a shift of lift from the rotor to the wing for zero collective and $V_T = 230$ ft/s. The shift to the high efficiency wing, coupled with the reduced air density, reduced the power required by more than 40% between sea level and 20,000 ft.

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