GUST LOAD ALLEVIATION ON AIRBUS A 300

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Abstract

The fuel saving technology of new transport aircraft implies the design of passive or active load alleviation. For instance the increase of wing aspect ratio without structural weight penalties would be a desirable feature.

A 10% increase in wing span results in a 17.4% reduction of vortex drag. Since vortex drag is about half of the total drag and the total surface is almost unchanged we would have 8.7% less drag. Considering the additional weight of the tip extension and a slight deterioration in lift distribution at least 5% drag reduction could be achieved.

In the first part of this paper the layout of an active gust load alleviation system is described for an airbus configuration with extended wing (10% span increase). Both open loop and closed loop concepts are considered. The analytical design is performed in the time domain using a quasisteady approach of the aerodynamics of the elastic aircraft. Maximum alleviation factors for the wing loading using actively controlled outboard ailerons, spoilers together with the actuated elevator are derived from discrete design gust analysis.

Effects of unsteady aerodynamic influences and gust length variations on the gust load alleviation efficiency are studied analytically in the frequency and time domain. Finally, fatigue load reductions are calculated using a PSD analysis of the elastic aircraft.

The second part of the paper deals with passive maneuver load alleviation. To demonstrate the reduction of maximum loads the different load distributions of the wing with tip extension, (designed for a desired load alleviation) and of the original wing are compared. The load reduction is achieved by aeroelastic tailoring where the wing has a drag optimal lift distribution for cruise flight and inboard redistribution of the lift at manoeuvre loads. To find the optimum elastic behaviour the wing tip bending as well as the elastic torsional deformation was increased by appropriate laying of fibers in composite material.

Introduction

Numerous development programs dealing with Active Control Technology (ACT) have been performed during the last years at MBB /2, 3, 4, 5, 6, 7/. In general, the application of load compensation systems leads - through the effect of redistribution of the wing lift - to reductions of the structural loads and may be used to increase the total life or reduce the structural weight. Therefore, load alleviation systems may play an important role for the design of transport aircraft with improved fuel economy /1, 8, 9/.

Special investigations have been performed at MBB to study the feasibility of load control during the ACTTA-Program which was sponsored by the ministry of research BMFT /1/. In this report, the layout of active and passive load control concepts is described for the Airbus A 300 with extended wing (Fig. 1).

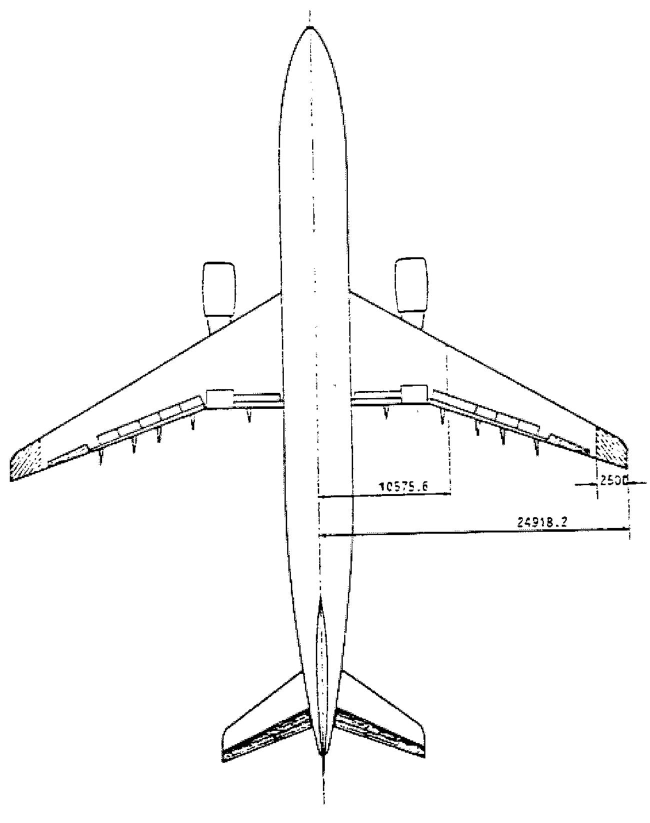

FIG. 1 AIRBUS A 300 WITH NEW TIP

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In the case of active load control maximum alleviations of symmetrical gust loads through the use of activated outboard ailerons, spoilers and elevator are derived with respect to realistic assumptions in the analytical model such as

- coupled flight and structural dynamics
- aerodynamic derivatives of the elastic (non rigid) aircraft
- aerodynamic derivatives of the elastic control surfaces
- introduction of the unsteady aerodynamic effects of the gust and motion induced aerodynamic forces
- introduction of the servo-actuator dynamics
- limitations of control surface deflections and -pitch rates in the nonlinear quasisteady calculation to account for nonlinear effects
- consideration of flying quality criteria

A comparison of design and fatigue loads of the airplane with and without active system demonstrates the effects of the active load alleviation.

Passive load alleviation is obtained by application of theoretical structural optimization methods and new composite materials in the structural design /13/.

The effect of passive load alleviation is documented by comparing the load distributions of the extended wing (added tip section) and of the original wing.

Design of an active Gust Load Alleviation System

Design Criteria

The active control system should minimize incremental structural dynamic loads at the wing caused either by wing span extension or by increased wing loading.

The increments due to gust loads should be compensated by the control system as far as possible to minimize the amount of a necessary structural redesign of the wing. The flying qualities should not be changed by the load alleviation system.

The most important design criterion for the active control system is its reliability. Probabilities of system failure must be investigated to define the probabilities of critical load exceedances. The choice of the criterion i.e. the level of redundancy depends on the procedure of certification. A possible procedure to guarantee the system reliability may be formulated as follows: The gust loads will be investigated through a dynamic response PSD calculation of the aircraft due to turbulent gusts to assure the equivalent reliability of the aircraft with (extended wing) and without (unextended wing) control system. In this manner, the RMS-value and the exceedance of a prescribed gust load will be calculated for different flight conditions for the unaugmented and the aircraft with load alleviation system. The total exceedance per hour of a design load level is then available. The total exceedance per flight hour of all load levels should be less or equal for the unaugmented and the aircraft with load control. Then, the design load is not exceeded.

A system redundancy is existent through the use of different control surfaces (elevator, outboard aileron and spoiler).

In case of total system failure, a manoeuver restriction as well as a speed limitation should be given, and severe turbulence should be avoided using weather radar.

Open Loop Gust Load Compensation

This concept is based on the evaluation of the incremental angle of attack due to gust measured by a vane or differential pressure sensor at the front fuselage and the knowledge of the time delay of the gust between vane and wing.

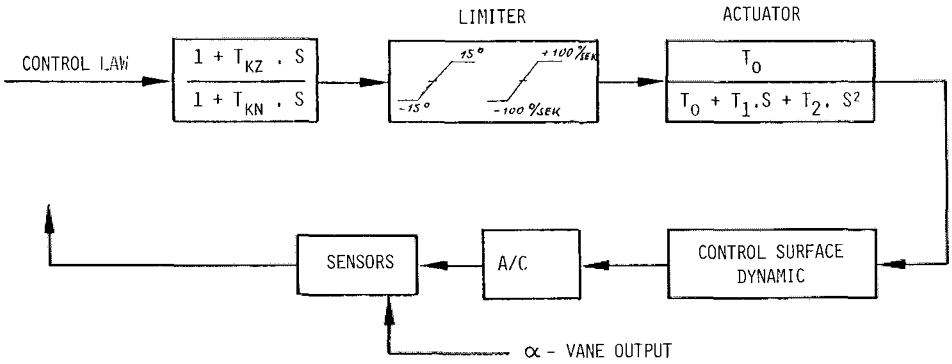
The incremental lift due to the vertical gust is partly compensated through aileron, spoiler deflection on the wing or through elevator deflection. A total compensation of the gust induced lift is not possible due to limited control surface efficiences.

The consideration of unsteady aerodynamic effects, the unsteady lift delay due to penetration of the gust, the aerodynamic wing horizontal tail interference and the delay vane to wing leads to the correct phase of the gust signal. Further correction of the phase is necessary when actuator transfer functions are introduced.

The main advantage of the open loop gust alleviation system is based on the fact that flying qualities are not influenced and that elastic structural vibrations are not affected. Therefore, the system may be designed separately and without modifications of the flight control system excluding nonlinear effects as rate and deflection limitations. Disadvantages of the system may arise through effects of the partial lift compensation which influences the aircraft dynamics.

The dynamical development of an incremental angle of attack produces a force which is not in phase with the gust induced lift. The phase relationship between vane and control surface deflection may be strongly affected. In addition, structural dynamic loads of elastic vibrations may not be reduced efficiently through the low pass characteristics of the system. The block diagram of the gust load open loop system is shown in Fig. 2.

The additional control of the elevator using the time derivative of the gust angle α_g may lead to important load alleviations on the wing.
This load reduction is produced through the effect of changing the wing incidence by rotating the aircraft into the gust. A phase advance of 90° represents the feed back of $\dot{\alpha}_g$. The combination of a gust observer and a PD-control is proposed for this purpose.



	SEC			1/SEC	1/SEC²
	T_{KN}	T_{KZ}/T_{KN}	T_0	T_1	T_2
AILERON, SPOILER A, S	.03	4.	1.	.1	.0025
HORIZONTAL TAIL E	.03	6.	1.	.1	.0025

FIG: 2 BLOCKDIAGRAM OF OPEN LOOP GUST LOAD ALLEVIATION SYSTEM

Closed Loop Gust Load Alleviation

This gust load control system is based on the measurement of the vertical fuselage and wing tip acceleration and its feedback to the servos of the outboard aileron and spoiler. The fuselage acceleration signal will be filtered to eliminate elastic effects. Low frequency contributions of the wing loads may be alleviated in this manner. The feedback of the difference signal of wing tip and fuselage is used to reduce high frequency structural dynamic loads.

Compared to the open loop gust load alleviation systems, this procedure will lead to additional problems. The system has to be integrated into the existent flight control and stability augmentation system. The flying qualities will be influenced by the low frequency feedback of the fuselage acceleration. Therefore it is necessary to produce artificially the flying qualities of the aircraft without gust load control system. This may be achieved by additional feedback of the fuselage acceleration signal to the elevator. The stability of the unaugmented elastic aircraft may be affected, and high frequency structural modes may be destabilized eventually leading to changes of the flutter margins of the aircraft. Adequate positioning of sensors and bandpass filtering could reduce these disadvantages. The block diagram of the closed loop system is shown in fig. 3.

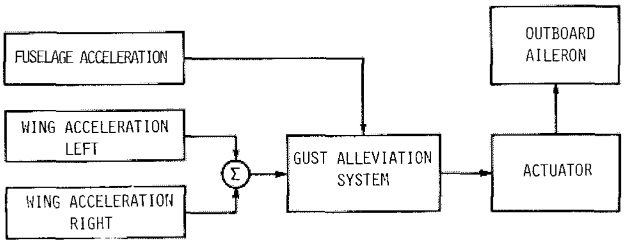


FIG. 3 BLOCKDIAGRAM OF CLOSED LOOP GUST LOAD ALLEVIATION SYSTEM

System Description

For the layout of the load alleviation system, a configuration of the Airbus was chosen. A wing extension of 10 percent, compared to the configuration A300B4 is considered (fig. 1). The investigated flight condition is cruise at 7.8 km altitude at Mach 0.85.

Outboard ailerons are used for load control. However, the efficiency of the outboard ailerons is highly reduced at high dynamic pressures. This leads to the additional application of spoiler and elevator motions for the design of a control system with high power. Disadvantages produced by increments of the total drag using spoilers must be considered.

Vanes with adequate dynamic properties are installed at the front fuselage, and, in addition, accelerometers are necessary at a fuselage position and at the left and right wing tip.

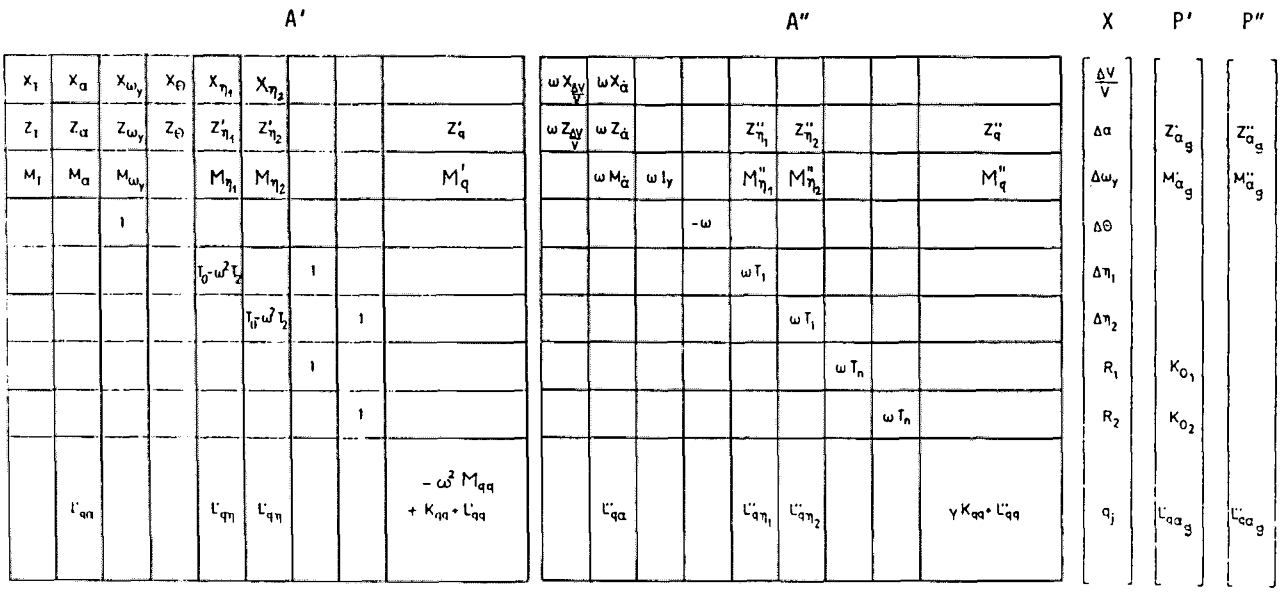
Highly effective servo and power actuator will be used, since the level of gust load reduction is approximately proportional to the control power. The rate of the control surface deflection needed is around 50 - 100°/sec for adequate load alleviation.

Modelling of the Elastic Aircraft

The longitudinal dynamics of the aircraft are formulated in a body axis system using Euler's equation to describe translatory and rotatory motions at sideslip zero. The equations of motion are then linearized at the trimmed condition. Axial normal force and momentum equilibrium are considered.

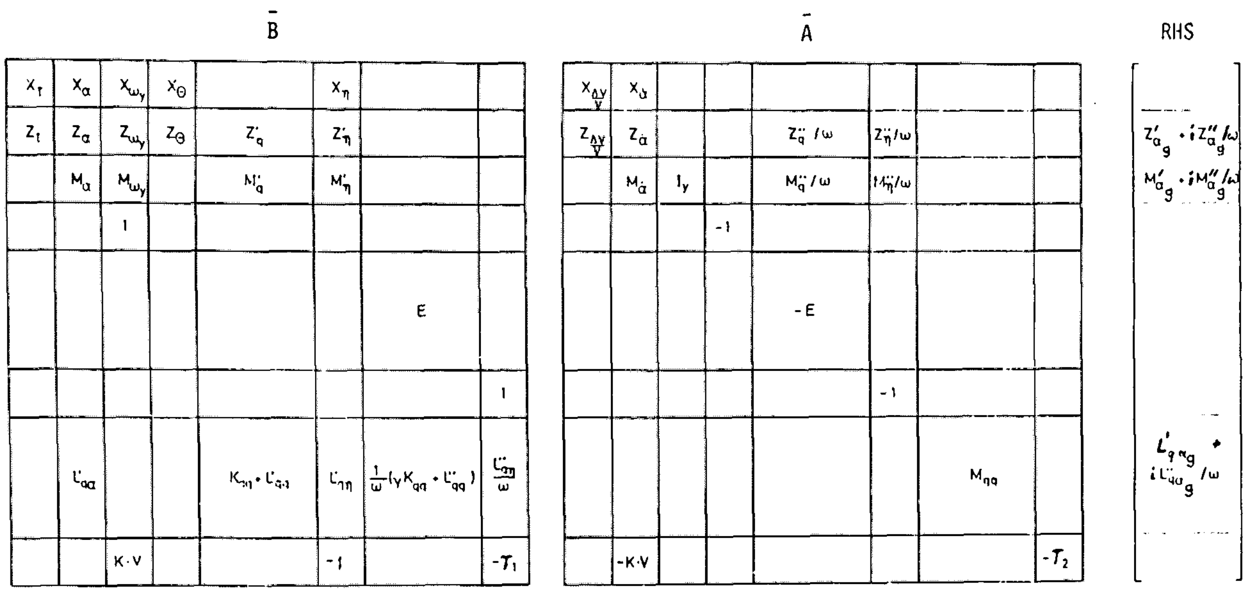
Modal analysis is used to formulate the structural dynamic equations /11/. The equations of motion of the rigid aircraft are aerodynamically coupled with the elastic equations, thus the rigid aerodynamic derivatives as well as the control surface efficiencies are modified by elastic deformations.

The coupled equations of motion are then transformed into the frequency domain to introduce unsteady aerodynamic effects due to gust and wing to tail interference using unsteady lifting surface theory /10/. The unsteady theoretical aerodynamic forces occuring in the flight dynamic equations are matched to the experimental stationary derivatives.



$$(A' + i A'')\, X = P' + i P''$$

FIG. 4 LINEARIZED EQUATIONS OF MOTION OF THE ELASTIC AIRCRAFT WITH OPEN LOOP SYSTEM



$$[\bar{B} + i\omega\bar{A}]\{X\}; \quad \{X\}^T = \lfloor \Delta V/V,\ \Delta\alpha,\ \Delta\omega_y,\ \Delta\Theta,\ q_j,\ \Delta\eta_i,\ \dot{q}_j,\ \Delta\dot{\eta}_i \rfloor$$

FIG. 5 LINEARIZED EQUATIONS OF MOTION OF THE ELASTIC AIRCRAFT WITH CLOSED LOOP SYSTEM

Additional equations are introduced which describe the dynamics of the control system. Transfer functions of the actuators and the dynamics of the control surfaces are taken into account. The control loop gains of the open loop and closed loop system are introduced as unknows which will be optimized during the design procedure. The linearized equations of motions of the elastic aircraft with gust load alleviation systems are demonstrated in fig. 4 and 5 using a matrix formulation.

This formulation is then used to investigate

- the stability of the elastic aircraft with and without gust load alleviation system
- to calculate the flutter margins
- to compute the gust response in the frequency domain

The abbreviations used in fig. 4 and 5 are listed below.

X - Force

$X_T = -qF2c_{X_T}$

$X_\alpha = -qFc_{X_\alpha}$

$X_{\dot\alpha} = -mV\sin\alpha$

$X_{\omega_y} = mV\sin\alpha$

$X_\Theta = mg\cos\alpha$

$X_\eta = qFc_{X_\eta}$

Z - Force

$Z_T = -qF2c_{Z_T}$

$Z_\alpha = -qFc'_{Z_\alpha}(\omega)$

$Z_{\dot\alpha} = -qF\dfrac{c''_{Z_\alpha}(\omega)}{\omega}$

$Z_{\omega_y} = -mV\cos\alpha - qFl_\mu\dfrac{c_{Z_q}}{V}$

$Z_\Theta = mg\sin\alpha$

$Z_\eta = qF[c'_{Z_\eta}(\omega) + ic''_{Z_\eta}(\omega)]$

$Z_q = qF\iint_{(F)}[\Delta c'_{p_q}(\omega) + i\Delta c''_{p_q}(\omega)]dF$

Pitch Moment

$M_\alpha = -qFl_\mu c'_{m_\alpha}(\omega)$

$M_{\dot\alpha} = -qFl_\mu\dfrac{c''_{m_\alpha}(\omega)}{\omega}$

$M_{\omega_y} = -qFl_\mu^2\dfrac{c_{m_q}}{V}$

$M_\eta = qFl_\mu[c'_{m_\eta}(\omega) + ic''_{m_\eta}(\omega)]$

$M_q = qFs\iint_{(F)}[\Delta c'_{p_q}(\omega) + i\Delta c''_{p_q}(\omega)](x - x_{C.G.})dF$

Generalized Forces

M_{qq}	Matrix of generalized masses
K_{qq}	Matrix of generalized stiffnesses
γK_{qq}	Matrix of model structural damping
$L'_{qq} + iL''_{qq}$	Matrix of theoretical generalized aerodynamic forces
$L'_{q\eta} + iL''_{q\eta}$	Aerodynamic coupling coefficients to describe flexible control surface efficiency
$L'_{q\alpha} + iL''_{q\alpha}$	Aerodynamic coupling coefficients to describe rigid A/A influence on elastic modes
$L'_{q\alpha_g} + iL''_{q\alpha_g}$	Vector of generalized aerodynamic forces due to gust
K_{01}, K_{02}	*Factors of gust compensation*
K	Vertical acceleration feedback gain

Unsteady normal force due to gust

$$Z_{\alpha_g} = qF \iint_{(F)} [\Delta c'_{\alpha_g}(\omega) + i\Delta c''_{\alpha_g}(\omega)]\, dF$$

Unsteady pitch moment due to gust

$$M_{\alpha_g} = qFs \iint_{(F)} [\Delta c'_{\alpha_g}(\omega) + i\Delta c''_{\alpha_g}(\omega)](x - x_{C.G.})\, dF$$

Gust incidence

$$\alpha_g(i\omega) = \exp[\frac{i\omega}{V}(x - \bar{x})]$$

E Matrix of unity

T_0, T_1, T_2 Transfer function of the actuator

$$F(s) = \frac{1}{T_0 + T_1 s + T_2 s^2}$$

T Coefficient of the control $\frac{1+T_z s}{1+T_n s}$

Gust Response Analysis

The procedure of the discrete gust and turbulence PSD analysis is given below.

Discrete Gust Analysis

Vertical gust velocity

$$w(t) = \frac{w_0}{2}(1 - \cos\frac{2\pi V}{L_g} t)$$

Angle of attack due to gust

$$\alpha_g(t) = \frac{w(t)}{V}$$

Analysis of the discrete gust in the frequency domain

- Fourier transform of gust

$$\alpha_g(i\omega) = \int_0^{t_0} \alpha_g(t)\, e^{-i\omega t}\, dt$$

$$t_0 = \frac{L_g}{V}$$

- Admittance function of the elastic aircraft with and without control system, unsteady aerodynamics with interference

$$H(i\omega) = A^{-1}(i\omega)\ P(i\omega)$$

- Transfer function of the response

$$Y(i\omega) = H_y(i\omega)\ \alpha_g(i\omega)$$

Elastic aircraft response in the time domain

$$y(t) = \int_{-\infty}^{\infty} Y(i\omega)\, e^{i\omega t}\, d\omega$$

PSD Analysis

Power spectral density of vertical gust velocity

v. KARMAN Spectrum:

$$\Phi_g = \frac{\sigma_g L}{\pi} \frac{1 + 8/3(1.339\, L\Omega)^2}{[1 + (1.339\, L\Omega)^2]^{11/6}},$$

$$\Omega = \frac{\omega}{V}$$ (see MIL-A-008861 A)

Power spectral density of the gust response y

$$\Phi_y(\omega) = |H_y(i\omega)|^2\ \Phi_g(\omega)$$

Evaluation of load exceedance

$$A_y = [\int_0^{\omega_c} \Phi_y(\omega)\, d\omega\,]^{1/2}$$

$$N_0 = \frac{1}{2\pi A_y} [\int_0^{\omega_c} \omega^2\, \Phi_y(\omega)\, d\omega\,]^{1/2}$$

$$N(y) = \Sigma\, t\, N_0\, [P_1 \exp(-\frac{y-y_{1g}}{b_1 A_y}) + P_2 \exp(-\frac{y-y_{1g}}{b_2 A_y})]$$

Loads

The calculation of the wing loading is performed using the dynamic response result. Sectional shear, bending and torsion moment due to gust are derived by introducing theoretical unsteady lift distributions of the angle of attack of the control surface and of elastic deformations. In addition, the spanwise distribution of the loads due to inertia forces are considered. The total load distribution is thus described by

- inertia forces
- gust induced forces
- motion induced forces
- aileron and spoiler forces

Quasi Steady Model

A simplified analytical model is used to optimize the control law. A quasi steady approximation of the lift and moment derivatives and the unsteady aerodynamic forces of elastic modes is used. The forces due to elastic modes are approximated each at the eigenfrequency. The equations of motion are transformed into the time domain. The calculation of the gust response is then easily performed, with a small amount of computer time and known procedures to optimize the control law may be applied.

Unsteady Analytical Model

The quasi steady design of the control law will be checked by calculations using the unsteady analytical model. In addition, the PSD analysis of the controlled aircraft is performed using the unsteady model. The PSD analysis leads to spectral densities of the load distributions due to turbulent gust and permits the calculation of RMS values and limit load exceedances per flight hour.

Results

Investigation of Stability and Flutter of the Unaugmented Aircraft

Frequency and damping of the phugoid, the short period and of the first twelve elastic modes are calculated for the cruise condition at 7.8 km altitude and Mach 0,86 (fig. 6). The frequencies of the elastic modes and of the flight mechanic indicate that there is only small coupling; the frequency of the short period is 0,22 cps and that of the first wing bending 2.37 cps. All elastic modes show positiv damping. The nacelle modes are almost undamped. The damping of the short period mode is high ζ = 0,59.

	σ	$\pm\omega$	ζ	ω_n
	- 0,0028	0,042	0,066	0,042
	- 0,84	1,13	0,59	1,41
1	- 0,0059	12,8	0,00046	12,84
2	- 1,08	14,7	0,073	14,81
3	- 1,20	19,3	0,062	19,34
4	- 0,52	22,3	0,023	22,34
5	- 1,23	23,3	0,052	23,42
6	- 0,0022	35,5	0,000063	35,58
7	- 3,68	40,3	0,090	40,50
8	- 2,60	42,5	0,060	42,66
9	- 6,61	50,8	0,128	51,31
10	- 1,12	54,3	0,020	54,31
11	- 1,03	68,6	0,015	68,60
12	- 2,46	79,3	0,031	79,38

FIG. 6 RESULT OF THE STABILITY ANALYSIS OF THE AIRCRAFT WITH OPEN LOOP SYSTEM (M = 0,86, H = 7,843 KM)

The result of the flutter investigation using the pk-method is shown in fig. 7. Flutter occurs at 380 kts (EAS), the cruise condition lies at 340 kts (EAS). Flutter is mainly caused by the coupling of the 6th and 9th mode.

The result demonstrates that an active flutter margin augmentation system may be necessary.

The presented results are the same for the aircraft with an open loop gust load compensation system.

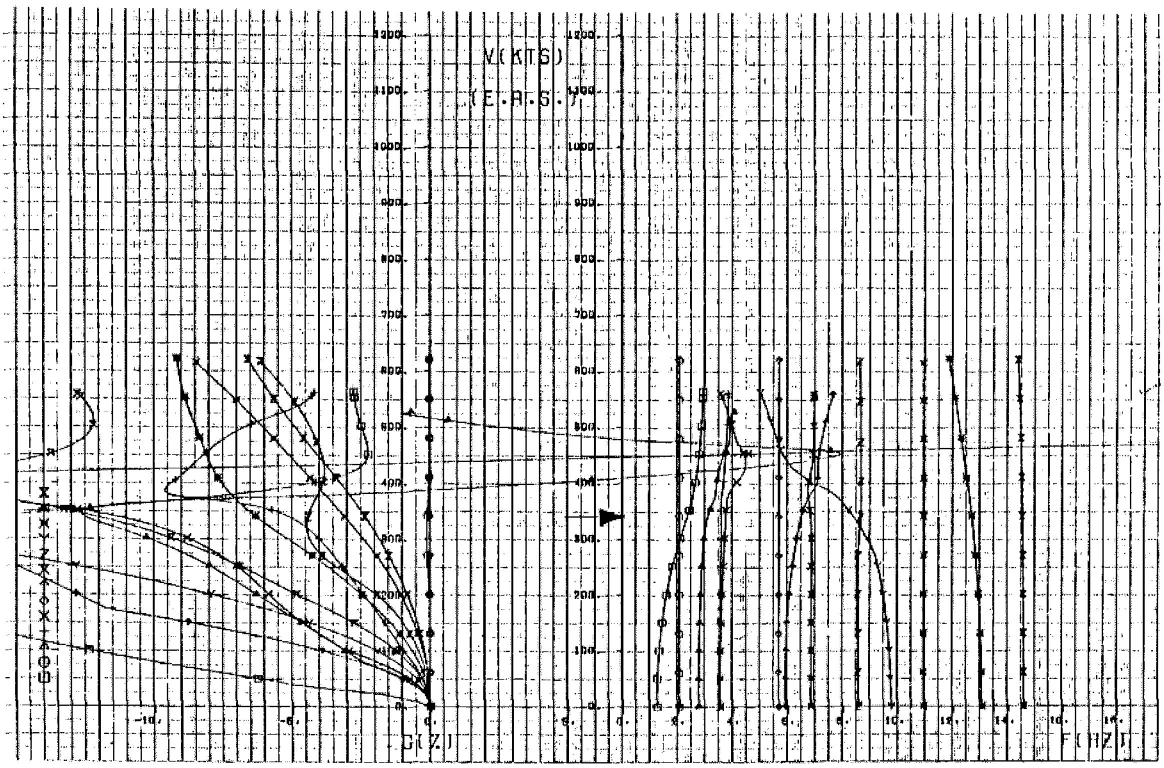


FIG. 7 RESULT OF THE FLUTTER ANALYSIS (UNSTEADY AERODYNAMIC FORCES FROM LIFTING SURFACE THEORY WITH INTERFERENCE)

Stability Investigation of the Controlled Aircraft

The closed loop gust load alleviation system based on acceleration feedback influences flying qualities and flutter. Control Systems to increase the damping of high frequency structural modes, for instance flutter damper systems will also lead to interference effects with the gust load alleviation system which should be investigated carefully for the design of an integrated system with high reliability. The interference of gust load, ride and flutter control systems will be investigated also by the GARTeur-group working on active gust load control (fig. 8) where MBB participates actively.

A result of the stability investigation on the Airbus with closed loop gust load alleviation system, is shown in fig. 9. The acceleration feedback of the fuselage signal to the outboard aileron leads to

- more than critical damping of the short period
- additional damping of different elastic modes without destabilising effects.

The more than critical damping of the short period mode may lead to undesirable flying qualities.

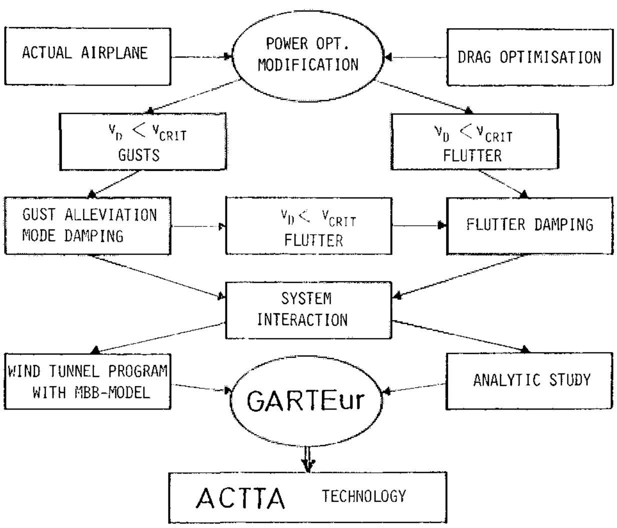


FIG. 8 INFLUENCE OF GUST LOAD ALLEVIATION AND FLUTTER MODE CONTROL

σ	$\pm\omega$	ζ	ω_n
- 0.068	0.017	0.96	0.071
- 0.10; - 1.40			
- 0.0053	12.84	0.0004	12.84
- 1.26	14.74	0.080	14.80
- 1.36	19.36	0.070	19.41
- 0.91	22.34	0.041	22.36
- 1.34	23.38	0.057	23.42
- 0.0031	35.58	0.0001	35.59
- 4.159	40.33	0.102	40.54
- 3.34	42.60	0.090	42.73
- 8.51	49.37	0.169	50.10 *
- 1.95	54.26	0.036	54.29
- 2.62	68.45	0.038	68.50
- 4.41	78.92	0.055	79.05

FIG. 9 RESULT OF THE STABILITY ANALYSIS OF THE AIRCRAFT WITH CLOSED LOOP SYSTEM (M = 0.86, H = 7.843 KM)

Gust Load Calculations

Maximum loads and load alleviation were calculated using a quasisteady approach. They are shown in fig. 10, 11 and 12. The figures demonstrate the time dependence of wing root bending moment as a function of gust incidence and state variables for a (1-cos) gust.

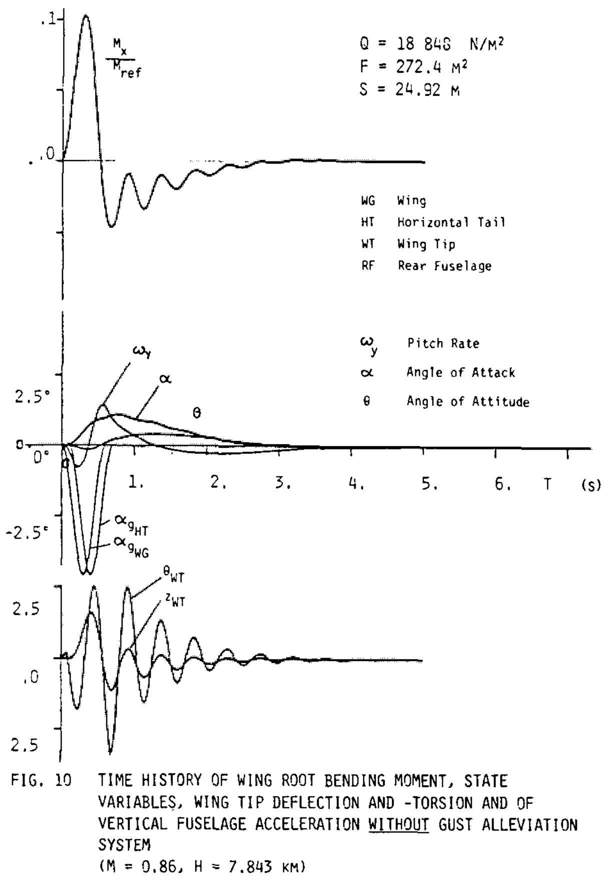


FIG. 10 TIME HISTORY OF WING ROOT BENDING MOMENT, STATE VARIABLES, WING TIP DEFLECTION AND -TORSION AND OF VERTICAL FUSELAGE ACCELERATION WITHOUT GUST ALLEVIATION SYSTEM (M = 0.86, H = 7.843 KM)

The alleviation of the maximum wing root bending moment due to active open loop control, using aileron, spoiler and elevator, is demonstrated in fig. 11.

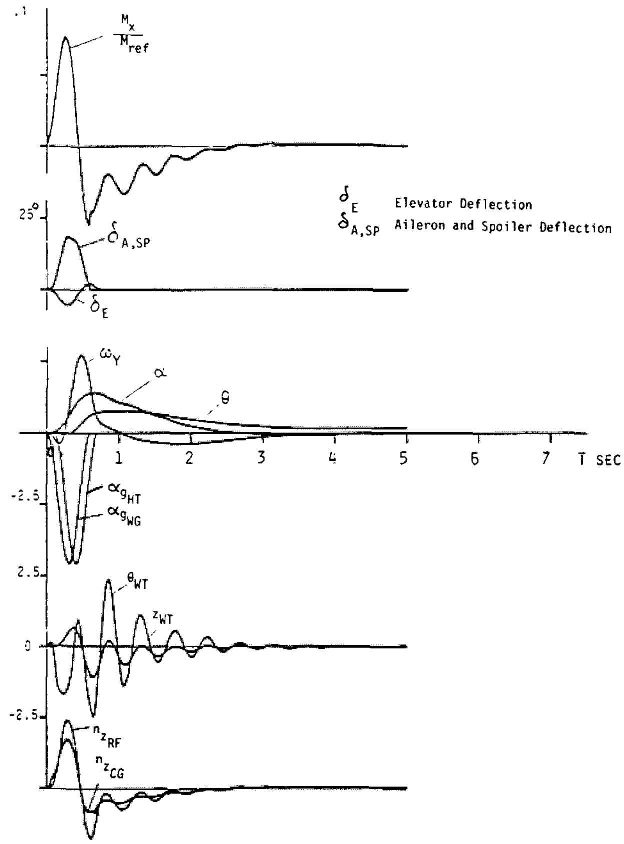


FIG. 11 TIME HISTORY OF WING ROOT BENDING MOMENT, STATE VARIABLES, WING TIP DEFLECTION AND -TORSION AND FUSELAGE ACCELERATION WITH OPEN LOOP GUST LOAD ALLEVIATION SYSTEM (M = 0.86, H = 7.843 KM)

Load alleviation of about 24% of the wing root bending moment may be achieved by open loop control and 40% with additional use of $\dot{\alpha}_g$ with the assumption of 100 degree/s control surface turn rate at a gust length of 160 m. The alleviation decreases with decreasing gust length.

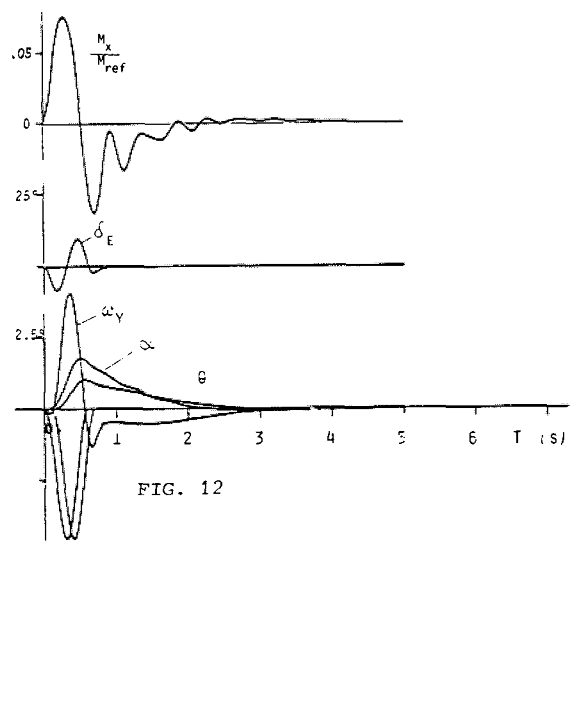


FIG. 12

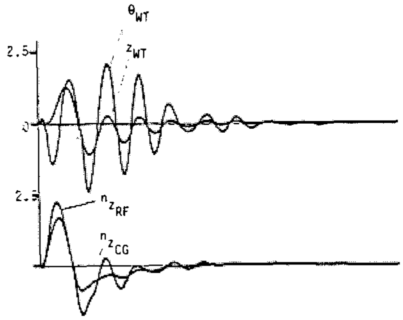


FIG. 12 TIME HISTORY OF WING ROOT BENDING MOMENT, STATE VARIABLES, WING TIP DEFLECTION AND -TORSION AND FUSELAGE ACCELERATION WITH CLOSED LOOP GUST LOAD ALLEVIATION SYSTEN (M = 0.86, H = 7.843 KM)

Result of the Unsteady Investigation

The unsteady model was used to calculate the loads on the aircraft with open and closed loop system in the cases without spoiler activity, since unsteady spoiler aerodynamics were not known. Further calculations should be performed with unsteady spoiler derivatives from Bernier and Parkinson /12/ or measured data.

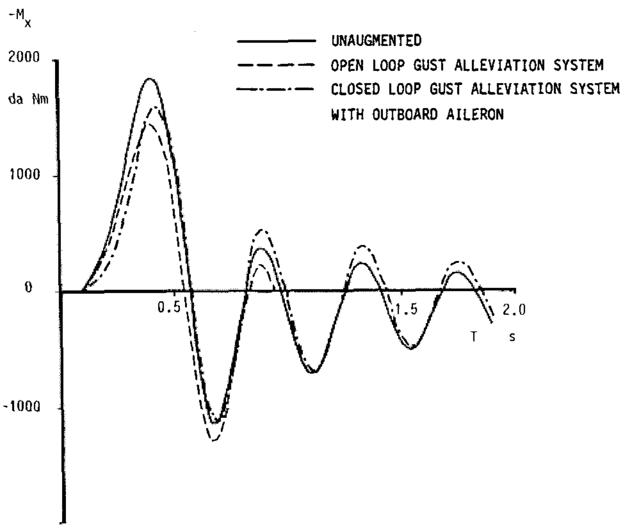


FIG. 13 EFFECT OF OPEN AND CLOSED LOOP GUST LOAD ALLEVIATION ON THE TIME HISTORY OF THE BENDING MOMENT AT WING SECTION Y = 17.4 M

Fig. 13 shows the effect of the open and closed loop gust load alleviation system on the wing bending moment at an outboard wing section.

In Figure 14 the spanwise distribution of maximum shear and bending moment due to (1-cos) gust is depicted.

The alleviation factors of the spanwise shear and bending moment distribution at a gust length of 25$\bar{c}$ are presented in fig. 15.

Fig. 16 shows the effect of gust length on outboard aileron deflection and rate.

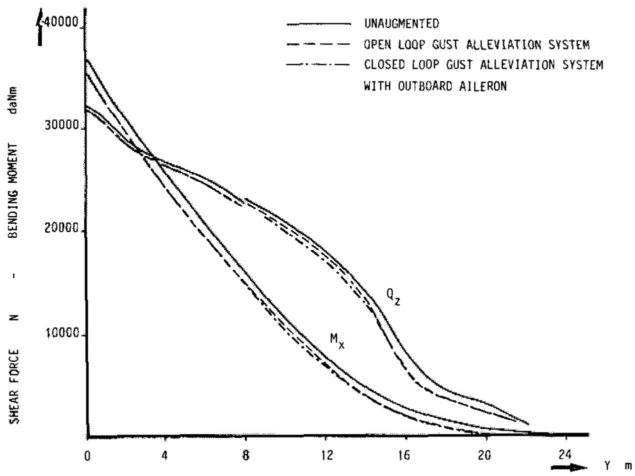


FIG. 14 SPANWISE DISTRIBUTION OF MAXIMUM SHEAR AND BENDING MOMENT - COMPARISON OF OPEN AND CLOSED LOOP GUST LOAD ALLEVIATION

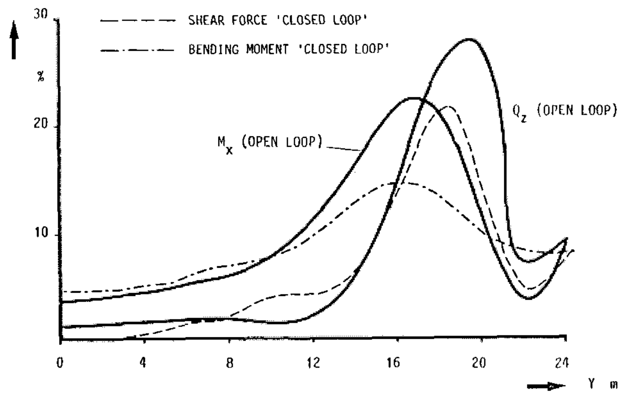


FIG. 15 ALLEVIATION FACTORS OF THE SPANWISE SHEAR AND BENDING MOMENT DISTRIBUTION AT GUST LENGTH 25 $\bar{c}$

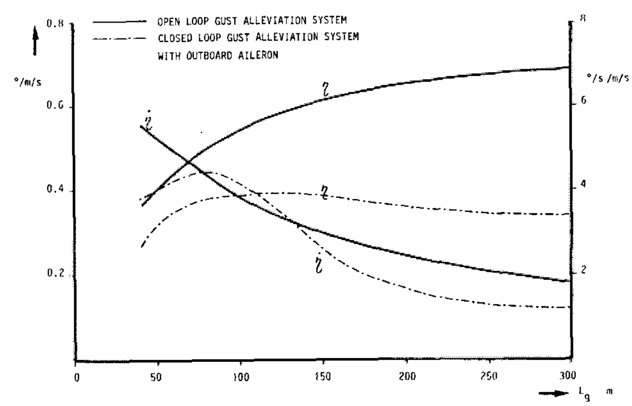


FIG. 16 EFFECT OF GUST LENGTH ON OUTBOARD AILERON DEFLECTION AND PITCH RATE - COMPARISON OF OPEN AND CLOSED LOOP GUST LOAD ALLEVIATION

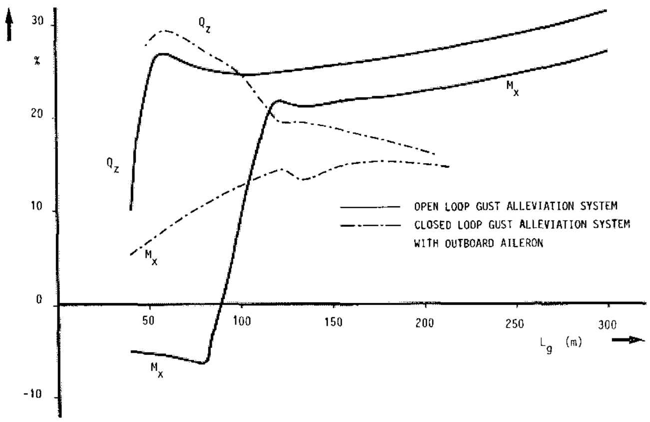


FIG. 17 EFFECT OF GUST LENGTH ON THE MAXIMUM SHEAR AND BENDING MOMENT REDUCTION AT THE WING SECTION Y = 17.4 M

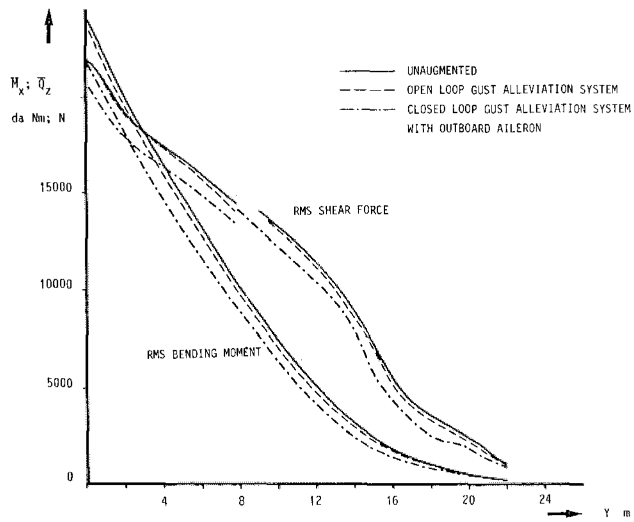


FIG. 18 TURBULENT GUST ANALYSIS:
SPANWISE RMS VALUES OF SHEAR AND BENDING MOMENT
- COPARISON OF OPEN AND CLOSED LOOP GUST ALLEVIATION

Fig. 17 illustrates the effect of gust length on the maximum shear and bending moment reduction.

The disadvantage of the open loop system is documented in this figure. the system is sensitive to different gust length. At gust lengths less than 100 m, the system is not effective and leads to increase of the load at the wing tip (y = 17.4 m). The closed loop system is not as sensitive. Load alleviation is achieved continuously along the span.

A summary of the results given in fig. 15 and 17 indicates that both, the open and closed loop system lead to 5 percent alleviation on the root at a gust length of 25 c. At the wing tip section, a 24 percent reduction was possible. At the outboard station, the closed loop system was not as effective (fig. 16).

Fatigue Loads

Power spectral densities are derived using the v.Karman spectral density of the vertical gust velocity. They are used to compute the intensity and probability of occurences. The investigation is performed for one flight condition and should be extended to cover the whole flight regime.

In fig. 18 a comparison of the RMS shear and bending moment distribution for the controlled and unaugmented aircraft is presented which was derived by the integration of the power spectra of fig. 19.

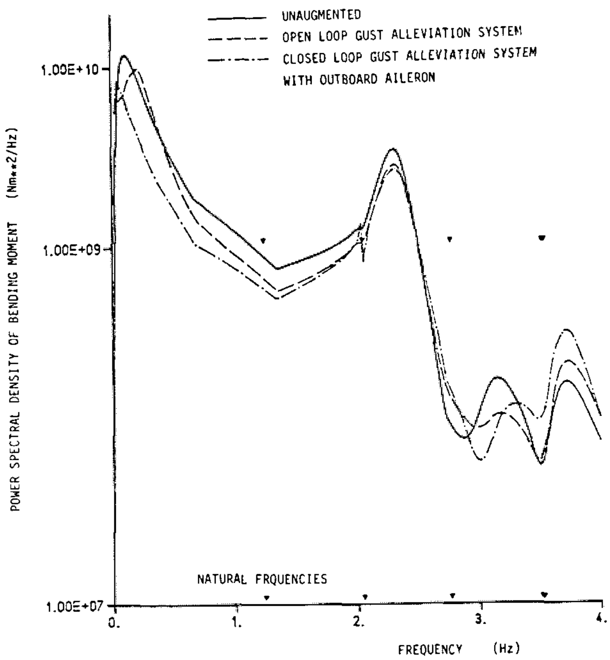


FIG. 19 POWER SPECTRAL DENSITY OF THE WING BENDING MOMENT AT y = 17.4 m - COMPARISON OF OPEN AND CLOSED LOOP GUST LOAD ALLEVIATION

The spanwise reduction of RMS shear and bending moment is shown in fig. 20

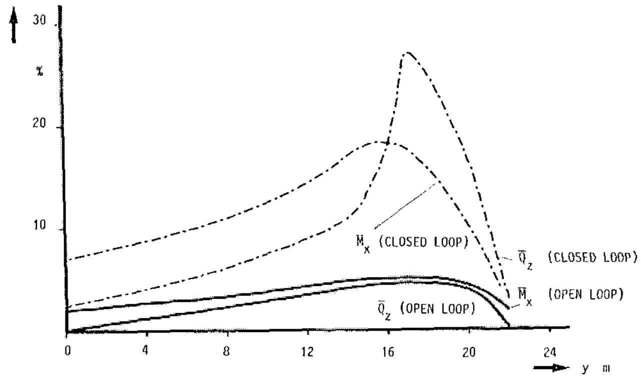


FIG. 20 TURBULENT GUST ANALYSIS: SPANWISE REDUCTION OF RMS SHEAR AND BENDING MOMENT - COMPARISON OF OPEN AND CLOSED LOOP GUST ALLEVIATION

It may be concluded that the closed loop load alleviation system is much more effective in comparison to the open loop control. At the wing root 8 percent in comparison to 2.5 percent with the compensation. At the wing tip, a 20 percent alleviation could be gained using acceleration feedback. The lower effeciency of the open loop system may be caused by the fact that the incemental pitch moment, due to elastic deformation, is not fully compensated.

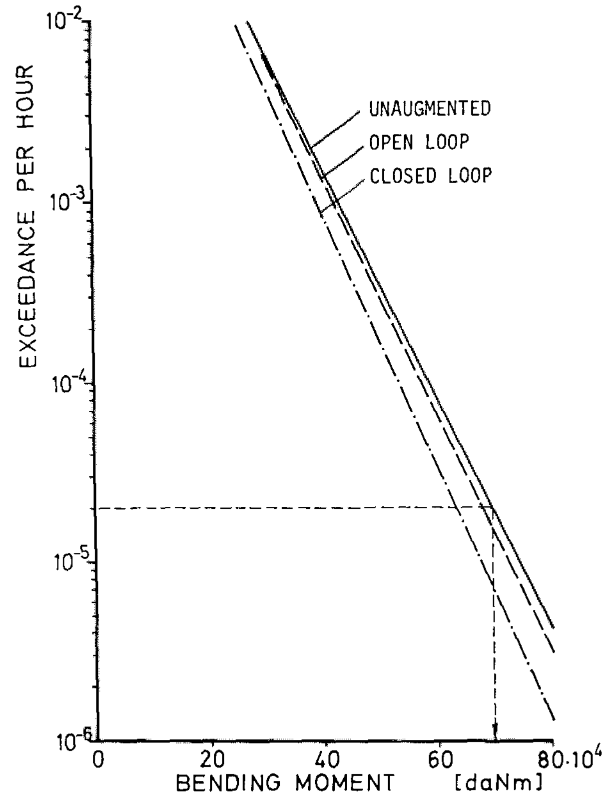


FIG. 21 **EXCEEDANCES PER HOUR OF THE BENDING MOMENT AT y = 2.78 m - EFFECT OF OPEN AND CLOSED LOOP SYSTEM**

Exceedances per Flight Hour

Exceedances of load levels are presented in Fig. 21-22. Bending moment at the wing root and wing tip is shown. Using active load control, high reduction of the fatigue loads can be achieved. For instance, the load level of $47 \cdot 10^3$ daNm is exceeded once in 50 000 flight hours for the Airbus without control whereas the same level will be exceeded once in 330 000 hours using the closed loop gust load alleviation system.

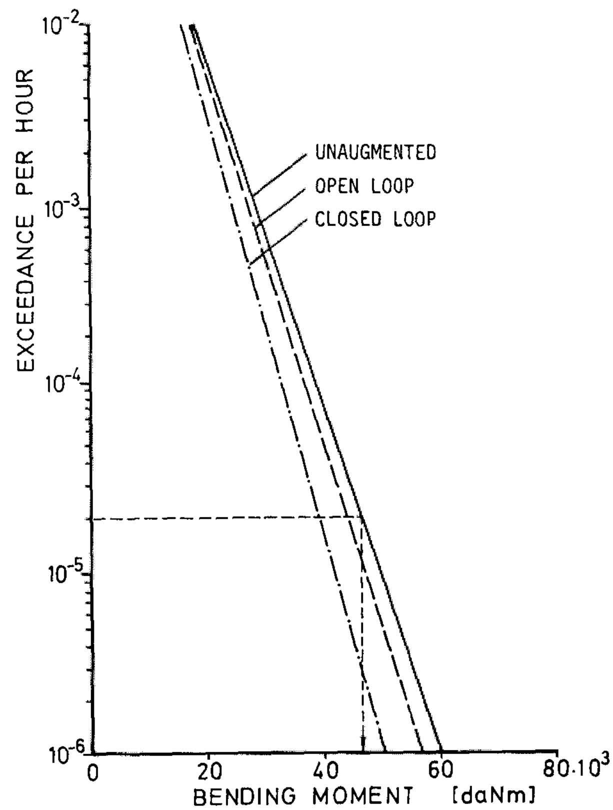


FIG. 22 **EXCEEDANCES PER HOUR OF THE BENDING MOMENT AT y = 17.4 m - EFFECT OF OPEN AND CLOSED LOOP SYSTEM**

Preliminary Investigations on Passive Load Alleration

Design Philosophy

Passive means of load alleviation would be preferable to active ones considering that maintenance and reliability problems are greatly reduced and actuator power requirements are relieved. Also passive control systems can be made fail safe without using expensive and heavy redundancy concepts. Passive load alleviation, using wing tip extensions could be implemented without changing the existing structure.

Aeroelastic tailoring, using composite materials has opened a wide field for aircraft designers. Aerodynamic improvements are possible because desired elastic deformations in different points of the flight envelope can be achieved.
Weight can be saved by getting favourable load distributions and the flight envelope can be enlarged compared to conventional constructions.

It is assumed, that the two wings with and without tip extension have the same main structure. For design limit load n_z = 2.5 and equal gross weight the wing root stresses must be the same. In cruise flight the wing tip extension leads to higher bending moments but structural stress/strain boundaries are not affected.

Analytical Approach

The investigations were performed with the ASAT computer program. This program system is a very effective theoretical design tool. It is based on a finite element method, capable to perform strength and flutter optimization. The different modules offer many analytical possibilities and they are capable to work interactive.

Investigations can be done for

- subsonic and supersonic aerodynamic load analysis
- strength analysis and optimization
- vibration calculations
- unsteady aerodynamic load analysis and flutter calculation
- interactive flutter and strength optimization
- steady state aeroelasticity (loads and efficiencies)

For this investigation the wing box is idealized by 70 elements (fig. 23). At fixed wing box geometry, the elements are sized to fulfill the stiffness distributions EI(y) and GJ(y). The relative thickness of the extension is reduced from 10 to 5 percent at the tip to increase bending. The cover sheet elements in the tip extension are used to study the effects of different materials and their anisotropic behaviour. In the ASAT Program the aerodynamic lift forces are calculated using a vortex lattice method with 78 elements and a subdivision, as shown in Fig. 24.

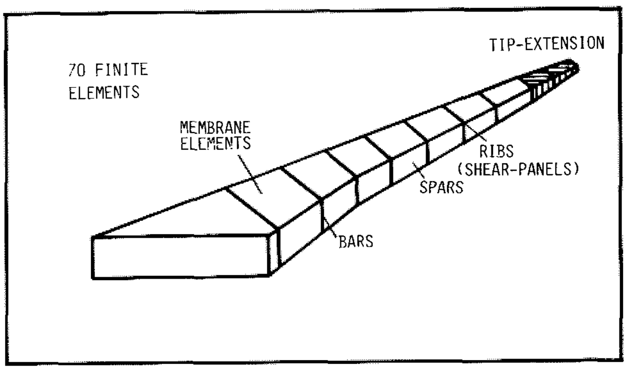


FIG. 23 ASAT - STRUCTURAL IDEALIZATION FOR A 300 EXTENDED WING

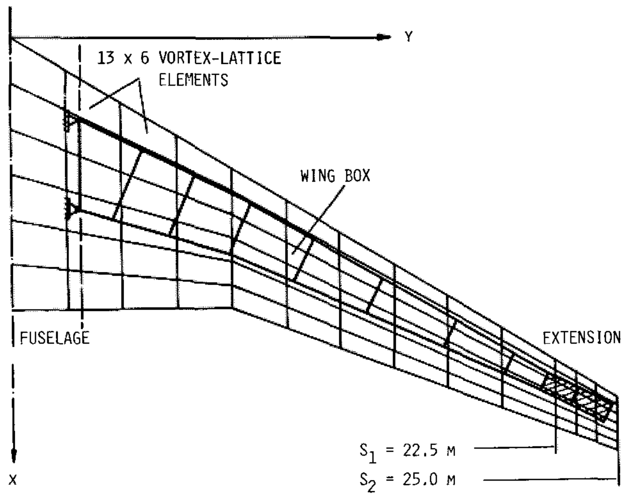


FIG. 24 STRUCTURAL AND AERODYNAMIC IDEALIZATION

In a first step, load distribution and structural stresses are analyzed for 2.5 g limit load for the baseline wing. This is performed for the undeformed wing and for steady state aeroelastic equilbrium.

For the extended wing the same is done using aluminium, glass fibre and carbon fibre composites with different layer combinations and orientations. During the calculation procedure also the cruise flight load case is considered with respect to optimum lift distribution.

Results

For the rigid extended wing, there is an increase of 7 percent in wing-root bending moment at 1g and 12 percent at ultimate load 3.75 g. Comparing however the elastic wing the best result was obtained for a wing tip extension structure consisting of a glass fibre composite (0°) 60 (+45°) 40 which is rotated 20 deg. forward of the wing box center line. At limit load 2.5 g the increase in bending moment is only 1.7% for the elastic wing.

Fig. 25 shows the increment in angle of attack for the selected material. The load distribution for both wings is compared in Fig. 26, while Fig. 27 shows the corresponding shear force and Fig. 28 the bending moment distributions. These results indicate that passive load alleviation is an efficient design tool but further investigations are necessary, for example to study unsteady effects (gust load investigation, flutter behaviour).

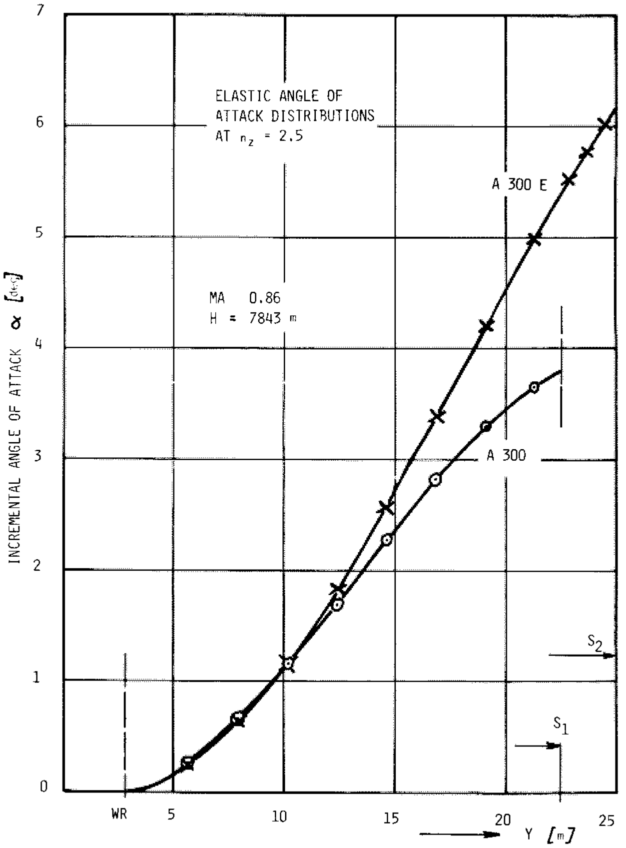


FIG. 25 ANGLE OF ATTACK DISTRIBUTIONS DUE TO ELASTIC DEFORMATION

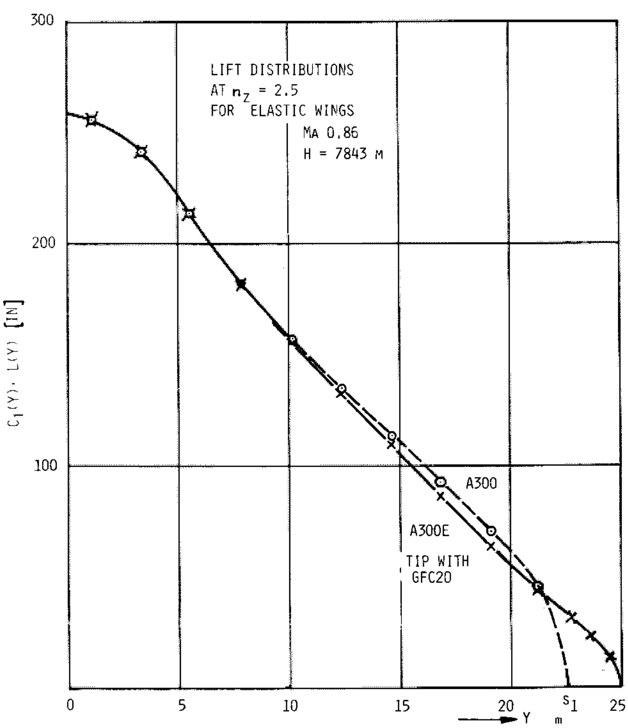


FIG. 26 LIFT DISTRIBUTIONS AT LIMIT LOAD FOR THE ELASTIC WINGS

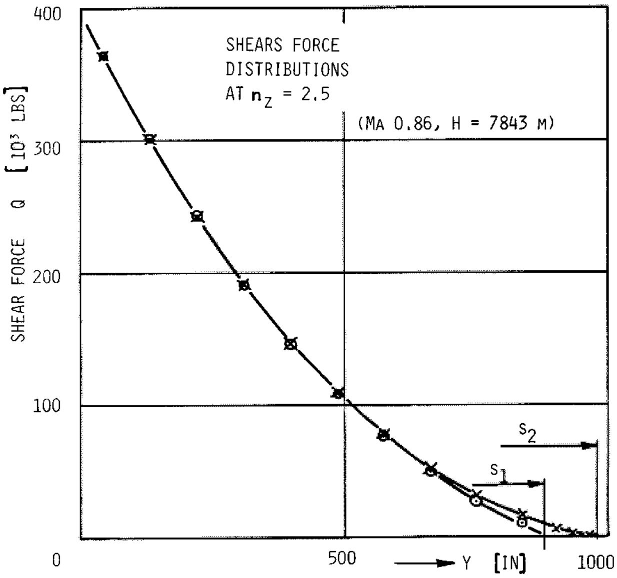


FIG. 27 SHEAR FORCE COMPARISON

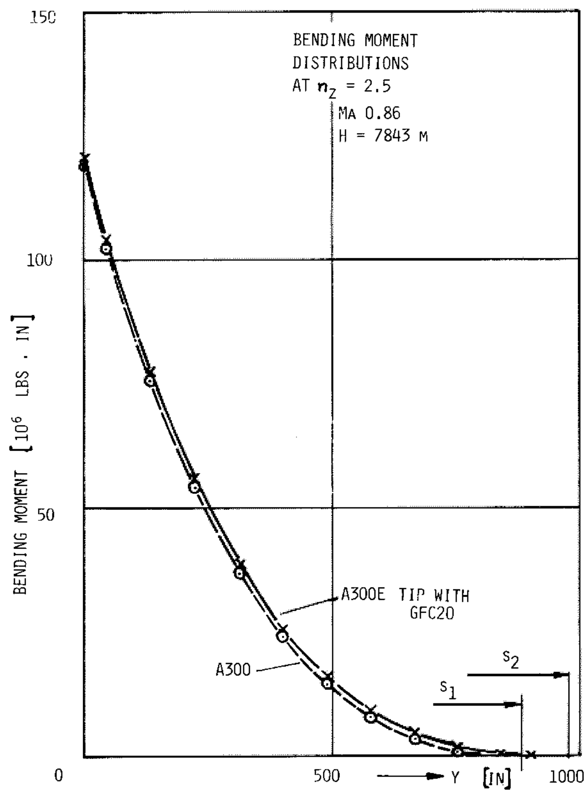


FIG. 28 BENDING MOMENT DISTRIBUTIONS

If passive load alleviation is applied to new wing designs over the whole span, the advantages may be much greater.

Besides passive or active load alleviation, a third option is possible, which is a combination of both. Free-floating wing tips /14/ may offer various design possibilities.

Acknowledgement

The valuable work of J. Schweiger on the passive load alleviation system was very much appreciated by the authors.

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