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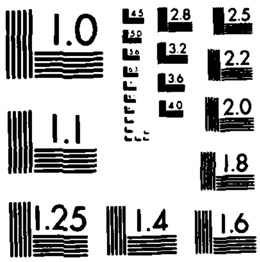


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# Gust Load Prediction and Alleviation on a Fighter Aircraft

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.728

# GUST LOAD PREDICTION AND ALLEVIATION ON A FIGHTER AIRCRAFT

by

J.Becker



Papers presented at the 61st Meeting of the Structures and Materials Panel of AGARD in Oberammergau, Germany on 8–13 September 1985.

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by

J. Becker

MESSERSCHMITT-BÖLKOW-BLOHM GmbH.
Airplane and Helicopter Division
P.O. Box 801160, 8 Munich 80
W.-Germany

Contribution to the AGARD-Activity
"Flight of Flexible Aircraft in Turbulence"

## INTRODUCTION

Turbulence induced dynamic loads and vibrations on a fighter aircraft may play a considerable role for certain configurations with respect to the design of the structure and the performance of special missions or they may cause on the other hand limitations of the flight envelope.

As far as aircombat aircraft are concerned typical restrictions may be found for instance with respect to design gust loads if wing tip mounted store configurations are investigated or with respect to ride comfort if low level high speed missions are evaluated. Here both aspects namely design gust critical cases and ride comfort are therefore reported in more detail in order to demonstrate the problem areas. In this context also some difficulties of turbulence response prediction methods will be described, especially with respect to the dynamics of the aircraft with FCS and the interaction of flight and structural dynamics, though these methods are well established. In addition problem areas of the aircraft with FCS and gust alleviation system are mentioned for the case of ride improvement. The design of such systems would strongly necessitate the full dynamic description of the flexible fighter aircraft in order to evaluate maximum loads, fatigue loads and structural coupling problems with the control system.

## CONSISTENCY WITH MILITARY REQUIREMENTS

The following problem areas may be of importance for the aircraft with FCS and for dynamic load alleviation and ride improvement systems. During the development of a system for the proper achievement of ride smooting, as for instance based on the requirements as specified in MIL-F-9490 D (USAF) chapter 3.1.2.12, or for the purpose of gust load alleviation (MIL-A-8861 requirements) of course the controlled aircraft must be investigated with respect to

- degradation of flying qualities and handling
- adverse effects on airplane strength and rigidity:

  flight loads, fatigue loads, vibration, flutter and aeroservoelastic stability, because conflicts could exist between the different specifications. In detail the below mentioned aspects should be considered.
- stability

  destabilisation of aircraft modes or structural modes. Structural coupling problems in flight followed by degrading effects on stiffness and on elastic mode damping or aeroservoelastic flutter.
- Static and dynamic loads:

  Change of maximum design loads and fatigue loads caused by control surface activities.

In addition all effects caused by system limitations (actuator power, control surface rates and deflection) should be investigated and a system failure strategy developped.

## METHODS FOR CALCULATING THE DYNAMIC RESPONSE OF FLEXIBLE AIRCRAFT IN TURBULENCE

Several methods are well established for the calculation of the flexible aircraft in turbulence. Of course these methods have there own advantages but are not necessarily in a stage for the solution of specific problems especially occuring if static unstable aircraft configurations are considered or gust alleviation systems are investigated. Two approaches will in general be used in parallel:

a) The solution of the *nonlinear* flight dynamic equations of motion of the aircraft with flight control system dynamic equations together with structural dynamic equations in time domain.

b) The solution of linearised flight dynamic equations of motion of the aircraft with coupled structural dynamic equations in frequency and in time domain.

The calculation of the dynamic response in time domain using a) includes the simulation of nonlinear effects at severe disturbance conditions, as for example aerodynamic nonlinearities (which are included in the static aerodynamic data set), rate and deflection limitations of the control surfaces due to marginal actuator power and inertia coupling at high rates.

Several disadvantages may arise in this approach if effects of the flexible aircraft on the total aircraft response are only treated in a pure quasisteady approach as normally used in flight dynamic simulation by the introduction of a flexibilised steady aerodynamic data set.

Consequently this approach could lead to a wrong prediction of local dynamic response and maximum dynamic loads.

In addition this quasisteady approach will not account for time correlated structural dynamic and flight dynamic responses since no aerodynamic coupling exists between structural dynamic and flight dynamic equations. A superposition of rigid and elastic aircraft vibrations in the right phase will not be possible. The disadvantages therefore could be found in not accurate predictions of maximum or stochastic vibrations and of dynamic loads. The analytical investigation of structural coupling effects, which are of interest especially for static unstable aircraft cannot be performed adequately by this approach.

The dynamic response approach using linearized equations of motion of the aircraft around trimmed condition coupled with structural dynamic equations and flight control equations will give the possibility to introduce the unsteady and coupling effects in a proper sense. Therefore flight dynamic and structural dynamic responses are described in the right phase and the superposition of vibration and dynamic loads from both contributions can be performed. In addition of course the stability of the total aircraft can be calculated for the flight control system closed. Open loop phase and gain margins for the total system can be investigated which would give more insight into the coupling effects of the flexible aircraft modes on the stability of the flight dynamic modes and the structural dynamic modes by evaluation of the Bode diagram in the frequency range 0 - $f_{max}$. ($f_{max}$ is the frequency of the *highest flexible mode used in the analytical model*). The linearised model in advance gives information about the transfer functions of all state variables, of local accelerations and of dynamic loads due to a gust input. These evaluations are also of interest especially if gust alleviation systems are studied. Besides the calculation of power spectral densities of the above mentioned variables also the incremental responses at trimmed condition can be calculated with the linearised model in time domain and nonlinear effects like rate and deflection limitations can be evaluated as well in a first step. Disadvantages can arise through the derivation of unsteady airloads at transsonic speeds or at higher incidences where some limitations of the theoretical procedures could be existent. Correction methods using experimental static or dynamic experimental results should be applied.

<u>APPROACH 1:</u>

Nonlinear flight dynamic equations in body fixed coordinates and structural dynamic equations without coupling.

Flight dynamic equations:

$$X = m(\dot{U}-VR+WQ)$$
$$Y = m(\dot{V}-WP+UR)$$
$$Z = m(\dot{W}-UQ+VP)$$

$$L = I_x\dot{P}-I_{xy}\dot{Q}-I_{xz}\dot{R}+Q(-I_{xz}P-I_{yz}Q+I_zR) -R(I_{xy}P+I_yQ-I_{yz}R)$$

$$M = I_{xy}\dot{P}+I_y\dot{Q}-I_{yz}R+(I_xP-I_{xy}Q-I_{xz}R)R -(-I_{xz}P-I_{yz}Q+I_zR)P$$

$$N = -I_{xz}\dot{P}-I_{yz}\dot{Q}+I_z\dot{R}+(I_{xy}P+I_yQ-I_{yz}R)P -(I_xP-I_{xy}Q-I_{xz})Q$$

| | |
|---|---|
| P, Q, R | roll, pitch yaw rate |
| $I_x$, $I_y$, $I_y$ | moment of inertia |
| $I_{xy}$, $I_{xz}$, $I_{yz}$ | |

| | | | |
|---|---|---|---|
| Normal force | $Z = \frac{\rho}{2} U^2 F c_z$ | Rollmoment | $L = \frac{\rho}{2} U^2 \, 2 s F c_l$ |
| Axial force | $X = \frac{\rho}{2} U^2 F c_x$ | Pitchmoment | $M = \frac{\rho}{2} U^2 \bar{c} F c_m$ |
| Side force | $Y = \frac{\rho}{2} U^2 F c_y$ | Yawmoment | $N = \frac{\rho}{2} U^2 \, 2 s F c_n$ |

$$c_x, c_y, c_z, c_l, c_m, c_n = c\,(\alpha, \eta_i, H, Ma)$$

The flexible aerodynamic coefficients are functions of incidence , control surface deflection $\eta_i$, altitude H and Machnumber Ma.

Additional structural dynamic equations:

$$M_r \ddot{q}_r(t) + \sum_{j=1}^{J} D_{rj} \dot{q}_j(t) + M_r \omega_r^2 q_r(t) + \sum_{j=1}^{J} A_{rj}(\alpha_o, Ma, t)\, q_j(t) = Q_r(\alpha_o, Ma, t)$$

| | |
|---|---|
| $M_r$ | generalised mass of natural mode r |
| $M_r \;\; r^2$ | generalised stiffness of natural mode r |
| $A_{rj}$ | generalised aerodynamic forces |
| $Q_r$ | generalised gust force of mode r |
| $q_r$ | generalised coordinate of mode r |

The deflection z at a point of the aircraft is assumed to be

$$z\,(x, y) = \sum_{r=1}^{n} \phi_r\,(x, y)\, q_r$$

$\phi_r$ total aircraft natural mode r

APPROACH 2:

Linearised flight dynamic equations, control and structural dynamic equations are here formulated in frequency domain.

The structure of the coupled equations of the aircraft dynamics shall be described in matrix notation as shown in Fig. 1.

$$\begin{bmatrix} M_{RR} & 0 \\ 0 & M_{EE} \end{bmatrix} \begin{bmatrix} \ddot{X}_R \\ \ddot{X}_E \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & D \end{bmatrix} \begin{bmatrix} \dot{X}_R \\ \dot{X}_E \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K_E \end{bmatrix} \begin{bmatrix} X_R \\ X_E \end{bmatrix} =$$

$$\begin{bmatrix} L_{RR} & L_{RE} \\ L_{ER} & L_{EE} \end{bmatrix} \begin{bmatrix} X_R \\ X_E \end{bmatrix} + \begin{bmatrix} P_R \\ P_E \end{bmatrix}$$

FIG. 1 FLEXIBLE AIRCRAFT DYNAMICS COUPLED FLIGHT AND STRUCTURE DYNAMIC EQUATIONS

The following notation are used:

| | |
|---|---|
| $X_R$ | Degree of Freedom Rigid Aircraft |
| $X_E$ | Degree of Freedom Flexible Aircraft |
| $L_{RR}$ | Matrix of Rigid Aircraft Aerodynamic Coeff. |
| $L_{EE}$ | Matrix of Generalised Aerodynamic Coeff. |
| $L_{RE}$ | Coupling Terms (Lift and Moment due to Defl.) |
| $L_{ER}$ | Coupling Terms of Rigid Motion to the Generalised Aerodynamics |
| $P_R$ | Rigid Excitation Forces |
| $P_E$ | Generalised Excitation Forces |
| $K_E$ | Matrix of Generalised Stiffness |

The aerodynamic terms and the degrees of freedom are complex functions in frequency consisting of real- and imaginary parts.

The rigid aircraft aerodynamic terms may be introduced using a experimental data set (rigid) or calculated derivatives $L_{RR}$ (except the drag terms) using computer programs for the calculation of unsteady aerodynamic forces (Ref. 1, 2, 3), which can be applied also for the derivation of the $L_{EE}$, $L_{RE}$, $L_{ER}$, $P_R$ and $P_E$ matrices.

A more detailed structure of the longitudinal symmetric dynamics of the total aircraft is shown in matrix notation in Fig. 2, where the first four equations describe the flight dynamics excited by gust induced forces and moments. They include the aerodynamic coupling terms $Z_j$, $M_j$ the normal forces and pitch moments due to total aircraft elastic modes and the control surface drag, normal force and pitch moment X , Z , M . The structure dynamic equations, excited by generalised gust forces $L_{j\alpha g}$, contain also the aerodynamic coupling terms $L_{j\alpha}$ , $L_{j\eta}$.

$$[\bar{B} + i\,\omega\,\bar{A}]\{x\} = \{RHS\}\,;$$

$$\{x\}^T = \{\Delta V/V,\ \Delta\alpha,\ \Delta\omega_y,\ \Delta\theta,\ q_j,\ \Delta\eta_i,\ \dot{q}_j,\ \Delta\dot{\eta}_i\}$$

$\bar{A}$

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $X_{\frac{\Delta V}{V}}$ | $X_{\dot\alpha}$ | | | | | | |
| $Z_{\frac{\Delta V}{V}}$ | $Z_{\dot\alpha}$ | | | $\frac{Z''_j}{\omega}$ | $\frac{Z''_\eta}{\omega}$ | | |
| | $M_{\dot\alpha}$ | $I_y$ | | $\frac{M''_j}{\omega}$ | $\frac{M''_\eta}{\omega}$ | | |
| | | | -1 | | | | |
| | | | | -E | | | |
| | | | | | | | |
| | | | | | | $M_{jj}$ | |
| | -K*V | | | | | | -T2 |

$\bar{B}$ and $\{RHS\}$

| | | | | | | | | $\{RHS\}$ |
|---|---|---|---|---|---|---|---|---|
| $X_T$ | $X_\alpha$ | $X_{\omega_y}$ | $X_\theta$ | | $X_\eta$ | | | $X_{\alpha_e}$ |
| $Z_T$ | $Z_\alpha$ | $Z_{\omega_y}$ | $Z_\theta$ | $Z'_j$ | $Z'_\eta$ | | | $L'_{\alpha_e} + iL''_{\alpha_e}/\omega$ |
| | $M_\alpha$ | $M_{\omega_y}$ | | $M'_j$ | $M'_\eta$ | | | $M'_{\alpha_e} + iM''_{\alpha_e}/\omega$ |
| | | 1 | | | | | | |
| | | | | | | E | | |
| | | | | | | | 1 | |
| | $L'_{j\alpha}$ | | | $K_{jj} + L'_{jj}$ | $L'_{j\eta}$ | $\frac{\gamma K_{jj} + L''_{jj}}{\omega}$ | $\frac{L''_{j\eta}}{\omega}$ | $L'_{j\alpha_e} + iL''_{j\alpha_e}/\omega$ |
| | K*V | | | | -1 | | -T1 | |

FIG. 2 LONGITUDINAL MOTION - FLEXIBLE AIRCRAFT DYNAMICS

The equations Fig. 1 are useful to calculate the flexibilised total aircraft derivatives for the steady case. The procedure which is recommended in case of known total aircraft normal modes is shown in Fig. 3

**MODAL APPROACH**
**SOLUTION FOR STEADY CASE**
**MATRIX OF ELASTIFIED AERODYNAMIC DERIVATIVES $\bar{L}_{RR}$**

$$\bar{L}_{RR} = L_{RR} + L_{RE} (K_E + L_{EE})^{-1} L_{ER}$$

**ELASTIFIED RIGHT HAND SIDE $\bar{P}_R$**

$$\bar{P}_R = P_R + L_{RE} (K_E + L_{EE})^{-1} P_E$$

FIG. 3 DERIVATION OF FLEXIBILISED AERODYNAMIC DATA SET

As an example Fig. 4 illustrates the effects of the flexibilisation on rigid flap derivatives of a delta-canard fighter aircraft configuration.

**ELASTIFIED NORMAL FORCE AND PITCH MOMENT**
**DUE TO FLAP DEFLECTION**
**MACH 0.8 at sealevel**
**contribution of the different modes**
**to the aeroelastic efficiency**

| | $c_{z\delta_{el}}/c_{z\delta_R}$ | $c_{m\delta_{el}}/c_{m\delta_R}$ |
|---|---|---|
| MODE 1 | 0.85 | 0.92 |
| MODE 2 | 0.75 | 0.84 |
| MODE 3 | 0.69 | 0.80 |
| MODE 4 | 0.65 | 0.77 |
| MODE 5 | 0.62 | 0.74 |

FIG. 4 APPLICATION OF FLEXIBILISATION METHOD

## EXAMPLES OF FLEXIBLE AIRCRAFT TURBULENCE RESPONSE PREDICTIONS

Some typical results of gust response calculations on a flexible aircraft are listed here in order to demonstrate the importance of arising problems.

The investigated aircraft is a delta canard configuration with wing tip mounted stores. The first example shall illustrate the prediction of vibration levels on external stores and resulting dynamic wing loads due to discrete gusts (Fig. 5).

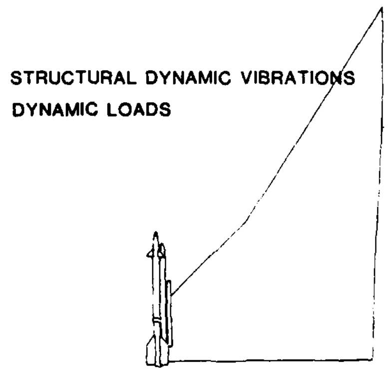


FIG. 5 WING WITH TIP MOUNTED MISSILE

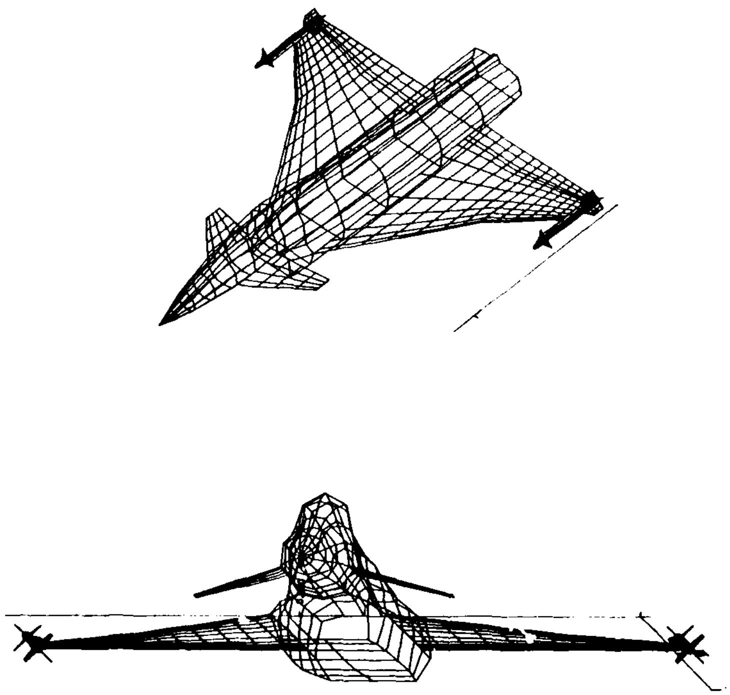

FIG. 6 AERODYNAMIC GRID

The total aircraft configuration is idealised for unsteady aerodynamic force calculation by the grid shown in Fig. 6. The unsteady aerodynamic derivatives and generalised forces together with load distributions on subcomponents are calculated with the program (Ref.3 ) for the degrees of freedom aircraft angle of attack, rotation around center of gravity, canard deflection, flap deflection and wing elastic normal modes shown in Fig. 7.

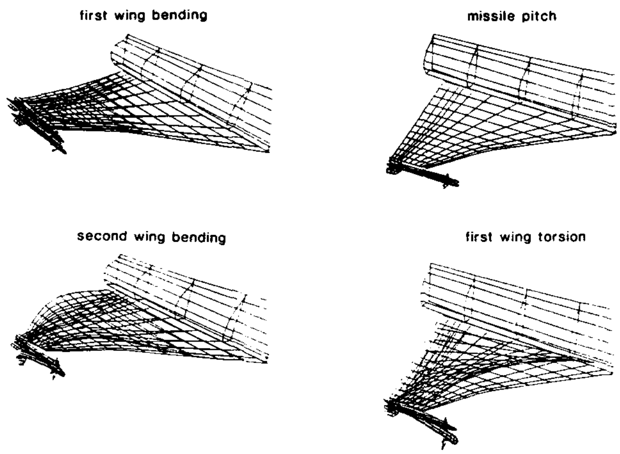


FIG. 7 VIBRATION MODES

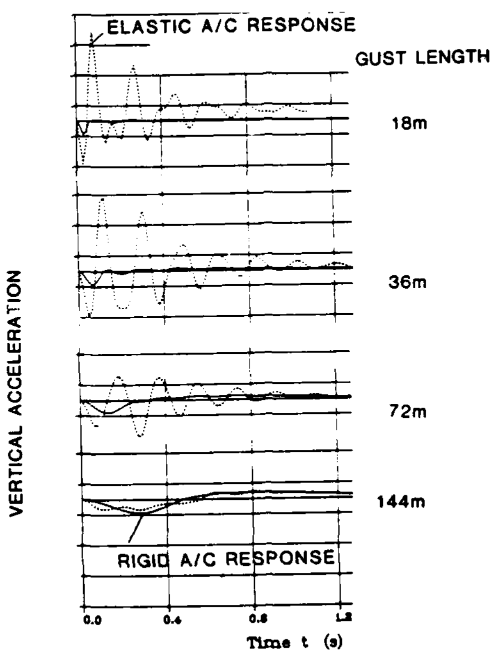


FIG. 8 DISCRETE GUST ANALYSIS: ACCELERATION AT MISSILE NOSE

Fig. 8 documents very high accelerations on the tip mounted missile due to discrete gust caused mainly at short gust length (18 m) by the second elastic mode of the wing and also shows alleviation effect of the elastic wing on the response at long gust length (144 m) compared to the rigid response (full line).

The discrete gust reponse of the flexible aircraft results in wing shear and bending distributions as depicted in Fig. 9.

Dramatic changes of wing loading are observed especially at wing outboard stations for different gust length compared to rigid response which indicate a problem area in the structural design. Gust loads may have influence on the structural design.

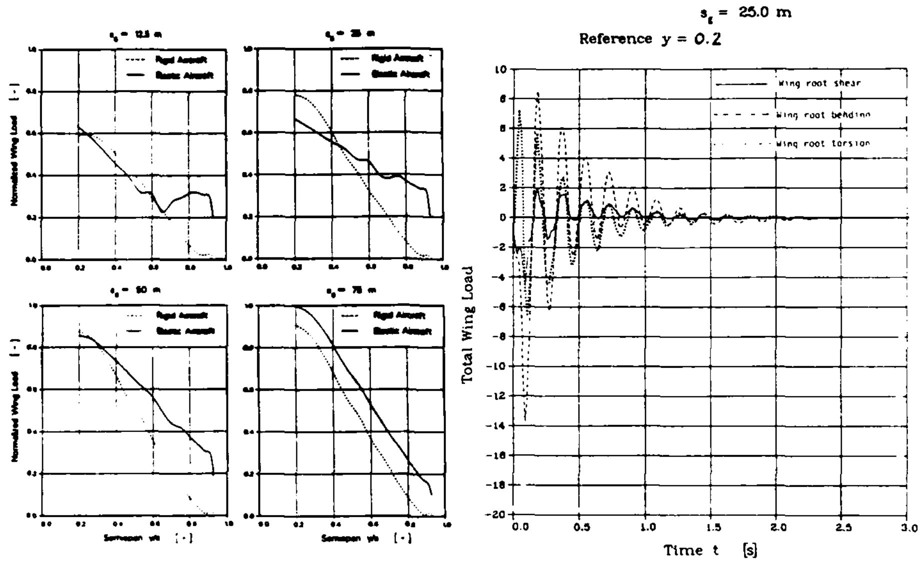


FIG. 9a DESIGN GUST CALCULATION: WING SHEAR FORCE

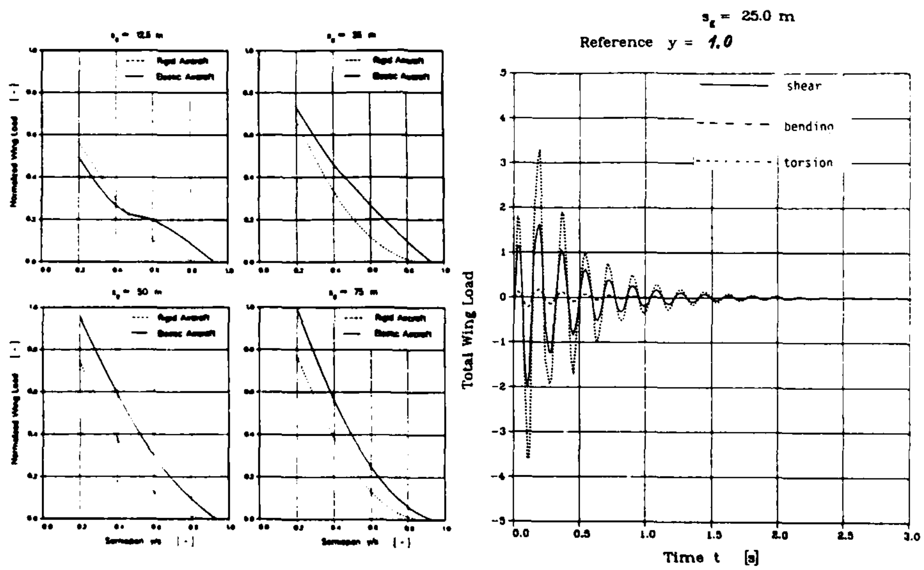


FIG. 9b DESIGN GUST CALCULATION: WING BENDING MOMENT

Summary:

Very high vibration levels and dynamic loads compared to rigid aircraft response are predicted in the tip store attachment region. Gust load alleviation can be of profit.

## RIDE COMFORT EVALUATION

According to MIL-F-9490 D the ride comfort at pilot seat is specified for a military aircraft with FCS. The ride comfort criteria for vertical and lateral vibrations are calculated from the PSD of the vibrations and a acceleration weighting function W for a defined v. Karman turbulence spectrum of the gust velocities (Fig. 10). A ride discomfort index $D_i$ is defined with upper limits, Fig. 11.

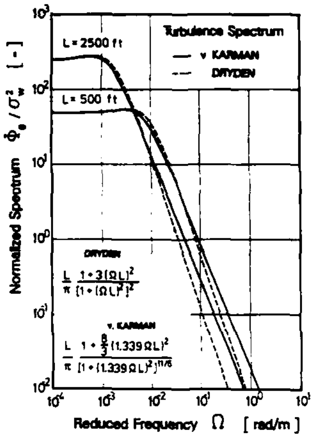


FIG. 10 TURBULENCE SPECTRUM

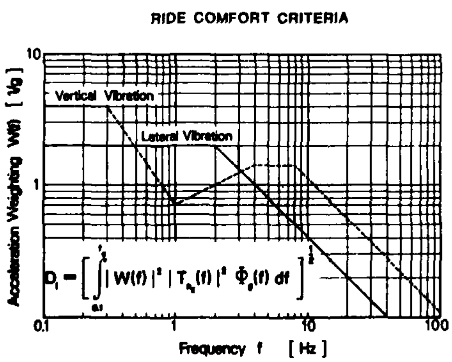


FIG. 11 RIDE DISCOMFORT INDEX

Fig. 12 shows the power spectral density of the investigated aircraft at low level and Ma = 0.9, based on a aircraft weight of 11.5 to. The ride discomfort index of the rigid aircraft is $D_i$ = 1.2 which really does not met the requirements.

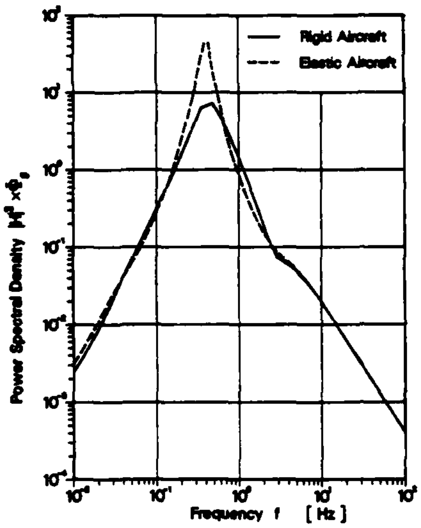


FIG. 12 POWER SPECTRAL DENSITY OF VERTICAL PILOT SEAT ACCELERATION

Another ride comfort evaluation could be based on the criterium of a certain acceleration level exceedance. In Fig. 13 the exceedances of 1/2 g bumps per minute for acceptable to unacceptable ride at low level flight are defined.

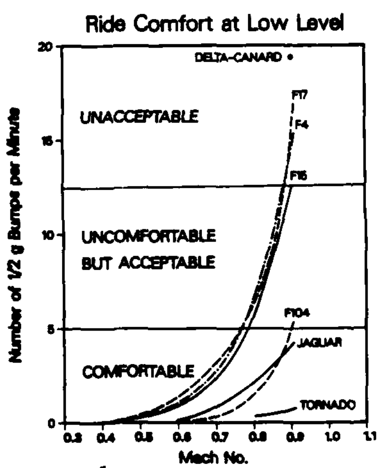


FIG. 13 RIDE COMFORT - EXCEEDANCE OF 1/2 G PER MINUTE AT PILOT SEAT

The exceedance is calculated using the normalised acceleration PSD and RMS value. Rice formala is applied. For the same flight condition this criterium leads also to unacceptable vibration levels for the Delta-Canard configuration at low level, Ma = 0.9.

Summary:

Ride comfort requirements are not met for a Delta-Canard-Configuration at low level high speed at low wing loading conditions. Ride improvement systems could be of interest.

## STRUCTURAL COUPLING PROBLEMS

A total flexible aircraft with FCS response calculation as described in the previous text would enable the prediction of open and closed loop stability for the coupled flight and structural dynamic modes. Open loop gain and phase margins can be evaluated for all modes including the interdependency. Structural coupling problems which will be of interest especially for orginally static unstable configurations can be investigated therefore more accurately.

Fig. 14 shows the Bode diagram of the pitch rate signal of the investigated aircraft with FCS and the effect of notch filtering of the signal on the gain and phase margins in the frequencies of the short period mode and the first two elastic fuselage modes.

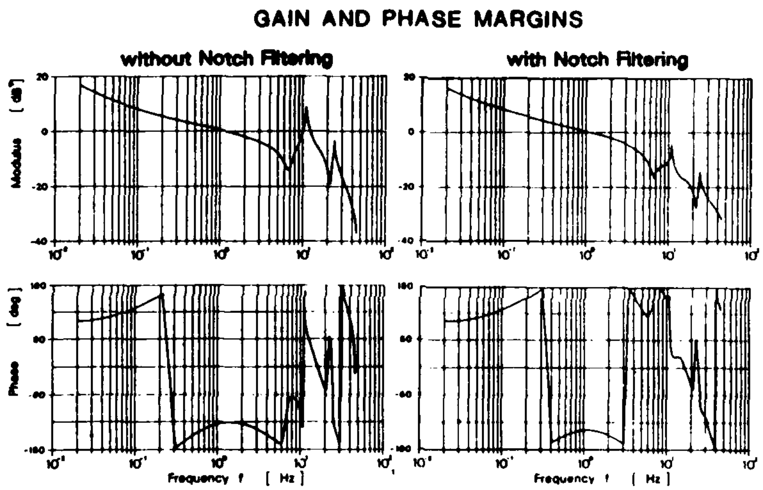


FIG. 14 BODE DIAGRAM OF OPEN LOOP PITCH RATE EFFECT OF NOTCH FILTERING

Summarizing these considerations one can say, that total flexible aircraft response calculations are necessary to predict structural coupling problems of the aircraft with FCS and will help to develop adequate notch filters.

Notch filter design will possibly be even a more pronounced problem for closed loop gust alleviation systems due to higher gains compared to FCS systems.

## ACTIVE GUST CONTROL ON FLEXIBLE AIRCRAFT

A ride improvement system or a gust load alleviation system may be based on the principle of incremental gust induced lift and moment compensation (open loop system). Compensation signals to the control surfaces, for instance canard and trailing edge flap deflections $\delta$ and $\eta$ on a fighter aircraft Fig. 15, can formally be evaluated inflight for each condition according to the expression given in Fig. 16.

In order to derive the compensation signals, the gust incidence $\alpha_g$ and its time derivative $\dot{\alpha}_g$ must be measured during flight. The measurement can be performed with flow sensors ($\alpha$-vanes) or in the future by laser-optical systems. Fig. 17 shows the procedure for the evaluation of the gust incidence from a vane signal, which of course consists of the combination of gust and aircraft incidence $\alpha_{eff}$. The gust incidence is extracted using platform signals, the pitch rate and the vertical acceleration.

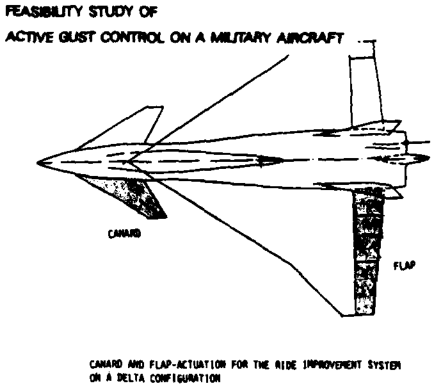


FIG. 15 INVESTIGATED AIRCRAFT

$$\begin{Bmatrix} \delta(i\omega) \\ \eta(i\omega) \end{Bmatrix} = \begin{bmatrix} c_{z_\delta}(i\omega) & c_{z_\eta}(i\omega) \\ c_{m_\delta}(i\omega) & c_{m_\eta}(i\omega) \end{bmatrix}^{-1} \begin{bmatrix} c_{z_\alpha}(i\omega) & \frac{\bar{c}}{V} c_{z_{\dot\alpha}}(i\omega) \\ c_{m_\alpha}(i\omega) & \frac{\bar{c}}{V} c_{m_{\dot\alpha}}(i\omega) \end{bmatrix} \begin{Bmatrix} \alpha_g(i\omega) \\ \dot\alpha_g(i\omega) \end{Bmatrix}$$

FIG. 16 EVALUATION OF COMPENSATION SIGNALS

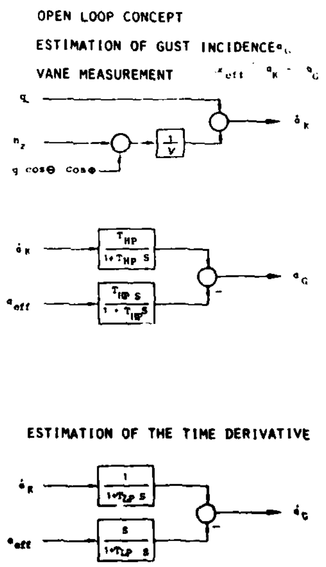


FIG. 17 DERIVATION OF GUST INCIDENCE BY VANE MEASUREMENT

Problems in the sucessful compensation will arise from the facts:

- contamination of the measured vane signal by aeroelastic deformations at the sensor position and elastic vibrations,
- the applied unsteady aerodynamic derivatives are not accurate enough, especially in transonic flight or due to aeroelastic effects,
- the installed actuator power is not sufficient, the required control surface rates are to high for compensation.

The attractive advantage of an open loop system however consists in its simplicity and in the possibility to develop it separately from the FCS system, since it does not interact with the FCS and does not change the flying qualities.

Ride improvement and gust load alleviation could be achieved also by a closed loop system. In addition to the feedback loop of the FCS system, the pilot seat or vertical acceleration together with pitch rate and pitch acceleration signals can be used to drive the control surfaces to alleviate the gust response or dynamic loads, as demonstrated in the block diagram in Fig. 18.

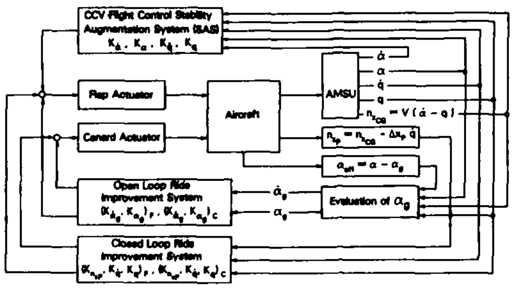


FIG. 18 BLOCK DIAGRAM OF FCS AND GUST ALLEVIATION SYSTEM

The problem areas here will be found in the complexitity of the system. The system has to be designed together with the FCS system, because the aircraft stability is affected. The command system must be modified in order to eliminate interaction between the system and pilot command inputs.

In the figures 19, 20 and 21 typical results of the effects of an open and closed loop ride improvement system investigated on a delta-canard are shown. The optimization of the systems was performed by stability analysis of the aircraft and PSD analysis of the C.G. and pilot seat acceleration. The rms pilot seat acceleration and the 1/2 g bumbs per minute were minimized with respect to a control surface maximum rate of 50 degrees/sec. Fig. 20 illustrates the changes in short period frequency and damping for different feedback gains and the corresponding peak values of control surfaces rate and deflection. The closed and lopen loop system provide the same alleviation factor in pilot seat acceleration.

| FEEDBACK GAINS | | | | rms | Dryden $\sigma_w$ = 2 m/sec (rms) | | | | | Short period | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k [s] | k [-] | k [s²] | k [s] | $\ddot{n}$ [m/s²] | $\dot{\eta}_C$ [deg/s] | $\dot{\eta}_F$ [deg/s] | $\eta_C$ [deg] | $\eta_F$ [deg] | Canard Efficiency | $\omega_n$ [Hz] | $\zeta_n$ |
| -1.3 | .9 | 11 | 2. | [illegible] | | | | | | 1.42 | 5.92 |
| k [-] | k [-] | | $k_{Canard}$ [-] | | | | | | | | |
| .5 | .0 | | 1 | 3 | 51.6 | 13.4 | 7.4 | 1.4 | 100 % | | |
| 1 | .0 | | 5 | 3 | 51.6 | 13.4 | 7.4 | 1.2 | 100 % | | |
| .7 | .0 | | .666 | 2.8 | 49.9 | 17.2 | 6.9 | 2.1 | +150 % | | |
| .7 | -2 | | .666 | 2.5 | 52.1 | 18.9 | 6.9 | 2.1 | +150 % | | |

Dryden Spectrum
$\sigma_w$ = 2 m/sec (rms)

(M = 0.93; LOW LEVEL)

FIG. 19 EFFECT OF OPEN LOOP RIDE IMPROVEMENT SYSTEM

| FEEDBACK GAINS | | | | | | | | | | | | Short period | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $(k_{nzp}$ | $k_q$ | $k_{\dot{q}})_F$ | $(k_{nzp}$ | $k_q$ | $k_{\dot{q}})_c$ | $n_{zp}$ [m/s²] | $\dot{\eta}_C$ [deg/s] | $\dot{\eta}_F$ [deg/s] | $\eta_C$ [deg] | $\eta_F$ [deg] | Canard Efficiency | $\omega_n$ [Hz] | $\zeta n$ |
| −.1 | 7.5 | .6 | .011 | .0 | .0 | 2.5 | 53.3 | 37.8 | 3.8 | .6 | 100% | 1.58 | .797 |
| −.1 | 7.5 | .55 | .0 | .0 | .07 | 2.75 | 55. | 48.2 | 3.4 | .4 | 100% | 1.52 | .492 |
| −.1 | 7.5 | .6 | .01 | .0 | .0 | 2.4 | 51.6 | 37.8 | 3.4 | .6 | 150% | 1.487 | .825 |
| −.1 | 7.5 | .6 | .0 | .0 | .085 | 2.55 | 51.6 | 51.6 | 3.4 | .6 | 150% | 1.275 | .437 |

(M = 0.93; LOW LEVEL)

FIG. 20 EFFECT OF CLOSED LOOP RIDE IMPROVEMENT SYSTEM

FEASIBILITY STUDY OF
ACTIVE GUST CONTROL ON A MILITARY AIRCRAFT

RIDE IMPROVEMENT INVESTIGATION ON A DELTA-CANARD
CONFIGURATION (TKF CCV)

WEIGHT 11600 KG
TURBULENCE INPUT V.KARMAN SPECTRUM
RMS VELOCITY = 2.01 M/SEC
FLIGHT CONDITION MACH=0.93 SEALEVEL
RESULT : RMS PILOT ACCELERATION IN (G)
A/C WITH FCS WITHOUT GUST SYSTEM 0.7
A/C WITH FCS AND OPEN LOOP SYSTEM 0.25
A/C WITH FCS AND CLOSED LOOP SYSTEM 0.24
PROBLEMS: CONTROL SURFACE EFFICIENCY AND FLAP RATE
THE NEEDED FLAP RATE WILL BE ABOUT 100 DEG/SEC
FOR ELASTIFIED CONTROL SURFACE LIFT AND MOMENT

FIG. 21 RESULTS OF THE RIDE IMPROVEMENT INVESTIGATION

A further example of the effect of a ride improvement system is demonstrated in Fig. 22. The PSD of C.G. acceleration is shown for an transport aircraft flying at cruise condition. High alleviation could be found with a closed loop system (C.G. acceleration feedback), however, the frequency of the short period mode was strongly reduced.

TRANSPORT AIRPLANE WITH RIDE IMPROVEMENT SYSTEM
PSD OF C.G. ACCELERATION

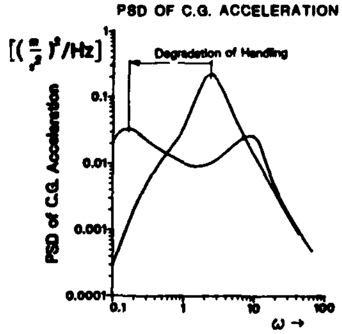


FIG. 22 EFFECT OF A RIDE IMPROVEMENT SYSTEM ON A TRANSPORT AIRCRAFT

An alleviation of vibration levels on this aircraft on all passenger seats could be achieved (Fig. 23). However, without notch filtering of the feedback signal the vibration level are increased with the system in action, which demonstrates the importance of notch filter design.

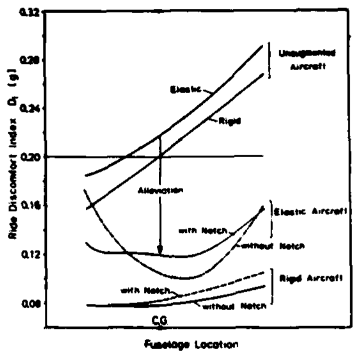


FIG. 23 RIDE DISCOMFORT INDEX ON PASSENGER SEATS OF A TRANSPORT AIRCRAFT

## CONCLUSIONS

- A description of fully dynamically coupled flight and structural dynamics of total flexible aircraft is of interest for the prediction of gust loads and for the investigation of gust load alleviation and ride improvement systems. Consequently unsteady motion and gust induced aerodynamic force prediction for the total aircraft will improve accuracy.
- Discrete gust analysis is of importance for military aircraft in the case of configurations with external stores carried on outboard wing stations. High wing dynamic wing loads may be observed.
- Continuous turbulence analysis of aircombat aircraft flying at low level high speed shows unacceptable ride comfort.
- Gust load alleviation systems and ride improvement systems could reduce the problems.
- The systems shall be designed with respect to the aircraft strength and rigidity and aircraft flying quality requirements.
- Realisation of compatibility between load alleviation systems and FCS system is problematic.

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**14. Abstract**

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