Influence of EFCS-Control Laws on Structural Design of Modern Transport Aircraft

by

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Abstracts

This paper follows up on a presentation held on the 27th SDM Conference (20. - 22.05.86) in San Antonio, USA (1) and develops a further aspect of EFCS in connexion with the loads situation.

In order to understand the influence of EFCS on A/C loads calculation the main points of that presentation have been repeated.

Here, however, the effect of the variation of control law data on loads will be the major point of discussion.

Up to the present our work has primarily concerned itself with the influence of new aircraft (A/C) features (control laws and side stick) on the current means of compliance (MC) as to the possible necessity of regulation revision.

Here especially the problem was, whether the introduction of a side stick and the (possible) danger of pilot-induced oscillation (PIO) could result in horizontal tailplane overloading, when proceeding according to former MC.

In this presentation results of a study will be shown which draw a comparison between conventional A/C and those with control laws including the implementation of the side stick.

Among other things flight- and handling qualities of the EFCS controlled A/C depend on a given control law and the gains and time constants introduced. These are said to be subject to modification up to the successful completion of the flight testing. The sensitivity of loads on changes in gains and time constants is demonstrated in this study.

1. Introduction

1.1 Former Situation

Based on past experience, it can be maintained, that the currently used MC and interpretations of existing Vertical Design Maneuver Requirements (2) guarantee an acceptable level of safety for the so called conventional A/C.

1.2 Today and Future Situation

The new A/C features such as control laws along with the introduction of EFCS, as well as side stick and A/C protection laws cause the question to arise as to whether former MC can guarantee at least the same level of safety for this new generation of aircraft.

The manufacturer is convinced that this demand is necessary. It must be possible to reap the benefits of these new A/C features not only where handling quality (HQ) is concerned but regarding structures as well, without conflicting with current safety standards.

2. Vertical Design Maneuver

Vertical design maneuvers are

- stylized, artificial maneuvers
- created to produce max. loads on the A/C esp. on wing
  horizontal tailplane
  rear fuselage
- not intended to define stability and handling properties.

Of course, these design maneuvers will also strongly be affected by the new EFCS-control laws as will be shown later.

Results of a study supporting the new vertical design maneuver interpretation demonstrate this while remaining in accordance with existing requirements.

3. Main Differences between Conventional A/C and EFCS controlled A/C with respect to Design Load Criteria

3.1 Comparison of Requirements

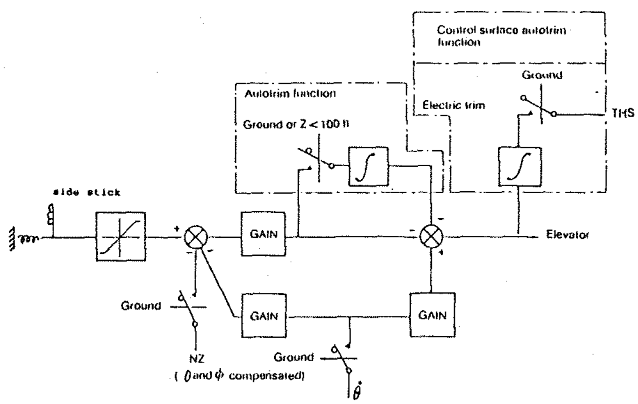
The basis for the investigation of the design loads calculation is the Joint Certification Requirement (JAR 25) for European large transport A/C, which complies with the FAR 25 requirements in all major points and additionally takes into consideration the national European variants.

In table 1 a short review of the requirement situation for both the conventional and EFCS controlled A/C is given.

3.2 Philosophy of Control Surface Actuation

For the EFCS controlled A/C the mechanical power transmission has been replaced by electrical wires (thus Fly-by-Wire), therefore, electrical signals are transmitted via on-board-computers.

That means, the pilot no longer has full authority over the control surface deflections, their deflections now depend on the present flight conditions processed by the fitted control laws (in the on-board-computers). Such a control law acting on the longitudinal A/C motion is shown in the following figure:



LONGITUDINAL CONTROL LAW (C*-LAW)

The existing requirements (related to conventional A/C only) for vertical design maneuver define specific control surface deflections regardless of the pilot's input.

The Table 2 shows a comparison between conventional and EFCS controlled A/C and highlights the main differences arising due to the application of computer technology with the special emphasis on design loads criteria.

4. Results from Checked Maneuver Study

The introduction of a side stick with nearly no artificial feel in place of the control column with a hand force dependent on flight speed (up to 90 daN at high speed) has made it indispensable to investigate the aircraft behaviour when excited by varying frequencies.

Thus, to validate the checked maneuver philosophy, a study (4) has been carried out showing the effects of the variation of the command input period.

To accomplish this the differential equations of the conventional A/C have been extended by adding the longitudinal control law (called C*-Law) as expressed by its specific differential equation.

This study has been carried out twice:

- firstly for conventional A/C
- secondly for EFCS-controlled A/C.

A frequency variation in control surface excitation for a conventional checked maneuver, which has not been required by Airworthiness Authorities up to now, was performed to show the behaviour of an open loop system in comparison to that of the EFCS controlled A/C (closed loop).

The checked maneuvers have been carried out in the total flight envelope for all critical mass/C.G. configurations.

In the last analysis the results of these extended calculations define the loads envelope of each component in relation to checked maneuvers.

One critical case from that loads envelope giving the max. negative shear at horizontal tailplane has been selected for the present study of frequency variations.

Fig. 1 to 4 show time histories of system disturbance, loadfactor and horizontal tailplane (HTP) loads (shear and bending) for the conventional A/C as function of maneuver period (resp. frequency). Fig. 5 to 9 show those of the EFCS controlled A/C.

Fig. 1 displays the elevator deflection of the conventional A/C as an initial disturbance of the system.

The increase in deflection amplitude at high frequencies (shortening of maneuver period) results from the JAR-interpretation to achieve an A/C loadfactor of

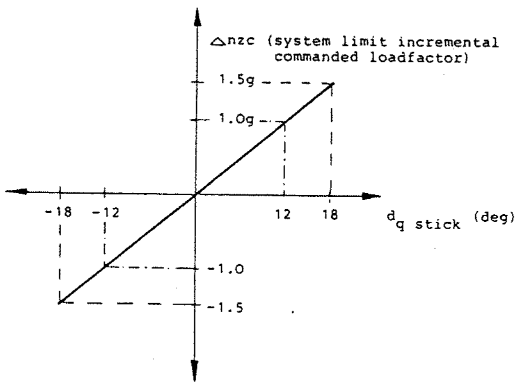
$$NZ^{C.G.}_{A/C} = 2.5 \text{ g}$$

over the whole range of frequencies calculated (fig. 2). The upper boundary (of frequency range) is formed by the control surface hydraulics which prevent the establishment of the deflection amplitude necessary to achieve this required loadfactor within the desired time.

Taking into account the a.m. criteria shear and bending at HTP (fig. 3 - 4) become max. values for the highest possible frequency.

The initial disturbance of the EFCS-controlled A/C results -with respect to design loads- from the pilot's action on the side stick.

The relationship between side stick deflection and incremental loadfactor command is described by a linear slope:



SIDE STICK CHARACTERISTICS

Fig. 5 gives the incremental loadfactor command Δn_{zc} , the amplitude being constant for all calculated periods.

The highest possible frequency is independent of the control surface hydraulics but influenced by the pilot's ability to move the stick very quickly.

Deflection shape of the elevator surface is shown in fig. 6. Here the effects of control surface hydraulics can be seen at high frequencies. After a steady increase of deflection amplitudes with a raise in frequency these amplitudes are reduced as a result of the max. hydraulic elevator hinge moment.

Achieved A/C loadfactor, shear and bending at HTP are given in fig. 7 to 9.

5. Sensitivity of HTP Loads on Changes in Control Law Data

The effects of control laws on both A/C flight- and handling qualities and loads are based on two major factors:

- the law architecture (evaluation and combination of A/C moving parameter for feedback signals)
- the applied control law data (gains and time constants, limits etc.).

While the architecture of the control law is clearly defined before the A/C's first flight, gains and time constants are subject to modification. Final tuning of control law data is completed during flight testing.

The reasons for doing so are

- flight- and handling quality aspects (flight crew demands)
- differences in aerodynamics between the real full flexible A/C and its windtunnel modelling
- fine adjustment of EFCS with regard to A/C structural response.

The nominal gain $K_{NZ(N)}$ which is situated in the direct lane side stick command / elevator, has been tuned to within the range of

$$0.33\ K_{NZ(N)} \leqslant K_{NZ} \leqslant 3\ K_{NZ(N)}$$

The associated variation of the other gains has been defined in such a way as to maintain constant damping.

By tripling nominal value K_{NZ} during a defined stick maneuver (fig. 10) the amplitude of elevator deflection is amplified (fig. 11), resulting in an increased loadfactor (fig. 12) and increased HTP loads (fig. 13 - 14).

Reduction of K_{NZ} to one third of the nominal value causes smoother A/C motion and, therefore, a loads level less than the nominal one.

6. Conclusions

Following main results of this study shall be highlighted:

"The HTP-loads-sensitivity on maneuver frequency is significantly lower for the EFCS controlled A/C than for conventional ones."

Fig. 15 describes the load development in relation to frequency for conventional A/C as opposed to EFCS controlled A/C.

The slope gradient for conventional A/C is significantly steeper than that of EFCS controlled A/C. Thus in EFCS-aircraft the load increase becomes relatively independent of frequency, especially at higher frequencies.

In conventional A/C the checked maneuvers had to be calculated in the short period mode. This practice has long been in use and has been generally accepted by the AA.

In view of the relative constant values in load development occuring in EFCS controlled A/C it is definitely a good approach to perform the checked maneuver in the short period mode (which is determined by the effect of the control law on it).

A frequency variation for EFCS controlled A/C therefore becomes less mandatory than it could have been for conventional A/C, without infringing on the level of safety.

Today it is commonly known that the European Authorities, e.g. the French (DGAC), the British (CAA), the Dutch (NLR) and the German (LBA) have acknowledged the interpretation for EFCS controlled A/C (5) whereby the study results (4) have been treated as official supportive background material, but with the additional note, requiring a study to be carried out for each new aircraft to validate this relationship.

Because of the shown influence of gains and time constants on the loads and thus on stress a loads check -using modified control law data within the expected range- must be carried out to

- justify the A/C structure

- prevent additionally structure reinforcements.

Tuning outside of the investigated range, e.g. due to handling quality aspects, could cause structural overloading, thus endangering the level of safety. Therefore the variation of control law data must be carefully analyzed with respect to design loads before flight testing.

7. References

(1) Influence of FBW-Control Laws on Structural Design of Modern Transport Aircraft
M. Besch
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(2) A310 / A300-600 Airworthiness Requirements Subpart C-Structures Flight Maneuver and Gust Conditions
FAR 25.331
AI/VC No. 600/78, issue 7
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(3) Interpretation of Design Maneuver Requirements for Aircraft with Fly-by-Wire (FBW)
M. Molzow, R. Möbest, MBB-UTE 24
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(4) The Influence of Fly-by-Wire System on Loads at Horizontal Tailplane
C.L. Tanck/M. Besch
MBB-Techn. Note TN-TE 242/03-85
- April 1985 -

(5) Interpretation of Design Maneuver Requirements / Interpretative Material
IM-A222 for JAR 25.331
- 02.12.1985 -

(6) Sensitivity Study for Gain and Time Constant Variation of FBW Controlled A/C
C.L. Tanck/M. Besch
MBB-Techn. Note TN-TE 242/06-85
- July 1985 -

TABLE 1 **Airworthiness Requirements for Vertical Design Maneuvers of both Conventional and EFCS-Controlled A/C**

	Conventional A/C	**EFCS-Controlled A/C**
Joint Certification Requirement	JAR 25.331	JAR 25.331
Interpretation	ACJ 25.331	SCTF 02/84 (ref. 3)
Balanced Maneuver Main Conditions	JAR 25.331 (b) - zero pitching accelerat. - loadfactor nz_{min} to nz_{max} - total flight envelope - all mass/C.G. config.	JAR 25.331 (b) needs no specific interpretation same manner as conventional A/C.
Pitching Maneuver Maximum Elevator Displacement at V_A	JAR 25.331 (c) (1) - pitching control surface moved to achieve extreme *nose-up pitching* - limitat. of time history by nz_{max} or by - max. aerodynamic load on HTP whichever criterion appears first	JAR 25.331 (c) (1) - cockpit pitching control device moved at critical displacement *rate to achieve extreme nose-up pitching* - limitation of the time history: same as conventional A/C
Checked Maneuver between V_A and V_D	- control surface deflection (elevator) $dq(t) \approx dq_{max} \sin \omega t$ with o dq_{max}: amplitude necessary to achieve loadfactor nz_{max} or zero o ω: undamped natural frequency of short period mode whereby $\omega = \frac{\Pi}{2} \frac{V}{V_A}$ V_A is the maneuver design speed V is the speed in question both at the relevant altitude - loadfactor nz_{max} or zero has to be achieved - *limitation of loads evaluation to initial three quarters of the period*	- cockpit pitch control device movement $q_{stick}(t) = q_{stick(max)} \sin \omega t$ with o $q_{stick(max)}$ being the system limits of stick movement o ω: circular frequency of the movement of the cockpit control device, equal to the natural frequency of the short period rigid mode including the EFCS-effect on its frequency but not being less than - the transient load factors due to the response of the A/C need not exceed nz_{max} equal to the maximum maneuvering loadfactor nz_{min} equal to zero - *limitation of loads evaluation to initial three quarters of period*

TABLE 2 Comparison of Conventional Aircraft and EFCS–Controlled Aircraft Features of Pitch Control Actuation

	Conventional A/C	EFCS–Controlled A/C
Pitch Control	Control Column	Side Stick
Artificial Feel in Pitch	Force up to 90 daN as function of speed	Constant friction independent of flight speed
Signal Transmission Cockpit–Control Surface	By steel cables (bowden) Transmission is not subject to loads calc.	By electrical wires Transmission is subject to loads calc.
Maneuver Actuation	Pilot demands a change in control surface position	Pilot demands a change in attitude; control surface position is controlled by the control laws
Flight Envelope Protection	Non active systems; only lamps or acoustic warnings	Active protection system have a certain authority above the pilot

CONVENTIONAL A/C
CHECKED MANEUVER
SINUSOIDAL POSITIVE

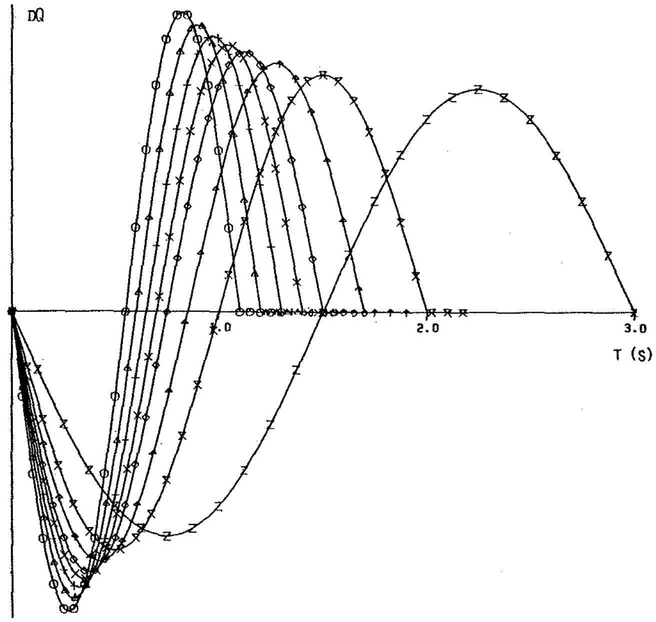


FIG 1
ELEVATOR DISPLACEMENT TO OBTAIN NZA/C = 2.5 G
AS FUNCTION OF PERIOD

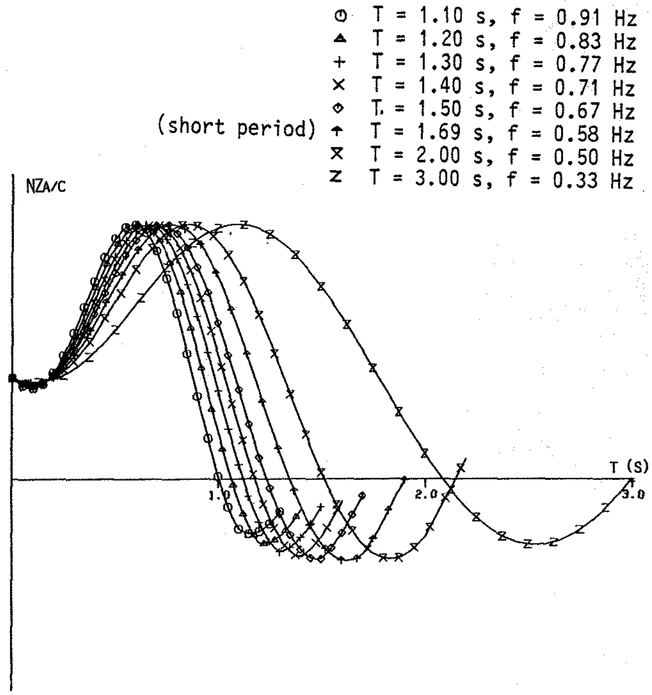


FIG 2
AIRCRAFT LOAD FACTOR AT C.G. (Z-DIRECTION)
AS FUNCTION OF PERIOD

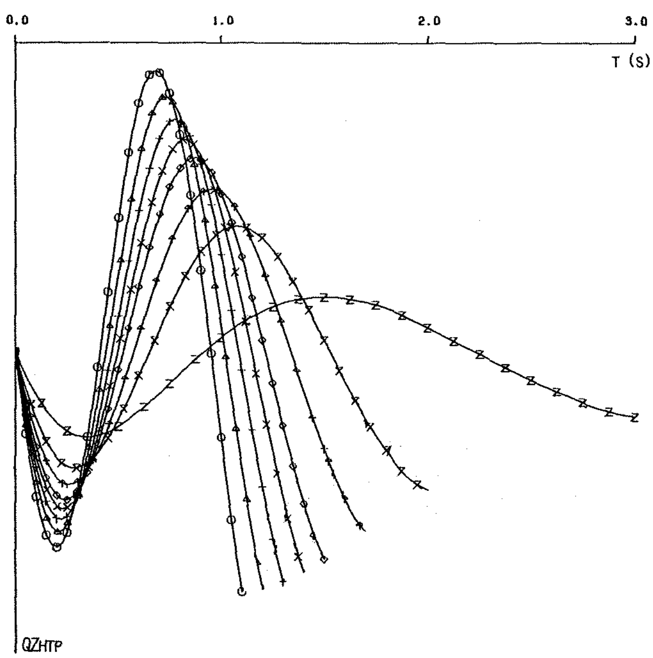


FIG 3
SHEAR AT HORIZONTAL TAILPLANE (ROOT STATION)
AS FUNCTION OF PERIOD

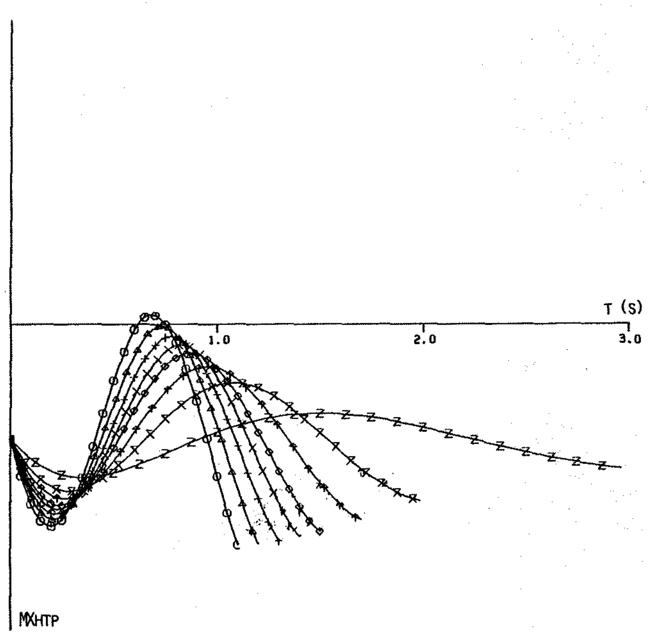


FIG 4
BENDING AT HORIZONTAL TAILPLANE (ROOT STATION)
AS FUNCTION OF PERIOD

EFCS CONTROLLED A/C
CHECKED MANEUVER
SINUSOIDAL POSITIVE

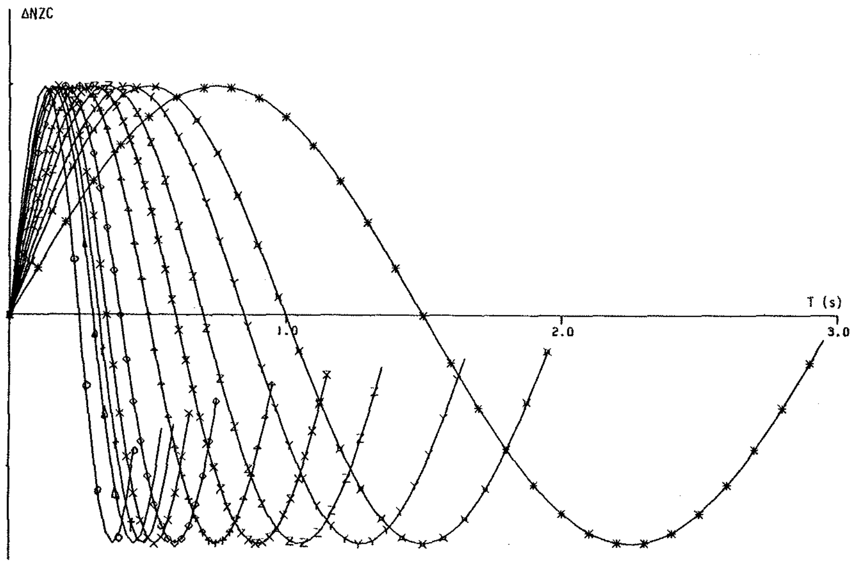


FIG 5
INCREMENTAL LOAD FACTOR DEMANDED BY PILOT (FUNCTION OF PERIOD)

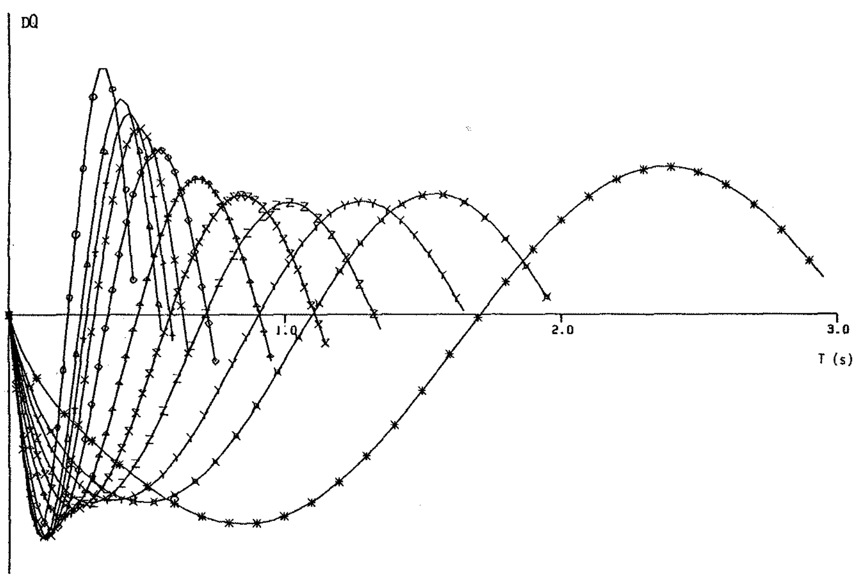


FIG 6
ELEVATOR DISPLACEMENT RESULTING FROM INCREMENTAL LOAD FACTOR DEMAND AND ACTUAL FLIGHT PARAMETERS (FEEDBACK) AS FUNCTION OF PERIOD

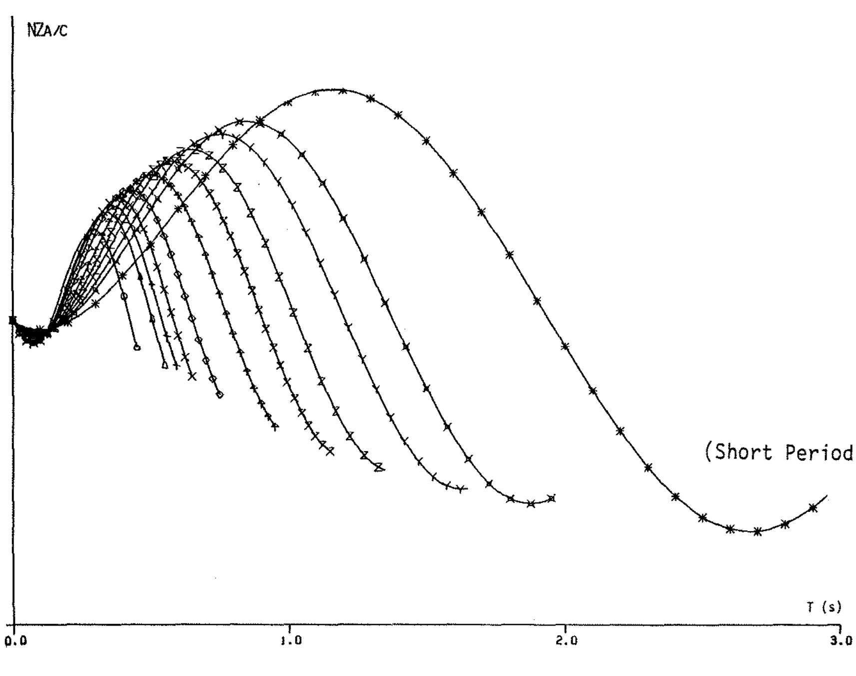


FIG 7
AIRCRAFT LOAD FACTOR AT C.G. (Z-DIRECTION)

(Short Period incl. FBW)

- ⊙ T = 0.50 s, f = 2.00 Hz
- △ T = 0.60 s, f = 1.67 Hz
- \+ T = 0.64 s, f = 1.56 Hz
- × T = 0.70 s, f = 1.43 Hz
- ◇ T = 0.80 s, f = 1.25 Hz
- ↑ T = 1.00 s, f = 1.00 Hz
- ⌅ T = 1.20 s, f = 0.83 Hz
- Z T = 1.40 s, f = 0.71 Hz
- Y T = 1.69 s, f = 0.58 Hz
- ⌘ T = 2.00 s, f = 0.50 Hz
- ✱ T = 3.00 s, f = 0.33 Hz

EFCS CONTROLLED A/C
CHECKED MANEUVER
SINUSOIDAL POSITIVE

(Short Period incl. FBW)

⊙	T = 0.50 s, f = 2.00 Hz
▲	T = 0.60 s, f = 1.67 Hz
+	T = 0.64 s, f = 1.56 Hz
×	T = 0.70 s, f = 1.43 Hz
◇	T = 0.80 s, f = 1.25 Hz
↑	T = 1.00 s, f = 1.00 Hz
X	T = 1.20 s, f = 0.83 Hz
Z	T = 1.40 s, f = 0.71 Hz
Y	T = 1.69 s, f = 0.58 Hz
¤	T = 2.00 s, f = 0.50 Hz
*	T = 3.00 s, f = 0.33 Hz

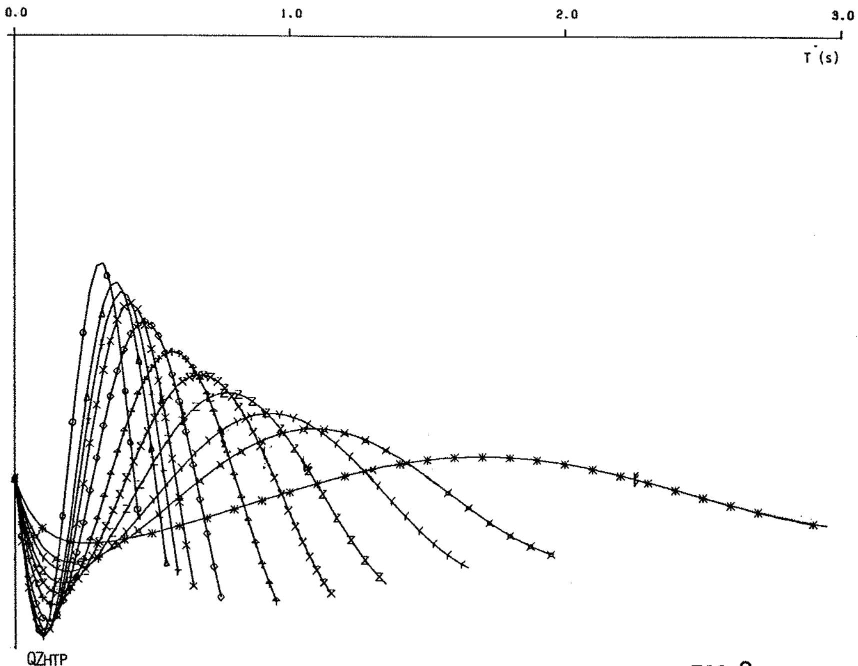


FIG 8
SHEAR AT HORIZONTAL TAILPLANE (ROOT STATION)
AS FUNCTION OF PERIOD

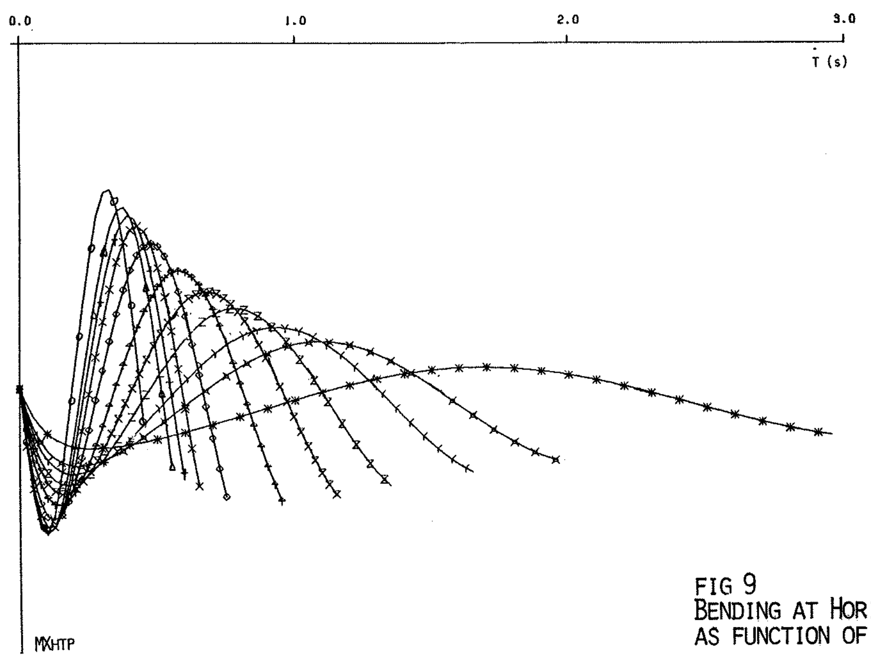


FIG 9
BENDING AT HORIZONTAL TAILPLANE (ROOT STATION)
AS FUNCTION OF PERIOD

EFCS CONTROLLED A/C
SENSITIVITY ON
GAIN VARIATION

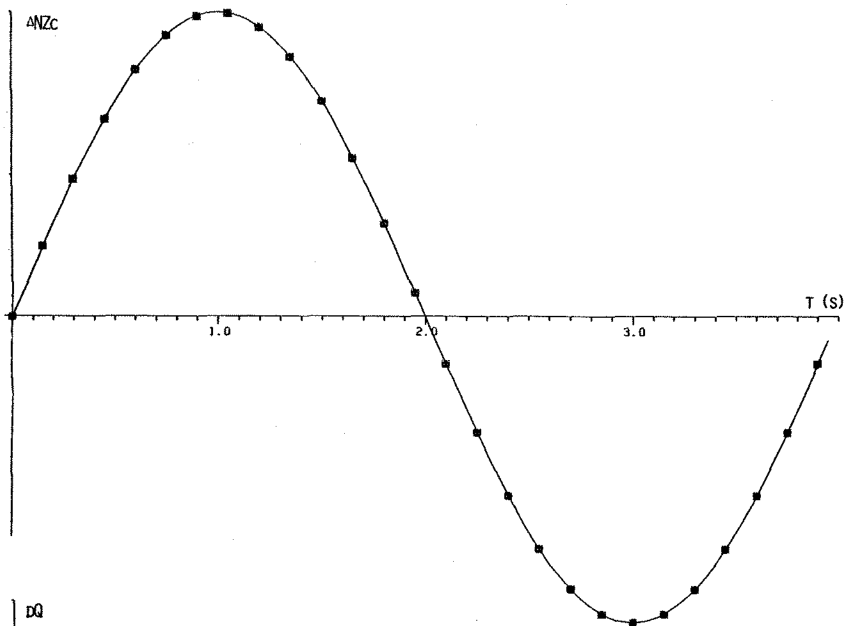
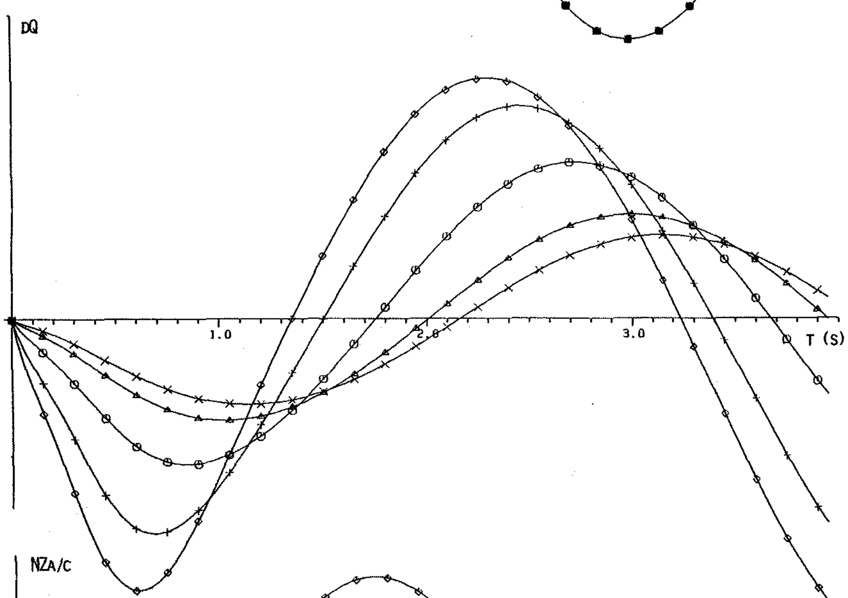


FIG 10
INCREMENTAL LOAD FACTOR DEMAND



○ K4 = K4NOMINAL
△ K4 = 1/2 K4N
+ K4 = 2 K4N
× K4 = 1/3 K4N
◇ K4 = 3 K4N
AND ASSOCIATED VARIATION OF OTHER GAINS

FIG 11
ELEVATOR DISPLACEMENT RESULTING FROM INCREMENTAL LOAD FACTOR DEMAND

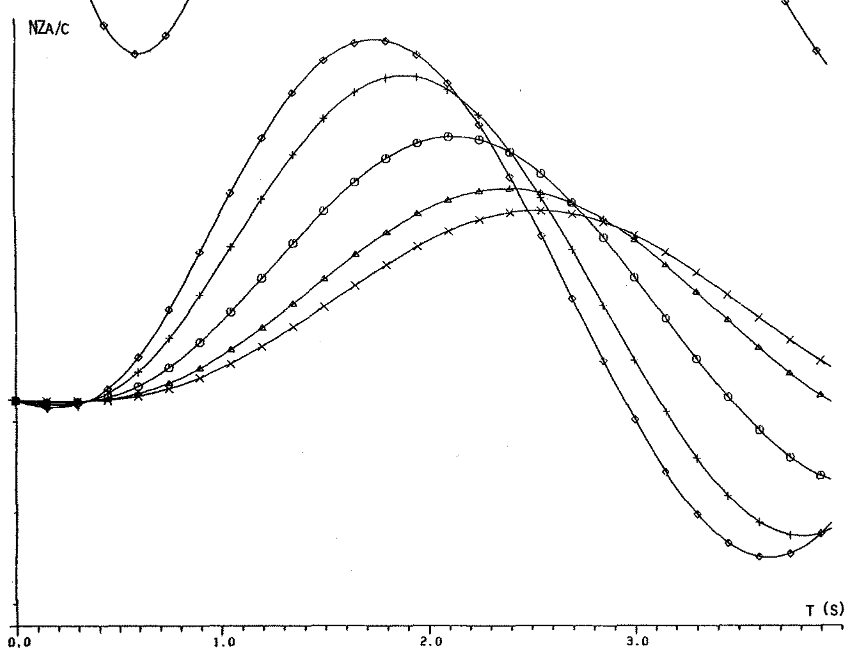


FIG 12
AIRCRAFT LOAD FACTOR AT C.G. (Z-DIRECTION)

EFCS CONTROLLED A/C
SENSITIVITY ON
GAIN VARIATION

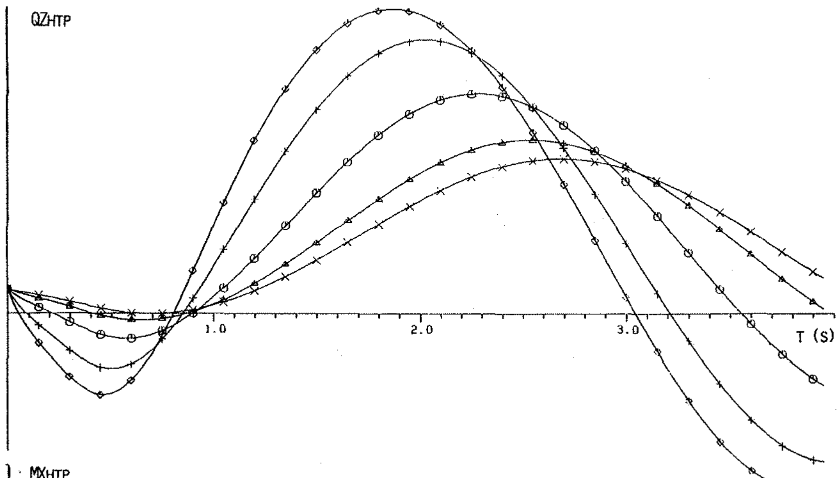
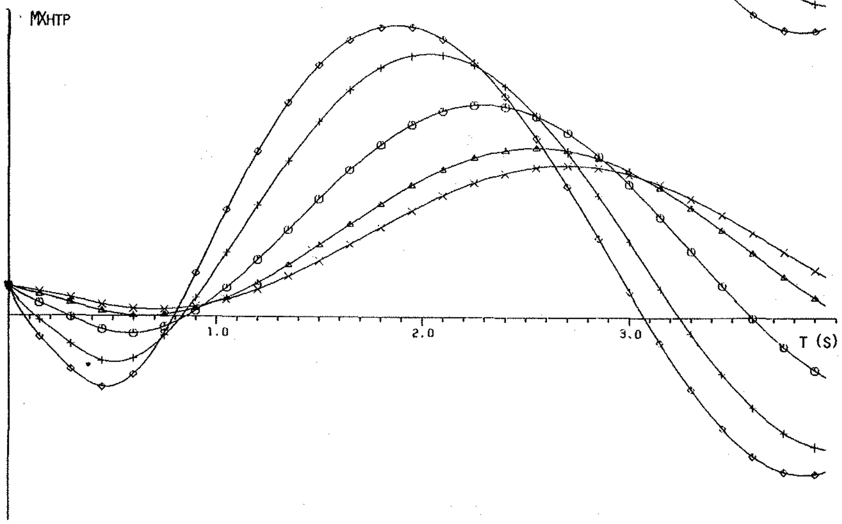


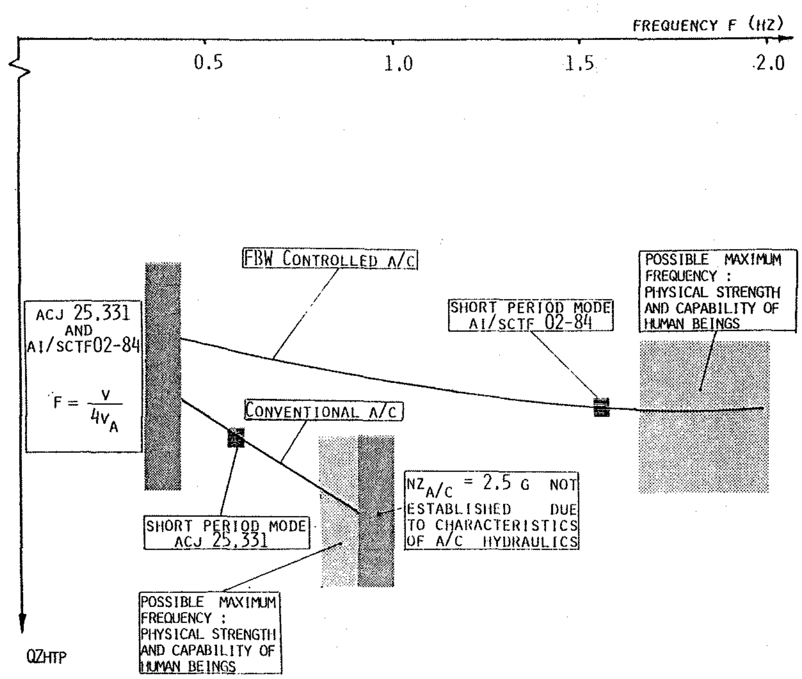
FIG 13
SHEAR AT HORIZONTAL TAILPLANE



○ K4 = K4NOMINAL
△ K4 = 1/2 K4N
+ K4 = 2 K4N
× K4 = 1/3 K4N
◇ K4 = 3 K4N

AND ASSOCIATED VARIATION OF OTHER GAINS

FIG 13
BENDING AT HORIZONTAL TAILPLANE



COMPARISON OF CONVENTIONAL A/C AND EFCS CONTROLLED A/C

FIG 15
SHEAR AT HORIZONTAL TAILPLANE
AS FUNCTION OF FREQUENCY