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THE INTERACTION OF FLIGHT CONTROL SYSTEM AND AIRCRAFT STRUCTURE

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ABSTRACT

Results from structural coupling investigations are presented which include the design and verification of structural filters for a flight control system. The advantages of an integrated interdisciplinary flight control system (FCS) design on the basis of the coupled dynamic model of the structural dynamic model and the flight dynamic model of the aircraft are described.

The design strategy of the Flight Control System development is improved through the integrated design optimisation procedure which includes the modelling of the coupled system of the flight dynamics, the structural dynamics, the actuators and sensors as well as the effects of the digital system.

Different examples are demonstrated which document the advantages of the integrated, interdisciplinary design. Methods to avoid structural mode-flight interaction are described. Especially the design of filters to minimise interaction is outlined, which is based upon a model of the aircraft describing the coupled flight dynamic, flight control dynamics and structural dynamic behaviour and on ground and in flight structural coupling tests. The paper explains design procedures, design and clearance requirements, correlation between model predictions and structural coupling tests and model update for on ground and in flight.

1. INTRODUCTION

The development of advanced digital flight control systems for a modern military aircraft, for example Figure 1, is strongly influenced by aeroservoelastic effects. The flexible aircraft behavior, especially for this artificially stabilised aircraft configuration with outer wing missiles, tip pods and heavy under wing stores and tanks, has significant effects on the flight control system. The signals from the Aircraft Inertial Measurement Unit (IMU) - the gyro platform – contain, in addition to the necessary information of rigid aircraft rates and accelerations, flexible aircraft rates and accelerations at the frequencies of the aircraft elastic modes. The flexible aircraft rates and accelerations measured by the IMU are passed through the flight control system control paths, multiplied by the FCS gains and FCS filters, and summed into the control surface actuator inputs, which then drive the controls at the frequencies of the elastic modes of the aircraft. The flexible aircraft is excited by the high frequency control deflections and therefore may experience aeroservoelastic instability i.e. flutter or limit cycle oscillations, and dynamic load and fatigue load problems may arise. The FCS design therefore has to minimize all structural coupling effects through all available means, including optimum sensor positioning, notch filtering and additional active control. This paper describes the major aspects and problem areas to be considered in the FCS design with respect to aeroservoelastic effects, as also previously described in References 1-6, and outlines an integrated design of FCS gains and phase advance filters together with notch filters, see also Reference 8. The integrated design process has been followed for the current project since independent design of notch filters or FCS has not led to a satisfactory solution for stabilization of rigid aircraft or elastic modes.

2. INTEGRATED DESIGN FOR ADVANCED FLIGHT CONTROL SYSTEMS

2.1 Design philosophy

Within the integrated process, structural coupling influences are minimised by the traditional means of notch filtering, but here an optimum solution is reached by exchanging notch attenuation and phase lag with FCS gain and phase advance filtering. The scope of the integrated design therefore covers FCS gains, phase advance and notch filtering across the full rigid and flexible aircraft frequency range, addresses both aircraft rigid mode and structural coupling stability requirements, and encompasses all possible aircraft configurations and configuration changes, (missiles on, off, tanks on and off etc.). Thus all structural coupling

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changes with configuration etc will be covered by a single, fixed set of notch filters, avoiding the system complexity associated with configuration switches for different sets of notch filters, and avoiding any scheduling of notch filters with flight conditions.

In order to simplify the design process wherever possible, the basic stability criteria for the flexible modes were based on gain margin only, with no phase margin specification. In practice this principle was not wholly practicable for the pitch axis, where high levels of FCS stability augmentation were required and the integrated design task was particularly difficult. Here, 'gain stabilisation' was applied only to the higher frequency modes, with phase and gain margins taken fully into account ('phase stabilisation') for the lower frequency regime.

For 'phase stabilisation', the notch filter design utilised an analytical model of the aircraft structure incorporating a linear representation of the FCS. In this application, the analytical model was subject to extensive verification against results both from ground resonance and structural coupling testing, and from in-flight flutter and structural coupling testing. Where necessary, the model was updated to improve the match to the test results.
Due to restrictions in the absolute accuracy of the analytical model predictions at higher frequencies, design for gain stabilised elastic modes was based on ground measured data, augmented where necessary with aerodynamic effects derived from the model.

To cover all of the possible sets of aircraft store configurations required under the weapon system specification, those that were critical to the filter design were established by analytical model investigation in advance. These were then treated in test and analysis.

2.2 Design Requirements

2.2.1 Stability Requirements

The design requirements are primarily linear stability margin specifications covering all flight control rigid / flexible aircraft modes, and were developed from the Military Specification MIL-F-9490D.
The open loop frequency response requirements are demonstrated in Figure 2 for two cases, A and B.

Case A describes (in a Nichols diagram) the gain and phase margin requirement for early prototype flying, and indicates that all elastic modes shall be 'gain stabilized'.

Case B describes gain and phase margins applicable following model validation through structural coupling ground and flight tests. The low frequency flexible modes are phase stabilized while higher frequency modes remain gain stabilized.

2.2.2 Vibration / Dynamic Load Requirements

In addition to the stability requirements for structural coupling, unacceptable vibration levels must be avoided. The vibration levels induced by poor structural coupling stability might create high fatigue loads to actuators and to aircraft structure. The notch filters have to be designed with specific vibration requirements accounted for.

2.2.3 Flutter Requirements

The FCS / notch filter design solution has to fulfill the same flutter requirements as the aircraft without FCS. The aircraft with FCS must meet the 15% flutter speed margin as well as the minimum elastic mode damping requirements as described in Military Specification MIL-A-8870 B.

2.3 Design Tools

The integrated FCS design for the flexible aircraft is possible with the assumption that the aircraft characteristics are predictable to the necessary accuracy. The characteristics of the controlled flexible aircraft are described in the form of open loop frequency transfer functions of the FCS/flexible aircraft control path feedback loops to a sufficiently high frequency; see block diagram in Figure 3. For the longitudinal control system, the pitch rate, normal acceleration and flow sensor α open loop signals at the control loop break point have to be known. For the lateral system, the roll rate -, yaw rate-, lateral acceleration - and flow sensor signal β open loop signals are required. The open loop signal consists of the transfer function of the aircraft response to control surface input, sensed at the IMU (rates and accelerations) and flow sensors, combined with the transfer functions of the FCS from the sensor to the opening point and from the opening point to the actuators.
The individual transfer functions are composites covering gain stabilised and phase stabilised modes. As noted, phase stabilised modes use the analytical dynamic model calculation directly, while the gain stabilised modes use on ground measured sensor response to actuator input transfer functions superimposed with calculated magnitudes of unsteady aerodynamic transfer functions.
The applicability of the analytical dynamic model calculation depends on the accuracy of the modeling and its verification. Both methods depend on the accuracy of the unsteady aerodynamic transfer functions, which are in both methods derived from linear potential flow theoretical predictions of unsteady

aerodynamics for elastic modes and control surface deflection.

2.3.1 Analytical Model of the Flexible Aircraft with Flight Control System

The analytical model of the flexible aircraft –plus- FCS consists of a linear dynamic description of the flight mechanic equations of motion, flexible aircraft, and FCS. The flexible aircraft is represented in a modal description, using generalized coordinates, generalized masses, stiffness and structural damping and generalized aerodynamic forces of the flexible modes. Generalized control surface inertia and unsteady aerodynamic terms provide the link to the FCS. The FCS is described through linear differential equations, covering both hardware and software, i.e. all sensors, actuators, computer characteristics and control laws.

The equations of motion for the forced dynamic response of the aeroelastic system can be written in matrix differential equation form:

$$m_r b_r^2 \begin{bmatrix} M_{qq} & M_{q\delta} \\ M_{\delta q} & M_{\delta\delta} \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \ddot{\delta} \end{Bmatrix} +$$

$$+\frac{s_R}{kV}\left\{ \omega_r^2 m_r b_r^2 \begin{bmatrix} gK_{qq} & 0 \\ 0 & K''_{\delta\delta} \end{bmatrix} + \frac{\rho}{2} V^2 F s_R \frac{b_r}{S_R} \begin{bmatrix} C''_{qq} & C''_{q\delta} \\ C''_{\delta q} & C''_{\delta\delta} \end{bmatrix} \right\} \begin{Bmatrix} \dot{q} \\ \dot{\delta} \end{Bmatrix} +$$

$$+\left\{ \omega^2 m_r b_r^2 \begin{bmatrix} K_{qq} & 0 \\ 0 & K'_{\delta\delta} \end{bmatrix} + \frac{\rho}{2} V^2 F s_R \frac{b_r}{s_R} \begin{bmatrix} C'_{qq} & C'_{q\delta} \\ C'_{\delta q} & C'_{\delta\delta} \end{bmatrix} \right\} \begin{Bmatrix} q \\ \delta \end{Bmatrix} = \{Q(t)\}$$

Equation 1

where m_r b_r and ω_r are the reference mass, length and frequency and M, K and C are referred to as the generalized mass, stiffness and aerodynamic matrices, which are non-dimensional. The generalized mass and stiffness matrices are calculated using a finite element mode (FEM) of the total aircraft. For dynamic response calculations, the FEM is reduced to representative generalized dynamic degrees of freedom. The true airspeed V, and semi-span s_R of the reference plane are used to form the reduced frequency $k = (\omega s_R)/V$. F is the area of reference plane and g is the structural damping of the elastic modes. The generalized forces Q(t) are equal to zero for the conventional flutter problem. The generalized coordinate 'q' describes the amplitude of the elastic airplane modes, including elastic control surface modes, whereas 'δ_0' (subscript omitted above) denotes the rotation of the rigid control surface according to the complex actuator stiffness represented by the impedance function of equation (2).

$$K_{\delta_0\delta_0} = K'_{\delta_0\delta_0} + iK''_{\delta_0\delta_0} \qquad \textbf{Equation 2}$$

For the controlled aircraft, the FCS-commanded control deflection '$\Delta\delta$' has to be introduced as an additional degree of freedom for each control surface. The generalized forces generated by the servo induced control deflections ($\Delta\delta$) can be described as the right-hand term of equation (1) by

$$\{Q(t)\} = -m_b b_r^2 \begin{Bmatrix} M_{q\Delta\delta} \\ M_{\delta_0\Delta\delta} \end{Bmatrix} \Delta\ddot{\delta} - \frac{\rho}{2} V^2 F s_R \frac{b_r^2}{s_R^2} \frac{s_R}{k \cdot V} \begin{Bmatrix} C''_{q\Delta\delta} \\ C''_{\delta_0\Delta\delta} \end{Bmatrix} \Delta\dot{\delta}$$

$$-\frac{\rho}{2} V^2 F s_R \frac{b_r^2}{s_R^2} \begin{Bmatrix} C'_{q\Delta\delta} \\ C'_{\delta_0\Delta\delta} \end{Bmatrix} \Delta\delta$$

Equation 3

Assuming normalized rigid control surface modes δ_0 and $\Delta\delta$, the rotation of each control surface can be superimposed by

$$\delta = \delta_0 + \Delta\delta \qquad \textbf{Equation 4}$$

δ here represents foreplane, inboard and outboard flap or for rudder, and differential inboard and outboard flap. The state-space-description of (1) is as follows:

$$\{x\} = [A]\{x\} + [B]\{x\} \qquad \textbf{Equation 5}$$

As already described, the matrix equation (1) describes the flexible aircraft, FCS and linearized rigid flight mechanic equations, and thus the state vector for longitudinal control includes the rigid aircraft state variables, as follows:

$$X = \lfloor \Delta V/V; \Delta\alpha; \Delta\omega; \Delta\theta; \dot{q}; \dot{\delta}_0; \Delta\dot{\delta}; q; \delta_0; \Delta\delta \rfloor$$

The flight mechanic equations may, in a first approximation, contain elastified aerodynamic derivatives as function of incidence and Mach number. For low frequency the flight mechanic equations may be assumed to be decoupled from the flexible aircraft equations. Alternatively, the fully rigid flight mechanic equations are introduced, and theoretical inertia and unsteady aerodynamic coefficients may be used.

The flight mechanic equations for longitudinal control are described below, including rigid aircraft equations with flexible coupling terms.

Normal Force equations:

$$\sum Z = -\frac{\rho}{2} V^2 F \left[C'_{z\alpha}(\omega) \cdot \alpha + C''_{z\alpha}(\omega)/\omega \cdot \dot{\alpha} \right]$$

$$-mV \cos(\alpha\omega_y) - \frac{\rho}{2} V^2 F \cdot \bar{c} \left[C'_{zq}(\omega) \cdot \omega_y + C''_{zq}(\omega) \cdot \dot{\omega}_y \right]$$

$$-mg \sin(\alpha\theta)$$

$$-\frac{\rho}{2} V^2 F \left[C'_{z\delta}(\omega) \cdot \delta + C''_{z\delta}(\omega)/\omega \cdot \dot{\delta} \right] - Z_{m\delta} \cdot \ddot{\delta}$$

$$-\frac{\rho}{2} V^2 F \left[\sum_j C'_{zqj}(\omega) q_j + \sum_j C''_{zqj}(\omega) q_j \right] = 0$$

Elastified normal force 'rigid' aircraft equations

$$\sum Z = -\frac{\rho}{2} V^2 F \cdot C_{zq}(\alpha)\alpha - mV \cos(\alpha\omega_y)$$

$$-\frac{\rho}{2} V^2 F \cdot \bar{c} C_{zq} \omega_y - mg \sin(\alpha\theta) - \frac{\rho}{2} V^2 F \cdot C_{z\delta}(\alpha)\delta = 0$$

Pitching moment equation with flexible coupling terms

$$\sum M = -\frac{\rho}{2}V^2 F \cdot \bar{c}\left[C'_{m\alpha}(\omega)\alpha + C''_{m\alpha}(\omega)\dot{\alpha}\right]$$

$$-I_y\dot{\omega}_y - \frac{\rho}{2}V^2 F \cdot \bar{c}^2\left[C'_{mq}(\omega)\omega_y + C''_{m}(\omega)\dot{\omega}_y\right]$$

$$-\frac{\rho}{2}V^2 F \cdot \bar{c}\left[C'_{m\delta}(\omega)\delta + C''_{m\delta}(\omega)/\omega \cdot \dot{\delta}\right] - M_{m\delta}\ddot{\delta}$$

$$-qFs\left[\sum_j C'_{mqj}(\omega)q_j + C''_{mqj}(\omega)/\omega \cdot q_j\right] = 0$$

Elastified Pitch Moment 'rigid' aircraft equations

$$\sum M = -\frac{\rho}{2}V^2 F \cdot \bar{c}C_{m\alpha} + \alpha + I_y\dot{\omega}_y - \frac{\rho}{2}V^2 F \cdot \bar{c}C''_{m\delta}(\alpha)\delta$$

$$-\frac{\rho}{2}V^2 F \cdot \bar{c}^2 C_{mq}\omega_y - \frac{\rho}{2}V^2 F \cdot \bar{c}^2 C_{m\dot{\alpha}} \cdot \dot{\alpha} = 0$$

C'	Real part of calc. aerodynamic coefficient
C''	Imag. part of calc. aerodynamic coefficient
$\rho/_2 V^2$	Dynamic pressure
F	Reference area
$\bar{c}, s$	Reference length
q_j	Generalized coordinate

2.3.2. Modelling and Analysis Assumptions

Particularly where the analytical model is being used directly, to predict characteristics for phase stabilised modes, the assumptions be made in dynamic model formulation and subsequent analyses have to be conservative in order to cover, for example, system failures. Particular considerations are outlined below.

Actuator Characteristics

The actuator model transfer function should follow the actuator specification upper gain boundary. When tuning the actuator model phase characteristics, both minimum and maximum phase lag boundaries need to be considered, since either case may be critical for phase stabilised modes. In general, actuator non-linearities reduce gain and structural coupling, and therefore linear characteristics may be modelled.

Inertial Measurement Unit (IMU)

The transfer function of the sensor platform should to describe the upper gain boundary and the minimum and maximum phase boundary. Only the upper linear boundary is necessary to be represented.

Flow Sensors

Measured flow sensor transfer functions must be used.

Structural Modeling

Consideration of the full variation of the flexible mode frequencies with flight condition, fuel contents and actuator failure cases is necessary, and separate models may be created for the critical store cases. In order to be accurate, the analytical model has to be updated from ground test results, principally with respect to mode frequencies, but also considering response amplitude. The model update must consider the effects of structural non-linearity, notably the variation of mode frequency with excitation amplitude.

The minimum measured structural damping must be applied.

Unsteady Aerodynamic Modeling

The unsteady forces used in the dynamic model calculation shall be represented in a conservative manner.

The predicted magnitude (modulus) of the unsteady forces of the flexible modes and control surface deflection represents a high (i.e. conservative) value for all Mach numbers and incidences, since, in practice, flow separation at higher incidences leads to reduction in the motion induced pressure distributions compared with pure linear theory. Special attention has to be paid to transonic effects, however.

Since the predicted criticalities in structural coupling conditions are at high incidence conditions, because of FCS gain scheduling, the adoption of linear unsteady subsonic and supersonic aerodynamics derived by linear theory or numerical Euler code calculations in the linear range (Reference [10],) is believed to be conservative throughout the full flight envelope.

The unsteady forces must be calculated for a number of reduced frequencies to cover the full frequency range.

For the phase stabilization of low frequency flexible modes such as the first wing bending, the unsteady aerodynamic phase is again derived directly from the application of linear theory. Experience for different wing configurations indicates that at high incidence and high FCS gains, the aerodynamic damping is increased compared to low incidence. In terms of phase stability margin, Reference [3] explains the difference in a Nichols diagram, linear theory showing the more critical condition.

For the gain stabilised, higher frequency modes, only the magnitude of the unsteady aerodynamic forces is needed for the design of the notch filters, because only a gain margin is required, and phase is excluded from the analysis.

FCS Control Laws Model

In order to design in a robust manner the calculation of open loop transfer functions shall consider the worst FCS gain conditions. The highest end to end trimmed gain conditions have to be included into the model calculations. Special consideration shall be also given to

the maximum out of trim gain conditions with respect to structural coupling criticality.

2.3.3 Ground Test Result - Update of Dynamic Model

Ground vibration test results and structural coupling tests are needed to verify or update the calculated results from dynamic model. In general the total aircraft structural dynamic model consists of subcomponents. Sub-component models can be refined by updating the sub-component stiffness and damping, using the results from component ground resonance tests. Updating of the total aircraft model then uses overall aircraft ground resonance and structural coupling tests. The update of the analytical model is described in Reference [6].

In Reference [8] a typical result was demonstrated for the comparison of predicted and measured IMU open loop response due to control surface input, showing that dynamic inertia coupling modelling has to be updated with on ground measured results. Both the sensor signal in each aircraft normal mode, and the control surface inertia coupling terms in each mode, have to be tuned to test results.

2.3.4 Flight Test Results - Update of Control Surface Unsteady Aerodynamics

Flight test results from structural coupling/flutter tests are needed to verify or update the predicted results of open loop frequency response functions, by the update of unsteady aerodynamic forces used in the dynamic model. This can be achieved through the comparison of predicted open loop frequency response functions and flight test-measured closed loop converted into open loop frequency response functions.

The flight test results are derived through frequency sweep excitation of the control surfaces, which is possible through special software in the FCC's.

In Reference [8] a typical result for the comparison of predicted and measured IMU open loop response due to control surface input is documented, showing that unsteady aerodynamic coupling modelling has to be updated with in flight measured results both for low and high angle of attack α. From the flight test results it is concluded that the theoretical control surface unsteady aerodynamic coupling terms used in the total dynamic model have to be tuned to test results for low up to high incidences.

The flight test results also shown in Reference [8] demonstrate the alleviation effect resulting from application of the phase stabilisation concept to the first wing bending mode compared to gain stabilisation. Alleviation of IMU pitch rate is found to be at least 3dB.

2.4 FCS Design with Optimization of Structural Decoupling

Different procedures are available to minimize structural coupling effects in the Flight Control System. The practical tools are to minimize structural coupling are:

- Optimum sensor location
  The IMU shall be put to the anti node of the first fuselage bending mode, since the elastic pitch-yaw angle/pitch-yaw rate is minimum at this location. Optimum sensor location is meaningless for first wing bending mode coupling since the fuselage counteracts wing bending with a linear pitch motion.
- Stiffening of the IMU platform
  A very high stiffness of the sensor platform is favorable, since local medium-to-high frequency elastic modes will then be eliminated.
- Actuator transfer function
  A strong decay in the actuator transfer function at medium to high frequencies would minimize coupling effects. Actuator frequencies at medium frequencies (10 - 30 Hz) shall be well damped. Actuator phase shifts at low elastic mode frequencies shall be known for the absolute minimum and maximum value.
- Minimum weight/inertia of control surfaces
  High frequency 20 - 80 Hz structural coupling effects are small using light weight controls.
- Notch Filter Configuration Optimization
  Figure 3 demonstrates schematically the feedback paths for the longitudinal stabilization. Signals from the FCS sensors are filtered in the IMU initially, by notch filters that minimize the high frequency flexible aircraft signal components. The remaining signals are then modified by the FCC notch and phase advance filters. After multiplication with the FCC gains the signals are passed to the different control surface actuators. Upstream of the actuator input, the signals are filtered by flap, foreplane and rudder notch filters. This combination of IMU, FCC and actuator input filters, leads to a better minimization of phase shifts at low frequency, which is necessary to meet the handling criteria.
- Optimization of phase advance filters
  Phase advance filters used in the FCS maximise rigid stability margins by counteracting the low frequency phase shifts due to notch filtering and other delays. However the high frequency gain increase associated with the phase advance exacerbates structural coupling. The optimization of phase advance filter should therefore be combined with the notch filter optimization. This might be performed in a iterative manner, or preferably in a combined optimization with the notch design

frequency response functions covering the rigid aircraft frequency regime.

- Optimization of notch filter
  The notch filter optimization is the major tool for decoupling the aircraft control from aeroservoelastic influences. Since the coupling has a severe impact on the FCS on the current aircraft project, a mathematical filter optimization had to be developed in order to achieve flight dynamic stability requirements. The optimization is described below.

In order to optimize the filters it is necessary to establish the open loop frequency response functions at the opened summation points of the longitudinal and lateral control S_{L1}, S_{L2} and S_{A1}, S_{A2}.
For example, the open loop frequency response function at the longitudinal open loop point S_{L1} of Figure 3 can be formulated using the separate transfer functions of the loop response without notch filters due to flap and foreplane excitation (S_{L2} closed), and by sequentially setting each separate flap or foreplane loop gain to zero.

a) $G_{nz} = 0,\ G_\alpha = 0,\ G_q \pm 0$
a$_1$) flap excitation only to generate $F_F{}^q$ at S_{L1}
a$_2$) foreplane excitation only to generate $F_c{}^q$ at S_{L1}
b) $G_{nz} = 0,\ G_\alpha \pm 0,\ G_q = 0$
b$_1$) flap excitation only to generate $F_F{}^\alpha$ at S_{L1}
b$_2$) foreplane excitation only to generate $F_c{}^\alpha$ at S_{L1}
c) $G_{nz} = 0,\ G_\alpha = 0,\ G_q = 0$
c$_1$) flap excitation only to generate $F_F{}^{nz}$ at S_{L1}
c$_2$) foreplane excitation only to generate $F_c{}^{nz}$ at S_{L1}

The total open loop transfer function F at S_{L1} can be formulated to:

$$F_{Total} = G_q \left\{ F^q_{\delta_0} F_{NF_{O1}} F_{NF_{O2}} + F^q_{\delta_i} F_{NF_i} + F^q_\eta F_{NF_{FP}} \right\}$$
$$\cdot F^q_{NF1_{FCC}} \cdot F^q_{NF2_{FCC}} \cdot F^q_{NF3_{FCC}} \cdot F^q_{NF1_{IMU}} \cdot F^q_{NF2_{IMU}} \cdot F^q_{NF3_{IMU}} \cdot F^q_{Ph.adv}$$
$$+ G_\alpha \left\{ F^\alpha_{\delta_O} \cdot F_{NF_{O1}} \cdot F_{NF_{O2}} + \frac{G_I/G_\alpha}{s} \left[F^\alpha_O \cdot F_{NF_{O1}} \cdot F_{NF_{O2}} \right] + \right.$$
$$+ F^\alpha_{\delta_i} \cdot F_{NF_i} + \frac{G_I/G_\alpha}{s} \left[F^\alpha_{\delta_i} \cdot F_{NF_i} \right] +$$
$$\left. + F^\alpha_\eta \cdot F_{NF_{FP}} + \frac{G_I/G_\alpha}{s} \left[F^\alpha_\eta \cdot F_{NF_{FP}} \right] \right\}$$

G_q	pitch rate gain
G_α	flow sensor signal α gain
G_I	integrated α gain
$F^q_{\delta_O}$	pitch rate frequency response function due to outboard flap
$F^q_{\delta_i}$	pitch rate frequency response function due to inboard flap
F^q_η	pitch rate frequency response function due to foreplane
F^α_δ	α frequency response function due to outboard flap
$F^\alpha_{\delta_i}$	α frequency response function due to inboard flap
F^α_η	α frequency response function due to foreplane
$F_{NF_{FCC}}$	Flight Control Computer notch filter
$F_{NF_{IMU}}$	ASMU notch filter
$F_{NF_{FP}}$	Foreplane notch filter
F_{NF_O}	Outboard flap notch filter
F_{NF_i}	Inboard flap notch filter
s	Reference length

A similar formulation can be derived for all other summation points S_{L2}, and lateral S_{A1} S_{A2}.
The open loop frequency response functions F_{Total} can be calculated at arbitrary frequency steps as described in the previous sections.

Since the FCS of the current project is digitally implemented, digital effects must be accounted for in the notch filter design
The notch filter transfer functions are designed and specified as second order numerator and denominator functions in the continuous Laplace domain but take into account frequency warping effects.

$$\omega_Z = \frac{2}{T} \tan \frac{\omega_L \cdot T}{2}$$

ω_L	Laplace domain frequency
ω_Z	digital domain frequency
T	sample period

The frequency in the continuous domain corresponds to a downward frequency warping in the digital domain.
For the phase stabilised modes, the digital effects caused by IMU sensor signal processing transmission delay and sampling of the IMU output by the FCC's is represented in the dynamic model by IMU hardware assumptions using a defined transfer function. For gain stabilised modes, these effects are implicit in the measured results on which the filter design data are based. The effect of aliasing is included in the analysis by a folding back procedure.

Having assembled the required frequency response function data, the notch filter coefficients are optimized using a notch filter optimization program. The computer program is based on the FORTRAN subroutine of

solving constrained non-linear programming problems from K. Schittkowski, see Reference [9] . A finite difference gradient approach is applied.
From the total open loop frequency response function, the phase shift at low frequency due to notch filters can be derived which is the primary variable to be minimized:

$$\min \text{Phase } (F(f = 1 \text{ Hz}))$$

The total open loop frequency response function including optimized notch filters shall meet the stability requirements, -9 dB for gain stabilization or the gain/phase requirements described in 2.2.
With these requirements the constraints of the optimization can be formulated. The number of frequencies at which the requirement has to be fulfilled defines the total number of constraints.

The number of variables is known from the number of notch filters. An initial guess of the solution is prescribed in the input, and used in initial optimization runs. Lower and upper bounds of the variables are prescribed.
Notch filter numerator, denominator frequencies are selected using the frequencies response peak characteristic for the selection of numerator frequencies, the asymptotic behavior of the notch filters at high frequencies for the denominator frequency, and the denominator critical damping for each notch filter. The notch filter critical damping for IMU filters is prescribed to be > 0.25 for FCC filters, with the minimum value prescribed to be 0.1. A scaling matrix is used for the variables.
Figure 4 demonstrates the results derived from notch filter optimization. Figure 4 upper part shows the open loop frequency response with optimized notch filters in pitch for the design.
Figure 4 below is showing by open loop frequency response functions with the designed notch filters the case where during notch filter design the design information for additional structural configurations or flight conditions was not available and therefore the requirements are not met.

Figure 5 demonstrates the advantages of integrated FCS design in a Nichols diagram of open loop frequency response.

- Case A shows the pure 'rigid' A/C design (flight mechanics design)
- Case B presents the result on open loop frequency response function of using separate, independent, notch filter design (elastic design), applying a full gain stabilization concept for elastic modes, leading to a higher phase shift at the rigid aircraft frequencies, and conflict with the requirements.
- Case C demonstrates the advantages of phase stabilization on the 1st wing bending (WB1) and rigid A/C motion.
- Case D shows the profits of integrated design; both the rigid A/C and elastic modes have sufficient phase and gain margins.

3. DESIGN AND CLEARANCE PROCEDURE

Figure 6 shows the design and clearance procedure, which is based upon a series of on-aircraft and rig tests for identification and clearance, and consequently a series of dynamic model updates from testing and from updated FCS definitions.
Initial design will be made without the benefit of full-aircraft testing. Following the tests, an update phase of the FCS gains, phase advance filters and of notch filters may be necessary depending on the criticality of mismatch between design assumptions and test, for example, if:

- the structural coupling test on ground shows different frequencies of the elastic modes than assumed in the design (for instance a special configuration was not included in the design etc.).
- the in flight structural coupling test shows different dB's and different phase of the low frequency elastic modes than assumed during design
- the on aircraft actuator characteristics are different from design assumptions.
- redesign of structural parts local weight changes, change of pylon stiffness' etc. during development phase.

It is the task of the structural coupling/notch filter design and clearance procedure to treat this situation.

4. CONCLUSIONS

From the results of structural coupling investigations performed for an advanced fighter aircraft, the following lessons have been learned:
Dynamic modelling of the fuselage response and the essential sensor response due to control surface inputs is limited to a certain low frequency range due to the total aircraft finite element model representation, being extremely complex and due to unsteady control surface aerodynamic representation.
An extensive series of structural coupling tests on ground are therefore necessary to update dynamic fuselage modelling, for and control surface inertia coupling terms. Structural coupling in-flight tests are

necessary to update the unsteady aerodynamic control surface coupling terms.
The integrated design of FCS gains, phase advance filters and of structural coupling/notch filter design and clearance procedure has shown advantages in comparison to the classical, separate FCS and notch filter design. The profits of integrated design are mainly found to be:

- less degradation effects on rigid aircraft stability margins
- improvements of elastic mode stability
- improvement of phase advance filters combined with lower high frequency end to end gains

A robust FCS design has to be adopted which includes the description of all worst case assumptions for the structure, the FCS gains and FCS minimum and maximum phase at low elastic mode frequencies, together with worst case assumptions for actuator and sensor hardware. Digital effects have to be fully included.

5. REFERENCES

(1) J. Becker, W. Luber
Flight control design optimization with respect to flight- and structural dynamic requirements
AIAA Seattle 1996

(2) J. Becker, V. Vaccaro
Aerservoelastic Design, Test Verification and Clearance of an Advanced Flight Control System
AGARD - CP- 566
paper presented at the SMP Meeting Àdvanced Aeroservoelastic Testing and Data Analysis',
Rotterdam 8-10 May 1995

(3) J. Becker
Aeroservoelastic Stability of Aircraft at High Incidence.
68th AGARD Fluid Dynamics Panel Specialist Meeting, Toulouse France; May 1991

(4) B.D. Caldwell
The FCS-Structural Coupling Problem and its Solution.
AGARD Conference Proceedings on Active Control Technology, FMP Symposium held at Turin, Italy, May 1994

(5) H. Hönlinger, H. Zimmermann, O. Sensburg, J. Becker
Structural Aspects of Active Control Technology
AGARD Conference Proceedings on Active Control Technology, FMP Symposium held at Turin, Italy, May 1994

(6) V. Vaccaro, J. Becker
Ground Structural Coupling Testing and Model Updating in the Aeroservoelastic Qualification of a Combat Aircraft.
AGARD SMP Meeting on Advanced Aeroservoelastic Testing and Data Analysis, Rotterdam, 8-10 May 1995.

(7) J. Becker, W. Luber
Unsteady Aerodynamic Forces at High Incidence and their Application in Structural- and Flight Control Design. International Forum on Aeroelasticity and Structural Dynamics; Manchester, UK; 26-28 June 1995

(8) J. Becker
The structural coupling resulting from interaction of flight control system and aircraft structure
International Forum on Aeroelasticity and Structural Dynamics, Rome,Italy, June 1997

(9) Schittkowski, K.,
NLPQL: A FORTRAN Subroutine Solving Constraint Non-linear Programming Problems.
Annuals of Operations, 5, 485-1 00 (edited by Clyde L. Mouna)

(10) G. Heller, E. Kreiselmaier
Eulerluftkräfte für Klappenschwingungen.
TUM-FLM-96/05, Lehrstuhl für Fluidmechanik, Technische Universität München

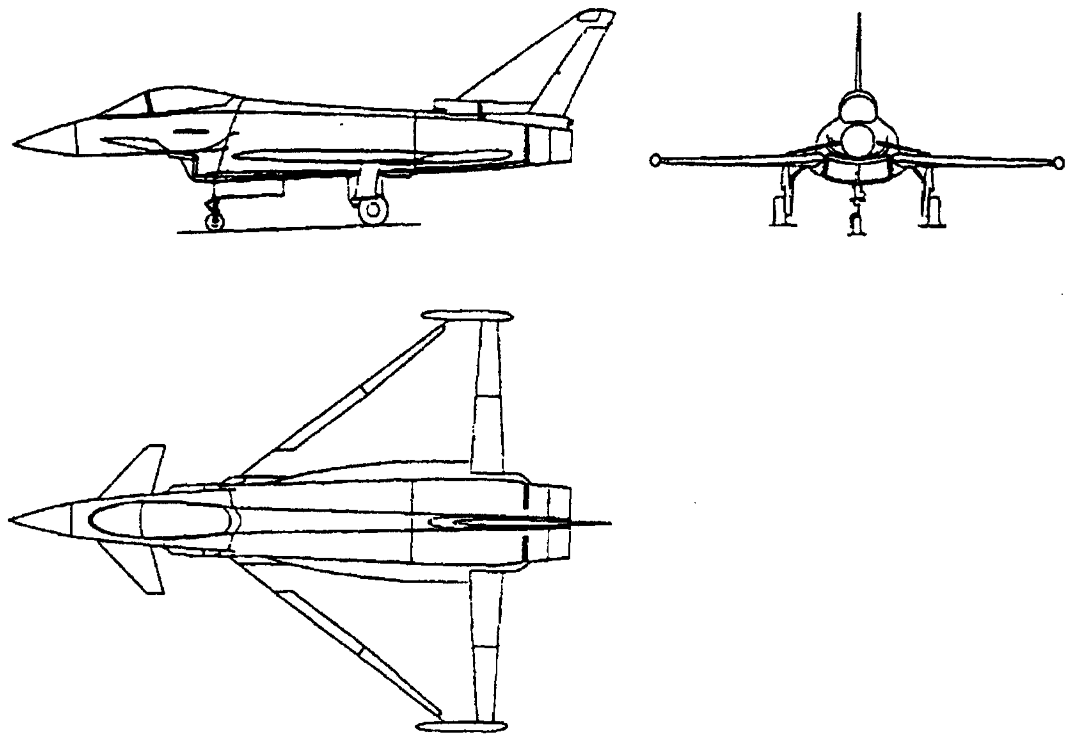


FIG.: 1 MODERN MILITARY AIRCRAFT

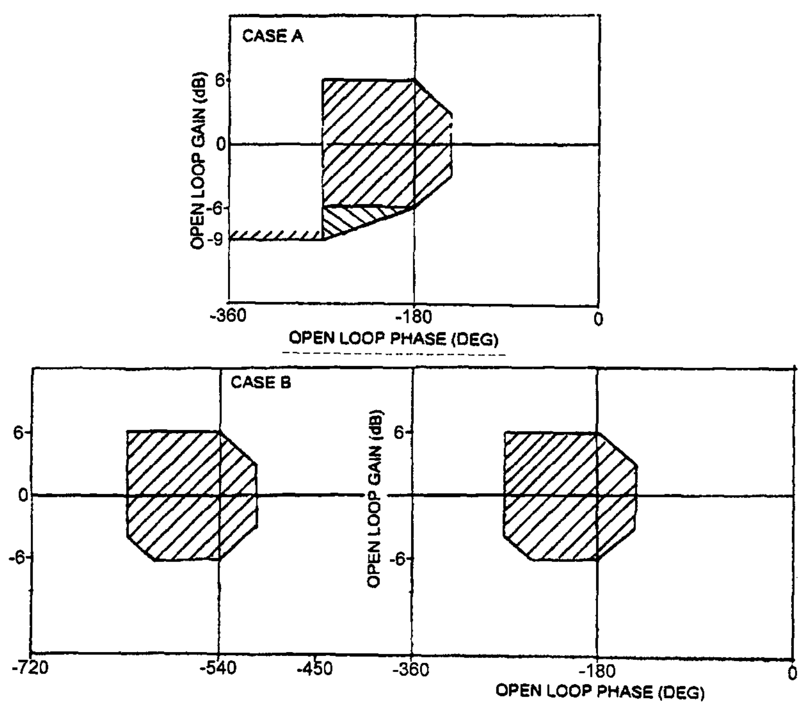


FIG.: 2 STABILITY REQUIREMENTS FOR OPEN LOOP FREQUENCY RESPONSE FUNCTIONS (NICHOLS DIAGRAM)
CASE A: EARLY PROTOTYPE FLYING
CASE B: PRODUCTION AIRCRAFT

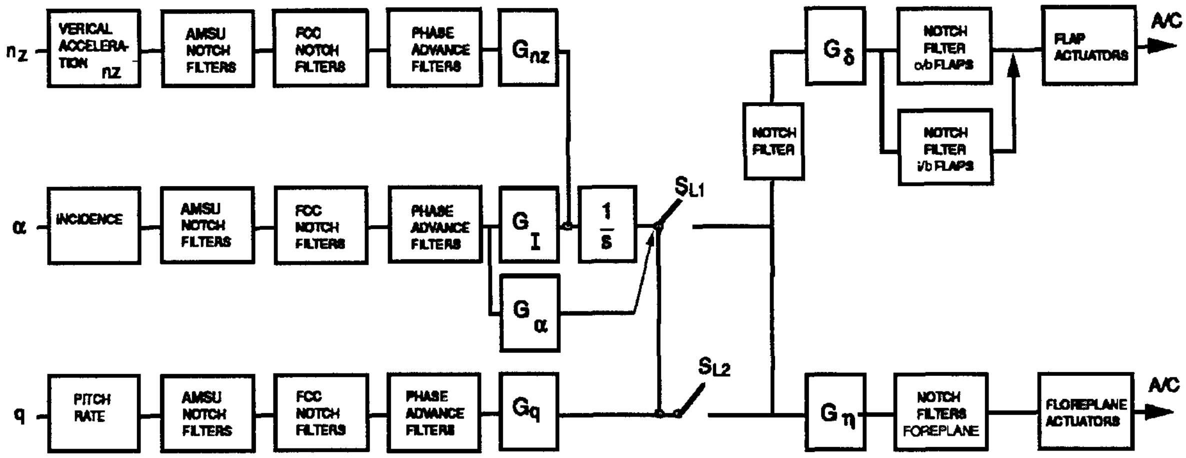


FIG.: 3 FLOWCHART OF LONGITUDINAL CONTROL

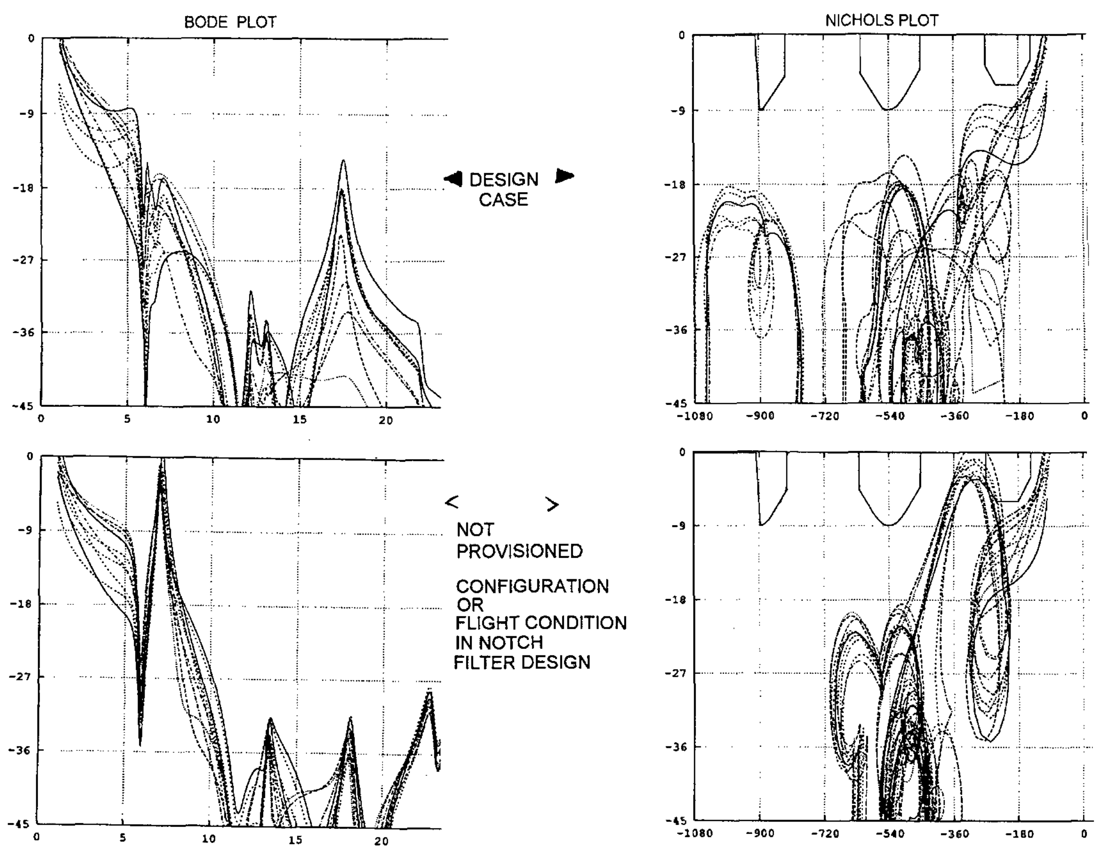


FIG.: 4 OPEN LOOP FREQUENCY RESPONSES WITH NOTCH FILTERS

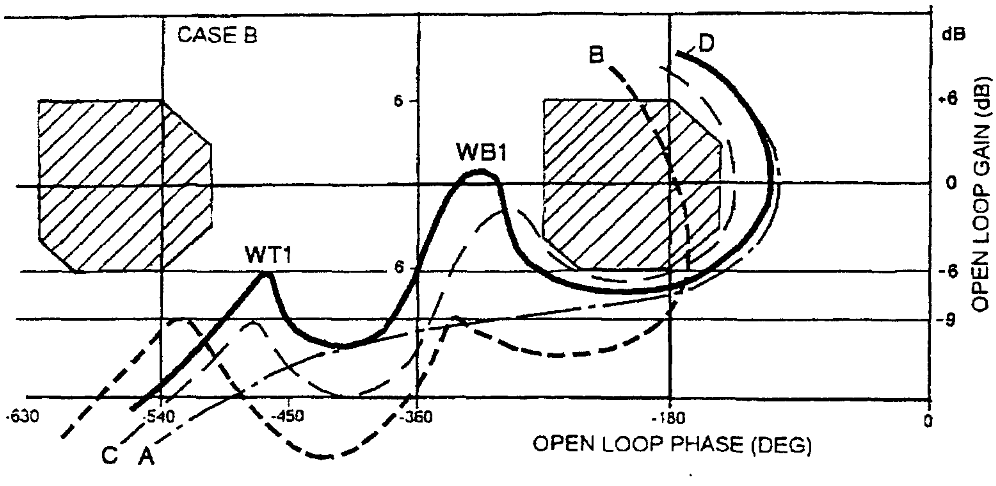
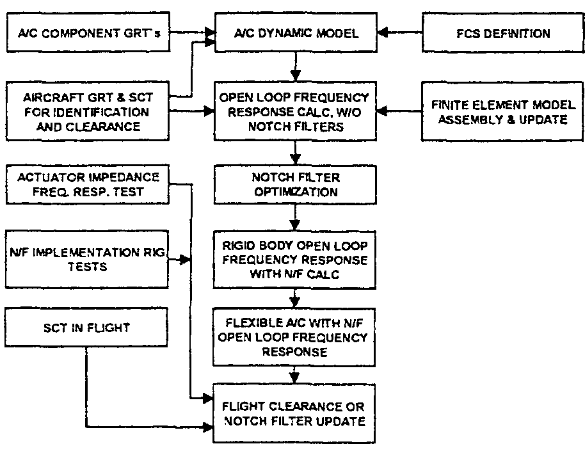


FIG.: 5 COMPARISON OF INTEGRATED TO CLASSICAL



FCS DESIGN

FIG.: 6 DESIGN AND CLEARANCE PROCEDURE