AEROSERVOELASTIC FLIGHT CONTROL DESIGN FOR A MILITARY COMBAT AIRCRAFT WEAPON SYSTEM

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Abstract

The aim of the aeroservoelastic flight control system design for a military aircraft weapon system is mainly to optimize the forward path and feedback structure for a given control law. The control law parameters like gains, phase advance filters and notch filters which cover all conditions in a full flight envelope for all envisaged aircraft configurations carrying external missiles, stores, bombs in all possible symmetric and asymmetric combinations. The control law gains and phase advanced filters which are derived during the optimization process are considered to be Mach number and flight altitude dependent, whereas the structure filters i. e. notch filters may be variables or constant for all flight conditions and groups of the huge number of external store configurations.

The design strategy of the Flight Control System development and the procedure is described which includes the modeling of the coupled system of the flight dynamics, the structural dynamics of representative selected external stores, the actuators and sensors as well as the effects of the digital flight control system.

Different examples are demonstrated which documents the design procedure. The design of FCS notch filters is based upon a model of the aircraft describing the coupled flight dynamic, flight control dynamics and in addition on the structural dynamic behavior measured on ground- and in flight structural coupling tests of a representative number of external store configurations. The paper outlines design procedures, design and clearance requirements, correlation 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 as shown is strongly influenced by aeroservoelastic effects of the large variety of multiple air to air and air to ground external stores, like air to air missiles, air to ground missiles, guided bombs and subsonic or supersonic fuel tanks. This paper describes the major aspects, problem areas to be considered in the FCS design with respect to aeroservoelastic effects of all possible combinations of the huge number of external stores; it outlines the process to achieve suitable notch filters.

The flexible aircraft behavior especially for artificial unstable aircraft configurations with outer wing missiles, tip pods and heavy under wing stores and tanks has significant effects on the performance of the Flight Control System (FCS). The aeroelastic effect on the FCS results mainly from the aircraft stabilization by the FCS through the feedback of signals of the Aircraft Motion Sensor Unit - called sometimes inertia measuring unit (IMU) - which contain besides the necessary information of rigid aircraft rates and accelerations also flexible aircraft rates and accelerations in the frequencies of the aircraft elastic modes. The 'flexible' aircraft rates and accelerations measured by the inertia measuring unit (IMU) are passed through the flight control system control paths, they are multiplied by the FCS gains and FCS filters and inserted in the control surface actuator input which then drives the controls in the frequencies of the elastic modes of the aircraft. The flexible aircraft is excited by the high frequency control deflections and might also experience aeroservoelastic instabilities i.e. flutter or limit cycle oscillations may occur, dynamic load and fatigue load problems can arise. The FCS design therefore has to minimize all structural coupling effects through the available means like optimum sensor positioning, notch filtering and additional active control. Many of the design and clearance aspects described here have been addressed in previous publications, Ref. 1 to 8. Aeroservoelastic design, test verification and clearance of an advanced flight control system have been documented in Ref. 1 to 6. However all References consider only a few configurations and not a complete weapon system.

2 Flight control system development

2.1 Process for elimination of aeroservo-elastic problems

During the design of a modern flight control system of a delta canard aircraft configuration flight control experts are faced by an important challenge. They have to deal with very high control law gain conditions that are partly strongly varying by flight conditions and store configurations caused by a very complicate aerodynamic data set. To meet ‘rigid’ aircraft stability requirements is one of the most difficult tasks. Moreover the flight control design process is also marginally affected by aeroservoelastic – structural coupling problems which contribute to the difficulty to satisfy stability margin-, flutter- and vibration requirements for all variations of weapon system air to air and air to ground stores. The main issues of the flight control development process including structural coupling aspects have been treated for simple configuration but not for a complete weapon system in Ref. 4 and also in Ref.‘ s 1 to 3. It is therefore the aim of this paper to describe the procedure for an entire store system.

2.2 Elements of the dynamic system of the military aircraft

The development process is based to a significant degree on the dynamic system of the aircraft with and without stores. The figure 1 below illustrates the interaction of different systems (structure, aerodynamics, flight mechanics, structural mechanics and flight control) which form the total dynamic system and their mutual interaction. The interaction of structure (inertia and elastic force) and aerodynamics also known as the Collar`s aeroelastic triangle describe the aeroelastic problem like flutter. The extension of the aeroelastic triangle with the Flight Control System and to put mass and stiffness together to structure describes the Aeroservoelasticity or structural coupling. Different elements (A, B, C, E, F and G) of the dynamic systems can be defined, which are shown figure 2. The block diagram in figure 2 contains mainly four boxes, which describe a feedback control loop with flexible aircraft, sensors, FCS control and actuators. The function of the single elements will be described in chapter 3.2.

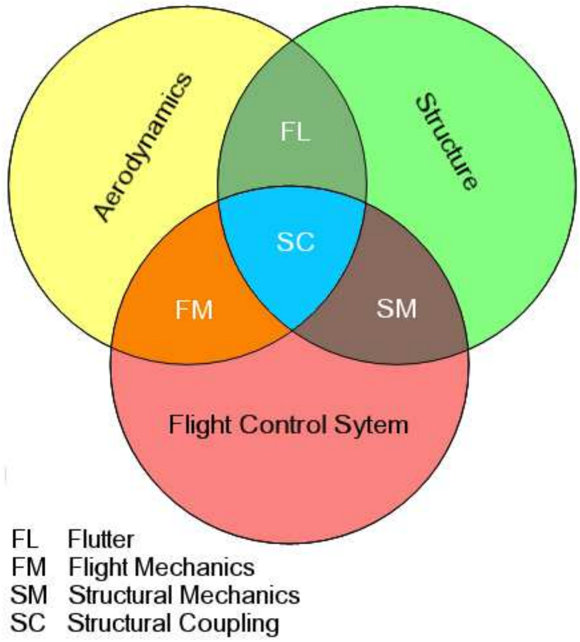

Figure 1: Definition of Structural Coupling System

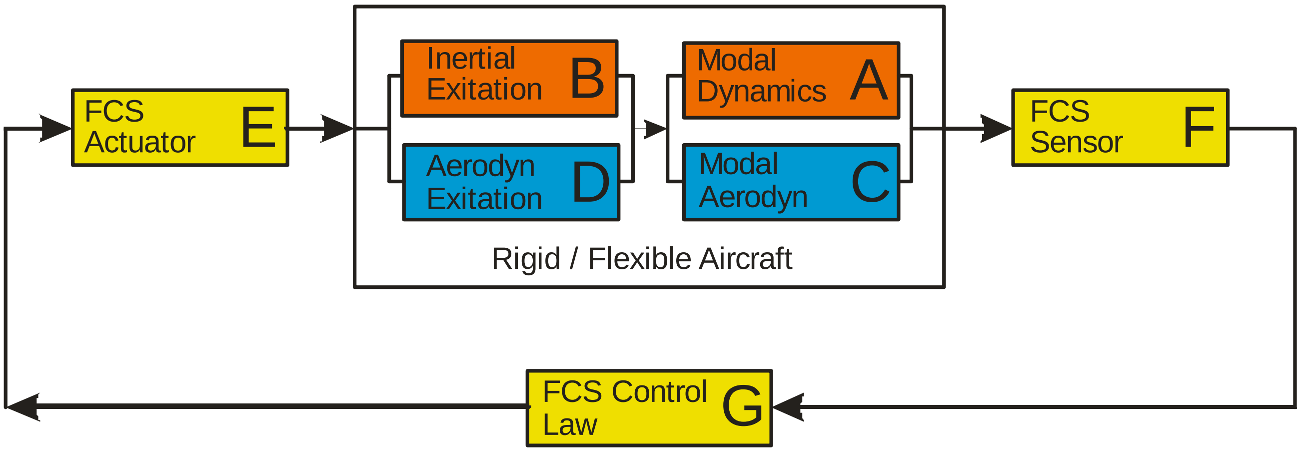

Figure 2: The Elements of the Structural Coupling System

3 Design Process

The design process involving the representative selected configuration concept is described below, and described more fully in the following sections, which are broadly linked to the boxes of the figure 2.
This 'Representative Selected Configuration' - based process is applied to the FCS design phases for the aircraft for Air-to-Air stores and the FCS for Air-to-Ground stores.

The design process is described by the following activities:

- Analytical model matching with Ground Resonance Test (GRT) results (Components and complete Aircraft GRT`s);
- Determination of representative selected configurations;
- Performance of Structural Coupling Test (SCT) for representative selected configurations;
- Model matching with SCT results;
- Validation of representative selected configurations with matched model;
- Set up Notch Filter Design data;
- Notch Filter optimization;
- Clearance calculations of Open Loop Frequency Responses for representative selected Air to Air (A-A), Air to Surface (A-S) configurations which should cover all weapon system configurations.

3.1 Selection process of representative configurations

To select representative configurations, the tactical task of the advanced fighter aircraft has to be analyzed in the early development phase of the aircraft weapon system. A lot of experience and very good analytical tools are required to select from the huge number of possible known configurations the representative selected configurations. It also must be checked that the key configurations contain all subsets of the expected flown configurations. Beside these key configurations possible follow on external stores should be considered. This is useful, because critical parameters of stores in view of structural coupling can be defined and adapted as structural design criteria of new external store development.

3.1.1 Weapon system configurations

A modern military aircraft weapon system has to fulfill a broad spectrum of different tactical areas of responsibilities like in air aircraft defense through flight protection from enemy air to air and ground to air missile attack and in air combat attack missions and air to ground attack missions. The systems for detection of enemy attack operations for instance by special avionic and radar equipment (for instance ECM pod, towed decoy, GPS pod etc.) as well as the attack capabilities like air to air missiles (sidewinder AIM9L, AMRAAM, ASRAAM) air to ground missiles and bombs (as for instance 1000lb bomb, guided bomb Pave-way, Taurus, Storm-shadow) are installed partly internally but mainly externally to the aircraft structure.

A huge number of stores therefore are placed on different locations like at the wing tip on outer-, center- and inner wing pylons and also under fuselage. Figure 3 illustrates some heavy weight configurations.

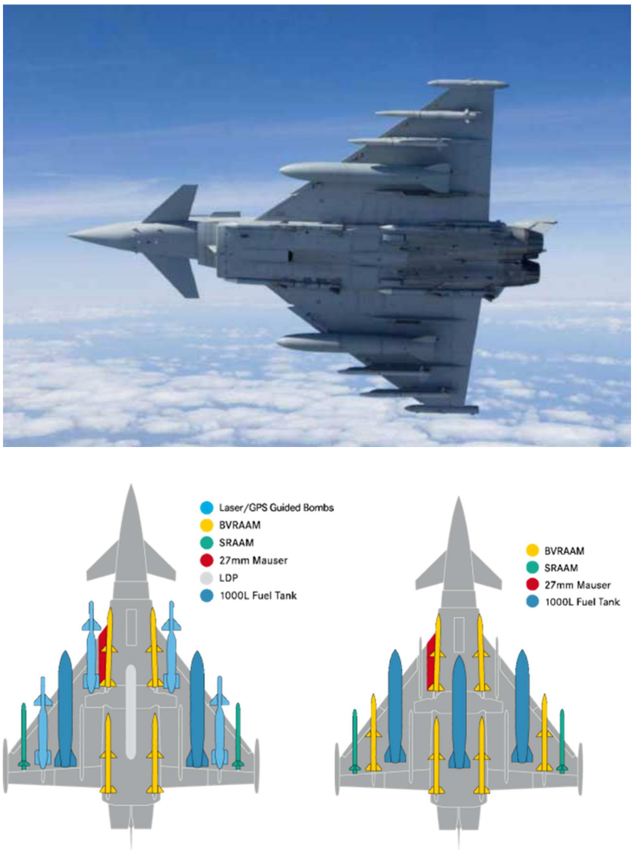

Figure 3: Illustration of some external store configurations of the weapon system

3.1.2 Dynamic system elements affected

As demonstrated in figure 2 and detailed in figure 4 the elements (A), (C) of 'flexible aircraft system' are strongly affected by the different store configurations and the element G 'flight control' is affected by the different control laws of store groups. Each configuration changes the modal characteristics of the flexible aircraft, the elastic mode frequencies, the mode shapes are different to other configurations. Therefore the output of the sensors (F), i.e. the frequency response due to control surface inputs is different for each configuration due to the change of modal characteristics. Hence the main task of the aeroservoelastic FCS part is to derive frequency response functions of all configurations or in order to minimize the effort to derive frequency response functions of selected configurations which cover in magnitude all other configurations. The frequency response functions of the elements E and F as well as the inertia and aerodynamics of control surfaces B and D remain unchanged with configuration change.

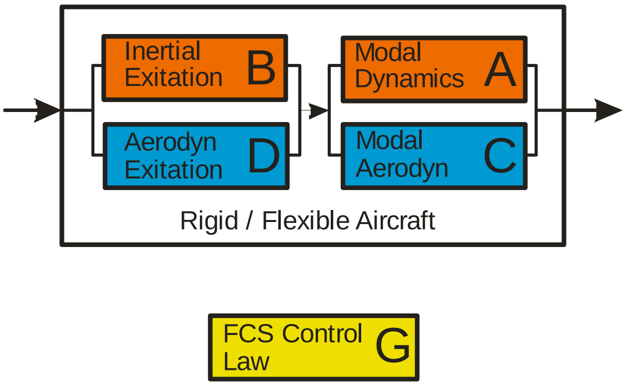

Figure 4: Structural Coupling System Elements affected by aircraft configurations

There are two main categories of the Structural Coupling Elements which are influenced by aircraft configurations.

- The element (G) – the FCS control laws are a function of single and twin seat aircraft and of air to air and air to surface store groups. The control law gains are defined for the different single and twin seat configurations and for defined groups of stores as a function of Mach number and altitude. The FCS gains are developed using the 'rigid' aircraft flight mechanical model first excluding the aeroelastic model of the flexible aircraft.
  The gains are optimized assuming a budget of phase loss caused by the implementation of the structural filters, the notch filters, necessary for the minimization of aeroservoelastic effects,

which are also part of the control law element. A simplified block diagram (Fig. 5) of longitudinal control for the application of structural coupling shows the location of the filters and control law gains.

- The elements A, B, C, and D of the flexible aircraft element are in contrast to the element (G) (see figure 2) at the beginning a function of all individual configurations and not a function of defined store groups. These flexible aircraft elements are part of the flexible aircraft model and are used to optimize the notch filters. In order to harmonize the development of the FCS notch filters with the defined store groups for the FCS gains a special structural coupling procedure has to be followed. The procedure is detailed in the following paragraphs.

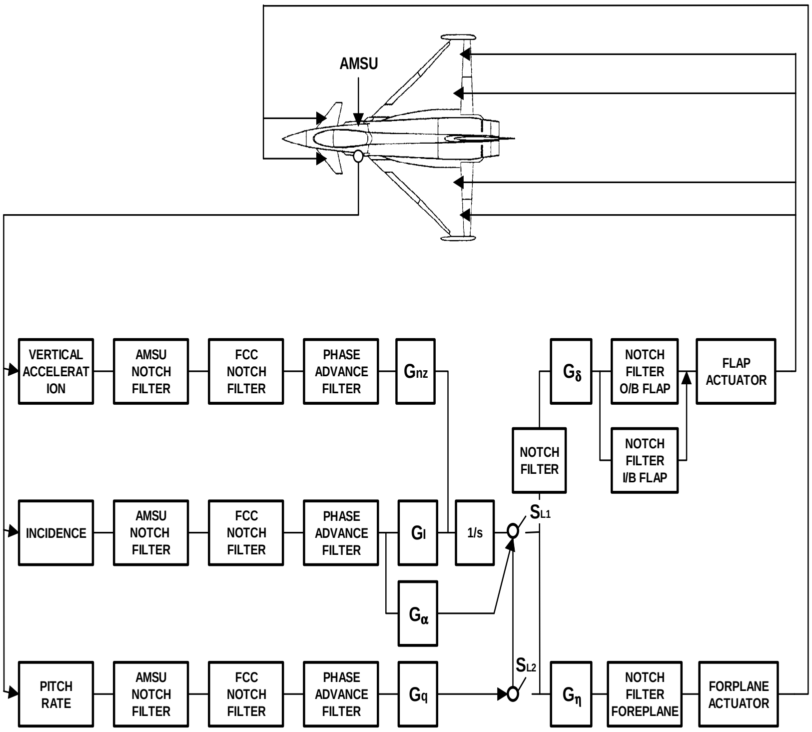

Figure 5: Simplified block diagram of longitudinal controller

3.2 'Representative selected' Configurations

The process of selecting representative configurations is described in the next step by:

- Selection by comparison of mass and radius of gyration of all configurations;
- Selection by comparison of maximum mass and cg boundaries;
- Selection by comparison of calculated frequency response functions for stores;
- Enveloping of the calculated frequency response functions.

3.2.1 Selection by comparison of mass and radius of gyration of all configurations

Mass and radius of gyration characteristics of external stores as demonstrated for illustration in the figure 6 below for the center wing station can be applied in a preliminary step to derive an indication of configurations which might cover others, this is performed through inspection of maximum values of mass and radius of gyration. Since the modal characteristics of the Structural Coupling system have to be defined for minimum weight and maximum weight conditions in such a manner that intermediate conditions are covered by extremes, indications might be found for the definition of selected configurations. However the definition of selected configurations needs to be confirmed by analytical calculations, specific ground structural coupling testing and analytical model update.

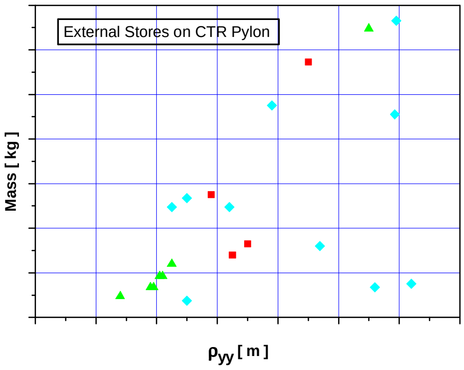

Figure 6: Mass and radius of gyration characteristics of external stores at center wing station

3.2.2 Selection of representative configs by comparison to max mass c. g. boundaries

The structural coupling criticality of external stores is not only influenced by the mass and inertia properties, moreover the criticality depends in addition on the FCS control law gains. The maximum control law gains and control law filters define the maximum amplitudes of the flexible aircraft frequency response functions. A first indication of a situation of maximum gains might be derived from the mass c. g. diagram as schematically shown in figure 7. Figure 7 displays three main information:

- Overall boundaries
- cg moving window for selected configuration
- dry mass/cg box for selected configuration

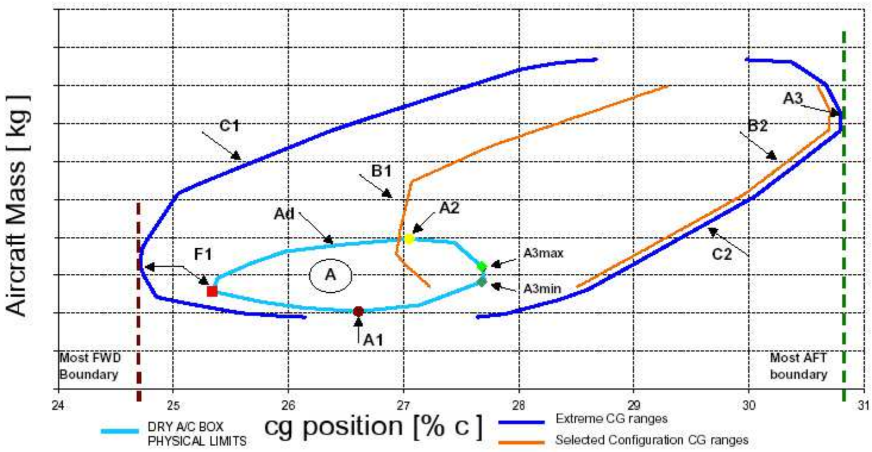

Figure 7: Mass – c.g. diagram

In detail:

- Line **Ad** represents the dry mass and dry cg box which are the physical limits for a given configuration
- Lines **C1**(FWD), **C2**(AFT) represents the extreme cg ranges for a given configuration, including all subsets.
- Lines **B1**(FWD) and **B2**(AFT) represents the cg moving window to the selected configuration.

Area **A** dry Mass/cg box contains the following characteristics points:

- **A1➔** Min Mass
- **A2➔** Max Mass
- **A3min➔** corresponding to most AFT cg (A3) maximum tolerances
- **A3max➔** corresponding to most AFT cg (A3) minimum tolerances
- **F1➔** corresponding to most FWD cg (F1)

All the other points comprised along and within the lines Ad represents the subsets of the selected configuration

Maximum gains will be present for the pitch control of an unstable aircraft configuration mainly for the maximum aft c. g. boundaries.
These boundaries are a function of the store groups for which different control laws are valid. The corresponding structural coupling criticality of different store groups might be found through attributing the structural coupling critical configurations derived from figure 7to the store groups and combination with the corresponding maximum control law gains. Mass and c. g. position of selected configurations for structural coupling should be in line with the characteristics of store group definitions installed in the FCS control laws.
The definition of representative selected configurations for structural coupling from these considerations needs to be confirmed by analytical calculations with the flexible aircraft model using control law gains for both maximum aft and forward c. g. positions by application of the updated model from ground structural coupling testing and comparisons of calculated frequency responses to the results of structural coupling tests.

3.2.3 Selection by comparison of calculated frequency responses for stores and enveloping of frequency response function

Evaluation of representative selected configs:
The derivation of the representative selected configurations is based on the study of the effects of individual ‘configuration parameters’ on modes within three frequency ranges. The ranges are defined on the basis of the model reliability:

- up to 13 Hz (i.e. Phase stabilized modes);
- between 13 Hz and 25 Hz; and
- above 25 Hz.

In the investigations, frequency, gain, and (where appropriate) phase trends are monitored by tabulation and by examination of Bode frequency response presentations. An understanding of the effect of adding combinations of stores is thus derived and the representative selected configuration set defined. For the phase stabilized (P.S.) modes, changes in mode frequency, gain and phase with respect to the reference configuration (for instance clean empty) will be tabulated.
For Gain stabilized modes less than 25 Hz changes in mode frequency and gain (not phase) are tabulated. Above 25 Hz, more qualitative measures of criticality in mode frequency and gain will be applied, consistent with the poorer model accuracy and the less critical dependency of stability margin on precise mode gain and frequency.
The factors investigated within the different frequency ranges illustrated are considered in the design input.
The frequency range 13 Hz to 25 Hz is separated out, since there a more detailed gain factorization has to be considered due to small frequency band characteristics in contrast to the very high frequency modes above 25 Hz.
Flight test results indicate that the phase up to 15 Hz is not abruptly changing at 13 Hz. Therefore the ‘overlap’ region at 13 Hz between high and low frequency pitch system representation, which is due to phase stabilization used for pitch up to 13 Hz and gain stabilization from 13 Hz onwards can be reconciled. Gain stabilization down to 13 Hz is assumed to be very conservative at frequencies below 15 Hz and the jump in the open loop frequency responses at 13 Hz shall be interpreted accordingly. Only paths significant for SC (rate and acceleration feedback) considered.
The main part of the study is made at zero speed, with the effect of aerodynamics considered for more representative selected cases only.
Parametric Configuration studies cover all Air-to-Air and Air-to-Surface stores together with additional factors affecting mode frequencies.
The clearance expansion will be achieved efficiently by definition of a set of 'representative selected configurations', which define the boundaries of SC characteristics, in terms of SC System response gain, phase and frequency, of all possible stores combinations, including subsets.

4 ‘Representative selected’ configuration procedure

In this chapter the different procedures described which are essential for the selection of the representative configurations. Beside some test methods also the modeling and structural update techniques for the aircraft with and without external stores are explained. In particular the calculation of the low and high frequency design input is discussed in detail.

4.1 On-ground and in-flight structural coupling testing

Structural Coupling Tests on representative selected store configurations:
The configurations identified as being ‘representative’ will be tested on the ground to provide fundamental data for the filter design and clearance process. The structural coupling test may be preceded by a Ground Resonance Test (GRT) to supply information for the finite element model update (FEM).
In terms of the SC System elements, the SCT and GRT, provide information for update of element (A) (Figure 2) for modes in the frequency region up to 25 Hz. For analyses

where phase stabilization is not applied, the SCT data itself forms the basis of the representation of element (A), see Figure 2.

4.2 Modeling technique for air to air and air to surface configurations and model update technique for store

Model Matching is performed by finite element model (FEM) frequency and mode shape updating on the basis of GRT results, by factoring the stiffness matrix.
Structural Coupling Test (SCT) data is used to define correction factors to be applied to the sensor output to better match predicted frequency response gain to measure. The factors are applied to each elastic mode / control path response separately, and take the form of a multiplicative factor defined as a function of frequency. The magnitude of the factor is the ratio of the measured and predicted response gain in a mode. Rather than calculate a different factor for each configuration, all factors for similar paths are 'enveloped' to provide a worst-case set.

4.3 Calculation of the low and high frequency design input

The figures 8, 9, and 10 below show Bode and Nichols plots of the calculated pitch rate open loop frequency response functions due to outboard, inboard and fore-plane excitation for different configurations for a number of Mach number and altitude conditions for the low frequency range up to 13 Hz. Envelopes for Mach numbers, altitudes and configuration groups are demonstrated in figure 11 for the high frequency range, these high frequency responses are based on ground measured responses and superimposed calculated aerodynamic increments in the elastic mode frequencies.
From the on ground and in flight calculated responses for a big variety of different configurations representative selected configurations are derived which cover all other configurations.

4.4 Summary of the selection procedure

The selection procedure is a cost effective procedure for the treatment of all Air-to-Air and Air to Surface Configurations by selection of representative configurations to cover all possible combinations of configurations

Selection Procedure:

- Pre-selection of critical configurations from all Weapon System Design Specification configurations using extreme corners of Mass / c. g. / radius of gyration diagrams as criteria.
- Calculation of on ground and in air open loop transfer functions using the flexible aircraft element model, the actuator model and sensor model of the SC-System for the selection of structural coupling representative configurations using max. dB values in each elastic mode frequency band.
- Definition of a set of representative selected configurations which cover all Air to Air and Air to Surface Configurations.
- Validation of representative selected configuration selection.

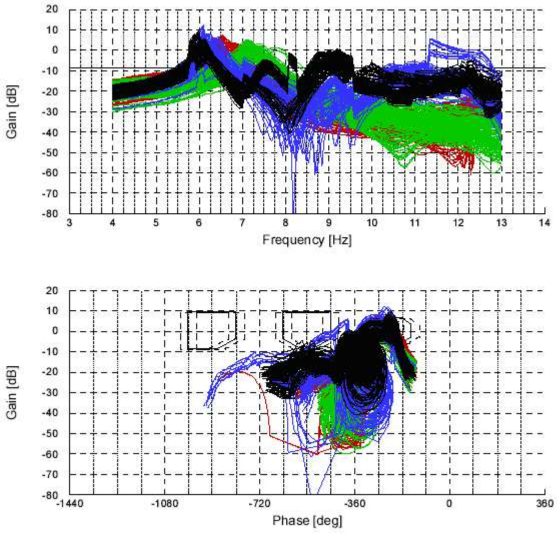

Figure 8: Bode and Nichols diagram of the design input pitch rate due to outboard excitation

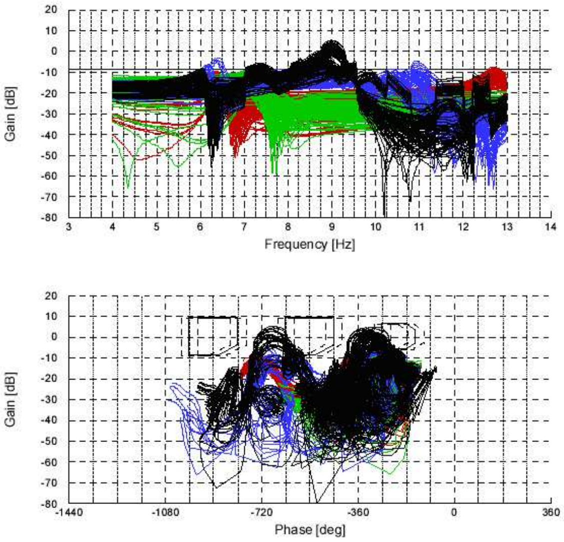

Figure 9: Bode and Nichols diagram of the design input pitch rate due to inboard excitation

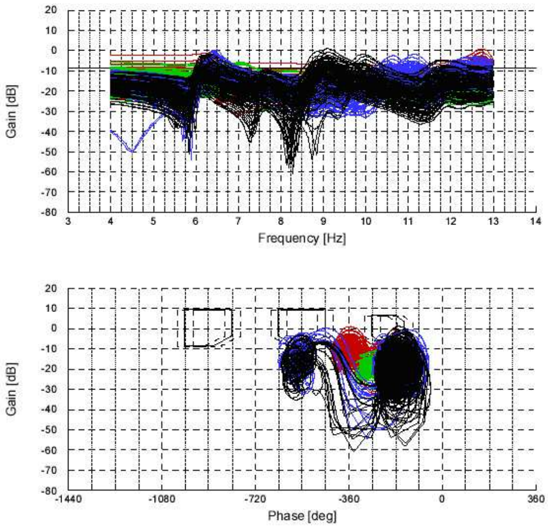

Figure 10: Bode and Nichols diagram of the design input pitch rate due to foreplane excitation

5 Development of FCS for the elimination of aeroservoelastic problems

The open loop frequency responses shown before in the figures 8 to 11 also demonstrate the challenge of the FCS design: It is demonstrated by the Bode and Nichols plots that the overall frequency response is very broad band and characterized by maximum amplitudes in the frequencies of the normal modes which shift with the different configurations. Notch Filters designed to meet the stability criteria (which are indicated in the figures by -9 dB for high frequency and dB and phase criteria for low frequency required by the diamonds in the Nichols plots) will lead to unacceptable low frequency phase shifts which would extremely destroy the flight mechanic stability in the range 0 to 4 Hz

To give an example for acceptable and unacceptable Notch Filter characteristics:

- For the FCS design the phase shift of the open loop frequency response of the `rigid´ aircraft at 1 Hz due to Notch Filters shall not exceed 18 degrees.
- The optimization of a Notch Filter set for the shown design input open loop frequency responses would lead to a phase shift at 1 Hz of about 40 degrees!

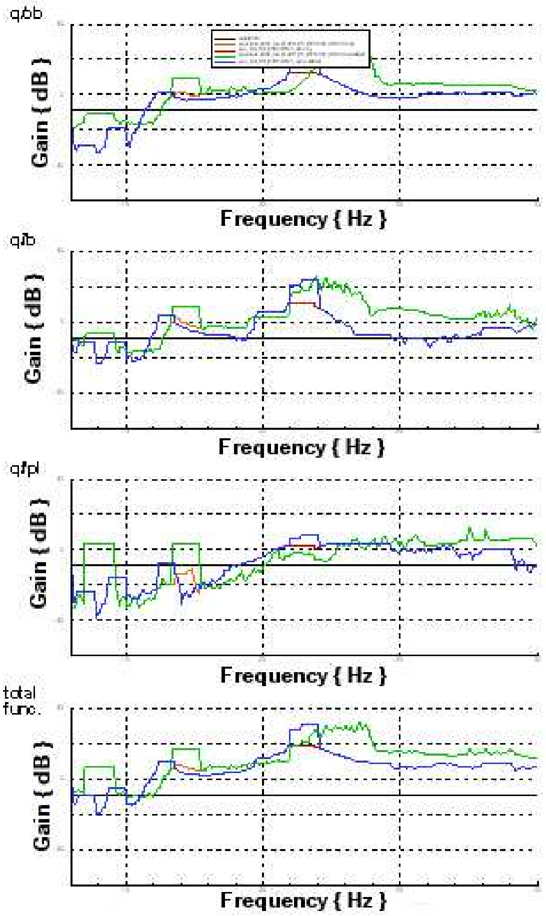

Figure 11: Bode and Nichols diagram of the high frequency design input pitch rate due to outboard, inboard and fore-plane excitation

Therefore special means have to be applied for the filter design Minimization of aeroservoelastic problems. General means for minimization of aeroservoelastic influences on the FCS design which have to be applied during the development phase:

- Optimal sensor position to minimize the low frequency pitch rate response;
- High stiffness of the sensor tray to minimize the high frequency response;
- Very high wing stiffness to reach high normal mode frequencies for the decoupling of elastic modes from flight mechanic modes;
- Optimal number of Notch Filters in the feedback loops including also Notch Filters in the control surface paths (outboard-, inboard and foreplane filters);
- Introduction of second order phase advance filters instead of first order ones;
- Application of optimization techniques;
- Application of in-flight measured frequency responses.

However all these means have shown not sufficient efficiency to fulfill the requirement for the low frequency phase shift, therefore additional techniques had to be used.

Main techniques for improvements in the aeroservoelasic design of the FCS for the total weapon system:

Application of optimization techniques including interdisciplinary optimization using the coupled analytical flight mechanic-structural dynamic and flight control model

- Store groups- configuration switching technique;
- Scheduling of Notch Filters with flight condition.

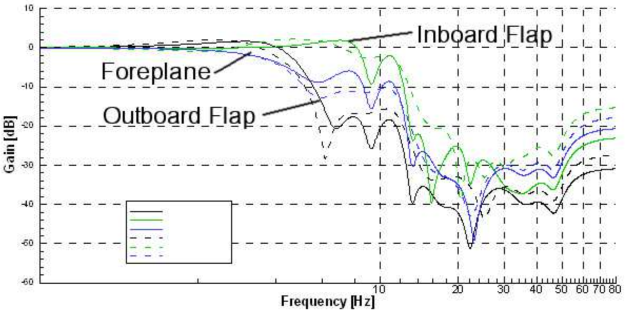

Figure 12: Notch Filter characteristics for outboard, inboard and foreplane path

The above figure 12 illustrates a typical optimized characteristic of the Notch Filter for the total inboard, outboard and foreplane path.
The upper part shows the frequency transfer function of inboard, outboard and foreplane up to 80 Hz (only the magnitude in dB)
The lower part illustrates the dB and phase values up to 5 Hz.
In order to minimize the phase shift at low frequencies in addition to all other mentioned means the characteristics demonstrate that an increase of the dB values for the inboard and outboard path was applied in the region up to 4 Hz for the outboard and up to 8 Hz for the inboard Notch Filter path. This behavior was iteratively obtained together with the flight mechanic optimization.
This special approach was necessary to achieve the low frequency phase shift requirements to meet flight mechanic stability.

6 Flight Certification

The clearance process is described by the following activities

- Analytical model matching to SCT' s and GRT 's;
- Determination of representative selected configurations;
- Performance of SCT for representative selected configurations;
- Model matching with SCT and GRT results;
- Validation of representative selected configurations with matched model;

- Set up Notch Filter Design data and Notch Filter design;
- Clearance Calculations for representative selected A-A and A-S configurations which cover all weapon system configurations.

An example of the clearance calculations is demonstrated in Figures 13 and 14 below for low frequency and high pitch stability assessment. The figures document that the stability margins requirement are met.

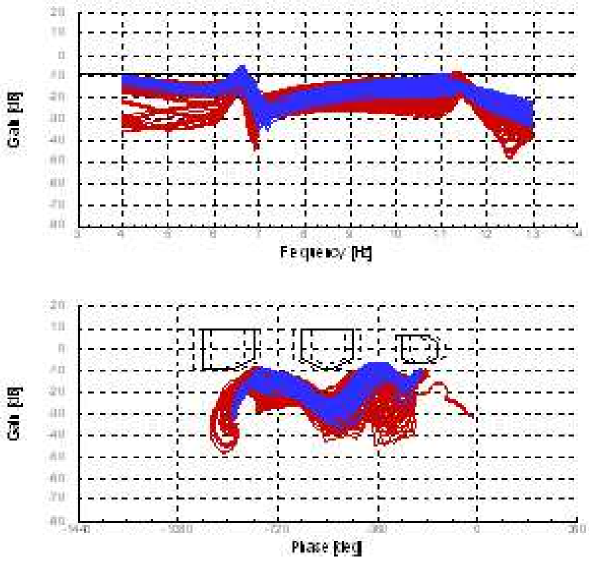

Figure 13: Low frequency stability margin assessment

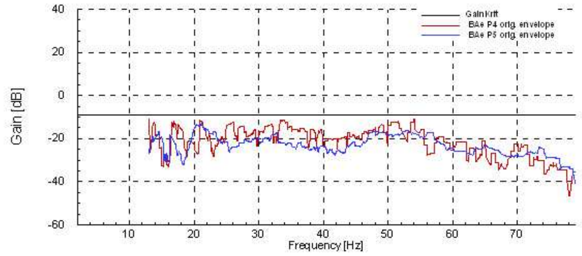

Figure 14: High frequency stability margin assessment

7 Conclusions

The Flight Control Law design for a modern military aircraft weapon system had to face many problems with respect to the aeroservoelastic stability.

Especially the fulfillment of the flight mechanic low frequency stability requirements for the flexible aircraft and aeroservoelastic effects is very difficult to achieve for all weapon system stores.

A very complex approach had to be followed which includes mainly ground and in flight testing of structural coupling characteristics of so-called representative selected configurations and the set-up of an analytical model of the coupled dynamics of flight and structural dynamics for the evaluation of representative configurations, it includes also the update to ground test and flight test results.

An important step to minimize aeroservoelastic effects was the applications of an interdisciplinary FCS design, the introduction of Notch Filters which can be switched with identified stores or store groups together filter scheduling with flight condition. Important was also the fine tuning of the filter characteristics at low frequency to the flight mechanic stability requirements.

The described process of the FCS design including the aeroservoelastic effects was successfully applied for the control law design for the total weapon system of a modern fighter aircraft (EF2000-Typhoon). The efficiency could be demonstrated by flight test results of the full range of air to air and air to surface configurations.

8 Acknowledgements

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