

## Constrained notch filter optimization for a fly-by-wire flight control system

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### Abstract

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Alenia Aeronautica S.p.A. developed high skills in Notch Filter design and assessment processes. A fundamental step was taken in the integration of existing software and procedures with a new tool that allows Notch Filter optimization, enhanced with an extra feature for the high-frequency Open Loop Frequency Response Function calculation. The Notch Filter design is based on a constrained optimization routine, which processes data provided by a mathematical and experimental model describing the aircraft coupled flight dynamics and the interaction between the flight control system and the structural dynamics.

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### Nomenclature

FCC = Flight Control Computer  
FCS = Flight Control System  
FP = Foreplane  
GRT = Ground Resonance Test  
IB = Inboard Flaperons  
IMU = Inertial Measurement Unit  
NF = Notch Filter  
OB = Outboard Flaperons  
OLFRF = Open Lop Frequency Response Functions  
SC = Structural Coupling  
SCT = Structural Coupling Test  
SQP = Sequential Quadratic Programming

### 1. Introduction

Modern high-performance fighter aircraft are characterized by a reduced or negative stability aimed at improving their handling and manoeuvring capabilities. In order to allow unstable aircrafts to fly, a fly-by-wire Flight Control System (FCS) is provided. The FCS is designed to generate a feedback based on the analysis of the signals coming from the Inertial Measurement Unit (IMU). Since the IMU is fitted on an elastic airframe, its sensors capture the structural vi-

brations superimposed to the aircraft rigid body motions. In this way, both signals are sent to the Flight Control Computer (FCC) and, in particular, the “flexible” aircraft rates and accelerations pass through the FCS paths, and are subsequently processed and injected as control surface actuator inputs, which then drive the controls in the frequencies of the aeroelastic modes of the aircraft. As the control surface inertia is quite high, the forces induced by high frequency oscillations of control surfaces play a fundamental role in exciting the airframe. This coupling between FCS and elastic structure is called Structural Coupling (SC). SC should always be avoided as it is likely to degenerate in potentially dangerous loops, which may result in flutter or limit cycle oscillations. These aeroservoelastic instabilities lead to increased dynamic loads and give rise to fatigue problems. Among the several solutions to counteract the SC problem the introduction of a set of Notch Filters (NF) proves particularly efficient. The NFs allow the selective attenuation of the airframe vibration content running in the FCS paths. Thus, the elastic modes are filtered out from the signal injected to the actuator and the phase loss is reduced to a minimum [1, 2].

The FCS shall be designed to cover all possible aircraft configurations, taking into account also changes due to external stores release and jettison. This implies that the NF design shall cover the full range of stores

and fuel levels in the whole flight envelope. From this point of view, the structural coupling clearance of a complete military A/C weapon system can be considered an engineering challenge, since a high number of external stores configurations have to be taken into account, including all possible variations due to store release and missile firing sequences in the whole flight envelope. The NF optimization procedure described in this paper is based on a complete flexible aircraft model, established and validated for existing reference configurations. Furthermore, the code validation process takes advantage of a set of NFs previously cleared for the same configurations. The structural coupling clearance is efficiently achieved by the definition of a set of so-called critical configurations, which define a kind of envelope of all possible store/fuel configurations, in terms of gain and phase of the Open Loop Frequency Response Functions (OLFRFs). Both analysis and testing are carried out on this critical configuration set.

## 2. Augmented aeroservoelastic model

### 2.1. Inertial excitation of flexible aircraft

The aircraft, like any other flexible structure, is characterized by many characteristic or normal modes of vibration with the corresponding resonant frequencies and modal shapes. Each mode can significantly vary in terms of amplitude and normal frequency with payload, fuel distribution and flight condition (referred to as a combination of Mach number, altitude and load factor). The normal modes might be excited by the hinge forces of oscillating control surfaces (Fig. 1), resulting from their unbalanced inertia and aerodynamic loads. Fig.2 shows an example of one of the IMU outputs during a simulated ground test.

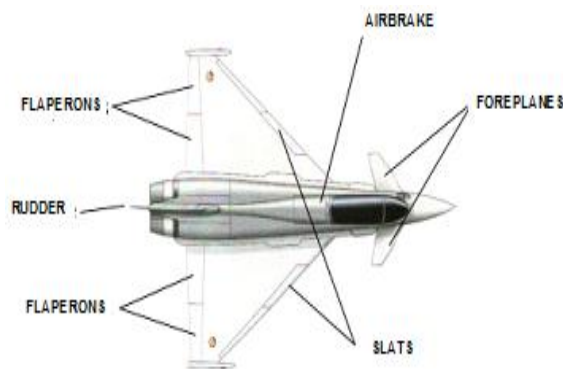


Figure 1. Eurofighter EF2000 control surfaces

### 2.2. Aeroservoelastic model

Structural Coupling problems and consequent NF design may be analyzed through a refined linear aeroservoelastic model [1] which simulates the flight dynamics, the FCS dynamics and the elastic structural behavior of the aircraft. This mathematical model may be described by linear differential equations in state-space notation:

$$\dot{\bar{x}} = A\bar{x} + B\bar{u} \quad (1)$$

where the state vector  $\bar{x}$  contains the generalized coordinates of selected elastic structural modes, their time derivatives, the rigid body state variables and the FCS state variables. Unsteady aerodynamic forces are properly treated as well as sensor and actuator dynamics. Moreover, the model accuracy seems not to be always satisfactory and hence experimental data obtained through ad hoc tests should be used to update and validate the linear mathematical model.

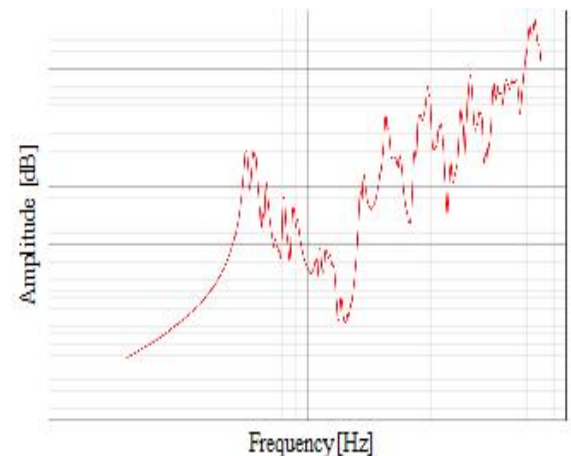


Figure 2. Sample of OLFRF in the Bode plane

### 2.3. Ground tests

The theoretical predictions resulting from the aeroservoelastic mathematical model of the aircraft are initially updated and validated by means of Ground Resonance Test (GRT) and Structural Coupling Test (SCT), both performed in open-loop. The former is a classical resonance test and it is focused on the resonance peak characterization and model updating in terms of mass, inertia and stiffness properties. The latter is crucial to verify the extent of the IMU perception of the modal content concerning vibrations induced by the control surface oscillation, given by the absence of aerodynamic contributions. The

SCT results allow the definition of corrective factors and their subsequent introduction into the theoretical model [3, 4], especially in the high frequency domain where model predictions are very poor.

**2.4. In-Flight test**

The in-flight test practically corresponds to the SCT, with the difference that the flying aircraft is controlled in closed-loop. Flutter and SC tests are usually performed in order to update the model in terms of unsteady aerodynamic contributions by means of suitable aerodynamic alleviation factors [5]. The aeroservoelastic model accuracy, however, is not adequate to simulate a correct behavior in the high frequency range and hence match the OLFRRFs as measured in flight. Therefore, the OLFRRFs measured on ground are combined with the predicted aerodynamic effects of the aeroservoelastic model. The fundamental hypothesis behind this approach is that the theoretical aerodynamics is sufficiently accurate and predictive, while the high frequency on-ground response does not match the behavior in flight. The calculation of the aerodynamic effects (as a difference between in-flight and on-ground OLFRRFs in terms of peak amplitudes) and the merge with FCS control laws at different points of the flight envelope, has represented the first step of the research program with Polytechnic of Turin. It must be noted that the number of calculations needed to cover the whole flight envelope and all the possible store and fuel level configurations is really huge.

**3. Approach to the structural coupling problem**

**3.1. Stability requirements**

The primary design requirements concern the stability of the flexible aircraft equipped with the flight control system. Stability is achieved by the introduction of NFs which have to satisfy requirements expressed in terms of amplitude and phase margins of the OLFRRFs. The clearance requirements are strictly connected to the ground and flight test analysis and verification, and depend upon the OLFRRF frequency range. Basically, in the low frequency range the stability margins can be acceptably relaxed due to the extreme accuracy of the theoretical model and to the moderate rate of change of modal response phase with frequency. It is obvious that only great confidence in the model prediction can guarantee the actual fulfilment of the stability criteria when small stability margins are accepted. This confidence is achieved by an extensive test activity which provides experimental evidence.

In the Eurofighter EF2000 program [6], stability of



Figure 3. Stability requirements for open loop frequency response functions: gain/phase stabilization criterion

the first longitudinal modes are evaluated according to gain/phase stability criteria, which impose that the OLFRRF remains outside the convex areas in the Nichols chart as defined in Fig. 3. In the high frequency domain the lack of accuracy makes more stringent requirements essential. In this situation, in fact, these stability requirements are just a sort of “basic” or “initial” clearance requirements and are provided in terms of additional gain margins of the OLFRRFs, according to the gain stabilization concept which prescribes not to exceed a given threshold value (Fig. 4).

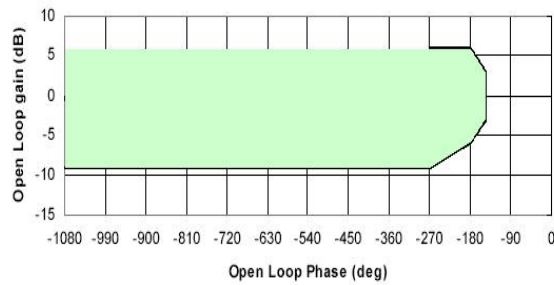


Figure 4. Stability requirements for open loop frequency response functions: gain stabilization criterion

**3.2. Vibration/dynamic loads and flutter requirements**

In addition to stability requirements, NFs must satisfy vibration and flutter requirements. In fact, high vibration levels induced by structural coupling must be avoided in order to reduce fatigue problems, which might become unacceptable for aircraft structure and actuators. The relevant requirements are defined in

MIL-A-8870B, which prescribes a flutter-free margin of 15-percent increase of the equivalent airspeed beyond the design limit speed envelope at constant altitude and constant Mach number.

### 3.3. Structural coupling solutions

Different means can be provided in order to minimize the effects of the SC in the aircraft FCS [2]:

- *Sensor location*: the IMU shall be placed at the anti-node of the first fuselage bending mode, where pitch and yaw rate due to the elastic modes are minimum. Moreover, sensor supports should be extremely stiff in order to prevent the introduction of extra local elastic frequencies;
- *Actuator transfer function*: the coupling effects are minimized by a strong decay in the actuator transfer function in the medium-high frequency range. Response at medium frequencies ( $10 \div 30$  Hz) shall be well damped;
- *Control surface inertia*: low weight/inertia surfaces reduce significantly SC problems;
- *Notch filters*: the introduction of NFs in the FCS feedback paths are the best way of de-coupling elastic structure and FCS;
- *FCS Optimization*: a good optimization of the FCS is achieved by the introduction of a set of NFs also in the actuator paths. This concept allows the minimization of the phase delay at low frequencies;
- *Phase advance filters*: a set of phase advance filters aims at reducing to zero the phase delays brought about by NFs as well as other delays at low frequencies.

### 4. Notch filter design and optimization

Initially, NFs are introduced in each FCS feedback path with an initial guess of the NF coefficients, which are supposed to suppress the resonance peaks of the undesired structural modes, expressed in terms of OLFRFs. NFs are characterized by second-order transfer functions in the form:

$$NF(s) = \frac{1 + a_1s + a_2s^2}{1 + a_3s + a_4s^2} \quad (2)$$

where  $a_1$ ,  $a_2$ ,  $a_3$  and  $a_4$  are the NF coefficients. However, for the characterization of NFs, it may be useful to adopt a different set of parameters, which are more directly related with the NF features. In particular, four parameters can be selected for each NF:

1. the notch frequency *Freq* (in Hz), which is the frequency where the maximum decline in gain should be observable;

2. the slope in gain *Gain* (in dB) at the notch frequency;
3. the non dimensional frequency band *Breite*, where the effects of NFs are significant;
4. the non dimensional gain value  $G_\infty$  for infinite frequency.

NF coefficients and parameters are related to each other through the following expressions:

$$\begin{aligned} Freq &= \frac{1}{2\pi\sqrt{a_2}} \\ Gain &= 20 \log \left( \frac{a_1}{a_3} \right) \\ Breite &= \frac{a_3}{2\sqrt{a_4}} \\ G_\infty &= \frac{a_2}{a_4} \end{aligned} \quad (3)$$

In this way, such parameters can be easily selected analyzing the characteristics of the signal component which should be filtered. The selected parameters, however, must be optimized to make sure that the aircraft, equipped with the FCS, satisfies the stability criteria described in the previous section. Furthermore, the NF parameters shall not be dependent on flight conditions and aircraft configurations in order to achieve a realistic clearance procedure. Therefore, a common NF set should be designed and refined through an optimization process involving several flight conditions and the most critical aircraft configurations. Obviously, the OLFRF data concerning these different conditions are not managed separately by the optimization algorithm but an envelope of all flight conditions and/or configurations is estimated through two different methods which will be analyzed in the following section. The introduction of NFs in the aircraft FCS produces a phase loss in the OLFRFs (with NFs included) especially in the low frequency domain with negative effects on aircraft flight dynamic stability. Hence, in order to accomplish the NF optimization it is necessary to define the total OLFRF at the opened summation points for both longitudinal and lateral control schemes.

Considering, for example, the entire longitudinal control path of Fig. 5, which includes three sensors (pitch rate  $q$ , vertical acceleration  $N_z$ , angle of attack  $\alpha$ ) and three control surfaces (outboard flaperons *OB*, inboard flaperons *IB*, foreplane *FP*), the total OLFRF can be expressed as follows:

$$\begin{aligned} F_{TOT} &= (F^{q/OB} + F^{q/IB} + F^{q/FP}) + \\ &+ (F^{N_z/OB} + F^{N_z/IB} + F^{N_z/FP}) + \\ &+ (F^{\alpha/OB} + F^{\alpha/IB} + F^{\alpha/FP}) \end{aligned} \quad (4)$$

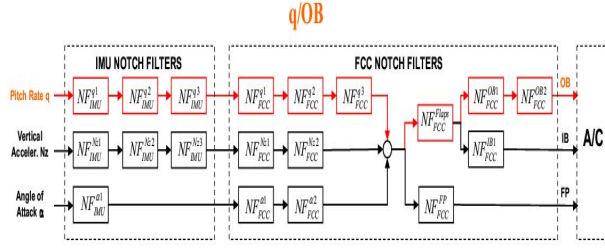


Figure 5. Block diagram of the FCS longitudinal stabilization path

where the total transfer function concerning the  $q/OB$  FCS path, red marked in Fig. 5, is represented by:

$$F^{q/OB} = F_{A/C}^{q/OB} \cdot F_{IMU}^{q/OB} \cdot F_{FCC}^{q/OB} \quad (5)$$

$F_{A/C}^{q/OB}$  represents the theoretical/experimental OLFRRF of the  $q/OB$  path without NFs, while  $F_{IMU}^{q/OB}$  and  $F_{FCC}^{q/OB}$  denote the transfer function product of the IMU and FCC notch filters respectively, and can be expressed as follows:

$$F_{IMU}^{q/OB} = NF_{IMU}^{q1} \cdot NF_{IMU}^{q2} \cdot NF_{IMU}^{q3} \quad (6)$$

$$F_{FCC}^{q/OB} = NF_{FCC}^{q1} \cdot NF_{FCC}^{q2} \cdot NF_{FCC}^{q3} \cdot NF_{FCC}^{flaps} \cdot NF_{FCC}^{OB1} \cdot NF_{FCC}^{OB2} \quad (7)$$

where the superscript  $q_1$ ,  $q_2$  and  $q_3$ , for example, refer to the three NFs necessary to cut the three picks over the threshold in the high frequency range.

Similarly, the other addenda can be computed by analyzing the corresponding FCS feedback paths. From the total OLFRRF the phase shift at low frequency induced by NFs may be derived and used in the optimization process. In fact, the objective of the optimization algorithm is to minimize the phase shift  $\Delta\Phi$  of the total OLFRRF, calculated at 1 Hz, and concurrently meet the stability criteria of gain stabilization at high frequency and gain/phase stabilization at low frequency. With these requirements the constraints of the optimization can be formulated and their number is defined by the number of frequencies at which the requirements have to be fulfilled. Initially, the algorithm verifies the fulfilment of constraints on each FCS path by analyzing the relevant OLFRRFs on the Nichols chart, then the constraints are evaluated on the  $F_{TOT}$  as well. After assessing the constraints imposed by stability criteria, the phase shift is calculated and compared with a threshold value that shall not be exceeded. The phase shift may be represented, for example, by a weighted average of the shifts of each single FCS path:

$$\Delta\Phi_{TOT} = \frac{10 \cdot \Delta\Phi_{q/OB} + 10 \cdot \Delta\Phi_{q/IB} + 10 \cdot \Delta\Phi_{q/FP} + 10 \cdot \Delta\Phi_{Nz/OB} + \dots + 10 \cdot \Delta\Phi_{\alpha/IB} + 10 \cdot \Delta\Phi_{\alpha/FP} + 20 \max(\Delta\Phi_i)}{110} \quad (8)$$

where the denominator is given by the sum of the weights of each phase shift.

#### 4.1. Software package description

The software package developed by the Aeronautical and Space Department of Polytechnic of Turin is based on a Fortran code and basically consists of two main parts concerning the theoretical/experimental OLFRRF calculation at high frequency and the NF optimization process. In particular, the former portion of the software package *HF-Code* allows the computation of OLFRRFs which identify the FCS sensor response to the control surface oscillations in high frequency. In fact, the aeroservoelastic model has to be updated and validated through experimental data measured during ground tests, such as GRT and SCT, and in-flight test by using the techniques described above. However, this procedure accomplishes excellent results only in the low frequency range (up to 20 Hz), while in the high frequency range the correspondence with test data is less satisfactory. Hence, a different approach used in the high frequency range consists of combining the OLFRRFs measured during ground tests with the model-predicted aerodynamic contributions, which are expressed in terms of gain increments (in dB) of OLFRRFs and are functions of the flight condition, given by Mach number and altitude. This approach is feasible since the predicted aerodynamic effects are assumed to be sufficiently accurate in the whole aircraft flight envelope, differently from theoretical OLFRRFs at zero-speed condition, which are affected by errors when compared with ground test results. First, the *HF-Code* acquires the aeroservoelastic model theoretical data in terms of real and imaginary part of OLFRRFs and the ground test experimental data in terms of gain (in dB) and phase of OLFRRFs. Next, the *HF-Code* estimates the aerodynamic contributions from theoretical OLFRRFs in terms of corrective factors  $g_{AE(M_i, h_i)}$  through the following expression:

$$g_{AE(M_i, h_i)} = \frac{|OLFRF_{TH(M_i, h_i)}|}{|OLFRF_{TH(M=0, h=0)}|} \quad (9)$$

where  $M_i$  and  $h_i$  are respectively Mach and altitude of the  $i^{th}$  flight condition and  $g_{AE}$  represent the corresponding aerodynamic effects (AE) in terms of corrective factors. Applying the logarithmic function with its properties it is possible to convert the aerodynamic

contributions into gain increments in  $dB$  expressed by  $G_{AE}$ :

$$G_{AE(M_i, h_i)} = G[OLFRF_{TH(M_i, h_i)}] + \quad (10)$$

$$- G[OLFRF_{TH(M=0, h=0)}]$$

Finally, the measured OLFRFs in GRT and SCT are combined in the high frequency range with the aerodynamic effects predicted by the aeroservoelastic model [1, 7]:

$$G[OLFRF_{CORR(M_i, h_i)}] = G[OLFRF_{EXP(GRT, SCT)}] + \quad (11)$$

$$- G_{AE(M_i, h_i)}$$

These corrected theoretical/experimental OLFRFs are then introduced as input data into the second part (*NF-Code*) of the software package concerning the NF optimization process, described in the previous section, which represents the core of the above-mentioned package. The *NF-Code* firstly acquires the NF characteristics, such as initial coefficients/parameters, upper/lower bounds, filter sequence, etc..., and the corrected OLFRFs of all flight conditions and aircraft configurations. Secondly, the desired scheme is defined for each FCS feedback path with NFs and the *NF-Code* evaluates the initial condition of the system, in terms of constraint violation extent, phase lags at 1  $Hz$  and OLFRFs with NFs for each FCS path. After setting up several options and optimization parameters, finally, *NF-Code* starts the optimization process by calling the *Nonlinear Programming* algorithm. The final condition of the optimized system is again specified by the constraint violation extent, phase lags at 1  $Hz$  and OLFRFs with tuned NFs for each path, and total OLFRFs. The NF parameters are, hence, optimized according to the user options. In particular, it is possible to optimize only the NFs selected in one or more FCS paths for one or more configurations and one or more flight conditions. If several flight conditions/configurations are considered, the *NF-Code* evaluates an envelope of all corresponding OLFRFs in terms of gain, adopting two different approaches. The former is a *Bode-plane* high-frequency envelope in the frequency domain of all the OLFRF gain peaks, and thus all flight conditions and configurations are represented only with one single frequency response curve as shown in Fig. 6. This is possible, as for high frequencies simply a gain stabilization criterion is considered, while no phase information is needed. The latter approach is based on a *Nichols-plane* low-frequency envelope in the phase domain of all the OLFRFs, corresponding to the selected flight conditions and configurations. This approach first evaluates an envelope in the phase domain for each OLFRF in order to define an unambiguous correspondence between phase and gain, and then calculates the global envelope, marked

by a red curve in Fig. 7, as the maximum of all the OLFRF envelope curves.

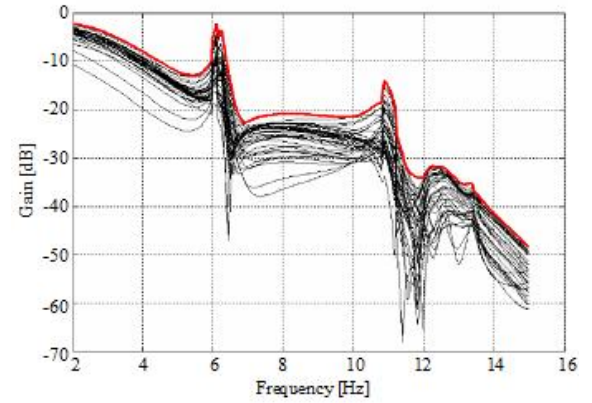


Figure 6. Envelope in the frequency domain *Bode-plane*

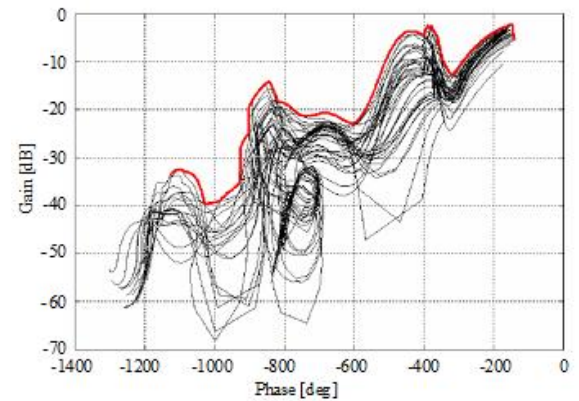


Figure 7. Envelope in the phase domain *Nichols-plane*

#### 4.2. Brief overview of the optimization algorithm

The NF optimization process in *NF-Code* software package can be mathematically formulated as a nonlinear multidimensional constrained minimization problem through the following expression:

$$\min F(X) \quad (12)$$

subject to nonlinear inequality constraints:

$$C(X) \leq 0 \quad (13)$$

where  $F(X)$  is the so-called scalar *cost function* defined as the phase lag at 1 Hz induced by NFs and  $X$  is the vector of NF parameters to be optimized and subject to the following boundary conditions:

$$X_{LB} \leq X \leq X_{UB} \quad (14)$$

The optimization algorithm is based on the Sequential Quadratic Programming (SQP) method [8, 9]. This method allows to closely perform Newton method for constrained optimization just as it is done for unconstrained optimization. At each major iteration, an approximation of the Hessian matrix of the Lagrangian function is estimated by using a quasi-Newton updating method. Successively, the Hessian is exploited to generate a QP subproblem whose solution is used to form a search direction for a line search procedure. In particular, the SQP implementation [10, 11] consists of three main stages:

- updating of the Hessian matrix of the Lagrangian function: at each major iteration a positive definite quasi-Newton approximation of the Hessian of the Lagrangian function  $H$  is calculated using the BFGS formula [12], where Lagrange multipliers are estimated;
- quadratic programming solution: at each iteration a QP subproblem is solved by implementing an active set strategy, also known as the *projection* method [13];
- line search and merit function calculation: the solution of the QP subproblem produces a vector  $d_k$ , which is used to form a new iterative line search direction  $X_{k+1} = X_k + \alpha_k d_k$ , where the parameter  $\alpha_k$  is determined in order to produce a sufficient decrease in a merit function [7].

#### 4.3. Cost function and nonlinear constraints

The optimization algorithm previously described should select a set  $X$  of NF parameters which satisfy the following requirements:

- suppress the undesired components induced by SC in the IMU signals;
- minimize the consequent phase lag in the FCS paths at low frequency.

These two requirements can be mathematically expressed in terms of nonlinear constraints and cost function, which can be effectively used to perform the nonlinear constrained optimization through the SQP method. In particular, the cost function  $F(X)$  is defined as the phase lag at 1 Hz induced by NFs in the FCS paths. According to the option specified in *NF-Code* two kinds of cost function can be evaluated: summation or weighted average of phase lags at 1 Hz

of the FCS paths selected by the user for optimization. In the first case, the expression of  $F(X)$  will be:

$$F(X) = \sum_{i=1}^{NPaths} \Delta\Phi(i) \quad (15)$$

where  $NPaths$  represents the number of selected FCS feedback paths in the optimization process, that is the paths including the NFs which have to be optimized. Differently, the cost function expressed as weighted average of phase lags  $\Delta\Phi(i)$  at 1 Hz can be defined by an expression similar to Eq. 8:

$$F(X) = \frac{\sum w_i \cdot \Delta\Phi(i)}{NPaths} \quad (16)$$

where  $w_i$  represents the weight of the  $i^{th}$  FCS path with phase lag  $\Delta\Phi(i)$ .

The nonlinear constraints  $C(X) \leq 0$  are evaluated for each frequency at which the stability requirements have to be fulfilled. In particular, the *gain/phase stabilization* criterion is used to provide nonlinear constraints in terms of Nichols-chart convex areas at low frequencies (Fig. 3), while the *gain stabilization* criterion simply establishes nonlinear constraints on the gain values at high frequencies in the *Bode-plane*.

## 5. Results

The operative validation of the *NF-Code* software package has been accomplished through the specific test case realized to qualify the Fortran code during the developing phase. This test case considers a specific aircraft configuration and forty flight conditions given by different Mach numbers, altitudes and angles of attack. The inputs to *NF-Code* are represented by the corrected theoretical/experimental OLFRFs in terms of Real/Imaginary part concerning the six feedback paths of the longitudinal FCS, respectively  $q/OB$ ,  $q/IB$ ,  $q/FP$ ,  $N_z/OB$ ,  $N_z/IB$  and  $N_z/FP$ . The configuration of the longitudinal FCS with the sequence of NFs is similar to Fig. 5 except for the angle-of-attack sensor. In particular, the optimization process of the test case involved 10\* NFs with a total of 40 parameters to be optimized. An initial guess of the filter parameters was estimated as a starting point for the optimization algorithm. The minimization calculation converged after 5 major iteration steps and at the optimum solution no constraints are violated. Results of the test case are presented in the form of frequency response function (FRF) plots of the total OLFRFs without NFs in Fig. 8 and with optimized NFs in Fig. 9.

\*The other 9 of the total 19 NFs, in fact, had scarce influence on the optimization process and did not represent criticality.

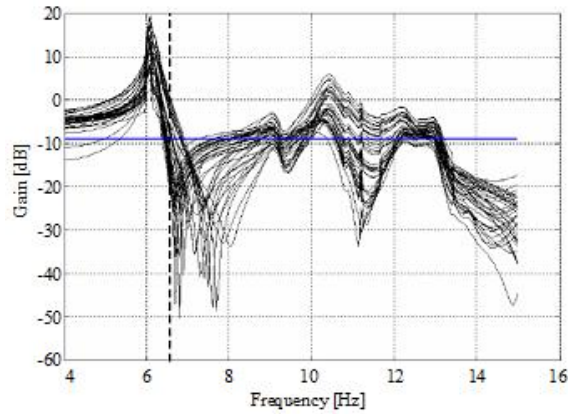


Figure 8. FRF-plot of the total OLFRFs without notch filters for one aircraft configuration and forty flight conditions

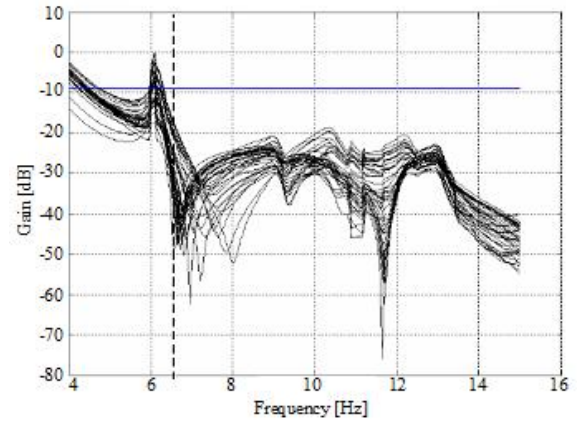


Figure 9. FRF-plot of the total OLFRFs with optimized notch filters for one aircraft configuration and forty flight conditions

The corresponding Nichols-plots are illustrated in Fig. 10 and Fig. 11, respectively for the cases without NFs and with optimized NFs. The plots perform OLFRFs for one critical configuration and forty flight conditions. Additionally, a comparison of the calculated phase-lag values at 1 Hz for each FCS feedback path before and after optimization is provided in Fig. 12, whereas Fig. 13 shows the optimized NF parameters constrained between their lower and upper bounds.

## 6. Conclusions

This paper describes the software package developed by Alenia and the Polytechnic of Turin, within the *Eurofighter EF2000* program. It has been shown how the aeroservoelastic model is updated and completed by the Ground Resonance and Structural Coupling Tests in order to produce a reliable tool for the FCS NF design. The updating procedure was based mainly on the correction of the stiffness characteristics of the model, using data gathered during tests carried out on a small number of external store configurations. The most critical aircraft configurations have been analyzed in different flight conditions, to produce an exhaustive database of OLFRFs for the design and optimization of NFs, which can be successfully employed for the selective attenuation of the airframe vibration content running in the FCS paths. NF parameters can be easily estimated by analyzing the characteristics of the structural modes which should be filtered out. The selected parameters, however, must be optimized to make sure that the aircraft, equipped with the FCS, satisfies the stability criteria given in terms of gain and phase margins. The developed optimization procedure is based on the Sequential Quadratic Programming

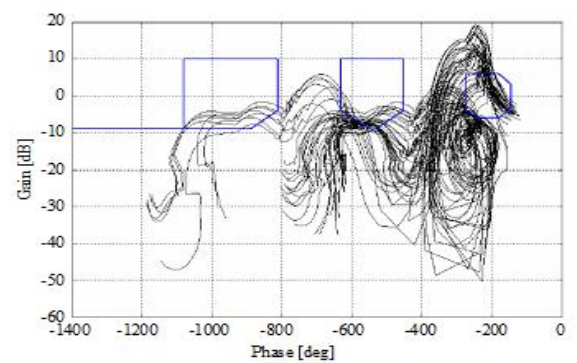


Figure 10. Nichols-plot of the total OLFRFs without notch filters for one configuration and forty flight conditions

(SQP) algorithm, which represents the state-of-the-art in Nonlinear Programming problems. The validation process performed on a very wide range of test-cases has emphasized the reliability and robustness features of the Fortran *NF-Code*.

## Acknowledgment

A special thanks goes to our friend Luigi Carano, of Alenia Aeronautica S.p.A., who has guided us through the code implementation. He prematurely lost his life, together with his young wife, Erica Ciancaleoni, in a terrible car accident, leaving their only daughter Ilaria, a nine months baby, who miraculously survived. Luigi was very fond of his job. Most of his short

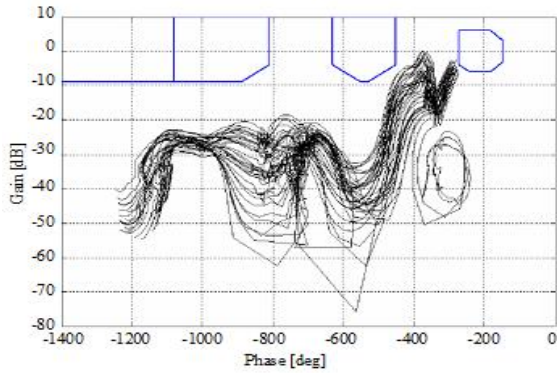


Figure 11. Nichols-plot of the total OLFRFs with optimized notch filters for one configuration and forty flight conditions

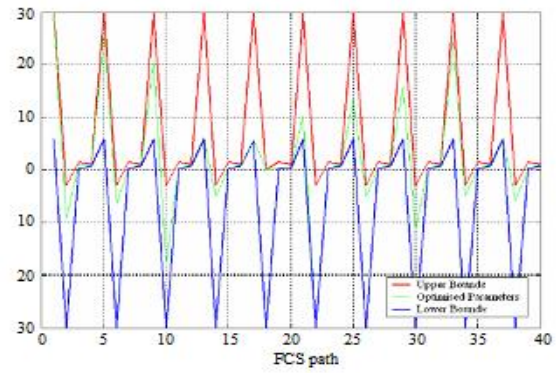


Figure 13. Optimized NF parameters with upper/lower bounds

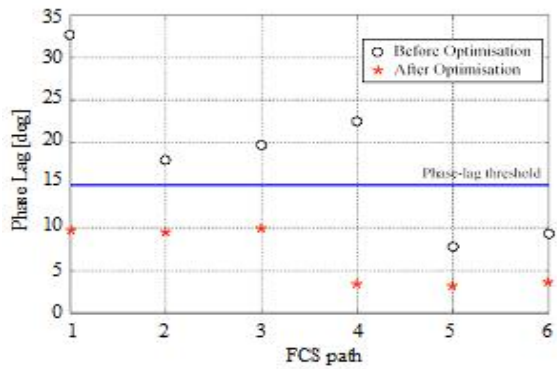


Figure 12. Phase-Lags at 1 Hz before and after optimization

carrier was spent working in the international team put up to solve the structural coupling issue for the Eurofighter. Not an easy task for a combat aircraft that can carry so many different stores, resulting in a huge number of configurations to be cleared. Neither the subject is something that can be easily found in engineering books. His contribution to this task was fundamental and the improvements to the analysis and calculation procedures were decisive to reduce the cost of design and qualification of the notch filters to be implemented in the Typhoon FCS. The contents of this paper was part of this process and witness of his will of improvement. It will be impossible for us, that will be using in the next years the tools he developed, not reminding him at every run.

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