STRUCTURAL FILTERS PRELIMINARY DESIGN FOR THE AEROSERVOELASTIC DECOUPLING OF A NEXT GENERATION CIVIL TILTROTOR TECHNOLOGY DEMONSTRATOR

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Abstract
The paper discusses the methodology used to design the structural notch filters used to guarantee the aeroservoelastic (ASE) stability of the NGCTR-TD tiltrotor. The complex configuration of a tiltrotor aircraft from one side, and the fly-by-wire control architecture from the other side, imply that several structural elastic modes can be sensed and excited by the Flight Control System (FCS), which on the contrary is intended to affect only the rigid aircraft motion. This control spill over can potentially affect the stability properties of the aircraft and a set of notch filters is then introduced to remove any adverse ASE coupling. The paper describes the numerical model used to assist the design of the notch filters and the optimization procedure used to get a configuration that achieves the best trade-off between ensuring ASE robust stability and keeping adequate (FCS) performances, that are inevitably affected by the introduction of the notch filters. The ASE stability assessment and the notch filters design need to be performed as early as possible during aircraft development, in particular this activity should be performed in conjunction with FCS design to allow the best compromise between aircraft handling qualities and stability. For this reason the analysis and filter design methodology described here allowed the management of several design iterations and will also accommodate further design adjustments that will be performed after prototype ground and flight tests.

NOMENCLATURE

A/C	Aircraft
ASE	AeroServoElastic
AW	AgustaWestland
CLAWs	Control Laws
DOF	Degree Of Freedom
FADEC	Full Authority Digital Engine Control
FEM	Finite Element Method
FBW	Fly-By-Wire
FCS	Flight Control System
HMI	Human Machine Interface
IADP	Innovative Aircraft Demonstrator Platform
LHD	Leonardo Helicopters Division
MASST	Modern Aeroservoelastic State-Space Tools
MIMO	Multiple-Input-Multiple-Output
NGCTR-TD	Next Generation Civil Tilt Rotor Technology Demonstrator
PAO	Pilot Augmented Oscillations
SISO	Single-Input-Single-Output
TF	Transfer Function
WoW	Weight on Wheel

1. INTRODUCTION

Within Horizon 2020 Clean Sky 2 Fast Rotorcraft IADP (Innovative Aircraft Demonstrator Platform) funding framework, Leonardo Helicopters Division (LHD) is leading the development of a Next Generation Civil Tilt Rotor Technology Demonstrator (NGCTR-TD). This vehicle represents one of the two Integrated Aircrafts Technology Demonstrators foreseen by the Clean Sky 2 Fast Rotorcraft IADP, which are planned to be flying within 2023. NGCTR-TD is an innovative tiltrotor characterized by a series of key enabling technology features, including – but not limited to – a split gearbox drive train concept for rotor shaft tilting mechanism that allows the adoption of non-tilting engines, an aeroelastic-tailored wing design with a highly integrated composite structure, and a full authority Fly-By-Wire (FBW) Flight Control System (FCS) architecture managing the combination of rotor, wing and empennage control surfaces.

When designing a full authority Flight Control System with fly-by-wire controls for a tiltrotor aircraft, particular attention needs to be paid to prevent any adverse aeroservoelastic interactions between the FCS itself and the aeroelastic response of the aircraft structure. This multidisciplinary topic (see Figure 1) is certainly applicable to conventional helicopters as well, but it does get particularly relevant when considering a powered lift architecture. It is in fact the very nature of this type of air vehicles that requires to harmonise the following distinctive features:

- a relatively high authority of the FCS that injects significant input to the control surfaces
- the relatively low frequency placement of the fundamental elastic modes of the aircraft.

One of the primary functions of the flight control laws is to provide the aircraft with good handling qualities and controllability while keeping the pilot workload to an acceptable level. This is achieved by the use of a flight control system whose aim is the sensing and control of the rigid aircraft rates and accelerations.However, the airframe is not rigid and has many structural modes of vibration that are excited by the control surface movements. The response of these possibly lightly damped modes is usually detected by the motion sensors and fed back to the control surfaces, with the potential for closed-loop amplification, detrimental coupling phenomena and, in the worst case, aeroservoelastic instability. In addition, when the frequency of the first elastic modes of the aircraft is relatively low – such as in powered lift rotorcraft –, the separation between the aeroelastic modal spectrum and the typical flight mechanics frequency range diminishes, so that the interactions between FCS and aircraft structure become more important [4].

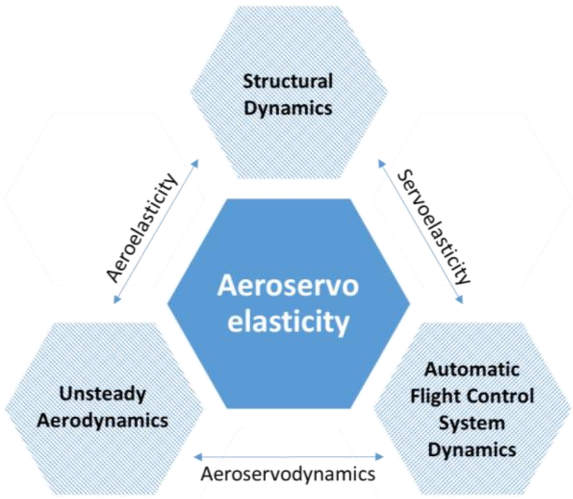

Figure 1: Aeroservoelasticity diagram

This paper deals with one of key elements of the analytical effort carried out within the preliminary design activities of the NGCTR-TD to address the ASE phenomena: the design of the FCS structural filters. Such filters represent a powerful and effective solution to prevent any possible detrimental ASE couplings as long as they are designed to ensure that the structural modes are filtered out with enough margin, and that the filtering action is robust against expected and unexpected variations in the aircraft response [7]. Generally such filters are preferred with respect to other control loop filtering strategies, such as aggressive low-pass or wide band-stop filters, as they are able to minimize the phase lag introduced into the affected Flight Control System loops, with also a localized impact on loop gain shape. Nevertheless, structural modes with relatively low natural frequency may fall not far from the typical crossover frequencies demanded to Stability and Command Augmentation loops. In these circumstances, the phase lag introduced by notch filters cannot be neglected and must be allocated also in the early stages of FCS design, although with a certain degree of approximation.

2. ASE DE-COUPLING

The idea can be outlined by considering the two complementary analytical methods that may be used to investigate the stability of the coupled ASE system:

- the closed loop analyses, that describe stability in the traditional structural dynamics terms of modal frequency and damping values
- the broken loop analyses, which are widely used in the control theory and allow to infer stability characteristics of the system from the transfer function obtained by

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deliberately opening the loop at a convenient point in the full model (see Figure 2).

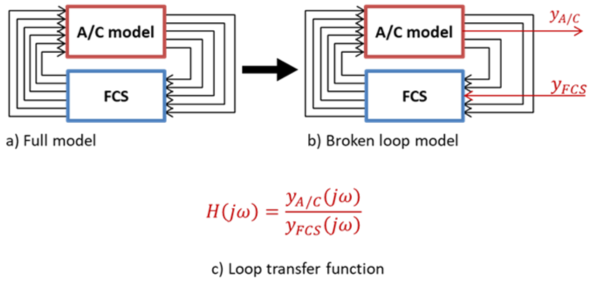

Figure 2: Aeroservoelastic broken loop TF

According to the Nyquist criterion the key parameters for the broken loop stability are the gain and phase margins: the former represents the maximum gain amplification a system can withstand on a particular control loop without incurring in any instability, the latter is the maximum delay that can be introduced in a feedback loop without causing any system instability. Although the physical system is a Multiple-Input-Multiple-Output (MIMO), as commonly adopted by aerospace control practice [1] it may be analysed as a conventional Single-Input-Single-Output (SISO). Within this assumption gain and phase margins are computed by breaking one single loop at a time and evaluating the transfer function from an input injected at the break point and the output evaluated at the same break point. Once the loop transfer function is available, gain margin (GM) and phase margins (PM) are obtained by evaluating all the crossings of the loop transfer function with the real axis and with the unitary circle respectively (Figure 3).

In mathematical terms:

$$GM = \frac{1}{|H(j\omega_{GM})|}$$

$$PM = 180° - |\measuredangle H(j\omega_{PM})|$$

Where $\measuredangle H(j\omega_{GM}) = -180°$ and $|H(j\omega_{PM})| = 1$

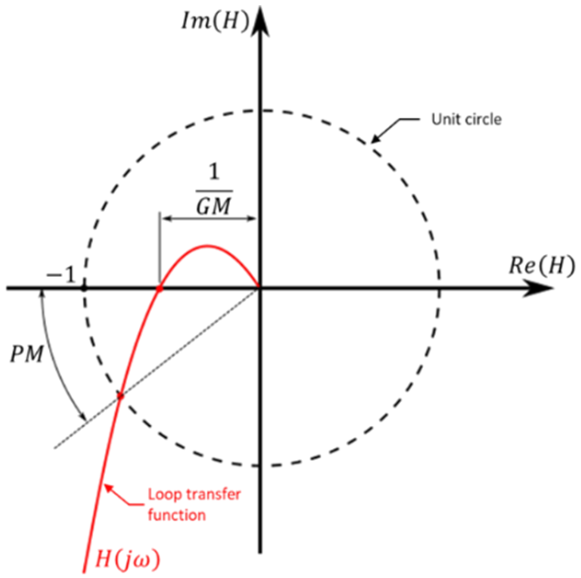

Figure 3: Broken loop TF gain and phase margins

Gain and phase margins do also give useful indications on how to shape the controller, if required, in order to improve the dynamic behaviour and the robustness of the closed loop system: this can be done by introducing a set of digital filters. The purpose of such filters is to prevent any detrimental couplings between the controller and the dynamics of the aircraft structure by limiting the amplitude of the broken loop responses to a certain acceptability threshold. This needs to be done for each individual feedback loop, and involves filtering out – or notching – the peaks of the transfer functions associated to the elastic aircraft modes. The challenge in doing so is to target as accurately as possible only the elastic frequency range, while making sure that the phase lag introduced by the filters at lower frequencies is manageable from an aeromechanics stability and controllability perspective. Nowadays FCS phase budget is still of paramount importance for controlling FBW aircraft: despite the computational delays minimisation allowed by the growing processing rates available for airborne digital processing units, increasingly popular distributed FCS architectures detrimentally affect end-to-end feedback signal latency.

The following paragraphs detail the main steps followed during this design activity: from the assembly of the AeroServoElastic (ASE) model of the NGCTR-TD and the structural filters design and optimization process, to the verification of the filters effectiveness and robustness.

3. NGCTR-TD ASE ANALYTICAL MODEL

The NGCTR-TD ASE model has been assembled using MASST (Modern Aeroservoelastic State-

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Space Tools), a MATLAB® suite designed to perform dynamic analyses of a linearized aircraft model, taking into account the interactions among its relevant ASE components [2], [3]. The tool is developed in-house by LHD with the support of Politecnico di Milano. Thanks to a strongly modular software philosophy, MASST offers the possibility to integrate a series of sub-components generated with dedicated tools in a relatively simple fashion: this allows to achieve the desired level of complexity in an incremental way and makes it particularly suitable to describe complex phenomena such as the aeroservoelastic interactions. Each component is processed individually and it is used to generate an equivalent dynamical model in state-space form; the various components are then connected and integrated to assemble the state-space model of the full aircraft.

The ASE model includes the aeroelastic aircraft subsystems (two rotors, drive train and airframe) connected to the linearized FCS representation in a feedback loop. The linearized FCS model embeds the most significant dynamic elements contributing to the small-amplitude feedback loop transfer function (sensor dynamics and transport delays, lever arm compensations, control algorithms, gearing laws, processing delays and closed-loop actuator models). It is fully parametrized so it can be easily configured to assess various operating conditions (i.e. by changing selected CLAWs operating mode and logic state vector) and to perform sensitivity analysis, i.e. by modifying the feedback gains of specific stability and command augmentation system control loops. It is worth highlighting that, in order to properly represent the closed-loop behaviour of elastic drive-system response and the associated dynamic coupling with aeromechanics, also the electronically (FADEC) controlled powerplant is accurately represented in the linear framework, as well as the dedicated CLAWs rotor speed and torque governing loops.

A brief description of the NGCTR-TD model components is given below:

Rotor model. The matrices defining the linear rotor aeroelastic model are obtained by a linearization of the system dynamic equations around a properly defined trim configuration. The assembly of the system equations, the computation of the trim configurations and the generation of the matrices of the linearized model are performed using CAMRAD II software [5].

Drive train model. The drive train is defined through its inertia and stiffness properties. It is connected to the rotors with the enforcement of identical rotation of the drive train with the rotor mast, and with transmission of mast torque from rotor to drive train and vice versa. The drive train model also includes the definition of gearboxes, and it allows the transmission to the airframe of the corresponding torques using the methodology described in [6].

Airframe model. The airframe structural and aerodynamic properties are represented by means of mass, stiffness, damping and generalized aerodynamic force matrices. These matrices are obtained by condensing the matrices of an FEM model using a set of deformation shapes that includes normal modes, aircraft rigid motion, control surface rotations and static deformation shapes. The computation of the full model matrices, the deformation basis, unsteady aerodynamic forces and condensed model matrices is performed by Nastran along with a set of ALTER instructions.

Sensors. Sensors are defined in the model to provide the correct input for the flight control system model, and for the correlation with experimental data. Sensor are defined directly on the FEM model of the airframe, rotors and drive train and can consist in displacements, velocities accelerations and internal forces. Since sensors are defined directly on the proper point of the FEM model, they are also able to represent the effect of local deformation in the measured signals. The motion measurements extracted from the FE model are then fed into dynamical systems representing the sensor bandwidth and time delay so to simulate the actual signal that is measured by the onboard sensors and provided as input to the FCS.

Actuators. Actuators are defined as linear models used to apply the actuator elongation command prescribed by the control system to the structural model. The kinematic of the control mechanism is defined directly in the airframe model, where a specific actuator Degree of Freedom (DOF) is defined representing the actuator elongation. The actuator model then generates the actuation force (acting on the actuator DOF) required to get the commanded elongation of the actuator shaft (variation of the actuator DOF). The actuation force is in the form:

$$F_{act} = \frac{1}{H_M(s)}(\delta - H_\delta(s)\delta_C)$$

Where F_{act} is the force applied on the actuator; δ is the actuator DOF elongation; δ_C is the commanded elongation of the actuator DOF; $H_M(s)$ is the dynamic compliance function (inverse

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of the actuator stiffness); $H_\delta(s)$ is the so-called servovalve function, that is the closed loop response to reference input.Irepresents the response of the actuator model in the ideal case of no compliance and includes the definition of the actuator bandwidth.

Flight control system. A linear flight control system is defined in the form of a linear state space model. It receives the output of the sensors as input and provides the elongation command to the airframe and rotor actuators as output. It also includes a turboshaft engine model measuring the torque at the engine power turbine shaft and applying the engine torque to the drive train. The flight control system model is parametrized according to the flight condition (altitude and speed) and according to the control laws operational status (e.g. Direct Mode, Turn Coordination).

Pilot model. A linear system that has the acceleration of the pilot seat as input and as output the corresponding motion of the control sticks can also be added to the model. This can be used to represent the involuntary pilot action on the commands due to the vibration of the cockpit (biomechanical feedback).

A visual schematics of the NGCTR-TD MASST model with the FCS in the loop is given in Figure 4.

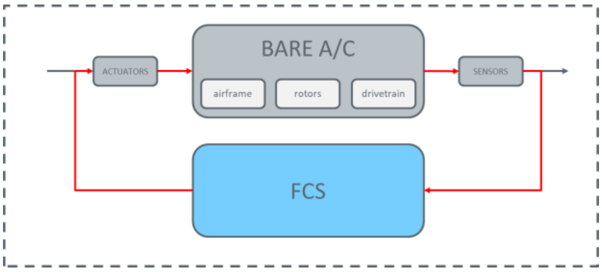

Figure 4: NGCTR-TD ASE MASST model

The model verification strategy made use of the modular logic of MASST: at first each structural sub-system was dealt with individually and then integrated with the others to generate the aeroelastic structural model of the bare aircraft. Both the actuator and control kinematics together with the sensors implementation were then verified before ultimately introduce the linearized model of the FCS and close the aeroservoelastic loop.

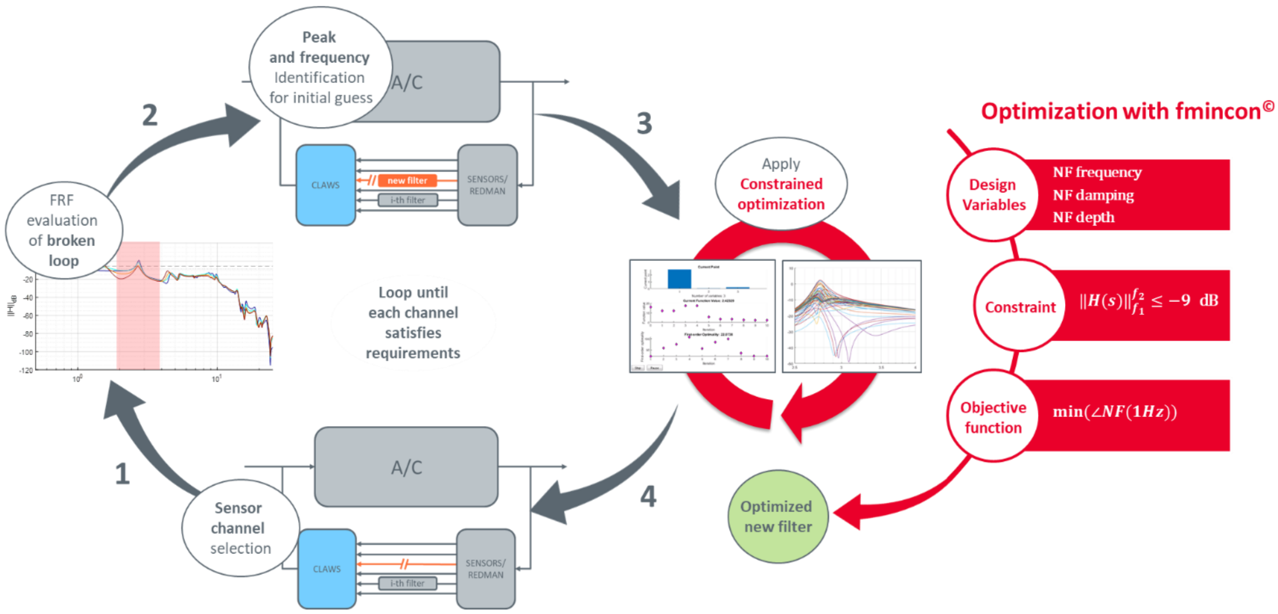

Figure 5: Structural filters optimisation process

4. STRUCTURAL FILTERS DESIGN PROCESS

The methodology adopted to carry out the notch filters design is discussed in this section. As explained above, an optimisation process is required for this purpose in order to achieve a reasonable compromise between filter effectiveness and low impact in the aeromechanics response.

This optimisation logic has been automated and implemented in a MATLAB® algorithm that allows to handle in a lean and efficient way the design iterations in a recursive refinement of control laws architecture and notch filter characteristics. The process is outlined in Figure 5 and has been

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applied to each control feedback loop: a description of the main elements of this process follows.

Design requirements
The design requirements are listed here below:

1. The filters design shall follow a gain stabilisation approach given the non-verifiable fidelity in correct phase estimation at the current stage of the program
2. The required gain margin is conservatively set to -9 dB
3. Different sets of filters shall be scheduled with each nacelle detent angle configuration.
4. On-ground conditions shall have a specific set of filters to be activated whenever the aircraft WoW logic is triggered
5. Filters performance shall be valid for whole speed and altitude envelope
6. Filters shape shall be designed minimizing delay introduced at 1 Hz (selected reference threshold), to be compared with FCS phase budget requirements.

Design variables
The design variables considered are the mathematical quantities defining frequency, depth and width of a symmetric notch filter (see Figure 6): assuming the characteristic transfer function below, these quantities are associated to the parameters freq, g_{min} and c respectively:

$$NF(s) = \frac{s^2 + 2 \cdot g_{min} \cdot c \cdot \mathrm{freq} \cdot s + \mathrm{freq}^2}{s^2 + 2 \cdot c \cdot \mathrm{freq} \cdot s + \mathrm{freq}^2}$$

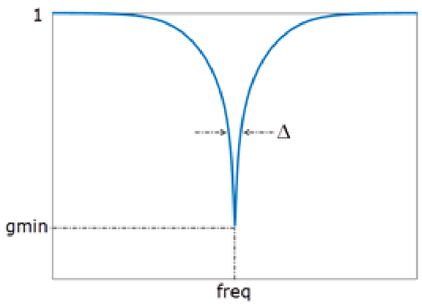

Figure 6: Symmetric notch filter shape

By modifying these parameters, the algorithm is able to automatically:

- centre the filter at the most effective frequency (typically the frequency at which the ASE response amplification is at its highest)
- change the depth to achieve the required margin
- shape the width to limit the response under the required margin also in the frequency range around the identified peak

Additional parameters can be introduced to expand the possibilities of filter shaping to obtain asymmetric filters: this allows for a more tailored filtering action whenever the broken loop transfer function does not present an isolated and well defined single peak modal response. In particular, it was found that an effective, practical approach in this sense is to introduce the asymmetry parameter a in the equation:

$$NF(s) = \frac{a \cdot s^2 + 2 \cdot g_{min} \cdot c \cdot \mathrm{freq} \cdot s + \mathrm{freq}^2}{s^2 + 2 \cdot c \cdot \mathrm{freq} \cdot s + \mathrm{freq}^2}$$

Cost function and design constraints
The process is structured as a single-objective optimization, thus the only cost function defined is the minimization of the delay introduced by the notch filters at the frequencies where the controller is acting. The delay is evaluated always at the same reference frequency, which is chosen to be 1 Hz (i.e. on the boundary between the typical rigid aeromechanics dynamics and the aeroelastic response of the aircraft). The constraint of the optimization is defined on the gain margin, which must be kept under the required threshold of -9 dB in the frequency range of interest for the notch filters design.

This particular choice of optimization cost function and constraint is supported by the following arguments:

- In general, different control loops tend to have their own phase budget depending on the characteristic control frequencies and performance requirements; therefore, no real advantage is achieved by fixing a specific constraint on the maximum acceptable delay.
- On the other hand, a specific requirement is generally set on the gain and phase margins, which for this reason are more adequate to be chosen as a constraint for this optimization process.

This approach has a direct parallel on the typical aeroelastic tailoring optimization problem where the weight of the structure is minimized to preserve stable damping within the prescribed speed envelope of the aircraft, rather than maximizing the flight speed keeping the weight constrained (usually the target cruise speed is fixed by other mission and market requirements).

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A practical example of how this process is being applied is given in Figure 7: a KEAS sweep in tiltrotor airplane mode conditions is considered and the broken loop transfer function associated to one of the sensor signals feedback is generated using the MASST model and plotted at different airspeeds (only the bode plot magnitude is represented). The unfiltered response shows a significant amplification corresponding to the frequency of one of the elastic modes of the airframe and highlights the need for a filtering action. The optimisation algorithm is then used to generate a convenient notch filter transfer function that can be introduced in the loop in order to limit the system response within the required gain margin while minimising the delay introduced at low frequency.

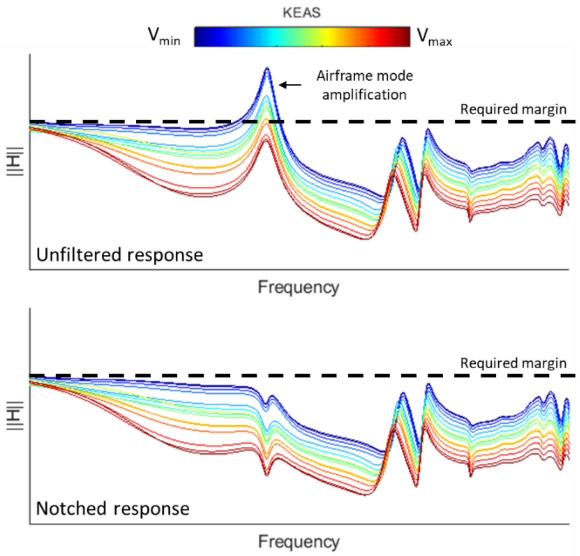

Figure 7: Open loop transfer function response – notch filter impact

It is interesting to consider the relation between the Nyquist stability criterion and the eigenanalysis approach. For this purpose a useful example may be derived from the low speed unfiltered response presented in Figure 7 above. A phase sensitivity was performed by introducing a second order Padé delay to the feedback loop breaking point and considering a phase shift range up to 250ms. The broken loop results are shown in Figure 8 and Figure 9 using the amplitude of the Bode plot and the Nyquist diagram respectively; the eigenanalysis results are presented in Figure 10. In this example the maximum gain amplification peak in the frequency range of interest is found to be just in excess of the 0dB line: this peak is associated to an airframe mode. As expected the phase lag sensitivity does not affect the response amplification, but the impact on the phase is clear from the Nyquist plot in Figure 9. In nominal conditions (0ms delay), despite the exceedance in the response amplification, the phasing of the transfer function is quite favorable (~180ms), and no instabilities are highlighted in the eigenvalues plot in Figure 10. As the Padé delay is increased though, the phase margin gets eroded and the open loop transfer function response eventually encircles the (-1;0) point in the Nyquist plot: in this condition the closed loop system becomes unstable. Note that if the gain of the open loop transfer function remains limited below the 0dB line, the phase margin is infinite and the closed loop system is stable whatever the phasing of the transfer function: this is the idea behind the gain stabilization approach discussed earlier.

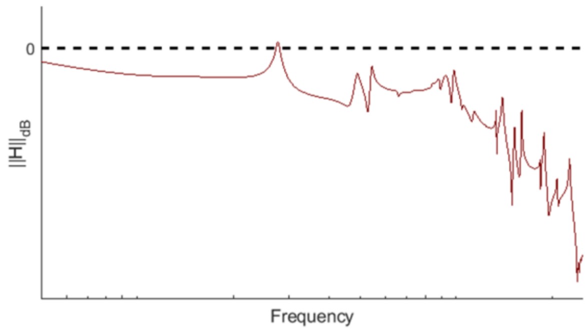

Figure 8: Broken loop stability phase sensitivity – TF Bode plot magnitude

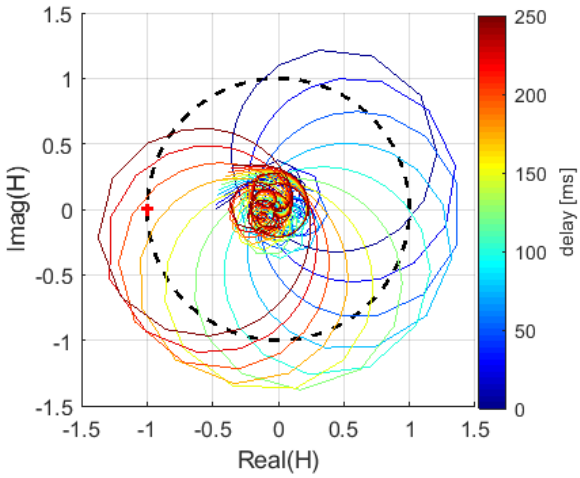

Figure 9: Broken loop stability phase sensitivity – TF Nyquist plot

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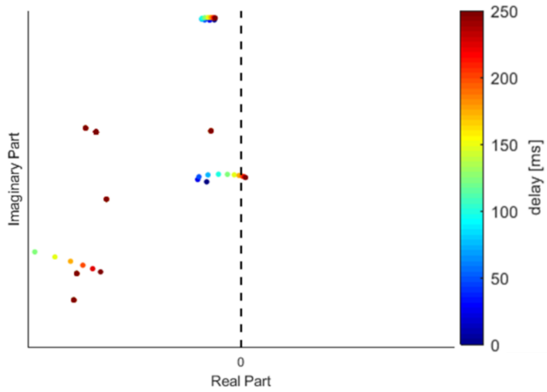

Figure 10: Closed loop stability phase sensitivity – eigenanalysis results

5. RESULTING FILTERS ROBUSTNESS VERIFICATION

The first release of the notch filters has been based on models which have still no direct validation from experimental data (either from laboratory tests or flight tests). For this reason, a robustness study has been performed in order to assess how the performance of the filters could be affected by deviations in the response currently predicted by the models. Deviations in the aerodynamic control surfaces effectiveness as well as rotor control derivatives would typically affect the amplitude of the broken loop responses so that adjustments in the filters shape would simply be in their depth with relatively low impact in terms of delay. On the other hand, a deviation in the airframe modes frequency placement would demand a heavier modification of the filter to re-centre it a the correct frequency with possibly higher impact on the delay introduced in the control. For this reason, the robustness assessment has been focused on the uncertainties in the airframe modes frequency placement.

The assessment has followed an approach based on deliberately modifying the airframe stiffness matrix in MASST to achieve up to a +/-10% frequency variation in the fundamental airframe modes, one at a time. This operation is not strictly physically correct since it does not derive from actual mass/stiffness changes in the airframe model but it is extremely more convenient and efficient with respect to introducing the modification in the airframe FE model. The assessment has been performed in a subset of flight conditions that can still represent the envelope.

<u>*Example on symmetric vibration mode*</u>

In Figure 11 is reported the sensitivity on the broken loop transfer function to the variation of the mode frequency (while keeping the notch filter active as per initial design). The effect is clearly visible in the peak of the response increasing as the mode frequency is moved farer from the central frequency of the notch (red peak and blue peak).

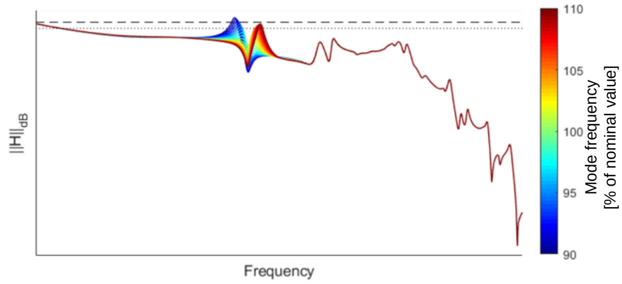

Figure 11: Broken loop stability frequency sensitivity

From this analysis it is possible to calculate how the gain margin is affected by the mode frequency shift. This is reported in Figure 12 where the gain margin variation is plotted against the frequency. The variation (from -9 dB) is 0 for 0% frequency shift and then increases almost symmetrically for a larger shift. The dark dashed vertical lines represents the expected variation of the mode natural frequency for different A/C weight and CG configurations. The red dashed horizontal line represents the 3 dB variation of the gain margin thus indicating that the notch filter is effectively keeping the response under -6 dB. For this mode, the associated filter remains effective in the range of expected variation (±2%) and possibly for a larger variation (±3%, intersection between red and blue lines). For mode frequency shifts larger than this limit, the filter is not keeping the response under -6 dB, this means that a modification of the filter would be necessary to re-center the filter frequency. The impact in terms of delay by this modification is described in the Figure 13 where the plot indicates that less 1 deg of phase delay would be introduced to keep the filter effective.

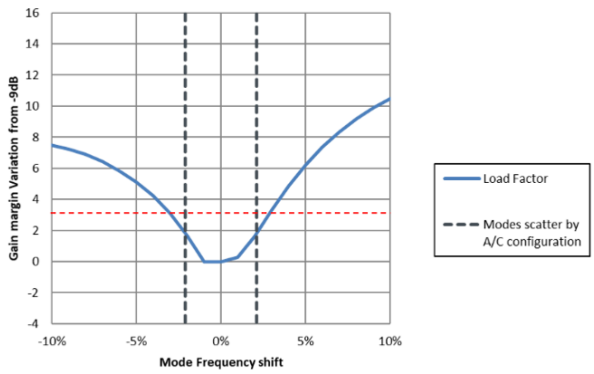

Figure 12: Gain margin variation with frequency shift

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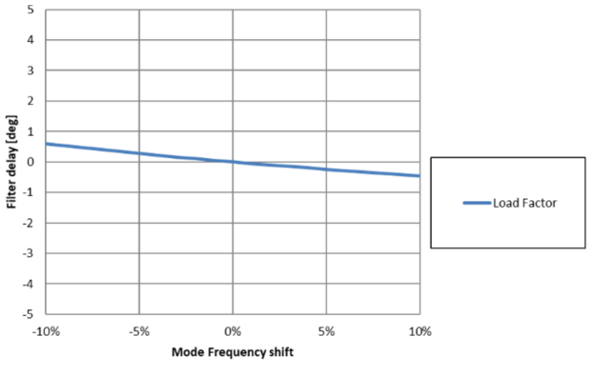

Figure 13: Delay impact variation with frequency shift

From this assessment, the filter is considered robust against expected mode frequency variations, less robust against larger shifts but little impact is expected if modifications in the filters are needed.

6. STRUCTURAL FILTERS DATABASE MANAGEMENT

The design of the structural filters is an integrated process involving a number of disciplines from the very early development stages of the aeroservoelastic model of the aircraft. An effective approach to the iterative design output management is of paramount importance to guarantee a lean control over the process throughout the aircraft design and development phases. For this reason, a dedicated GUI has been implemented specifically to comply with the control approach in terms of dedicated storage area for the data, versioning control, shared database access.

The GUI allows the user to:

- Create a notch filter specifying the shape parameters (either frequency, damping gain for the symmetric, or directly the numerator and denominator for a more generic TF), the flight conditions (flight mode, nacelle angle), the feedback channel name, and the information about the versioning control (user, creation date, creation version, database release version).
- Load the notch filters database (which is saved in Matlab table format with extension *.mat*), filter the database through a set of parameters and visualize the bode plots of the filters individually and of the combined response with the related delay introduced at 1 Hz.
- Export the database (or a subset of selected filters) for a specific release or a simple pull from the database.

Figure 14 gives an idea of this NF database management tool.

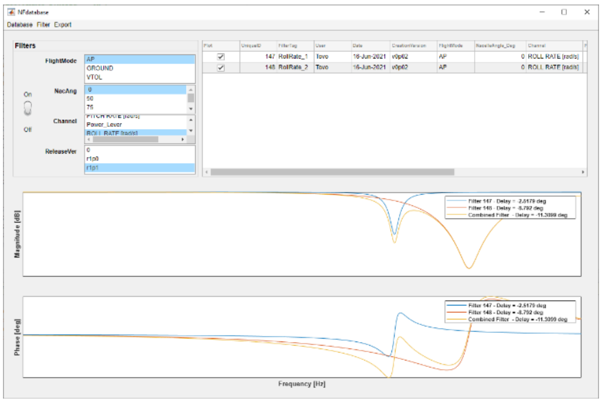

Figure 14: NF Database Management GUI

This is a simple but effective solution to the more general question on the integrated data management process and tools. In the future, either an improvement of the current GUI is foreseen or the use of a more sophisticated software.

7. CONCLUSION

The paper presents the details of a preliminary analytical aeroservoelastic assessment in support of the design activities of the NGCTR-TD program.

An overview is given on the process followed to build and verify the MASST model, focusing both on the individual subsystems and on their integration into the fully coupled aeroservoelastic analytical model. Such model is being used to drive the design of the structural filters required to minimise the adverse interactions between FCS and aeroelastic response of the aircraft: a detailed discussion is presented on the methodology developed for this purpose, and in particular on the iterative design process between the disciplines involved.

Some preliminary ASE broken loop stability predictions are discussed including a number of sensitivity analyses to various parameters that are expected to drive the structural filters definition. The results of the first iteration of the notch filters design process are presented together with the proposed tools for managing the notch filters database through the next iterations.

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It is important to underline that at the current stage of the NGCTR-TD program, a comprehensive set of experimental data to be used for validating the MASST ASE model is not yet available. As soon as these data will become available, the model will be updated accordingly allowing for a gradual increase in its confidence and maturity and to refine the notch filter design compromise between ASE and fight mechanics stability requirements.

It is vital, though, to start performing the ASE investigations as early as practically possible during the aircraft design and development process in order to assess its impact on the design choices of the aircraft structure and the control laws. This allows to minimise the risks of costly modifications or necessary redesign activities further down the line. A number of structural filters design iterations have already been performed using the methodology described in the paper and a preliminary full set of these filters has been produced.

In the near future the level of confidence in the NGCTR-TD ASE analytical model representativeness will be significantly improved thanks to the planned experimental activities at both component and platform level. Actual feedback signal latencies and command transport delays will be measured with the real FCS hardware, including identified actuation transfer functions, and airframe structural characteristics validated initially by means of vibration test results. A series of dedicated correlation activities, both on ground and in flight, will then be performed providing material and potential for further investigations on the topic. Finally, future research activities will focus also on the exploitation of MASST for addressing and optimizing the structural filters preventing adverse biomechanical coupling with pilot inputs (PAO): this topic is of particular interest due to NGCTR-TD innovative HMI aspects such as the cockpit controls embracing a state-of-the-art active sidearm controller.

8. REFERENCES

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