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STRUCTURAL STABILITY MARGIN CRITERIA FOR ACCELERATED CLEARANCE OF DEVELOPMENTAL FLIGHTS

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ABSTRACT: *Inertial motion sensors in the flight control system pick up high frequency signals due to the flexible modes in addition to the rigid body responses and could lead to instability at the structural frequencies when the rigid body stability augmentation feedback loops are closed. To attenuate the effects of this structural coupling, notch filters are designed and placed in series with the inertial sensors in each of the feedback paths. During the initial phase of control law design and development, aircraft structural response data is generally not available. Therefore, while designing the rigid body control laws, an additional budget is allocated for phase lags introduced by the structural notch filters. Once the structural coupling tests are carried out on the aircraft, structural filters are designed in order to meet the certification requirements. During developmental flight tests with multiple prototype vehicles there are likely to be variations in the structural response characteristics as the production processes are maturing and also, due to minor updates to the aircraft standard of preparation and addition of different external stores. This calls for the redesign of structural filters and subsequent onboard software development and testing which is a lengthy process. Hence, in order to meet project schedules without compromising safety, the clearance procedure was modified so that it could be efficiently used for flights during the development phase. This paper presents a revised clearance procedure based not only on values of the nominal stability margins, but also on the sensitivity of structural stability margins to the modal frequency perturbation. This change in the clearance philosophy was considered acceptable for the developmental phase of flights but for the final production vehicle standard one would need to strictly follow the MIL-F 9490 D Standard guidelines. This paper discusses the changes carried out to the clearance procedure, the rationale behind the changes made, and also gives directions for future research in robust stabilization of structural modes as well as notch filter design.*

1. INTRODUCTION

The flight control system (FCS) is provided to enhance the aircraft's natural stability or to provide artificial stability for an unstable airframe configuration. Aircraft, like any flexible structure, exhibits several vibration modes which are within the bandwidth of the FCS. These modes will vary significantly in frequency and amplitude when additional stores are carried, or because of variations in fuel state / flight condition. These flexible modes get excited during normal aircraft flight. The term Structural Coupling refers to the interactions between the FCS, the structural dynamics, and the airframe aerodynamics. The FCS motion sensors will sense not only the rigid body motion of the aircraft, but also the flexible modes of the structure on which they are mounted. These high frequency signals if not properly attenuated, could be amplified by the flight control laws and thus lead to instabilities at the structural frequencies when the loops are closed. The operational FCS bandwidth has also increased with the increase in demands placed on the performance and agility of the aircraft. At the same time, the use of composite materials in the production of the airframe and carriage of external stores has led to a decrease in the frequencies of the flexible modes of the airframe. As these rigid body and structural mode frequencies come closer, the problems associated with structural coupling become more pronounced.

In general, structural coupling is addressed as part of the FCS design process, and thus the frequency-domain methods used in the analysis of the rigid aircraft stability, needs to be extended or adapted to cover the higher frequency flexible modes. Additional structural notch filters are introduced in the control laws in series with the inertial sensor outputs to attenuate these modes. This requires a valid and appropriate model of the FCS-flexible aircraft system which can facilitate analysis of the structural modes for the design of the notch filters. To generate this data, special ground tests called Structural Coupling Tests (SCT) are carried out on the fully equipped aircraft where in, the structural modes picked up by the inertial sensors are quantified, and is subsequently used for design of the notch filters. The inclusion of these filters in the feedback loops allows the designer to meet the required stability margins over the entire range of structural frequencies.

During developmental flight tests with multiple prototype vehicles there are likely to be variations in the structural response characteristics because the production processes are maturing and also due to updates to the aircraft standard of preparation / store configuration. This calls for the redesign of structural filters and subsequent onboard software development and testing, which is a lengthy process. Hence, in order to meet project schedules without compromising safety, the clearance procedure was modified so that it could be efficiently used for flights during the development phase. This paper presents a revised clearance procedure based not only on values of the nominal stability margins, but also on the sensitivity of stability margins to the modal frequency perturbation.

2. STRUCTURAL RESPONSE QUANTIFICATION

Structural coupling tests are carried out on the aircraft, and during these tests the servo elastic structural responses are measured by monitoring the outputs of the aircraft inertial sensors by injecting sinusoidal test signals into the actuators. The measured response data consists of 15 transfer functions from the three control inputs elevator, aileron, and rudder (δe, δa, δr) to the five sensor outputs namely, the pitch rate (q), normal acceleration (Nz), roll rate (p), yaw rate (r) & lateral acceleration (Ny). The signal peaks picked up by the sensors correspond to structural-mode resonances and these magnitudes depend on the efficiency with which each control surface excites a particular mode. SCT are carried out on various configurations of the fully equipped aircraft to quantify the structural mode responses picked up by the inertial sensors, and the worst case structural responses data is used for design of the notch filters. The worst-case data at each frequency is generated by taking the maximum values of the measurements for all possible configurations

Typical worst-case structural response plots across all tested configurations for a typical fighter plane are shown in Figures 1(a-c) for the elevator, aileron, and rudder excitations respectively. These figures reveal that the magnitude of the cross transfer functions (i.e. δe to p and δa to q) is of the same order as the direct transfer functions (i.e. δe to q and δa to p). This cross coupling between axes complicates the notch-filter design process, since a structural filter in one sensor path attenuates not only the direct structural response but also attenuates the cross responses to a certain extent. In this case an iterative process is inevitable to determine the attenuation requirements in each of the sensor paths. Analytically computed Aero-Servo-Elastic (ASE) corrections are added to derive the final plant envelopes to ensure robustness against variations in the natural frequencies and damping factor of the structural modes. The ASE corrections are a function of Mach number and altitude, and generally the magnitude of the correction increases with dynamic pressure. However, the control law gains in general drops as the dynamic pressure increases. Therefore, in order to avoid an over conservative design, the ASE corrections are multiplied with the control law gain at each flight condition and then the worst of all these gains is added to the basic envelopes as the ASE correction. To account for a possible shift in frequencies of the structural modes, the worst-case magnitude envelopes smeared by ±5% frequency shift are used for designing the notch filters. The percentage frequency shift allows for a greater uncertainty in the high frequency modes compared to the low frequency ones.

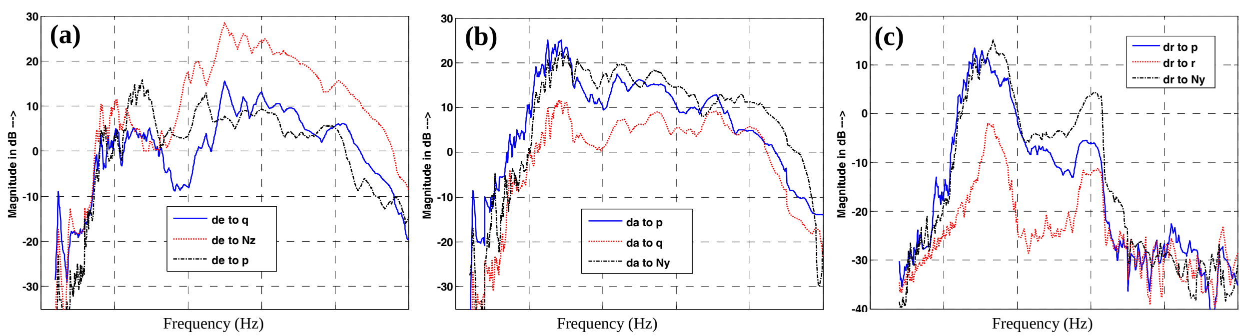

Fig.1 Typical Structural Frequency Response Plots

3. NOTCH FILTER DESIGN REQUIREMENTS

It is standard practice to design the notch filters after the rigid body control laws have been designed or are in an advanced stage of their development. Because the structural response data are not available in the early stages of the design cycle, a certain phase budget in the rigid body stability margins is provided for the introduction of notch filters. This is because additional phase lags are introduced by the notch filters in the rigid body gain crossover region. The filters, however, do not contribute much to the magnitude at these lower frequencies. Hence, the notch filters have to be designed with a predetermined constraint on their phase lag in the rigid body gain crossover region which is approximately around 1 Hz.

The budget provided during initial design for the phase lags introduced by the notch filters is 14° in each sensor path based on experience. Hence it is required that, at 1Hz, the phase-lag contribution of each bank of notch filters should not exceed 14°. This is required to ensure that the designed rigid body stability margins are not violated. The phase information of the servo elastic response available from SCT is not as reliable, mainly because the aerodynamic effects are excluded during the ground-based tests. It is therefore necessary to gain stabilize all the flexible modes of the aircraft. It is also assumed that the structural modes are adequately separated from the rigid body modes so that gain stabilization is feasible. For multi-loop systems, MIL-F-9490D[1] recommends that the gain margin for every loop be determined while keeping the other loops closed at their nominal values, and the notch filters be designed so that this margin is in excess of 8dB.

3. NOTCH FILTER DESIGN

A combination of analog and digital second order notch filter sections are provided in the sensor paths. An analog notch filter section is added in series with the digital filter sections in each path to cater for the attenuation requirements in the band of 30-50Hz (for a 80 Hz sampled data system) because the performance of the digital filters degrade significantly around half the sampling frequency (i.e. 40Hz). The MIL design requirement is to achieve 8dB gain margin (uniform gain stabilization over the entire structural frequency range, in this case >5Hz) at each actuator consolidation point with the other loops closed. The introduction of notch filters can reduce the effective bandwidth of the actuators, which in turn deteriorates the performance of control laws in flight. The notch filter design becomes complicated if the structural responses show significant cross coupling between aircraft axes.

A novel two-step optimization procedure is used to design notch filters. This approach[2] differs from the conventional methods in that, it is a single-step procedure that enables notch filters of each sensor path to be designed independent of those in other sensor paths while guaranteeing the stability margin requirements. As a result, this approach can result in a less conservative design when compared to the conventional methods. The design proceeds by first finding out the required optimal attenuation for the notch filters in each sensor path at each frequency using numerical optimization techniques. The Bode Integral[3] is used to estimate the theoretical least value of the phase lag introduced by notch filters. The Bode Integral enables the assessment of the phase lag introduced in each sensor path directly from the optimal attenuation envelopes, without having to design the filters. The proposed approach not only helped in synthesizing efficient and non-conservative notch filters, but also in determining the number of filter sections required in each sensor path. In the second step, the individual notch filter sections are designed based on the optimal attenuation envelopes. The use of Bode Integral speeds up the entire design process, by restricting the individual filter-design cycle to the optimal envelope and helps to keep the phase lag introduced by the notch-filters at the rigid body gain crossover frequency (~1Hz) at a minimum possible value.

4. CLEARANCE CRITERIA

During an experimental aircraft developmental phase using multiple prototype vehicles there are always likely to be variations in the structural response characteristics as the production processes are maturing, and also due to minor updates to the aircraft standards of preparation / store configurations (See Figure 2). Structural frequency response therefore starts deviating from the data for which notch filters were designed. Figure 3 shows variation of stability margins with different airframes/stores configurations computed for the same set of notch filters with ±5% frequency perturbation. It can be seen that the elevator margins meet the Mil-Std. requirement of -8 dB with ±5% frequency perturbation when there are no external stores. But with addition of external stores stability margin violates -8 dB requirement. Thus redesign of structural filters and subsequent onboard software coding and testing becomes necessary.

In this section we describe the modified clearance procedure which was efficiently used for flights during the development phase in order to meet project schedules without compromising safety. The revised clearance procedure is based not only on values of the nominal structural stability margins, but also on the sensitivity of structural stability margins to the modal frequency perturbation, i.e., determining the extent of frequency perturbation that is required to reduce the structural stability margins to zero. Figure 4(a) presents structural stability margin results for the worst case response envelope computed from the above three envelopes of figure 2 with ±0% (nominal data), ±5% ±10%, ±15%, ±17% and ±18 % frequency perturbation for the same set of notch filters. Figure 4(b) presents sensitivity of Elevator, Aileron and Rudder margins to frequency perturbation. It can be seen from these figures that even with ±15% frequency perturbation these margins do not deteriorate to 0 dB. So the degradation in margin is very gradual and hence is not a cause for concern. Moreover, during SCT tests it was also observed that as the amplitude of actuator excitation increases, there is a reduction in magnitude of the structural response outputs picked up by the feedback sensors and hence it improves the margins (See Table 1).

Table 2 tabulates the measured margin during SCT on aircraft for each configuration and it also lists the computed margins for the worst case configuration with and without 5% frequency perturbation. The measured margins are better than computed margins since on aircraft the loop closure gets the advantage of phase which is not considered while computing the worst case margins. These two facts give additional confidence to the designers for clearing the aircraft with slightly lower nominal structural stability margins, but with adequate robustness to frequency perturbations as deterioration in margins could at the worst, lead to small amplitude limit cycle oscillations. This change in the clearance philosophy was considered acceptable for the developmental phase of flights, but for the final production vehicle standard one would need to strictly follow the MIL Standard guidelines.

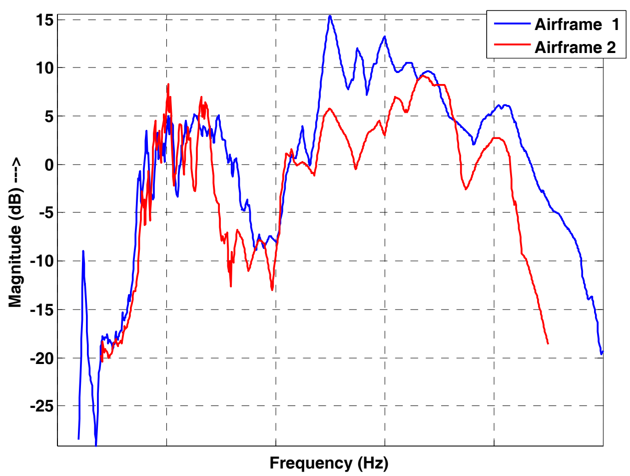

Fig.2 Structural elevator to pitch-rate response for different airframes/stores configurations

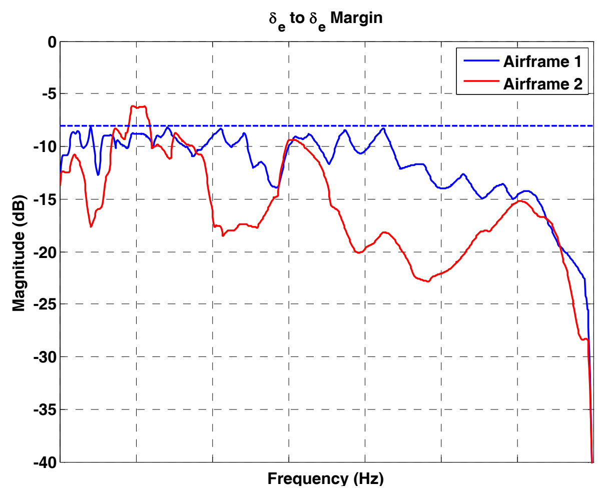

Fig.3 Variation of elevator stability margin with different airframes/stores configurations

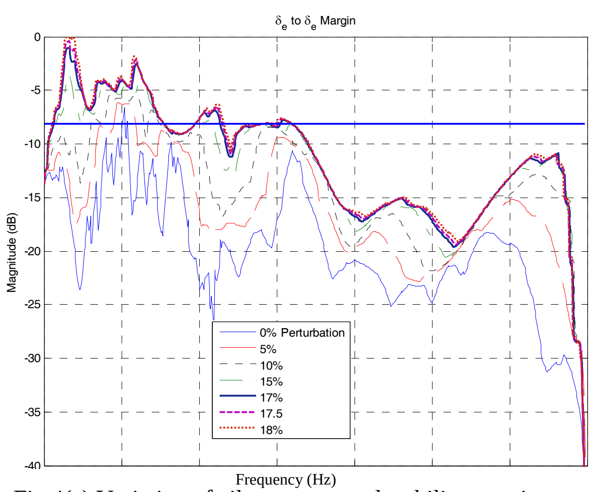

Fig.4(a) Variation of aileron structural stability margin with percentage frequency perturbation

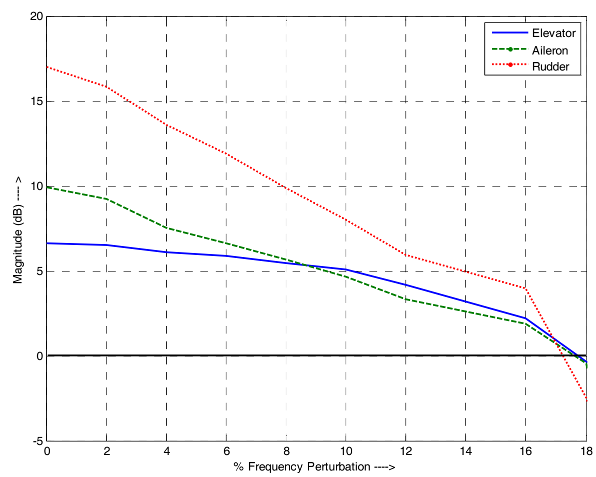

Fig.4(b) Variation of worst case margin with frequency perturbation

Table 1. Margin improvement with increasing actuator excitation amplitude

Configuration	Excitation Amplitude	Margin (dB)	
		Elevator	Aileron
Landing Mass	0.5%	16.07	24.00
	3.0%	18.56	27.67
Full Fuel	0.5%	16.53	18.25
	1.5%	18.72	24.53

Table 2. Computed and measured margins

Worst Case Margin (All Configurations)	Elevator Margin (dB)	Aileron Margin (dB)	Rudder Margin (dB)
Measured	10.4	18.8	21.8
Computed	10.1	18.57	21.0
Computed with ±5% Frequency Perturbation	9.93	18.57	19.72

5. CONCLUSION

This paper presents a revised clearance procedure based not only on values of the nominal structural stability margins, but also on the sensitivity of structural stability margins to the modal frequency perturbation for an experimental aircraft program during its developmental phase. This technique was successfully used for LCA to clear a unified set of notch filters for several prototypes (till now a total of seven aircraft have successfully flown with various combinations of stores). This has enabled the designers to accelerate the project schedule without taking major risks.

This paper brings out the fact that robustness in the design of structural filters could be obtained either by designing for higher structural stability margins or by providing more frequency perturbation for the worst case plant data. Future studies are aimed at finding out an optimal blend of these two alternatives which enable minimizing the phase lag introduced by structural filters at 1 Hz.

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