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FLIGHT CONTROL DESIGN TO IMPROVE AIRCRAFT PERFORMANCE BY REDUCING THE FLUTTER AND DYNAMIC LOADS MARGINS

Luca Benassi [1]

[1] Airbus Defence and Space GmbH
Rechliner Str., 85077 Manching, Germany
luca.benassi@airbus.com

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Abstract: In order to ensure the maximum possible aircraft performance, the flight control laws of a modern combat aircraft were designed by minimising the flutter and dynamic loads safety margins. Based on a recent development programme, this paper shows the design principles that led to such improved aircraft performance and it identifies the changes in the design process which are necessary to ensure safety of flight from a Structural Dynamics and Aeroelasticity point of view. Fitness for purpose was demonstrated by flight test and analysis, whose results validated the method, which is now considered for all new store integration programmes.
This work would not have been possible without the fundamental technical contributions of several colleagues at Airbus Defence and Space, Leonardo and BAE Systems.

1 INTRODUCTION

On a modern fighter aircraft, like the one shown in Figure 1, each store integration or aircraft modification is a new challenge in terms of the aircraft flight physics and Flight Control System (FCS). Some stores can even weigh ~20% of the aircraft clean configuration. Almost regardless of the configuration, the aircraft performance and handling qualities must be kept. For example, Figure 2 shows a typical pilot stick trace during a mission, demonstrating the aircraft care-free handling capabilities, which must be ensured for any of the possible store combinations in Figure 1.

Structural Coupling is the disturbance to the aircraft inertial sensors caused by the flexibility of the airframe. Within this frame, the interactions between the closed-loop FCS and the aircraft Structural Dynamics and Aerodynamics must be carefully designed to avoid potential instabilities. Although Structural Coupling exists in any flexible aircraft with a closed-loop FCS, the phenomenon becomes of critical importance for combat naturally-unstable aircraft. Even before instability, Structural Coupling can cause oscillations of the control surfaces (Figure 3) and this may lead to a degradation of the aircraft safety, fatigue life and flight mechanics performance. In order to avoid such effects, the closed-loop magnitude, frequency, phase response and their possible variations must be correctly predicted. To cater for these close-loop interactions, an analysis method, which combines both model and test data, was developed and validated. The method includes an uncertainty management in terms of "known unknowns" (f.i. build tolerances, sensor inaccuracies and failure cases) as well as "unknown unknowns" (f.i. aerodynamic alleviations). The method was validated with an extensive ground and flight test campaign and proven to be robust: no additional design margins are needed and therefore it can be used to trade such additional margins against aircraft performance. In other words, the tool implements a margin policy where within the FCS design, the notch filters and control law gains can be determined in order to reduce the additional margins, therefore allowing the best possible flight mechanics performance.

Figure 1: Modern fighter aircraft and possible store configurations

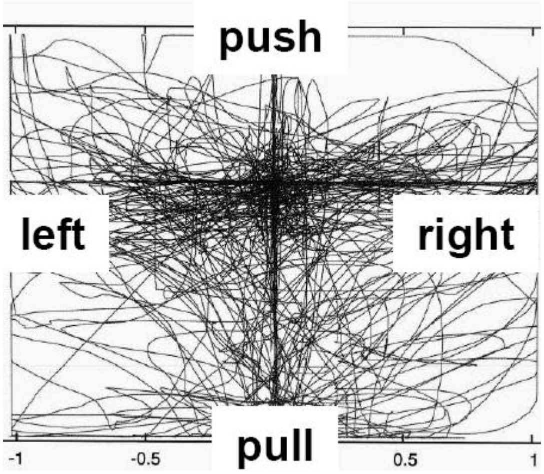

Figure 2: Example of fighter pilot stick trace

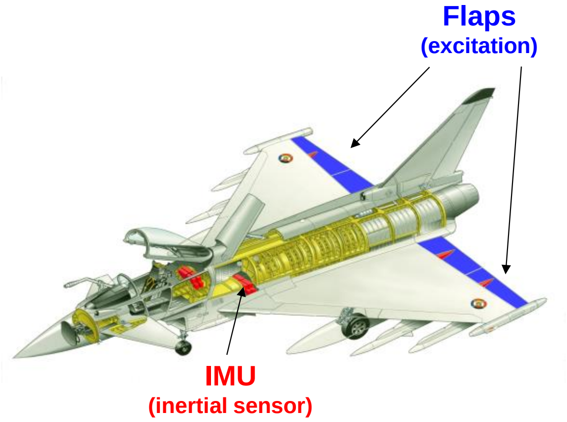

Figure 3: Inertial Measurement Unit sensor location and flap excitation on a modern fighter aircraft

Figure 4 shows an example of a Nichols plot. According to aircraft design standards, like MIL-F9490D, the aircraft response must lie outside the ‘diamonds’ shown in black [1]. The green line is the rigid body aircraft response, whilst the blue line is the flexible aircraft response. It can be seen that such response violates one or more diamonds. This indicates that the FCS must be augmented with notch filters which make the FCS insensitive to the aircraft flexibilities. However, such notch filters introduce delays in the FCS response and therefore their impact on the aircraft flight mechanics must be minimised. At the same time, the notch filter design must cover the envisaged aircraft configurations and flight envelope. Therefore, it is not uncommon to design the notch filters with additional safety margins in order to cater for uncertainties [2]. This leads to a conflict between the FCS requirements for high performance and the notch filter robustness requirement [3].

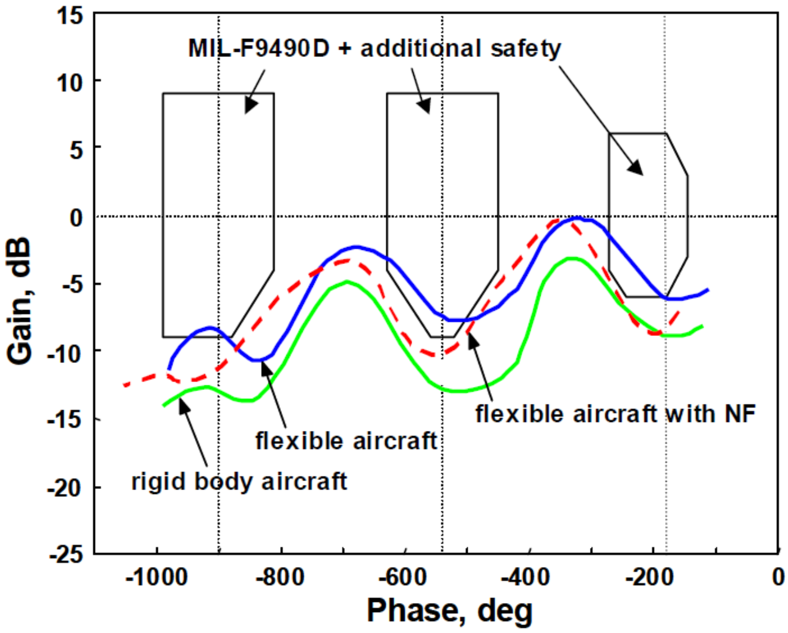

Figure 4: Structural Coupling Nichols plot

2 FLIGHT CONTROL SYSTEM DESIGN

The inputs to the analysis tool used at Airbus Defence and Space are generally model and test data. As explained above, the tool includes a robust uncertainty management where the known unknowns as well as the unknown unknowns are included. Once the analysis tool is validated and robust, we do not need additional safety margins and therefore it can be used to trade margins against performance. Therefore, once it is demonstrated that the analysis tool can safely be used to trade margins, the main idea presented in this paper is the creation of one or more FCS „electronic“ modes which couple with the structural modes of the aircraft. By doing so, the FCS gains can therefore be used to tune the closed-loop response ensuring that any extra margin is ‘donated’ towards improving the aircraft performance. In other words, the magnitude of the closed-loop response turns out to be greater than the open loop response in a known and controlled manner.

Figure 5 shows a Nichols plot with one of the diamonds in red and with the green line indicating the exclusion zone, which is the area where the system closed-loop response is higher than the open-loop response. By design, the aircraft response must lie outside the red area in order to comply with the MIL specifications and it should lie outside the exclusion zone to avoid that the closed-loop response is higher than the open-loop response. If the open loop modes, like the one depicted with blue circles in Figure 5, lie outside the exclusion zone, then the aircraft response is guaranteed to be no worse once the system is put in closed-loop. However, by doing so, the system may turn out to be unnecessarily robust and the safety margins are generally greater than the required minimum. By creating FCS electronic modes, the structural moved can be moved inside the exclusion zone (red circles in Figure 5) by a known and completely predictable amount. As a result, the closed-loop response can be tuned by design (Figure 6) and the safety margins can be reduced to the required minimum. It is important to notice that this approach is fail-safe. In the very unlikely event (given the high design assurance level of the FCS) that the FCS-induced electronic modes fail, the system would revert to a state where the structural modes are outside the exclusion zone and therefore the closed-loop response would be smaller than with the electronic modes. Another important consideration is that Figure 5 is applicable to SISO (Single Input Single Output) systems and it was presented to simplify the explanation. In reality, the vast majority of systems are MIMO (Multiple Input Multiple Output) and therefore the approach above must be extended. However, the basic principle described above remains valid. Finally, Figure 6 shows an enhancement in closed-loop of the main modes. However, the electronic modes can be selected to enhance only a subset of them.

Fortunately or unfortunately, an aircraft design is not just the summation of disciplines. Therefore the implication of the above strategy on other disciplines must be investigated and clearly understood. In other words, if we create electronic modes to enhance the closed-loop response of selected modes and we reduce the Structural Coupling safety margins, what does it mean to the flutter margins or the dynamic landing loads, buffet loads and gust loads criticalities? Moreover, what does it mean to the structural fatigue life? These aspects must be considered in order to provide a satisfactory safety of flight clearance.

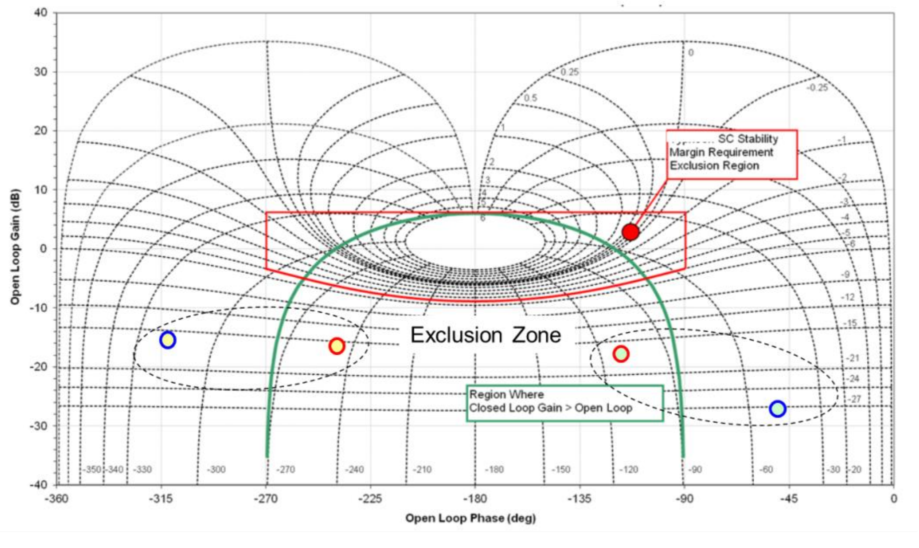

Figure 5: Nichols plot. Contours of constant gain and phase. Using the FCS, the “blue” modes are moved towards the “red” modes inside the green exclusion zone.

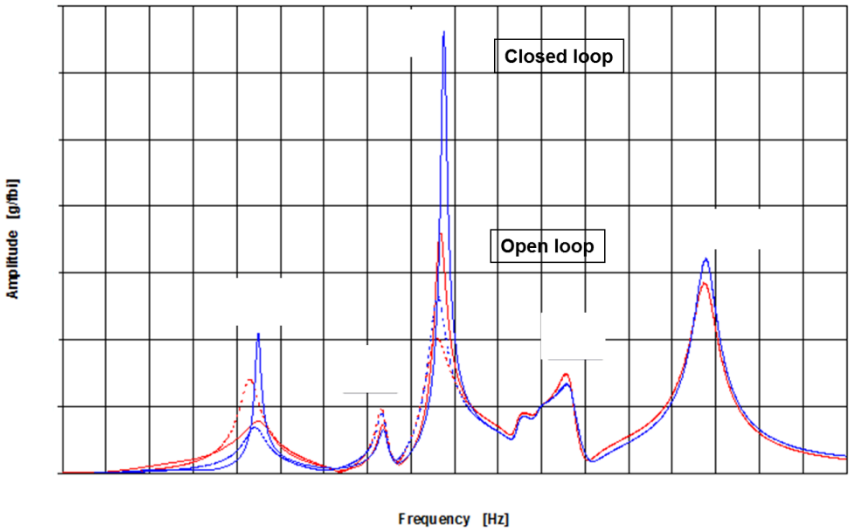

Figure 6: Structural Dynamic open- (red) and closed-loop (blue) response.

3 FLUTTER EFFECTS

According to MIL-A-8870, the Flutter design requirements are as follows:

“Airspeed margin: 15% equivalent airspeed margin on the applicable design limit speed envelope, both at constant altitude and constant Mach number;

Clean Aircraft Damping: Damping coefficient “g” for any critical flutter mode or significant dynamic response mode shall be at least 3% “g” for all altitudes at flight speed up to the design limit speed;

Aircraft with Stores Damping: Critical flutter modes whose zero airspeed damping is less than 3% “g”, the damping coefficient “g” need only be greater than the zero airspeed damping coefficient in that mode”.

With the introduction of coupling electronic modes, the Flutter behaviour must be analysed with the FCS in the aeroelastic loop, as shown in Figure 7. It is important to note that the process ensures compliance with the MIL-A-8870 requirements. However, any extra margin beyond such requirements may be used to improve the flight control laws performance. Figure 7 shows a comparison between open loop results and close loop results. Comparing the V-g plots, the coupling of the FCS electronic mode with the structural mode and the damping shift due to the FCS are clearly visible. In conclusion, the margin policy strategy introduced in this paper reduces the flutter margins as well. However, this is also considered as an advantage. In fact, since the modes can be electronically placed by design, the flutter margin can be reduced to the minimum required 15% (for example), therefore allowing the FCS gains to be higher than what they would be otherwise. In other words, if the margin policy is adopted across the FCS, Structural Coupling and Flutter disciplines and the FCS design is carried out in parallel and in synch with the other disciplines, the Structural Coupling and flutter margins can be reduced and such extra margins can be donated to improve the Flight Mechanics performance.

Table 1 shows that Flight test results match well with the numerical simulations. In particular, Table 1shows that the numerical model underestimates the measured damping and this ensures some level of, arguably not necessary, conservativism. A good matching with the flight test result is a fundamental prerequisite for the validation of the margin policy method described in this paper [4]. Without a validated analysis tool, this method would have never found its way to its implementation within the control laws of a fighter aircraft.

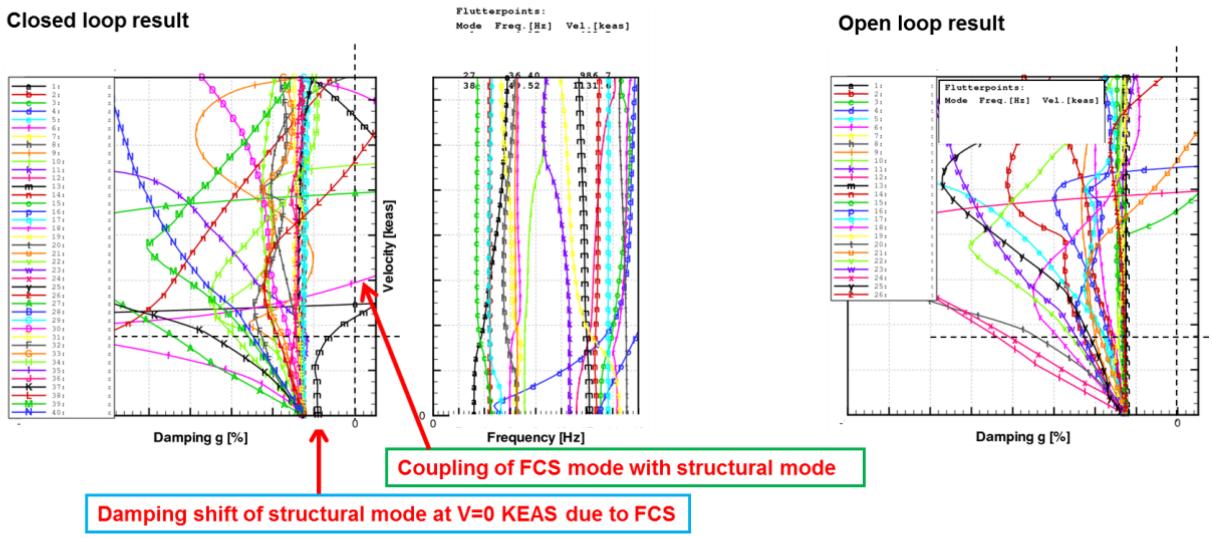

Figure 7: Flutter behaviour with (left) and without (right) Flight Control System.

				Critical Mode 1						Critical Mode 2					
Flight Test Number	Altitude [ft]	Mach	Airspeed [keas]	Flight Test Measurement			Numerical Model (deltas)			Flight Test Measurement			Numerical Model (deltas)		
				Frequency [Hz]	Amplitude [g/fbi]	Damping [g]	Frequency [Hz]	Amplitude [g/fbi]	Damping [g]	Frequency [Hz]	Amplitude [g/fbi]	Damping [g]	Frequency [Hz]	Amplitude [g/fbi]	Damping [g]
1	14800	0.60	300				-0.62%	11.96%	-13.29%				-3.23%	10.17%	-12.79%
2	25000	0.74	300				-0.62%	14.57%	-13.08%				-2.52%	27.50%	-31.37%
3	33500	0.90	300				0.15%	19.13%	-5.81%				-4.18%	39.57%	-14.85%
4	5000	0.58	350				0.78%	8.00%	-14.96%				-2.81%	10.00%	-23.14%
5	15000	0.70	350				1.56%	10.85%	-16.11%				-3.01%	8.52%	-22.42%
6	26500	0.90	350				-1.22%	9.03%	-1.37%				-3.50%	13.10%	-17.57%
7	5000	0.66	400				1.51%	12.97%	-18.46%				-3.78%	0.57%	-22.49%
8	15000	0.80	400				-1.22%	4.80%	-6.57%				-3.30%	-3.10%	-13.11%
9	5000	0.75	450				0.15%	6.47%	-1.54%				-2.87%	-5.98%	-22.48%
10	15000	0.90	450				0.92%	10.44%	-2.21%				-2.59%	2.30%	-25.87%
11	5000	0.83	500				1.90%	13.50%	-17.60%				-2.31%	-3.88%	-22.83%
12	4400	0.90	550				2.34%	16.79%	-3.44%				-0.59%	1.20%	-47.44%

Table 1: Model match with flight test results.

4 DYNAMIC LOADS EFFECTS

The effect of the margin policy method on dynamic loads criticalities can be determined in two ways. Following a pragmatic approach, in a SISO system or in a MIMO system where the paths can be approximated as a combination of SISO systems, Figure 5 reveals that below the -9dB open-loop stability margin line, where phase is not considered, a closed-loop gain increase up to 60% is allowed. Such maximum increase leads to a modal damping reduction in closed-loop of

$$g_{closed-loop} = \frac{g_{open-loop}}{\left(\frac{\Delta Q}{Q_{open-loop}} + 1\right)} \tag{1}$$

and, in turn, this leads to a criticality increase. For example, a 2% modal damping is reduced to 1.5%, leading to a criticality increase of +5%. If adding 5% to the open-loop dynamic loads leads to acceptable criticalities, then this pragmatic approach may be used to ensure that the margin policy method does not lead to unwanted loads criticalities. If, on the contrary, the resulting computed loads criticalities are not acceptable, then a more accurate analysis must be performed. However, in this case, the price to pay is that such loads analysis must be carried out with the FCS in the loop. This is arguably the biggest disadvantage of the method: if traditional dynamic loads calculations can be carried out neglecting the FCS effects, because of the response enhancements that the FCS introduces, this forces the dynamic loads calculations to be performed in closed-loop. In addition, they must consider the known unknown and the unknown unknowns described above.
As a partial mitigation, with reference to Figure 5, dynamic loads whose amplitudes are below -30dB can be considered as negligible regardless of their close-loop gain. This helps in reducing the number of cases to analyse. On the contrary, Figure 7 shows how small frequency variations (+0.2 Hz) and phase uncertainties (+30 deg for example) in a modal response can easily lead to a 60% gain increase.

Figure 8 shows an example of a dynamic landing loads allowable loads envelope where the criticalities increase by introducing the electronic FCS modes. Although it is reasonable to expect that the FCS does not play a significant role in the dynamic landing loads, Figure 8 demonstrates that even a small effect can cause the loads to exceed the limit load.

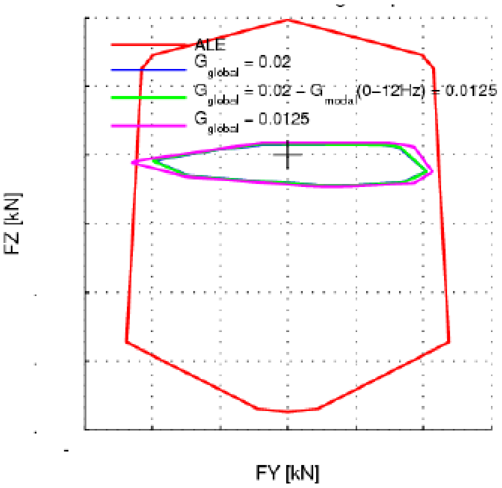

Figure 8: Example of dynamic landing loads allowable load envelope.

Similarly, Figure 9 shows an example of dynamic buffet loads with FCS in the loop. Interestingly, the response of some modes decreases in closed-loop and the response of other modes increases. This clearly demonstrated the added complexity of the analysis, compared to the traditional method where the FCS may be neglected from the analysis. Figure 9 shows that in open-loop the loads criticality is driven by a low frequency modal response, whilst in closed-loop the criticality is determined by a higher frequency mode. Finally, Figure 10 shows an example of the dynamic gust loads time response with and without FCS in the loop for a certain gust length. This example is particularly representative because it shows that the maximum positive force is greater in closed-loop than in open-loop, whilst there are instances where the maximum negative force is greater in open-loop than in closed-loop. Finally, the effect on fatigue loads must be assessed. Ideally, fatigue loads are only marginally influenced and therefore it turns out that the effect of the margin policy, compared to the open-loop case, is practically negligible. This result is of particular importance as it avoids an important design stakeholder (Fatigue) to having to assess new load cases.

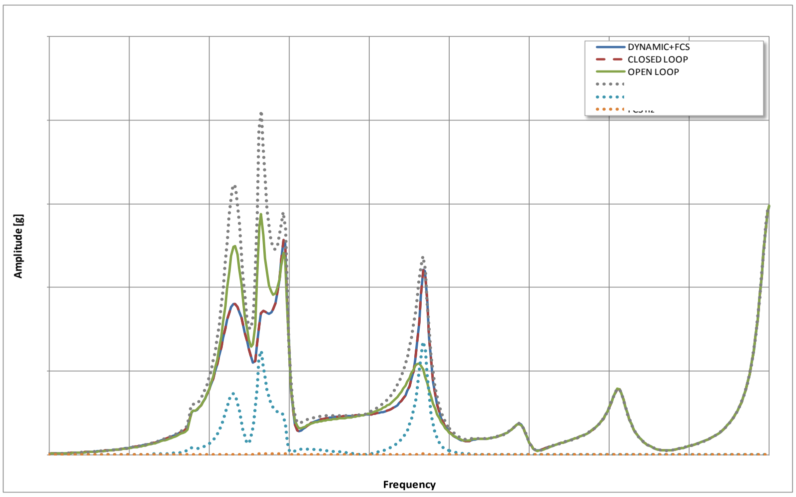

Figure 9: Example of buffet loads frequency response in open- and closed-loop.

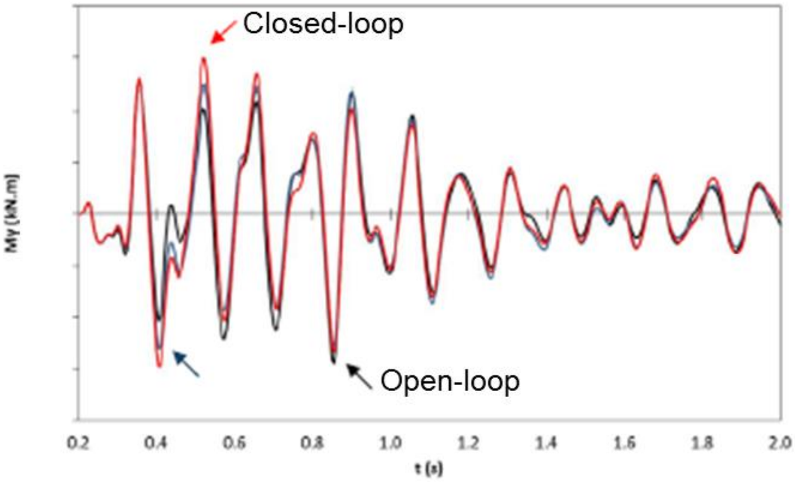

Figure 10: Example of gust loads time response in open- and closed-loop.

5 CONCLUSIONS

At Airbus Defence and Space, in the past, each discipline had its own required margins and it was often the case that additional margins were added. No margin policy was adopted and the analysis tools did not necessarily require the flight control system in the loop. The flight control laws were designed and their impact on Structural Coupling, flutter and dynamic loads was assessed subsequently. The result was an aircraft with an excellent performance for the given configurations and flight envelope. However, integrating new large stores would not have been possible as additional performance was required.

Following the AMK (Aerodynamic Mod Kit) design and extensive flight test campaign, Airbus Defence and Space demonstrated the fitness for purpose of the margin policy method. A second flight test campaign with a different store configuration confirmed the findings. Today, each discipline has its own required margins, as required by the Standards, and extra margins are reduced in exchange for aircraft performance. The analysis tools require the FCS in the loop and the flight control laws are designed together with structural coupling, flutter, dynamic and fatigue loads in a truly multidisciplinary effort. The result is a superior aircraft with the best possible performance.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Pratt, R. W. (2000). *Flight Control Systems – practical issues in design and implementation*. AIAA.

[2] Sura, N. K. *et al.* (2008). Structural stability margin criteria for accelerated clearance of developmental flights. INCAST 2008-117.

[3] Vaccaro, V., Caldwell, B. D. and Becker, J. (1999). Ground Structural Coupling Testing and model updating in the aeroservoelastic qualification of a combat aircraft. NATO RTO MP-36.

[4] Caldwell, B. D. and Felton, R. (1998). Validation of FCS Structural Coupling stability characteristics through in-flight excitation. NATO RTO MP-11.

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