DEMONSTRATION OF INNOVATIVE VIBRATION CONTROL ON A FALCON BUSINESS JET

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Abstract: In the objective of maximizing comfort in Falcon jets, Dassault Aviation is developing an innovative vibration control technology. Vibrations of the structure are measured at several locations and sent to a dedicated high performance vibration control computer. Control laws are implemented in this computer to analyze the vibrations in real time, and then elaborate orders sent to the existing control surfaces to counteract vibrations. After detailing the technology principles, this paper focuses on the vibration control ground demonstration and on the flight test preparation.
The ground demonstration was performed by Dassault Aviation in May 2015 on a Falcon 7X business jet. The goal of this test was to attenuate vibrations resulting from fixed forced excitation delivered by shakers. The ground test demonstrated the capability to implement an efficient closed-loop vibration control with a significant vibration level reduction and validated the vibration control law design methodology. This successful ground test was a prerequisite before the flight test demonstration planned in July 2017. The objective of the flight tests is the validation of the vibration level reduction thanks to the vibration control laws in real environment (natural aerodynamic excitation). This study has been partly supported by the JTI CleanSky and CleanSky 2.

1 INTRODUCTION

In the objective of maximizing comfort in Falcon jets, Dassault Aviation is developing an innovative vibration control technology based on control surfaces actuation.

The global strategy defined to corroborate the general control law design methodology and demonstrate the efficiency of the designed vibration control laws is first presented in this paper. The main challenges of this demonstration are to design vibration control laws based on numerical model simulations that are robust to aircraft mass variation (representing fuel consumption during flight). Moreover, the vibrations inside a wide frequency band have to be reduced while the vibration control laws should not have any impact on lower and higher frequencies.

In a second step, the vibration control law design method is detailed. The ground vibration control demonstration that was performed by Dassault Aviation in May 2015 on a Falcon 7X business jet is presented with the main results that assess the vibration control law design methodology.

Flight test demonstration of vibration control laws efficiency is planned in July, 2017. The design of vibration control laws and the implementation of this flight test are finally presented.

2 GENERAL VIBRATION CONTROL DEMONSTRATION STRATEGY

The vibration control presented in this paper aims at controlling aircraft response in the [5-15Hz] frequency band (comfort zone).

The objective of the vibration control ground demonstration that was performed by Dassault Aviation in May 2015 on a Falcon 7X business jet was to validate the capability to implement vibration control laws using the aircraft control surfaces. This first phase was necessary to validate the control law design methodology. In a second step, a flight test campaign is being prepared in order to demonstrate in flight the efficiency of vibration control. Figure 1 presents the flight control system and the vibration control loop.

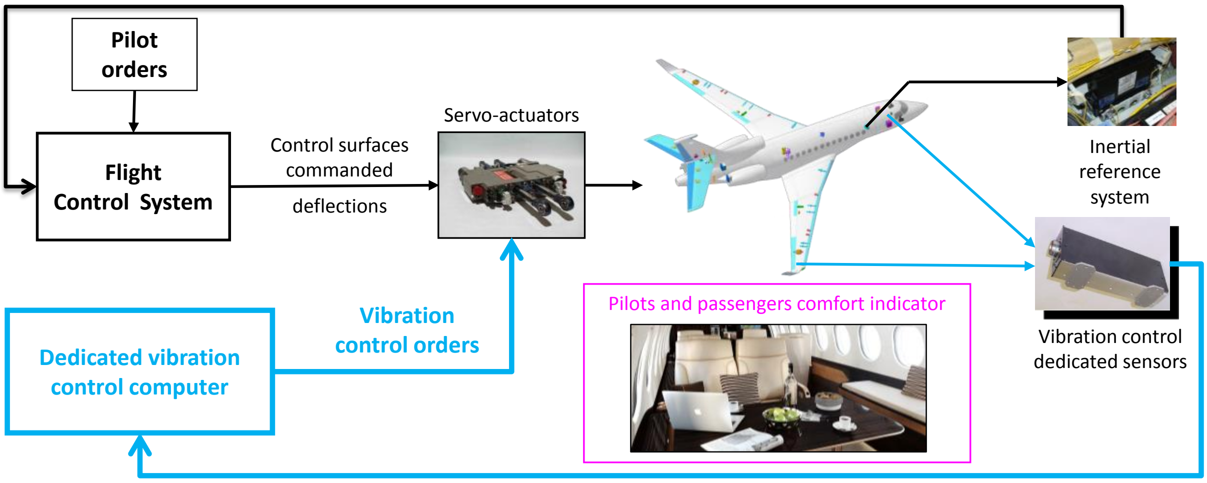

Figure 1: Flight control system and vibration control loop.

Theoretical studies have shown two major requirements for the design of an efficient vibration control system:

- Computer sampling rate should be higher than current flight control laws sampling rate.
- The analog to digital quantization of sensors should be higher than 12 bits.

In the vibration control demonstrator, these requirements are covered by:

- The use of dedicated computer.
- The use of dedicated analog sensors specifically chosen for their high sensibility, large bandwidth and low level of noise.

Figure 2 shows the vibration control demonstration of the study workflow.

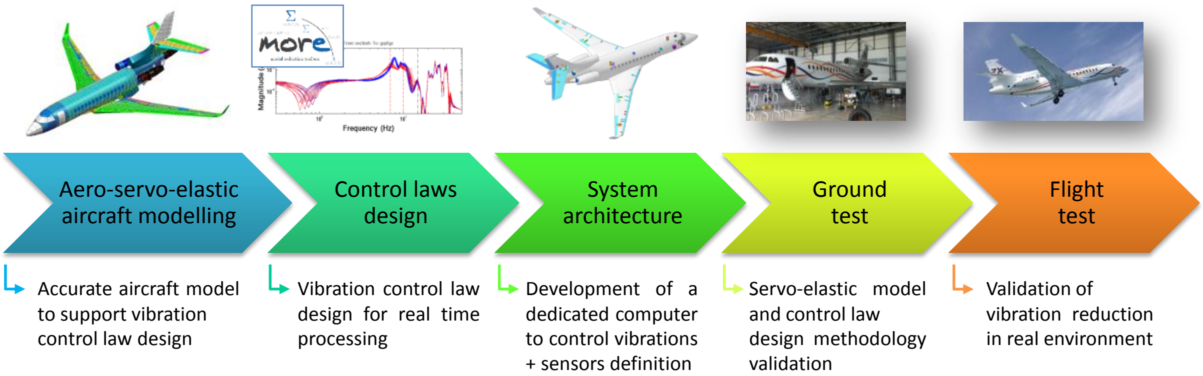

Figure 2 : Vibration control demonstration of the study workflow.

3 VIBRATION CONTROL LAW DESIGN METHODOLOGY

The vibration control law design methodology developed by ONERA and Dassault Aviation is based on the following three main steps:

- Development of accurate aero-servo-elastic state-space models of the aircraft (large-size state-space models).
- Reduction of these models in order to be compatible with control design methods.
- Design of vibration control laws.

The designed controllers are then analyzed on the large-scale models and the most performant ones are selected.

3.1 Business jet aero-servo-elastic modelling

The vibration control laws design methodology presented in this paper is based on an accurate aero-servo-elastic model. This model is used at several steps during the study workflow presented on Figure 2:

- Control laws design: laws design and selection.
- System architecture: vibration control sensors technology definition.
- Ground test analysis and comprehension.

The aero-servo-elastic model used is composed of:

- The general Falcon 7X finite element model (Figure 3), adapted to this specific vibration control demonstration (mass and fuel distribution, vibration control laws sensors location, control surfaces deflection, shakers excitation, landing gears extended).
- A rationalized aerodynamic model. Thanks to the enhanced aerodynamic rationalization algorithm developed at Dassault Aviation, models used for frequency-domain simulations and models used for time-domain simulations give very similar results.
- A servo-actuator non-linear model specifically adapted for low amplitude deflections.
- A flight control system.

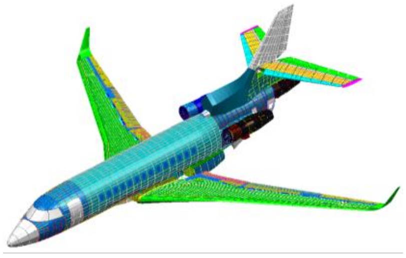

Figure 3: General Falcon 7X finite element model

Several models are built for various flight points and mass cases. State-space model assembly is then performed and leads to models of large size (570 states including aerodynamics in flight, or 250 states on ground). Vibration control study is based on these models. The general linear state-space model equation (taking into account a linearized servo-actuator model) is given below:

$$H:\begin{cases}\dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t)\end{cases} \tag{1}$$

where $x(t); u(t); y(t)$ are the state, input and output vectors of dimension $n; n_u; n_y$, respectively (matrices are real and of suitable dimension).

Models accuracy is validated by comparing modes and frequency response functions to ground vibration and flight tests performed on Dassault Falcon 7X aircraft.

3.2 Model reduction

The aero-servo-elastic models considered for vibration control laws design usually result to be of large dimension. In practice, such complex models render the simulation, analysis and optimization tasks very complex or even impossible. Indeed, for the control design step, such a large-scale model set is clearly inappropriate for any numerically-based optimization strategy (or leads to a prohibitive computation time). An approach to bypass this limitation is to perform a model reduction step. The main objective of the dynamical model approximation is to replace the original model, equipped with a large number of internal variables, by another one, with the same number of inputs and outputs but with a drastically lower number of variables. Obviously, a “good” low order model should “well” reproduce the original input-output behavior. Mathematically, and in the linear framework, given general state-space model equation defined in §3.1, the objective of the model approximation is to find:

$$\widehat{H}:\begin{cases}\dot{\hat{x}}(t) = \hat{A}\hat{x}(t) + \hat{B}u(t) \\ \hat{y}(t) = \hat{C}\hat{x}(t)\end{cases} \tag{2}$$

where $\hat{x}(t)$ is the reduced state vector of dimension $r \ll n$ and $\hat{y}(t)$ denotes the approximated output vector (still of same dimension as $y(t)$, i.e. n_y). The following optimization problem is traditionally considered:

$$\widehat{H} = arg\ min_G \|H - G\|_{H_2} \tag{3}$$

where G belongs to the rational and strictly proper complex valued functions set of order r, with n_u inputs and n_y outputs. In this case, the term $\|H - G\|_{H_2}$ can be viewed as a mismatch mean error over the entire frequency support, which is evaluated through the inner product, called the H_2-norm. In practice, this problem is non convex, non-linear and its resolution, especially in a large-scale context, is very complex. However, recent major results in the field of linear algebra and dynamical model approximation theory led to interpolatory conditions which can be satisfied at a very modest computational cost [1] [2]. In addition, since in practice the frequency support of interest for the control design purpose is often limited and bounded, the above presented optimization problem can be reformulated as the following frequency-limited H_2-norm approximation problem:

$$\hat{H} = arg\ min_G \|H - G\|_{H_{2,\Omega}} \tag{4}$$

where Ω is the frequency support of interest. To solve this problem, similar interpolatory results and algorithms have been developed [4] and implemented in the MORE toolbox, developed at ONERA [3].

In this way, the large dimension of numerical models (570 states including aerodynamics in flight, or 250 states on ground) can be reduced to less than 40 states. Based on the obtained models, the advanced control synthesis methodology can be applied using enhanced optimization procedures.

3.3 Vibration control law design

As previously mentioned, the main purpose of the vibration controller is (i) to minimize the vibrations inside the aircraft between 5 and 15 Hz (performance objective), while (ii) keeping low frequencies responses unchanged and having no effect on high frequencies responses (constraint).

3.3.1 Forewords and general approach overview

As rooted on the above presented ground-oriented reduced order models, taking into account varying configurations (such as the aircraft mass), the methodology to design a dedicated robust vibration controller is detailed. More specifically, a more generic framework providing high level tuning parameters to design the vibration control laws is described. This is done by formulating the vibration problem (performance objective and constraints) into an H-infinity-optimization one, and, based on the recently developed dedicated numerical tools, this problem can be efficiently solved, allowing synthesizing the controller in a numerically tractable manner [5]. The key point of the proposed solution is the so-called generalized scheme, illustrated on Figure 4. Secondly, the structured H-infinity controller design optimization approach is reminded and some controllers are provided to illustrate the proposed approach effectiveness on the considered models (real validation being presented in the vibration control ground demonstration section).

3.3.2 Generalized plant (starting point of the controller synthesis)

Within the many control design methods (such as H-infinity or H_2-norm, etc.), the first step consists in writing the so-called generalized control scheme P, which describes the interconnection of the considered system (here the ground dynamical model, purple block on Figure 4) and the performance objectives characterized by the weighting functions (green blocks of Figure 4). This first phase shapes the exogenous input w to output z performance signals, as illustrated on the following Figure 4.

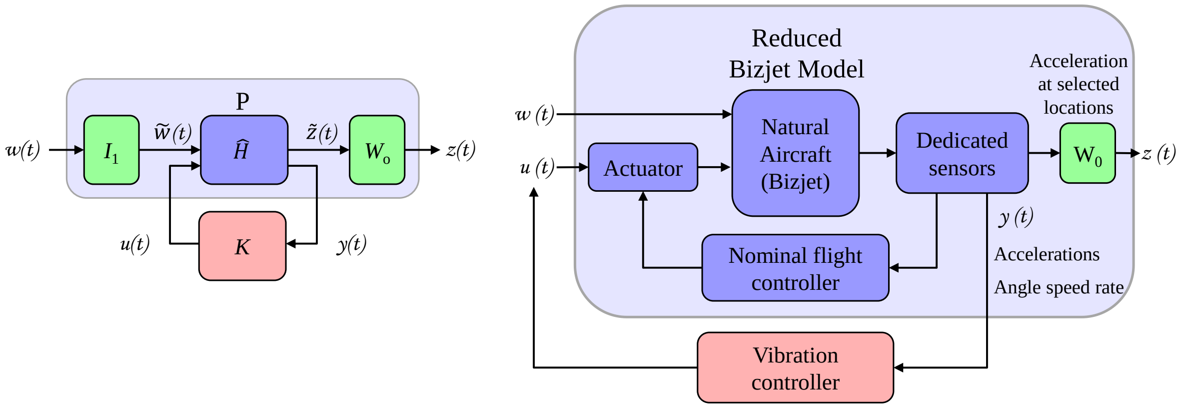

Figure 4: Generalized scheme - classically used in linear control (left)
and applied to business jet vibration control (right).

Without loss of generality, standard approaches exist to design the performance filters (green blocks). A choice of these filters can be found in [6]. In the closed-loop H-infinity norm minimization, these weighting functions determine the bandwidth over which the minimization of the closed-loop H-infinity norm will be applied.

3.3.3 Structured H-infinity controller synthesis

Once a generalized plant is available, the following problem is solved to design the vibration control laws:

$$K_{opt} = arg\ min_K \|F_l(P,K)\|_\infty \quad (5)$$

where F_l is the lower fractional operator. To achieve the above objectives, a structured H-infinity norm-oriented minimization criterion is selected. The main advantage to the structured multi-model approach is that the frequency response peaks level can be attenuated for all mass configurations, so that the control laws are robust to aircraft mass. This approach also imposes the controller mathematical complexity (e.g. its order and frequency shape), which is of great importance when the control law has to be implemented.

Based on a limited number of sensors, a set of vibrations control laws has been designed and selected. The structured H-infinity synthesis allowed to shape the vibration control laws in such a way that they behave like a band-pass filter with gain adaptation in the vibrations frequency range.

A vibration control laws analysis is performed on the full size bizjet models to check the vibration reduction level. On the left part of Figure 8, one can appreciate the reduction level of a selected control law. A compromise has to also be found between the slight increase of level around 6.5 Hz and the vibration reduction between 7 and 10 Hz.

A typical vibration control law controller frequency response is shown on Figure 5 (with order 10) with inputs measured by dedicated accelerometers and the output being the commanded elevator deflection.

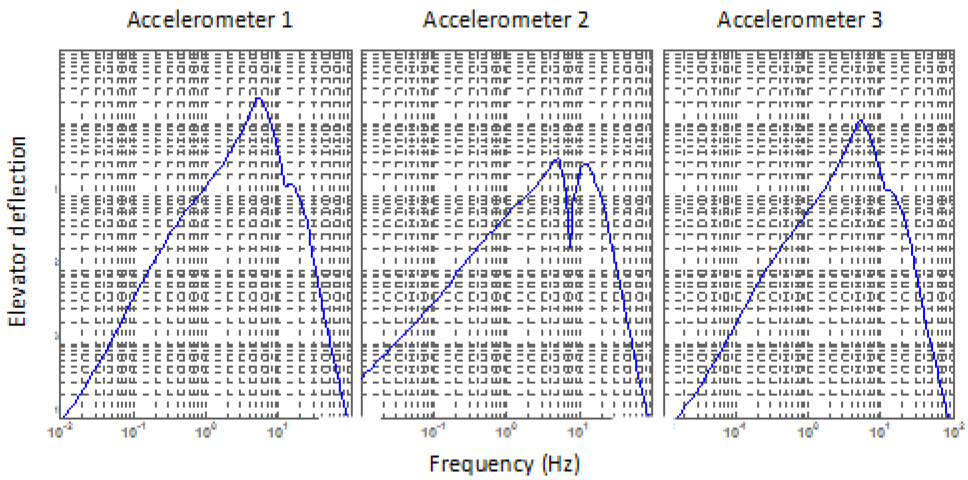

Figure 5: Optimal H-infinity controller frequency response

4 VIBRATION CONTROL GROUND DEMONSTRATION

4.1 Objectives of the ground vibration control test

Once an optimal controller is designed, synthesized and validated on the numerical model, the next step is to perform a validation on Dassault Falcon 7X business jet.

The objectives of the vibration control ground test are:

- The assessment of the overall vibration control law design methodology only based on numerical models.
- The validation of the servo-elastic model accuracy with and without control law.

These objectives are achieved by being able to understand and model the ground test results.

4.2 Ground test installation

The test was performed on the Falcon 7X S/N 1, property of Dassault Aviation, and based in Istres, France. Prior to the test, the aircraft was equipped with a dedicated vibration control computer and with specific vibration control sensors (4 accelerometers and 1 gyrometer). About 100 external accelerometers were also positioned all over the aircraft for test monitoring and analysis.

Figure 6 shows a picture of the Falcon 7X during the vibration control demonstration.

A test supervision station was installed close to the aircraft, providing shaker excitation, control surfaces excitation and vibration control selection.

Real time measured data was recorded and sent to a test monitoring and analysis station.

Figure 6 : Falcon 7X during vibration control demonstration

4.3 Ground test sequence description

The test sequence is described in Figure 7 and detailed hereafter:

- Control surfaces excitation without control (open-loop test). In order to estimate the stability and efficiency of the designed control laws, the vibration control computer computes the signals that would be sent to the control surfaces in closed-loop. These signals are analyzed in order to select the most performant laws.
- Shakers excitation without control (open-loop test). The shakers provide a fixed force excitation that provides “artificial” vibration in the cockpit and in the passenger cabin. This test brings out a reference aircraft vibration level due to a given force.

Both of those open-loop tests are also used for model calibration and analyses.

- Shakers excitation with active control (closed-loop test). Several control laws are tested with the aircraft excited by the shakers.

In order to correlate pilots and passengers comfort feelings with sensors measurement, some tests were performed with pilots in the cockpit and cabin. Pilots’ point of view on comfort while being seated in the aircraft has been recorded for various control laws.

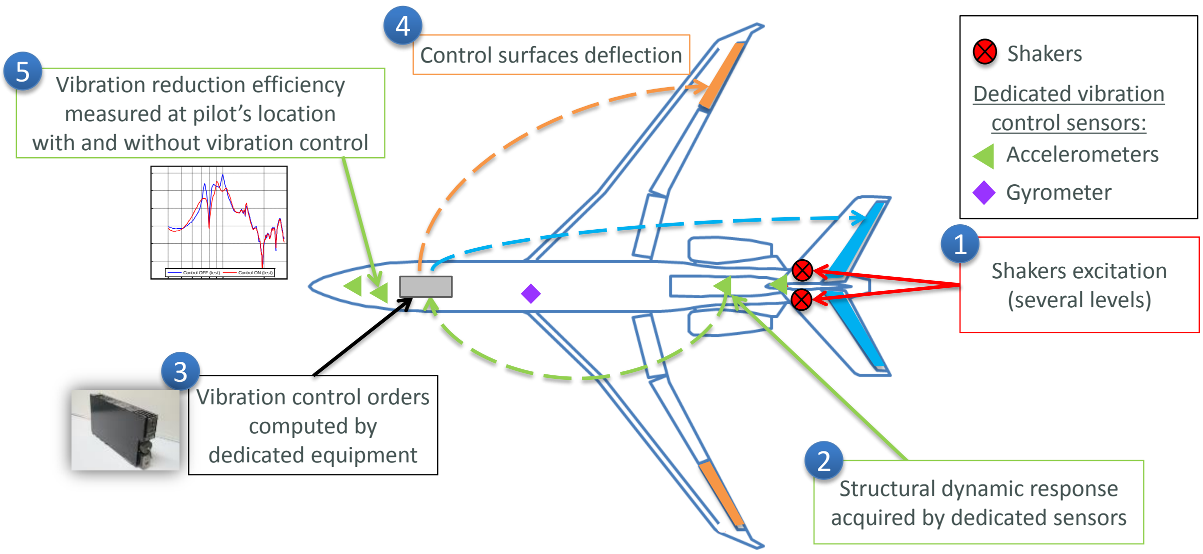

Figure 7 : Ground vibration test sequence

To validate the robustness of the control laws to the nature of the excitation, various excitation levels and signals were performed and two shakers locations were tested.
The robustness of the control laws to aircraft mass configuration was tested through three different aircraft fuel tanks filling.

4.4 Vibration control laws experimental results

During the ground vibration control test, the aircraft was first identified in open-loop in order to measure reference transfer functions and validate the numerical servo-elastic model. Then, the selected control laws were activated one by one, and the effect on the aircraft vibrations measured by comparing open-loop with closed-loop transfer functions. These results were finally compared with the numerical model simulations. A typical comparison is presented Figure 8; the simulated transfer functions (open and closed-loop) are compared with the ones measured during the ground test.

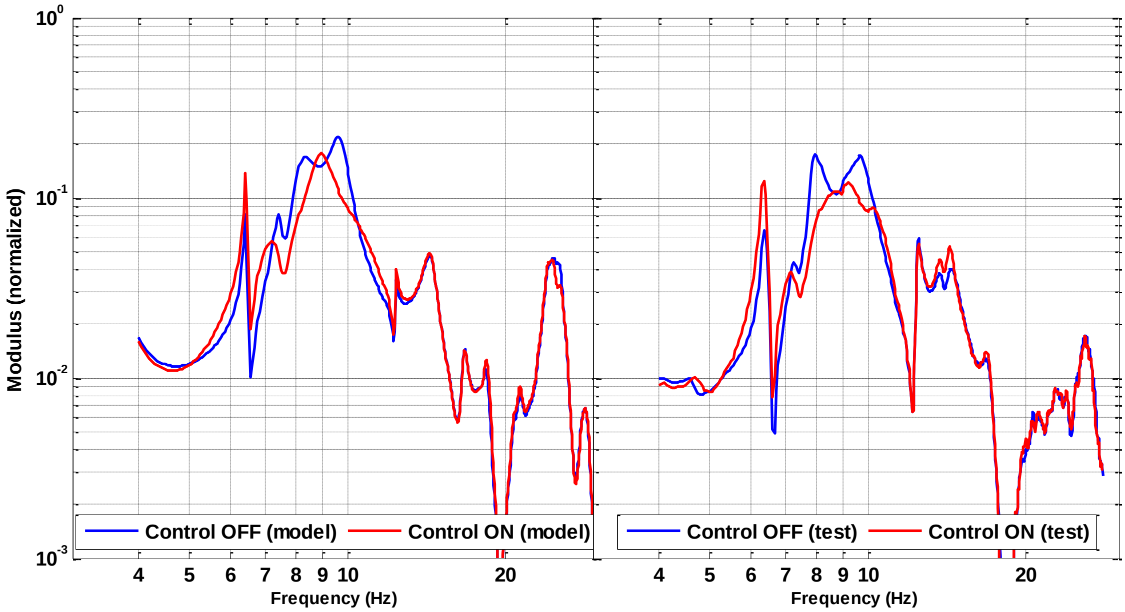

Figure 8: Measured transfer functions of a sensor in the cockpit (shaker excitation), open-loop (blue) and closed-loop (red). Numerical model prediction (left) and test measurements (right)

This figure shows that the vibration control law globally reduces the level of vibration between 5 Hz and 15 Hz. Moreover, the model prediction is quite accurate for both open and closed-loop transfer functions, and the level of attenuation is consistent between the test and the simulation.

Figure 9 compares the transfer functions of the system in open-loop and closed-loop for several laws which reduce some or all of the peaks level during the tests. Several pilots have been seated in the cabin and cockpit so that they could comment on the vibration control laws efficiency compared to their physical experience. The pilots were asked to share their opinion and feelings regarding each law in comparison with the open-loop test reference.

The pilots' assessment is that vibration control laws clearly reduce the perceived vibration level.

The pilots' specific comments on each vibration control law confirm the analysis based on the transfer function of pilot sensor with regards to shaker excitation (Figure 9):

- Law #1 is better than open-loop test
- Laws #2 and #3 are both better than law #1

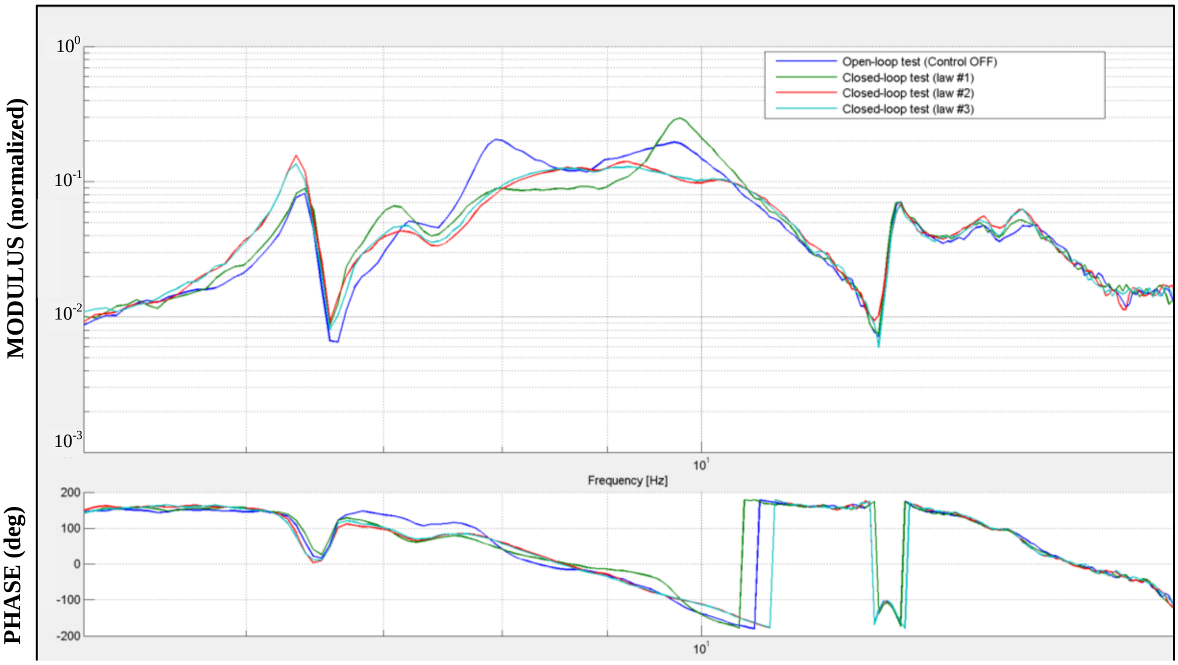

Figure 9: Open-loop and closed loop transfer functions on pilot's seat (3 different laws are presented)

This ground vibration demonstration test performed on Dassault Aviation Falcon 7X business jet was successful. Three different aircraft mass configurations were tested, and several control laws applied. The results analysis shows that the numerical model is accurate and delivers transfer functions very similar to experimental ones, in both open and closed-loop.

As expected in the simulation step, a substantial level of attenuation is observed when the vibration control is active.

Finally, several laws robust to the aircraft mass were successfully tested.

5 VIBRATION CONTROL FLIGHT DEMONSTRATION

Flight test demonstration of the vibration control laws is planned in July, 2017 on Dassault Falcon 7X business jet.

5.1 Objectives of the vibration control flight test demonstration

The objectives of the vibration control flight test are:

- The validation of the vibration reduction function in real environment with natural aerodynamic excitation.
- The evaluation of vibration control laws robustness to aircraft mass and flight point: vibration control laws must remain efficient when Mach and altitude vary.

These objectives are achieved by demonstrating an increase of comfort based on aircraft vibration measurement and on pilots and passengers feeling.

5.2 Design of vibration control laws for flight tests

A total of 19 vibration control laws are designed for flight tests according to the methodology detailed in §3. All vibration control laws are designed to be robust to aircraft mass, from take-off weight to landing weight (~65,000 lb to ~40,000 lb). Some of them are also robust to the flight point (from Mach 0.85 to Mach 0.88 and altitudes from 30,000 ft to 40,000 ft). Each vibration control law use between 2 and 4 vibration control sensors (among the 5 sensors available).

Based on numerical simulations, the vibration level reduction thanks to the vibration control laws is expected from 30% to 50% RMS between 5 Hz and 15 Hz (comfort frequency band). An example of computed open-loop and closed loop transfer functions is presented on Figure 10. The level of vibration is globally lower in the comfort frequency band [5-15Hz] when the vibration control law is active (red curve).

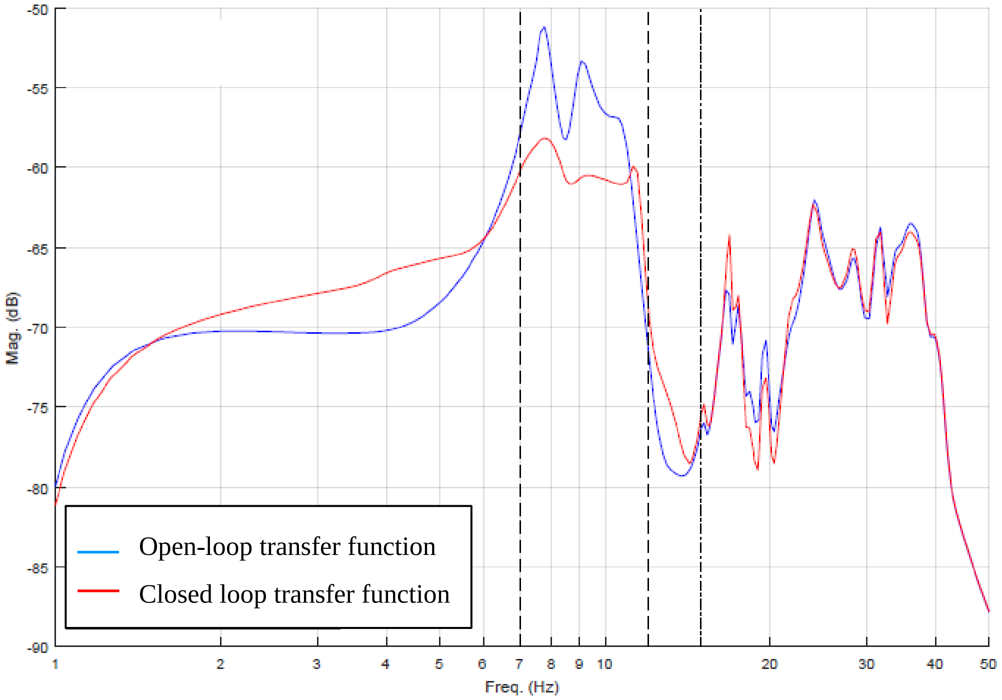

Figure 10: Open-loop and closed loop transfer functions on pilot's seat in flight (computation)

5.3 Flight tests implementation

Flight tests will be performed on Dassault Falcon 7X S/N 1 in Istres, France. The aircraft is equipped with:

- 5 specific vibration control sensors located in the fuselage (4 accelerometers and 1 gyrometer), used as inputs for the vibration control laws.
- Flight test instrumentation composed of ~30 accelerometers to analyse the dynamic response of the structure in open-loop and closed-loop.

For this specific flight test demonstration, the external shape of the Falcon 7X S/N 1 aircraft will be slightly modified in order to induce flow separation at the rear of the aircraft and thus amplify vibrations in the cabin and cockpit.
Measured data will be transmitted in real time to the ground via telemetry for test monitoring and analysis.

The test sequence is planned as follows:

- Open-loop tests with control surface excitation: stability and efficiency of all designed vibration control laws are simulated by the dedicated computer. The most performant laws are selected. Several flight points and aircraft mass are tested.
- Open-loop tests with natural aerodynamic excitation: the level of vibration without control is measured to provide a reference at various flight points and for different aircraft mass.
- Closed-loop tests with natural aerodynamic excitation: the performance of each selected vibration control law is evaluated in comparison to open-loop reference measurements. Robustness to flight point and aircraft mass is evaluated.

The correlation between measurements and pilots comfort feeling will be performed for all tested vibration control laws.

6 CONCLUSION

Dassault Aviation is developing an innovative vibration control technology in order to minimize the vibrations in the fuselage and thus increase pilots and passengers comfort in business jets.

The vibration control law design methodology is based on accurate aero-servo-elastic models which are used at several steps: for control laws design, for system architecture and for ground test analysis and comprehension. A preliminary size reduction of the models, without significant loss of accuracy, is performed thanks to the MORE toolbox developed at ONERA. The vibration control law design is based on the structured H-infinity approach. This method was selected as it attenuates the frequency response peaks in a restricted frequency range for several mass configurations at a time and because it offers the capability to constrain the controller mathematical complexity.

In order to demonstrate the efficiency of this innovative methodology for vibration control design, a ground test was performed in May 2015 on Dassault Aviation Falcon 7X business jet. In a first phase, the vibration control devices and the test instrumentation were installed on Dassault Aviation Falcon 7X S/N 1. Then the vibration control tests were performed. The effect of various vibration control laws have been measured for two shaker locations and three aircraft mass cases. Tests analyses and assessment with the numerical model predictions validates the vibrations control law methodology.

In order to validate the vibration reduction function in real environment, flight tests will be performed in July 2017 on Dassault Aviation Falcon 7X S/N 1. The level of vibration in open and closed-loop will be compared to measure the efficiency of each vibration control law with natural aerodynamic excitation. The robustness of the laws to flight point and aircraft mass will be performed by flying from Mach 0.85 to Mach 0.88 and 30,000 ft to 40,000 ft and from take-off to landing weight.

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