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INVESTIGATION ON THE EFFECTS OF CONTROL SURFACE FREEPLAY ON THE AEROELASTIC CHARACTERISTICS OF A TRAINER AIRCRAFT AND EXTENSION OF LIMITS IN SUPPORT OF MAINTENANCE TASKS

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Abstract: This paper describes activities carried out by Leonardo Aircraft Division (LAD), focused on the extension of control surfaces freeplay requirements for the M346 Aircraft. An engineering campaign was conducted, having the purpose of assessing the aeroelastic effects of backlash greater than the prescribed requirements, derived for MIL-A-8870. There were two main reasons for this choice. The first was the difficulty the actuator supplier had to provide spherical bearings respecting the current tolerance without incurring in production cost issues. On the other hand, backlash tests performed on in-service aircraft often failed thereby triggering expensive and time-consuming maintenance activity. Considering the complexity of the phenomenon, intrinsically nonlinear, this task was mainly based on a flight test campaign, preceded by analysis and two risk mitigation activities, meant to provide a preliminary insight on the expected outcome of the test, consisting in dedicated tests performed on the Iron Bird Test Rig and Resonance tests, conducted on the A/C with a simplified setup, to evaluate the effects of freeplay on modal frequencies and estimate the magnitude of nonlinear effects. Both these activities were focused on Horizontal Tail (all-movable) given the complexity of its kinematic layout with respect to aileron and rudder. The campaign was successfully concluded, demonstrating the possibility to extend backlash without occurrence of aeroelastic instabilities and Limit Cycle Oscillation (LCO) phenomenon.

1 INTRODUCTION

Freeplay is an intrinsic problem of mechanical systems, due to the presence of construction tolerances, that may lead to different kind of issues, such as wearing and fatigue.

In the case of control surfaces, freeplay may lead to aeroelastic issues: while its effect can be generally negligible for flutter phenomena, it is quite commonly a cause for Limit Cycle Oscillations (LCOs) that, while not immediately disruptive, produce nonetheless discomfort and wearing/fatigue issues. In fact, when the control surface is unloaded, the effect of freeplay is to produce a zero stiffness condition and a free floating condition: for an unbalanced surface, this may lead to an instability that, instead of diverging like in a classical flutter, ends up in a persistent oscillation, with amplitude generally of the same order as freeplay.

To prevent this kind of problem, MIL specifications [1] define requirements for the maximum acceptable freeplay: these limits, defined with the aid of wind tunnel and flight tests, are quite strict but limit the qualification process to traditional approach only (i.e. flutter), without the need for any nonlinear analysis dedicated to LCO.

The application of these limits to the M346 Aircraft Horizontal Tail (HT) has proven to be a challenge. This surface, in fact, is an All-Movable surface, for which a very strict requirement is prescribed and, in addition, presents a complex kinematic link that includes many components, each contributing with its tolerances to the overall freeplay of the surface. This has led to an extensive inspection and maintenance activity, with frequent occurrences of out of tolerance values.

To contain the effort on maintenance activity, without intervening on the mechanical design, which would have led to further complications in terms of production and assembly, an analytical and an experimental campaign were started to extend the prescribed requirements, evaluating the effects on aeroelastic stability and related phenomena.

The backlash extension activity for M346 was carried out in 2017, covering simulations by a non-linear model and experimental verification and validation by on ground (Iron Bird Test Rig and Ground Vibration Tests) and in-flight tests. The campaign was successfully closed demonstrating the possibility to extend initial backlash limits without incurring in aeroelastic instabilities and LCO phenomena.

2 APPLICATION TO M346 AIRCRAFT

M346 is an advanced trainer aircraft (see Figure 1) with a fly-by-wire management of irreversible control surfaces by a Flight Control System (FCS).

Figure 1: M346 Trainer.

It is worth to note that backlash values relaxation beyond the limits set in MIL-A-8870 [1], was already suggested by more recent specfications (such as JSSG-2006, [2]) and considered/adopted on other aircraft **Errore. L'origine riferimento non è stata trovata.**, since relaxing the backlash requirement beyond MIL-A-8870 values does not involve any risk of Flutter, LCOs being rather the more likely drawback to be considered (wearing of control line links, airframe fatigue and operational aspects). At this regard, the condition required for LCO's presence is that the surface is statically or cyclically unloaded at frequency low enough to allow for LCO development. This condition, not frequent on maneuvering aircraft, is unlike to happen unnoticed since it triggers vibrations propagating along the airframe up to the pilot seat. Moreover M346 operations demonstrated that no LCO problems were ever reported even if the HT rotational backlash was found on several A/C well beyond the required limit.

The concept developed and applied to the M346 was that of manufacturing calibrated elements of the command lines of the HT, aileron and rudder in order to increase in a controlled way the backlash within certain limits, preliminary determined by simulation. The effect of the increased backlash was first verified on ground, by measuring the impact on the frequency of most significant modes involved in flutter instabilities, through dedicated resonance tests. Then, the final verification was carried out in flight, performing flutter trials with the modified controls. Specific tests were also planned and carried out to demonstrate the aircraft was free from LCO phenomena.

As already mentioned, the focus of this task was on the HT, the most critical item for the complexity of its control line and because it shows the flutter instability with least margins. Figure 2 shows a typical example of results of a backlash measurement on the HT line.

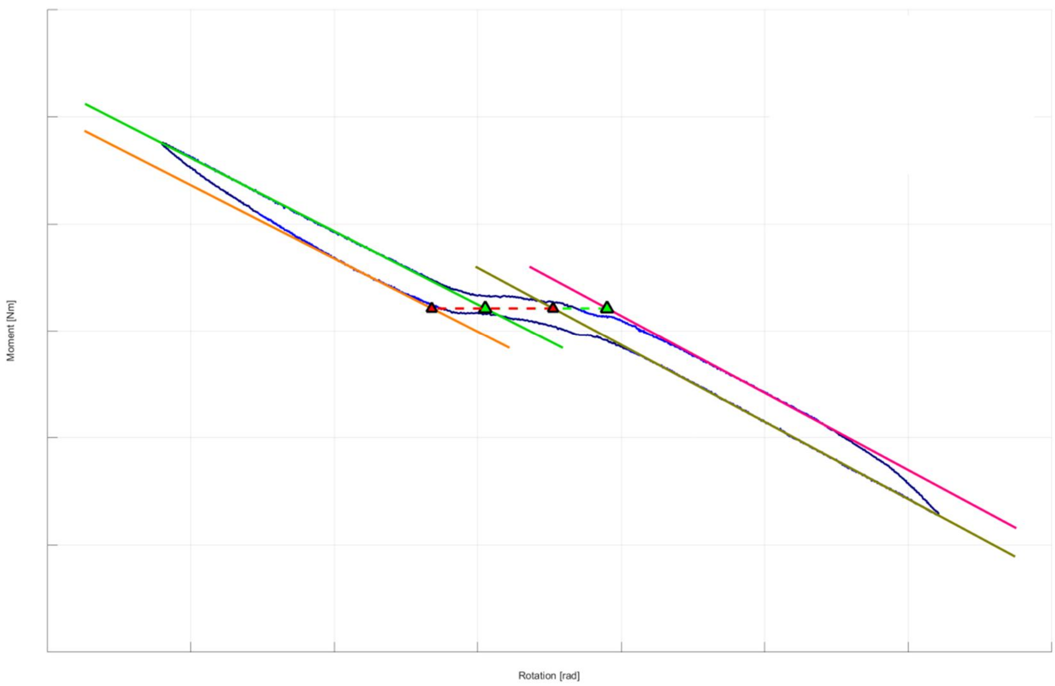

Figure 2: Typical Horizontal Tail backlash test results.

2.1 Non-Linear Model Development

Backlash (or freeplay, without considering the hysteresis effects) is a non-linear phenomenon where stiffness presents a dead zone, i.e. a band of displacement or deflection where the stiffness is null. In other words, if the structure (or, in this case, the control surface) is unloaded, the system is not constrained: in case of an alternating load, when applied force changes sign, the displacement presents a discontinuity.

Including this kind of nonlinearity in an aeroelastic analysis is not an easy task, since the basic tools for flutter analysis follow a linear approach, typically based on normal modes and frequency analysis.

The first level of approximation that can be used to treat freeplay is to consider that the dead zone acts as a reduction of stiffness: given a certain level of force, the resultant displacement is the sum of the freeplay plus an elastic displacement. With force and total displacement available, an equivalent stiffness may be computed. This stiffness is dependent on applied force and always lower than the nominal one, although they tend to be equal for infinite applied force.

A reduced stiffness leads to reduced modal frequencies. This behavior can be easily verified during experimental tests for structures with significant freeplay and can be reproduced easily even with very simple models.

Although useful to understand the phenomenon, this approach presents some issues:

- Since the equivalent stiffness is dependent on the amplitude of the applied force, it is difficult to find a value for stability analysis, since it is not easy to define the entity of the external loading (aerodynamic is a part of the system, rather than an applied load).
- The real structure will never experience the equivalent stiffness: depending on the displacement, real stiffness has either a null value or the nominal one.
- Transforming a nonlinear problem in a linear one means that some behaviors typical of nonlinear systems (like Limit Cycle Oscillation, bifurcations, etc.) cannot be identified since the model is not able to represent them.

On the other hand, developing a nonlinear model is a complex task and requires an extensive validation by experimental measures. Furthermore, a nonlinear model is intrinsically more erratic than a linear one and even small details not modeled can lead to large errors or entirely different behaviors (chaotic behavior).

These considerations led to the approach followed throughout this campaign that can be summarized as following:

- A purely analytical approach is unpractical
- The definitive evidence of the absence of aeroelastic instabilities is provided by flight test
- Flight test has to be conducted in a way that takes into account “classic” aeroelastic stability (flutter) but also aspects characteristic of nonlinear systems (LCO)

- A nonlinear model could be helpful to gain some sensibility of the matter and as a de-risking activity, its validation being based on tests developed on a simple system (Iron Bird Test Rig)
- Following the approach of equivalent stiffness, resonance test can be used to assess the effects of frequency shifting and as a de-risking activity prior to flight tests.

While the main demonstration of the feasibility of this requirement extension was by flight test, the development of a dedicated non-linear model was therefore deemed necessary to reduce the risk of instability during the tests and, on the other hand, to provide an indication of the most critical conditions to be explored in flight.

A simplified analytical model was built to provide a first insight on the topic: this model was based on Matlab/Simulink and was developed using a state-space approach to model the aerodynamic forces, as described in [4].
Considering only one mode, the surface rigid rotation, the unsteady aerodynamic forces can be computed using Nastran SOL 146 (aerolastic frequency response) by means of a dedicated solution alteration (ALTER). Generally, the output is a matrix, H_{am} , where each term represents the generalized component of the aerodynamic force (i.e, the force generated by a mode and projected on another mode) but since there is only one modal coordinate that corresponds to the physical rotation, the output is a scalar function that correspond to the transfer function between aerodynamic moment and surface deflection. The function is expressed in terms of reduced frequency $k = \frac{\omega c_{ref}}{2V_\infty}$, where ω is the pulsation (rad/s), c_{ref} is a reference length and V_∞ a reference velocity. H_{am} is computed at a fixed Mach number.
Using Rogers approximation [5], H_{am} can be converted to a state-space system:

$$H_{am}(p) = D_0 + D_1 p + D_2 p^2 + \sum_{i=1}^{n_p} \frac{E_i}{p - a_i}$$

Where p represents the complex k (defined as $p = \frac{s c_{ref}}{2V_\infty}$). The various terms in the above expression are computed by means of a fitting technique, except the poles a_i that are set evenly spaced in the frequency range under investigation and assumed stable.
The expression above can be set in a canonical form and expressed in terms of s:

$$\{\dot{x}_a\} = \frac{2V_\infty}{c_{ref}}[A_a]\{x_a\} + \frac{2V_\infty}{c_{ref}}[B_a]\delta$$

$$M_a = q_{\mathrm{d}}\left([C_a]\{x_a\} + D_0\delta + \left(\frac{c_{ref}}{2V_\infty}\right)D_1\dot{\delta} + \left(\frac{c_{ref}}{2V_\infty}\right)^2 D_2\ddot{\delta}\right)$$

Actuator dynamic behavior can be inserted as well, in terms of dynamic impedence that may be linear or include the freeplay behavior (or other non linear effects).
The equation below summarizes the resulting non-linear system, where the non linearity resides in $M_H(\delta)$, representing the amplitude of the hinge moment with its dependency on the position of the surface. Actuator internal dynamics (represented by the states x_{ACT}) are assumed independent from the deflection. J_H represents the inertia moment of the surface with respect to the hinge axis.

$$\begin{bmatrix} 1 & 0 & [0] & [0] \\ 0 & \left(J_H - q_d\left(\frac{c_{ref}}{2V_\infty}\right)^2 D_2\right) & [0] & [0] \\ [0] & [0] & [I] & [0] \\ [0] & [0] & [0] & [I] \end{bmatrix} \begin{Bmatrix} \dot{\delta} \\ \ddot{\delta} \\ \{\dot{x}_a\} \\ \{\dot{x}_{ACT}\} \end{Bmatrix} = \begin{bmatrix} 0 & 1 & [0] & [0] \\ q_d D_0 & -\left(c - q_d\left(\frac{c_{ref}}{2V_\infty}\right) D_1\right) & q_d[C_a] & [0] \\ \frac{2V_\infty}{c_{ref}}[B_a] & [0] & \frac{2V_\infty}{c_{ref}}[A_a] & [0] \\ [0] & [0] & [0] & [A_{ACT}] \end{bmatrix} \begin{Bmatrix} \delta \\ \dot{\delta} \\ \{x_a\} \\ \{x_{ACT}\} \end{Bmatrix} - \begin{bmatrix} 0 \\ 1 \\ [0] \\ 0 \end{bmatrix} M_H(\delta)$$

This model can be easily expanded to include the contribution from deformable modes, building modal mass, stiffness and aerodynamic forces matrices with an analogue technique. Simulation were performed in time, due to the presence of non-linear terms, using an ODE (Ordinary Differential Equation) solver for stiff problem and exploiting Matlab tools for event detection to switch between different behaviours (in/out of free-play region).

2.2 Non-Linear Model Validation

The model described above was used to gain some insight of the typical behavior, but needed some kind of experimental validation to be used as a predicting and derisking tool. This test should be conducted on a simple yet representive system and in a controlled environment: for these reason, a dedicated test was conducted on the M346 Iron Bird test rig, a rig developed to test the aircraft systems.

The Iron Bird is able to reproduce the behavior of the actuation system and the Flight Control system: for this reason it features fully representative moving surfaces, with series actuators installed on a simplified kinematic chain and a lumped mass representing the surface inertia. External actuators are present as well, to reproduce the effects of aerodynamic forces.

A dedicated nonlinear model of the Iron Bird control surface was developed to simulate the effects of freeplay and friction on stability. The core of the model was a 1-dof system that represents the rotation of the surface, like the one described above, including a nonlinear stiffness (with a dead zone) and a simple model of friction (lumped parameters, LuGre [6]) but without aerodynamic forces. Friction model was tuned using data from static (or quasi-static) backlash test, such those reported in Figure 2.

The Iron Bird Test Rig capabilities were exploited to run a series of test, enforcing an arbitrary external force (with assigned amplitude and waveform) and measuring the rotation of the dummy surface: these tests were repeated at different level of freeplay, introduced in the rig by means of dedicated parts, manufactured on purpose with reduced diameters.

Data gathered through these tests were then compared to the numerical model, run with the same input and the same level of backlash.

The results turned out to be not completely satisfactory, for several reasons:

- Data collected during tests were particularly noisy: a lot of harmonics were presents, due to dynamic response of the rig, to electrical noise and, probably, to poor signal conditioning. This has led to a difficult identification of the characteristic frequency of the phenomenon.

- Limits in the external loading system limited the capability of generating signals above or below certain level of amplitude, and also to use signals at moderately high frequency.
- Some other nonlinearities may could be present, for example actuator was probably exhibiting an amplitude-dependent stiffness.
- Apart from these aspects, a 1-dof model may be too simple to model such a complex phenomenon, particularly regarding friction.

Despite these considerations, both the test and the modelling allowed to gain some insight of nonlinear systems and to improve the sensibility on the matter.

Figure 3 illustrates a detail of the HT actuation system as implemented and tested on the Iron Bird Test Rig.

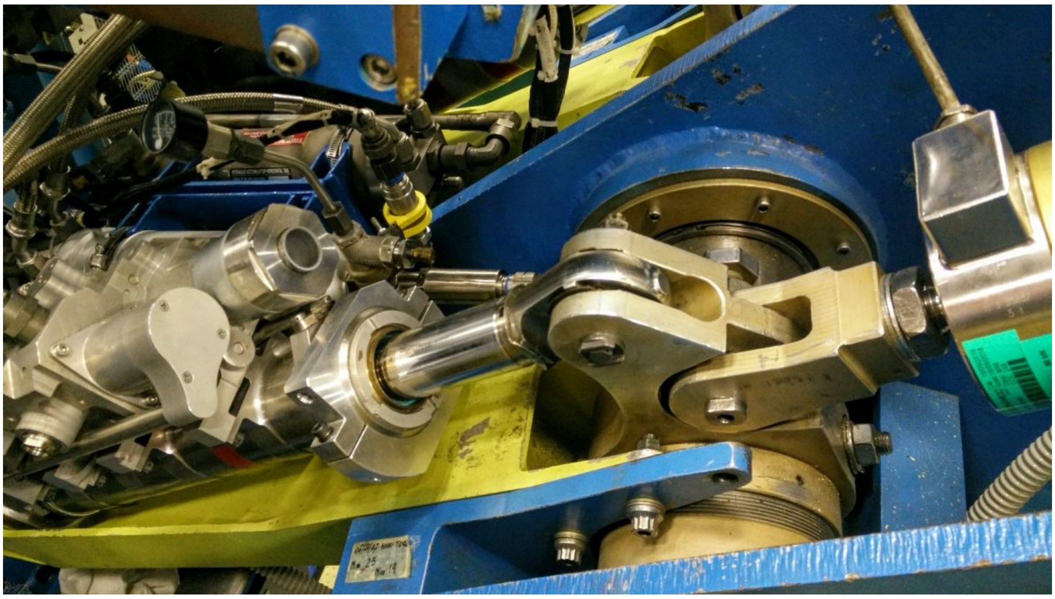

Figure 3: Iron Bird Test Rig - Horizontal Tail Actuation System.

The model, tuned as such, was then coupled with a linear aerodynamic model, expanded to include deformable modes and used to predict the behavior of the Horizontal Tail in flight, identifying the most critical regions of the flight envelope: target level of freeplay did not lead to any LCO or other instabilities, according to the model predictions.

2.3 Full-Scale Ground Test

Although flutter was not expected to be an issue in accordance to the model predictions, a check on modal behavior was performed on the complete aircraft, by conducting a Ground Resonance Test (GRT), mainly focused on the Horizontal Tail.
Experimental activity on the aircraft required the construction of some dedicated parts to provide an enlarged and known freeplay on the control surface. Backlash tests were conducted with different set of parts, until the target values of freeplay were achieved.

In general, measurable effect of backlash, in linear terms, is a reduction in modal frequencies, corresponding to an apparent reduction in stiffness. To evaluate this aspect, a REST

(Resonance Engineering Structural Test), i.e. a Ground Resonance test performed with a reduced setup, was performed on the full A/C just before the beginning of the flight test campaign. The test was focused on the Horizontal Tail and subdivided in three steps, each involving a different level of backlash. For each step, resonant frequency of the main modes of the HT were measured: on these modes, a linearity test was performed, varying the amplitude of the exciting forces.

The main results collected are the following:

- Tested values of backlash produce a lowering of the modal frequencies, in particular those of rotation control surface modes. This reduction is small and well within the range of frequencies covered by parametric analyses already performed.
- Surface rotation modes are nonlinear with respect to amplitude of excitation: nonetheless, the behavior highlighted is “softening” (at higher levels of force correspond lower frequencies and higher damping) which is typical of systems dominated by friction, rather than freeplay.

Figure 4 is a typical illustration of the effect of the level of excitation force during a GRT of a system with presence of backlash.

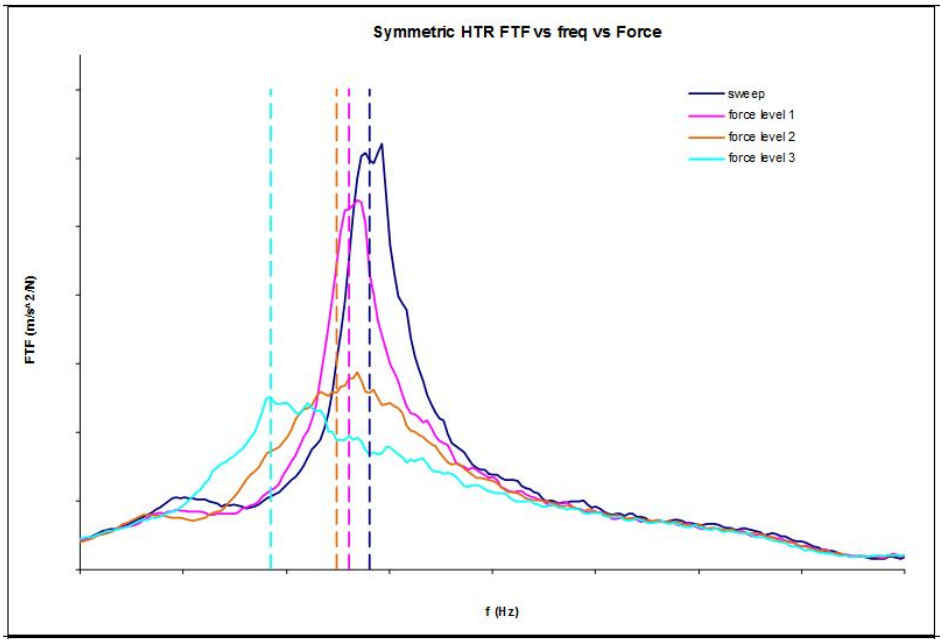

Figure 4: Ground Resonance Test – non-linearity checks

Results gathered did not highlight any significant frequency shift due to the presence of the increased freeplay, confirming the trends indicated by the analysis using the non-linear model. The evidences that the tested values of backlash produced only small changes in modal frequency, together with many parametric variations performed to cover modelling uncertainties and failure conditions, confirmed flutter stability with the required margins, so clearance were released for the flight testing phase.

2.4 Flutter and LCO In-flight Trials

The target of this part of the campaign was twofold: assessing the presence of any backlash impact to aeroelastic stability in classical terms (flutter) and investigating the possibility of LCO occurrence.

A limited number of flutter flight test, performed with freeplay within MIL requirements, were repeated applying excitation by means of the control surfaces driven by a sinusoidal logarithmic frequency sweep signal injected in the FCS and measuring accelerations on a strategic set of accelerometers. This was done in order to have a clear reference for comparison with results gathered during the extended backlash stage.

The next step was to perform flight testing following an approach similar to that of the ground test phase. To achieve the purpose of assessing the aeroelastic behavior of the aircraft in presence of freeplay much greater than specified requirements, dedicated parts were installed to deliberately increase the surfaces' backlash. After the installation of these modified parts, prior to the beginning of the flight activity, backlash tests were performed according to the standard procedure, in order to

The target levels of backlash expected to provide small effects on flutter margins. For this reason, a small set of flutter tests were performed and the main purpose of these tests was to repeat the most representative test conducted for Certification flights and examining eventual differences or variations. No significant differences were detected in terms of flutter margins, confirming the results of the Ground Resonance Test and the initial assumptions.

The flutter trials were followed by the most interesting phase, dedicated to the detection of potential LCOs. Actually, more effort was rather dedicated to exploring the characteristic phenomenon of LCO, task that required the development of a different testing technique and some trial-and-error process to reach the desired result. These kind of test required the control surfaces to be unloaded (zero hinge moment), in order to maximize the effect of backlash and to avoid it is recovered by loads acting on the control surface. The evaluation if any sustained oscillations arose was based on real time monitoring of accelerometers and pilots' feedback.

Whereas for the Rudder any symmetrical flight condition is expected to lead to a zero hinge moment, for HT specific maneuvers were required to attain this condition. A preliminary evaluation of suitable flight points was made with the help of Loads Department, which provided a map of flight points where HT hinge moments were predicted to be close to zero (within +/- 2% of Limit Load) in near straight and level conditions. This study was considered not more than a reference for flight planning purposes since the numerical model used for loads evaluation is more focused on high loads and may not be entirely reliable for near zero conditions.

Once in flight, loads were monitored by means of strain gauges, properly calibrated to give loads on surfaces and other control stations. Again it shall be taken into account that the calibration curves, that allow to convert electrical input generated by the unbalance of each strain gauges bridge into a load, were optimized on the upper ranges, near maximum loads. This implies that, inherently, when measured loads are very close to zero, uncertainty increases. To overcome this issue, the best technique was to slowly cross the displayed zero load conditions.

The identified conditions were verified during flights to be at low level of hinge moments, although not exactly zero: a corrective maneuver was then required to reach a condition of zero actuator load and to cross the zero as slowly as possible, to mitigate the risk of measurement error. The maneuver had to be performed keeping as constant as possible the flight conditions in terms of CAS and Mach number.

For the Horizontal Tail, these maneuvers were identified as proper steady turns. The pilot started to increase slowly the vertical load factor N_z until ground station signaled that the zero load condition had been achieved. In some cases, a wind-up turn with a significant g-level was required.

In any case, maneuvers had to be conducted as slowly as possible, monitoring actuator load (strain gauges) in telemetry, to allow for the detection of the unloaded surface condition. The use of telemetry and monitoring of strain gauges time histories in real time was essential to provide guidance to the pilot for achieving the required conditions. Several trials were necessary in order to determine the best way of performing the maneuver in order to get the best outcome to stimulate a potential LCO.

During these manoeuvres, accelerometers were monitored in addition to strain gauges signals, to identify any anomaly in structural response, such as a sudden increase in amplitude or sustained oscillations. The pilot was asked to give feedback about any anomalous vibration or other unexpected behaviour felt during the execution of the manoeuvre.

Emergency procedure were put in place to prevent structural damage or loss of control: as soon as an anomaly was detected by either the pilot or the ground station, the pilot had to throttle down and reduce AoA or roll rate, returning to a non-zero load condition on the surface and thus stopping the oscillations.

From an operational point of view, the most interesting flight points were those that presented an almost unloaded surface in levelled conditions. These were, in fact, the best conditions most likely to allow for the development of LCOs, since the aircraft was able to maintain a steady condition for a long period of time, facilitating the occurrence of a potential LCO. These flight conditions were the first points explored during the flight campaign. Nonetheless, other regions of the flight envelope were explored as well, investigating the effects of Mach, dynamic pressure and trim conditions.

During these tests, aircraft responses were constantly monitored in telemetry, to detect the onset of LCOs: none were detected during the entire flight campaign, as predicted by the mathematical model developed to support this task. Post-flight analyses confirmed the absence of any persistent oscillation in correspondence of unloaded surface conditions.

A better understanding can be provided by the analysis of the plots shown in Figure 5. They report the flight conditions (CAS, Mach number and Altitude), relevant aeromechanical parameters (N_z), hinge moment of the relevant surface and an acceleration measured on the surface itself during the maneuver carried out to stimulate LCO.
Hinge moment was recovered from strain gauges by means of a calibration aimed at describing correctly high-levels of load: it may not be exactly accurate for almost zero loads and in general an offset is present. In the figure, load may appear to be greater (or lower) than zero but this is due to the fact that hinge moment measured on ground was taken as the actual value of the offset.

As it can be seen, as the hinge moment approaches and crosses the zero value, there is not any change in the behavior of the surface accelerometer: no increase in amplitude or emergence of a sustained oscillation can be found in the time histories. As a further confirmation, pilots performing the maneuver during flight tests did not report any anomalous behavior, neither in terms of vibration felt nor in terms of aircraft behavior.

It was important that a long straight and levelled condition could be kept within acceptable ranges of these parameters. Real time monitoring allowed to judge the quality of the manoeuver and if a repetition was necessary to fulfill the requirements.

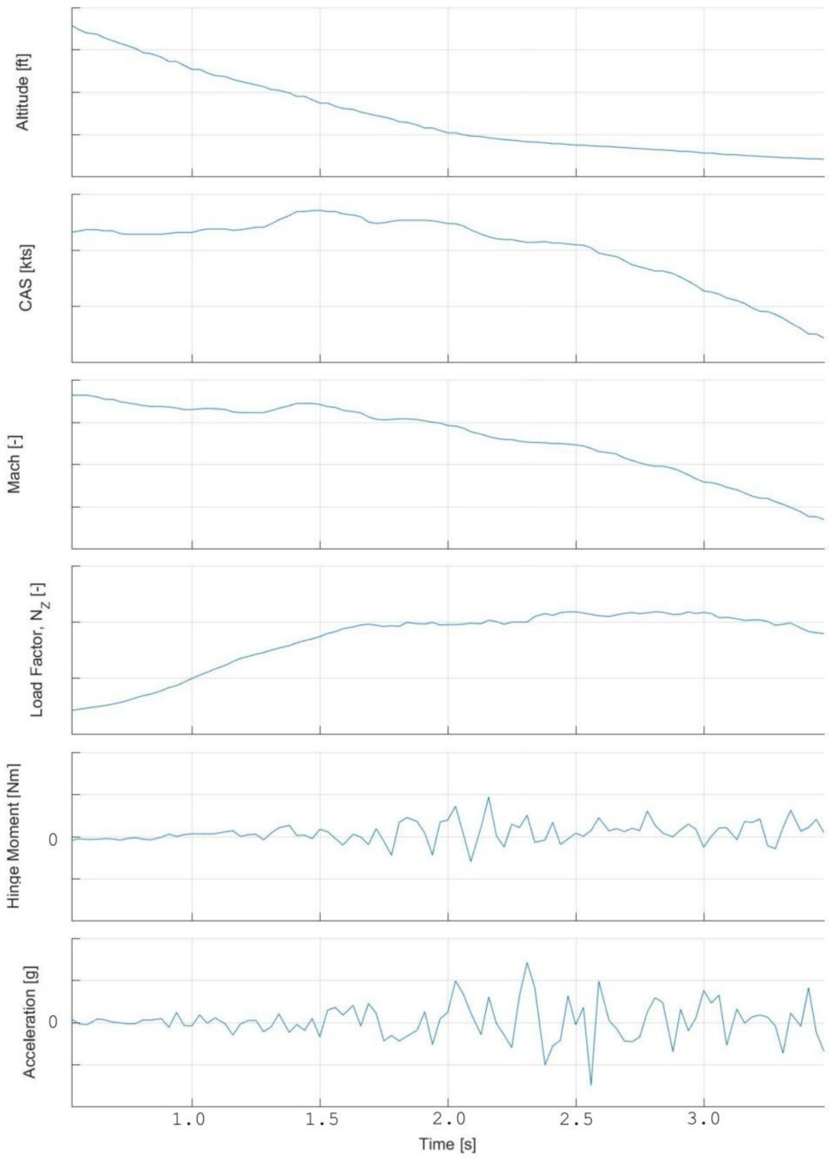

Figure 5: Flight Test - LCO testing (time histories).

3 CONCLUSIONS

Results collected during the test campaign described above have proven that the M346 aircraft is able to withstand freeplay greater than those prescribed by MIL specifications, without incurring in any aeroelasticity related issues, such as flutter or LCOs. This has allowed to extend the freeplay requirements, reducing the frequency of inspections of the aircraft in service and, especially, the occurrence of out-of-tolerances with relevant maintenance activities (replacement of parts of kinematic links).

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