International Forum on Aeroelasticity and Structural Dynamics
IFASD 2017
25-28 June 2017, Como - Italy

IMPROVING AEROELASTIC MODEL ACCURACY AND AFFORDABILITY BY EXPLOITING WIND TUNNEL TEST RESULTS

Marco Di Gifico[1], Vincenzo Vaccaro[2]

[1] Leonardo Aircraft Division
Corso Francia 426 – 10146 Torino - Italy
marco.digifico@leonardocompany.com

[2] Leonardo Aircraft Division
Corso Francia 426 – 10146 Torino - Italy
vincenzo.vaccaro@leonardocompany.com

Keywords: IFASD, aeroelasticity, wind tunnel test, aerodynamic correction.

Abstract: This paper describes the activities carried out by Leonardo Aircraft Division (LAD), in the context of a joined research project (JRP), carried out by Italian/Swedish industries and universities, mainly focused on the study of Limit Cycle Oscillation (LCO). LCO can occur because of the structural and aerodynamic non-linearities, often associated to the transonic range, but not only. Current industrial practice still relies heavily on linear methods, widely used for the prediction and analysis of flutter, and this has led to overly conservative design and envelope restrictions for aircraft. These methods are not adequate for LCO investigations and predictions, owing to the strong influence of non-linearity. As a consequence, during the aeroelastic qualification process, flutter trials have been used rather extensively to cover this deficiency, with significant impact on development risk and cost. For these reasons, it is clear that the inclusion of non-linearity in the mathematical and computational aeroelastic prediction tools is highly desirable. The scope of Italy-Sweden JRP has been that of creating a platform of validated linear and Hi-Fi analytical methods and tools for the investigation of LCO, mainly focusing on fighter external store configurations flying in transonic conditions. In order to reduce the project costs and to contain technical risks, the objectives of the JRP have been confined to the study of pylon-store structural nonlinearity and to the design, manufacture and testing of a flutter WT model in subsonic conditions. Laboratory tests and WT trials have been the source of data for the validation of methods and codes. The level of accuracy achieved by Hi-Fi aeroelastic simulations based on CFD and linear FEMs, in comparison with test results, can be considered very satisfactory and promising for future work opportunities.

1 INTRODUCTION

The aeroelastic effects, such as flutter and Limit Cycle Oscillation (LCO) of external stores, often impose a practical limit to the flight envelope or the load capability of fighter aircraft as well as increment in structural weight. Sometimes they can be discovered only by means of flight testing, above all when aerodynamic and structural non-linearity play a significant role.

LCO can be an aeroelastic problem on current fighter aircraft configurations and has occurred during flight testing activities aimed to the integration of external stores on modern fighters (F-16 and F/A-18). The phenomenon usually occurs for aircraft with external stores throughout, but not limited to, the transonic flight regime. With aerodynamic feedback, LCO sustains periodic oscillation characterized by the same amplitude over time for a given flight condition. Once LCO is well established, the external stores and all parts of the aircraft vibrate in a single mode, at a single frequency. Depending on the amplitude and frequency involved, the LCO-induced motion of the crew may result in an inability to read cockpit displays or accomplish flight or mission related tasks. Moreover, another important issue that has received attention in the past is that of fatigue.

LCO can occur because of the structural non-linearity (e.g. of the pylon-store system) and of aerodynamic non-linearity, often associated to the transonic range. Current industrial practice for the prediction and analysis of flutter relies heavily on linear methods and this has led to overly conservative design and envelope restrictions for aircraft. These methods are not adequate for LCO investigations and predictions, owing to the strong influence of non-linearity. As a consequence, during the aeroelastic qualification process, flutter trials have been used rather extensively to cover this deficiency, with significant impact on development risk and cost. For these reasons, it is clear that the inclusion of non-linearity in the mathematical and computational aeroelastic prediction tools is highly desirable.

High Fidelity (Hi-Fi) models used to study and simulate LCO phenomena are based on Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM), coupled by Fluid Structure Interaction (FSI) facilities. The use of CFD and CSM is quite common in industry and academia when no aeroelastic interaction has to be taken into account. Complex aerodynamic flows around undeformed shapes can be explored by CFD and the behaviour of nonlinear structures can be predicted by CSM tools, in both cases with a quite high level of accuracy but at high computational cost and time. The coupling of the two systems for aeroelastic studies has always been, instead, a very difficult task and the most common approach, when linear aerodynamic methods cannot be considered accurate enough, is to build up an aeroelastic model based on CFD and a linear dynamic model of the airframe.
The increase in affordable computational resources, together with major advances in algorithms, means that nonlinear aeroelastic tools are now viable within the aircraft design and qualification environment. However, validation through experimental data is essential for a correct use of these tools.

To face all these aspects an European join research project (JRP) between Italy and Sweden has been launched. The scope of this JRP has been that of creating a platform of validated linear and Hi-Fi analytical methods and tools for the investigation of LCO, mainly focusing on fighter external store configurations flying in transonic conditions. In order to reduce the project costs and to contain technical risks, the objectives of JRP have been confined to the study of pylon-store structural nonlinearity and to the design, manufacture and testing of a flutter WT model in subsonic conditions. Laboratory tests and WT trials have been the source of data for the validation of methods and codes.

In the European industry the demand for achieving a higher TRL in LCO is felt as very important and the estimated increase of TRL allowed by this JRP has has been from 3 to 4, through the validation of methods and tools by means of subsonic WT measurements and laboratory test. A further upgrade to TRL 5 needs validation in the transonic range, object of potential future work. The JRP is the first attempt in Europe to concentrate consistent industry and academic efforts in the study of LCO of fighter wings with external stores, following a structured approach. The project has been funded by Italy and Sweden and four partners have been involved:

- Leonardo Aircraft Division (LAD, Italy, leader of the project)
- Saab (Sweden)
- Politecnico di Milano (PoliMI, Italy)
- Kungliga Tekniska Högskolan (KTH, Sweden)

The current status of the art about LCO still requires the necessity to improve the quality of simulations, making them more reliable, manageable and, above all, affordable. Therefore, the JRP has covered all these aspects in the development of Hi-Fi models for LCO simulation. Reduced Order Models (ROM) and upgrade methods of linear flutter models have been developed as well, for a more practical and affordable industrial approach.

In parallel to the development of Hi-Fi structural and aerodynamic models, methods and computational tools for the study of complex aeroelastic phenomena and for the upgrade of linear models, has been carried out the task to design and manufacture an affordable WT flutter model. The model reproduces in proper scale half airframe of a generic fighter carrying a tip missile and an underwing bomb.

In order to mimic real fighter pylons, the JRP partners have developed a concept for a model of a pylon able to simulate the effects of preload conditions on the store and of contact forces exchanged at the pylon-store interface (sway braces), one of the suspected source for the nonlinear behaviour of this component. The study has been supported by Hi-Fi finite element model (FEM) techniques and has led to the design and manufacturing of the hardware underwing pylon of the flutter model.

The design of the flutter model has been tuned in order to mimic mild aeroelastic phenomena during the WT trials and to reach the instability conditions in a progressive approach. Laboratory tests (static pylon test and Ground Vibration Test GVT) and measurements gathered during the WT trials (static aeroelastic deflections and subcritical dynamic responses) have represented the basic source of data for the model validation and upgrade tasks.

The level of accuracy achieved by Hi-Fi aeroelastic simulations based on CFD and linear FEMs, in comparison with test results, can be considered very satisfactory and promising for future work opportunities. Moreover, the ability to handle complex geometrical meshes, aerodynamic meshes (wing-pylon-store) and managing the fluid-structure interaction has been an important outcome of the project. Several investigations have also been carried out to assess the effect of specific parameters on the results of the aeroelastic analysis, confirming that the complexity of the mesh of the pylon-store interface is a critical aspect, as it can be cause of numerical instability of the solution.

This JRP has been very important to develop and consolidate skills for the generation of Hi-Fi FEMs. Models of the pylon and of the store have been implemented in ABAQUS and ANSYS, among the most advanced nonlinear FEM codes, and upgraded to match laboratory test results. The latter have demonstrated to be fundamental for upgrading the FEM and to achieve a proper level of realism in the simulations. The expertise and skills acquired are important for future work and industry applications. Although the use of Hi-Fi FEMs linked to CFD meshes has been demonstrated to be feasible, an extensive use of this approach seems to be unpractical for industry aeroelastic processes owing to the complexity of models, computational effort and time required for the analysis. The JRP outcome is, instead, that this type of models can be very useful to predict, with a high level of realism, the characteristics of pylon-store components, above all when a test article is not yet available and thus experiment cannot be used to validate simpler linear models.

Due to affordability and fast prediction ability, industry is still very keen to use the ROM approach and more in general linear models. For this reason a quite significant effort has been devoted by Industry during the project to improve and refine existing computational tools and to develop new methods to improve the accuracy of linear flutter models. CFD is here the main tool to generate Generalized Aerodynamic Forces (GAF), normally computed by linear methods, achieving a higher level of accuracy. CFD has also been used to generate aerodynamic terms representing the reference for the correction and upgrade of linear models. Both the two aforementioned approaches have been followed to predict WT trial conditions and have been validated by comparison with test results.

As regards innovative approaches to design and manufacture more affordable WT flutter models, during the JRP several new technologies have been exploited in order to make the design, analysis and manufacturing loop more efficient, increasing at the same time precision and quality of the hardware. Most WT model parts were designed using CAD tools followed by Computer Controlled Machining. Although not cheap, the process has significantly reduced the workload while simultaneously improving quality and precision. The JRP has also enabled the use and application of so-called additive manufacturing, or 3D printing. This technique has allowed the design of certain rather complex components which could not be manufactured with more traditional techniques. Initially, the parts could only be made in simple thermoplastic materials, such as polyamide, but in the final stages of the project, also aluminium parts were designed and built using 3D printing. Another essential technology developed during the JRP is the use of a model internal data acquisition and control system (DAQ). With recent development in computer hardware and also the rather large size of the JRP WT model, it has been possible to place all DAQ hardware inside the WT model, with significant advantages for cable lengths, that can be much shorter thus improving signal quality, and for much quicker disconnection of the model and its handling during different tests.

2 DESCRIPTION OF THE TEST ARTICLE

The TA has been designed and manufactured by KTH and represented a canard type combat aircraft consisting in a half wing attached to a fuselage. The wing structure of the WT model was made by a frame of fibreglass beams having the function of spars. The aerodynamic surface was instead provided by a solid foam material properly shaped and assembled with an internal fibreglass structure. The clean model included a tip element designed to mount the missile. Three additional items completed the TA:

- The wing tip missile with internal movable mass (FWD and RWD positions)
- The pylon with store pre-load and monitoring system plus the sway brace interface
- A modular store with internal movable mass (FWD and RWD positions)

Considering all the mass positions, seven configurations have been derived and studied. With the aim of reproducing an actual sway brace scheme in the WT model, three types of pylon store connections have been considered: multi blade, single blade and stiff (low part of Figure 1). The stiff connection was aimed at rigidly linking the pylon and the store. The blades design was aimed at introducing non-linearities such as contact and friction.

Figure 1 - Detail of pylon system (up) and sway brace options (down - multi-blade, single-blade, stiff).

3 OVERVIEW OF THE LINEAR FLUTTER THEORETICAL MODEL (LFM)

The main components that characterized the LFM were:

- A linear FEM, able to simulate wing + stores dynamics
- A linear formulation for unsteady aerodynamics, based on flat meshes of main aerodynamic surfaces
- Interaction between the FEM and the aerodynamic mesh, with exchange of forces and displacements between the set of FEM grids and aerodynamic boxes (FSI)

The computational environment usually adopted by LAD to implement a LFM is MSC NASTRAN, that uses a DLM formulation to generate the unsteady aerodynamic forces. Figure 2 illustrates the simplified FEM adopted for WT model, Figure 3 shows the relevant DLM mesh. More in particular, Figure 3 emphasizes the evolution of the DLM. Initially the aerodynamic contribution of the tip missile and of the underwing bomb had been neglected and the wing mesh was rather coarse. When the WT predictions were produced a more accurate DLM mesh was designed, increasing the number of boxes of the wing and adding the tip missile and the underwing store meshes.

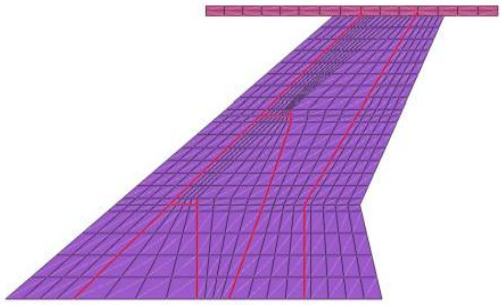

Figure 2 – JRP WT Model – Simplified Wing FEM

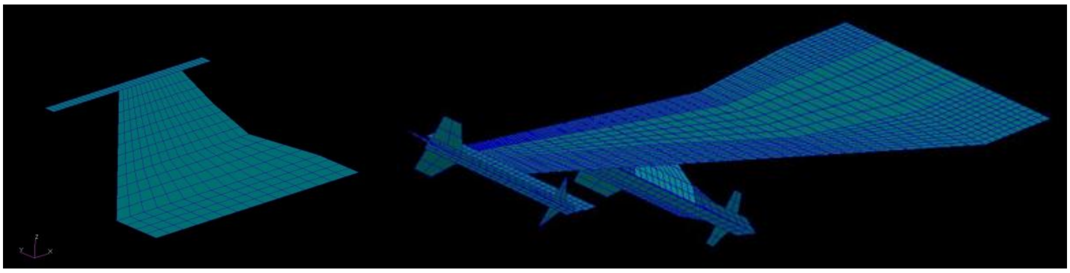

Figure 3 – JRP WT Model – Preliminary (left) and improved (right) DLM mesh

4 STRUCTURAL MODEL VALIDATION ON THE BASIS OF EXPERIMENTAL RESULTS

A first step in the LFM upgrading process was that of matching FEM predictions to the results of typical ground tests, like stiffness tests and GVT. The stiffness test, carried out at KTH [1], was mainly focused on the pylon system and was an essential step for the upgrade of the ABAQUS FEM (developed by PoliMI, [2]) initially generated to mimic the main characteristics of the test article. The comparison with the stiffness test results showed that to get a good matching, significant changes had to be introduced in the model. The goal was achieved refining the FEM in order to be closer to the test article, simulating most of the test setup elements and adopting specific assumptions for the mechanical behaviour (focusing particularly on the pylon sway braces). The main objective of the GVT was instead to validate the overall WT model, composed by the wing, the tip missile, the nonlinear pylon and the bomb. The GVT was carried out by a mixed team of LAD and KTH and the focus was mainly on the cases with stores, as the preliminary tests had already given a good feedback about the validity of the clean wing FEM. During the GVT specific checks of nonlinearity were performed, different combinations of missile and bomb mass positions were measured and the influence of sway brace flexibility was assessed trying blades with different characteristics. The outcomes of the GVT confirmed the validity of the wing FEM, that was not changed in the upgrade process. On the contrary, in order to match pylon store modes, it was necessary to modify the linear model of the pylon. After the upgrade of the dynamic model on the basis of GVT results, the FEM was used to validate the import of the NASTRAN FEM into ABAQUS and then the results of nonlinear FEM obtained replacing the linear pylon with the nonlinear component developed by PoliMI.

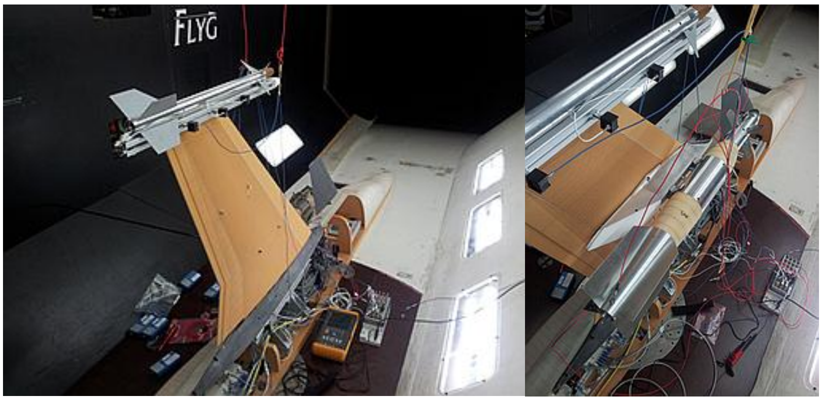

Figure 4 - GVT Layout

One of the characteristics of the missile and of the bomb was to have the central part of the body built from very stiff cylinders with a movable mass inside. Missile and bomb masses could be locked in a forward and rearward position and all possible combinations were tested. The model was excited by a rod linked to an electric shaker and accelerometers were used to pick up the response of the test article. The excitation and measurements system was supplied by KTH and linked to LAD modal analysis system for the computation of natural frequencies and modal shapes. The first four modes were measured (first wing bending, first wing torsion, second wing bending and second wing torsion) and a preliminary comparison with predictions was performed in real time. This allowed to address the test for specific checks, like the assessment of the influence of sway brace flexibility. Besides to natural frequency and modal shape, the measurement of each mode was completed by the assessment of the modal damping and by linearity checks to verify the influence of the level of the excitation force on the frequency. There was no need to change the FEM of the wing, because the measurements on the clean wing confirmed a very good match with the model. Measurements with the pylon showed instead discrepancies for the second wing bending and torsion modes, characterized by a noticeable participation of the underwing store. The solution adopted was that of introducing elastic elements that simulate the links between the pylon and the wing and the elasticity of sway braces. All these new elements were calibrate in order to match GVT measurements. Applying these changes to the model it was possible to significantly improve the matching of a mode characterized by a lateral motion of the bomb, very poorly predicted by the preliminary model, with negligible influence on other modes.

5 DYNAMIC AEROELASTICITY

After the formal GVT and the fully dynamic characterization of the WT model, aeroelastic predictions have been performed to carry out the WT trials with a proper level of safety. The predictions regarded flutter and frequency response analyses. FRFs to the WT shaker input were generated at different speeds, in order to supply also information on the amplitude levels that could be expected during the trials. This data was used to define acceleration thresholds to be not overcome for the safety of the model during the trials. After the WT trials, the same functions were compared to the experimental FRFs, computed from the time histories of the accelerations measured during the trials. The figure below (Figure 5) reports an example of comparison between theoretical and experimental results. On the top figure is relevant to a condition far from flutter. In blue are shown the experimental results and in green the theoretical prediction. The first peak represents the wing bending mode while the second the wing torsion. The flutter incoming condition (Figure 6), represented by the coalescence of the two modes, is well predicted by the LFM, as shown by the bottom plot.

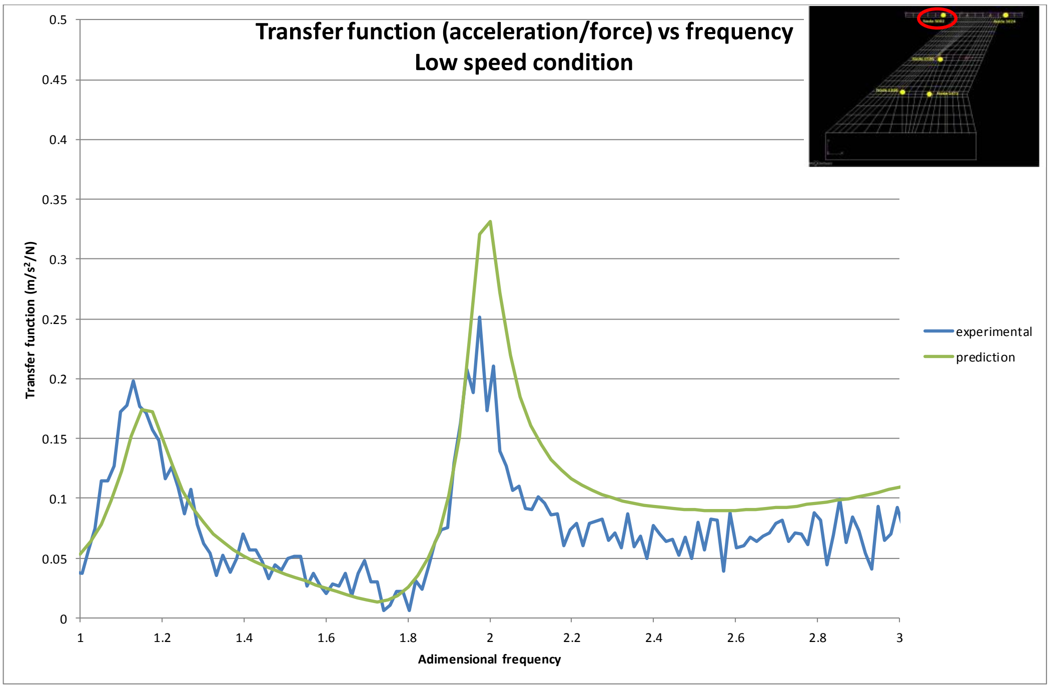

Figure 5 – Comparison between theoretical and experimental FRF at low speed range

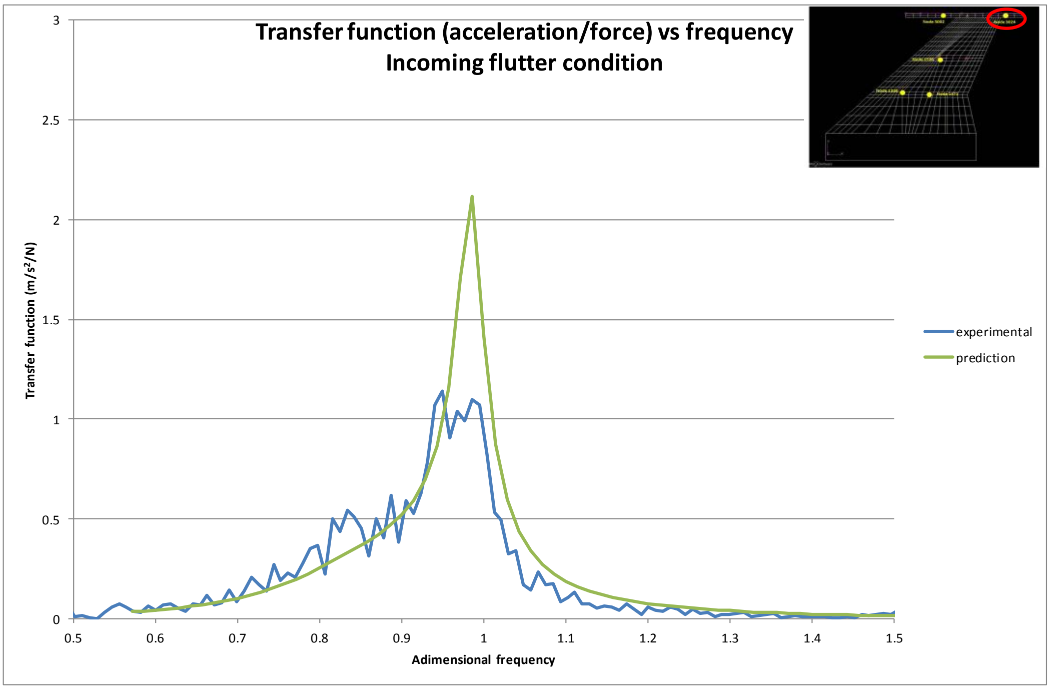

Figure 6 – Comparison between theoretical and experimental FRF in incoming flutter condition

5.1 Frequency Domain Correlation Through Assurance Criterion Indicators

The objective of an assurance criterion indicator is that of providing a figure that can help to quantify the level of correlation between two sets of data, quite often represented by predictions and experiments, respectively. The MAC (Modal Assurance Criterion) is likely the most well-known indicator and it is used to assess the similarity of two natural modes of vibration. It based on a least squares formulation, ranging from 0 (very poor correlation between the two modes) to 1 (perfect correlation) and it was computed by the code used by LAD during GVT, for the preliminary check and assessment of measure data. The advantages to have similar indicators also for the frequency domain correlation are evident:

- Availability of tables and plots that facilitate the analysis of data gathered during the trials
- The use of indicators can be easily implemented in codes and drive the automation of articulated and complex processes.

Many works in literature treated this topic ([3], [4], [5] and [6]) to which the reader can refer for a detailed analytical formulation. Among the various options suggested by literature, two indicators were considered suitable for the correlation process after the JRP WT trials and, without going into a too deep analytical detail, a short description of their characteristics and intended use is here reported. They helped to facilitate and speed up the correlation process, but a complete automatic process based on the analysis of these indicators only, without an overall supervision of an expert aeroelastician, would be very risky.

5.1.1 FDAC (Frequency Domain Assurance Criterion)

This indicator provides a feedback about the similarity of two FRFs over a certain frequency range, taking into account specific frequency functions for all the model grids at the same time. The formulation is in accordance to [6]:

$$FDAC(\omega_A,\omega_X) = S\sqrt{\frac{|\{H_X(\omega_X)\}^*\{H_A(\omega_A)\}|^*|\{H_X(\omega_X)\}^*\{H_A(\omega_A)\}|}{(\{H_X(\omega_X)\}^*\{H_X(\omega_X)\})(\{H_A(\omega_A)\}^*\{H_A(\omega_A)\})}}$$

Where $S = sign\big(Re(\{H_X(\omega_X)\}^*\{H_A(\omega_A)\})\big)$, * is the Hermitian operator, H_X and H_A are two vectors related at two sets of frequencies, ω_X and ω_A, respectively. In our specific case, for a fixed couple (ω_X, ω_A), the values (real and imaginary parts) of FRF(ω_X) and FRF(ω_A) of each accelerometer are extracted and arranged in the vectors (H_X, H_A). Then, the above formula is applied, a value of FDAC evaluated and a specific colour assigned in the plot that helps to visualize the similarity. The result of the application of this criterion to all the possible couples (ω_X, ω_A) is a coloured surface function, having as variables the analytical and experimental frequencies ω_A and ω_X, respectively. The function is an average of all the responses of the model and ranges between -1 and 1. The best correlation is found for values of the FDAC equal to 1, whilst -1 indicate that the values of the two frequencies correspond to modes that are out of phase. This tool is very useful also to identify discrepancies in the frequency between analytical and experimental modes. All the couples of ω_A and ω_X values of the function at which a maximum is achieved correspond to a good correlation. This means that the experimental and predicted modes associated to the two frequencies are well matched and the difference between the two frequency values is the error between the model and the experiment. This criterion provides an overview on the dynamic similarity between

experiment and model in addition to the MAC and to the typical frequency error plot ω_A vs ω_X, but no information about the spatial distribution of error can be deduced.
The analysis of figure below (Figure 7) helps to understand the basic meaning of the indicator and its use in the comparison between experiment and predictions. On the left hand there is an example of coloured map of the FDAC relevant to the comparison of the LFM based on a FEM with experimental results. On right hand is the same case but with a FEM upgraded to match the WT model. The vertical axis is relevant to normalized experimental frequency ω_X, the horizontal to the normalized prediction frequency ω_A. The black diagonal is the ideal line where the couples (ω_X, ω_A) would lie in case of perfect match. Red regions corresponds to range of frequencies characterised by a good correlation of FRFs (very similar shape).

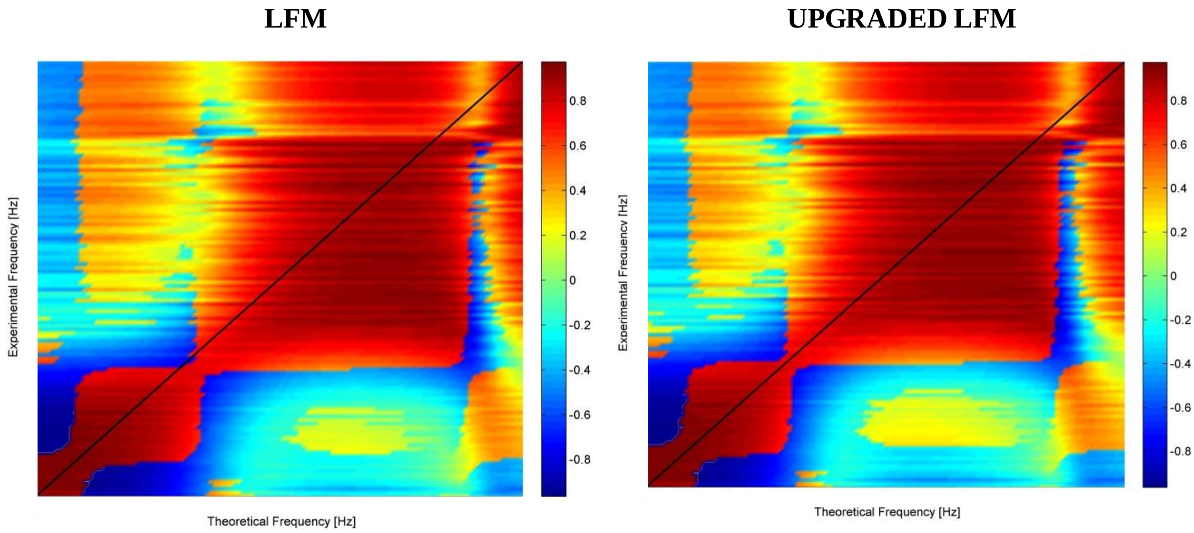

Figure 7 – FDAC representation. Experimental vs theoretical frequencies (left for LFM, right for tuned LFM)

5.1.2 FRAC (Frequency Response Assurance Criterion)

The other way to assess the correlation between FRFs is to try to detect the spatial distribution of FRF errors. The FRAC indicator operates on two FRFs, analytical and experimental, at the same grid and in the whole frequency range. The average is over the whole frequency range and the range of the indicator is between zero (poor correlation) and one (perfect correlation). As for the FDAC, [6] has been chosen also for the FRAC to define its formulation:

$$FRAC_j = \frac{\left|\{H_X(\omega)\}_j^* \,\{H_A(\omega)\}_j\right|^2}{\left(\{H_X(\omega)\}_j^*\{H_X(\omega)\}_j\right)\left(\{H_A(\omega)\}_j^*\{H_A(\omega)\}_j\right)}$$

In this case H_X and H_A represent respectively the portion of experimental and analytical FRF (real and imaginary parts) limited at the requested frequency range, * is the Hermitian operator and ω is the frequency varying in the range selected for the analysis. In addition, j indicates that the indicator is calculated for the j_{th} accelerometer of the set. The assessment can be also limited to a specific frequency range, if this can be more meaningful. A map of FRAC values over the model allows to identify those grids of the FEM that are poorly correlated with the experiment, thus restricting the area of correction to a limited zone of the model. Figure 8 illustrates the results of this type of analysis. Two pictures show the differences between the FRACs computed for a LFM based on a FEM before and after the updating process carried out to match WT test article (right) results. The FRFs of accelerations measured during the trials were used to calculate the indicator and at each accelerometer location on the wing the actual value of the computed FRAC (green line) is compared with the ideal goal of the unity (red line).

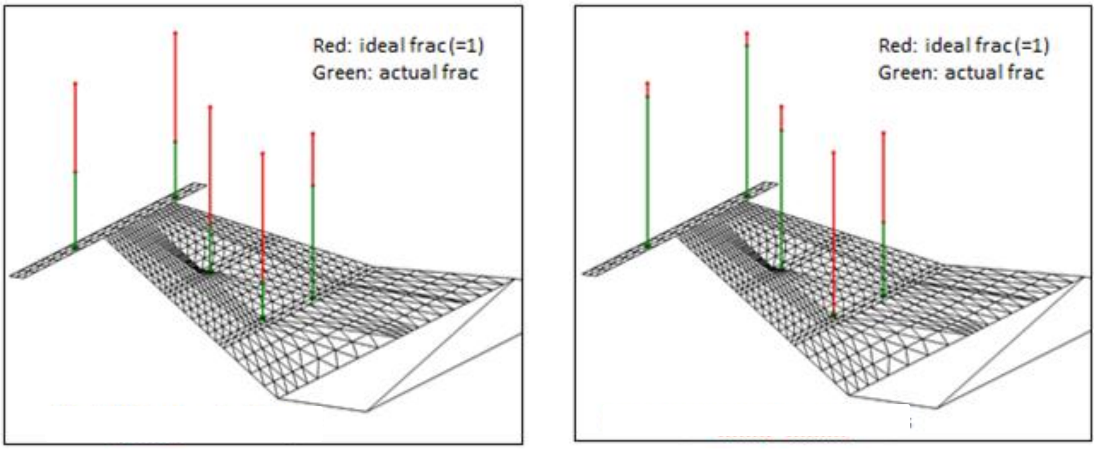

Figure 8 – FRAC representation. LFM (left) vs tuned LFM (right)

5.1.3 Frequency Domain Correlation by Analysis of FRF Integral Functions

This approach, developed by LAD, is to be used in combination with the use of assurance criterion indicators (FDAC and FRAC) and complementary to them. The concept is to quantify differences between two FRFs using their integral functions. In other words, the area below each curve is calculated (integral) and then from the computation of their difference it is possible to assess how similar the two curves are, not only in terms of shape, but also of amplitude of peaks. This is an important step as the main characteristic of FDAC and FRAC indicators is that they are close to unity when two FRFs have similar shapes, even though amplitude of peaks can be quite different. When this concept is applied to experiment and prediction FRFs, differences among integral functions can be useful to assess errors in the model matching and define strategy for correction. In theory, a necessary condition for the similitude of two FRFs is that the difference of the their integrals extended all over the frequency range of interest is close to zero. This is not sufficient as negative areas could compensate with positive ones, very common situation if a wide range of frequency is considered. To be more accurate, the integral check can be performed in selected frequency ranges, those around the peaks of main modes. Following this approach a quantitative assessment of differences can be made for each peak and a map of errors can be plotted comparing the integrals of the FRFs at different grids of the model. The process developed by LAD includes the generation of three different types of curve for the comparison of the integrals of two FRFs in a defined frequency range [f_{start}, f_{end}], useful to better identify areas of the model with the highest errors.

5.1.3.1 Error Integral Function (EIF)

It is a function of frequency and provides the difference of the two FRFs integral computed in the range [f_{start}, f], where f is a generic value of the range [f_{start}, f_{end}]. This curve quantifies the cumulative error vs frequency at the grid to which the two FRFs are associated. Some remarks about the reading of this plot:

- A curve floating around zero indicates a good matching between the two FRFs
- A sudden change of slope indicates a significant local difference

Sudden changes of the sign of the slope are typical of a peak with shift in frequency between the two FRFs.

5.1.3.2 Absolute Error Integral Function (AEIF)

One issue with the EIF is that it can be null at a certain frequency and this is not a sufficient condition to conclude that at that frequency the correlation between the two FRFs is good. In fact, this result can be a consequence of positive and negative differences that are summed up by the integration. In order to keep trace of the cumulative error along the frequency range a new function is introduced, the AEIF. It is essentially the same as the EIF apart from the fact that differences between the two integrals are taken as absolute values. The remarks in this case are:

- As for the EIF, a curve floating slightly over the frequency axis indicates a good matching between the two FRFs.
- There are no changes of sign of the slope of the curve (integrals always increase), but only changes of amplitude, indicative of where main errors occur (sudden change of slope)

This curve can be very useful to assess the effect of a model upgrade. If this operation is effective, the AEIF curve after the upgrade should lie below the curve associated to the uncorrected model, because the total delta area should be smaller.

5.1.3.3 Local Error Integral Function (LEIF)

In this case the difference between FRFs integrals is computed locally, around the frequency f, without adding up previous differences. A delta frequency Δf is fixed and the integrals calculated in the range $[f - \Delta f, f + \Delta f]$. The objective is to focus on frequency and to assess how much two peaks associated to the same mode differ, without accumulating or taking into account errors overall the frequency range. Also for this function a few remarks are here reported:

- This function is the most specific to assess differences between two FRFs and can be used to check the most significant peaks, associated to modes that can be important for flutter or LCO
- The Δf can be fixed case by case, depending on the shape and width of the peak under control

The LEIF can be very helpful to present the FRF error distribution over the model at a specific frequency or for a specific mode. In fact, once f and Δf are fixed, the LEIFs computed for a significant set of grids allow to assign to each grid a quantity expression of the local error. LEIF is a powerful way to show the parts of the model which presents the highest levels of error. Thus, the correction strategy can be focused on worst areas of the model and finalised in the most affordable way.

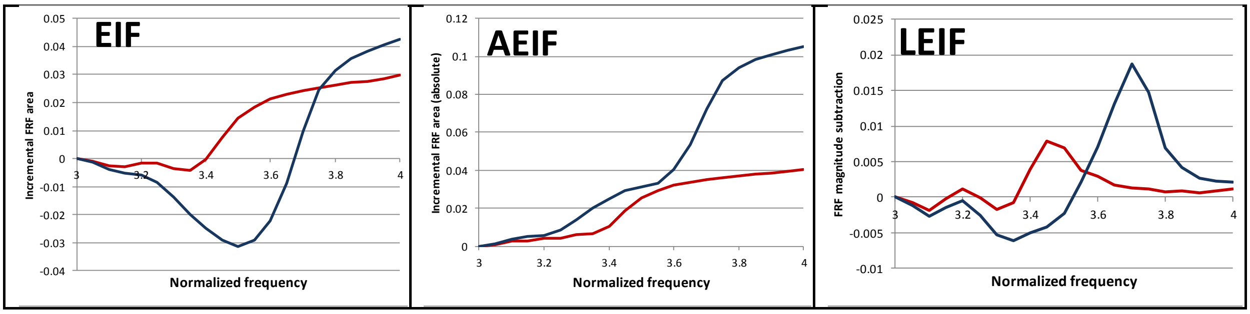

Figure 9 - FRFs integral indicator functions evaluated around a WT TA mode (blue – theoretical LFM, red – updated LFM)

6 UPGRADE OF DLM MODEL

A first improvement was applied to the DLM component of the LFM using measurements from aeroelastic static tests. The deformed shape under aerodynamic static loading were the reference data for comparison and error identification. WT measurements were, as usual for such tests, gathered only for a small set of check points (Figure 10). For the TA (Test Article) they were out of plane displacements measured at seven markers placed on the upper side of the half span model. An optical motion system was used to measure these displacements.

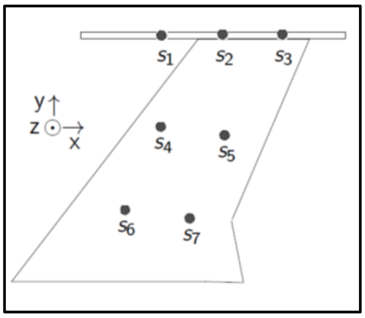

Figure 10 - Locations of optical system markers

Displacements were measured for the clean wing at different dynamic pressure and AoA (Angle of Attack) conditions. Plots of the displacement curves have been used to identify the type of error and how to correct the DLM model.

As concerns the methods, two different types of correction approaches have been developed and implemented in the LAD aeroelastic qualification process:

- Correction of local downwash
- Correction of aerodynamic coefficients of influence (AIC), by factoring the area of DLM boxes

The first approach is applied to upgrade static aeroelastic predictions and has no effect on unsteady predictions (flutter). The second can be used for a more general correction of DLM, valid for both static and dynamic aeroelastic applications. In general, the correction process is articulated in the following steps:

1. Correction of local downwash and verification of the upgraded model vs WT/CFD data for static aeroelastic cases
2. If the outcome of step 1 is not satisfactory, a further correction to match WT/CFD static cases is carried out and consists in the optimization of AICs by factors applied to the

area of each DLM box. The goal of the optimization is to reproduce steady aerodynamic coefficients like C_L, C_m, etc., with the constraint that the pressure distribution is still physically acceptable.

3. For dynamic aeroelasticity the correction is the same adopted for step 2, using in this case unsteady values of aerodynamic coefficients as target and applying the same factor to both real and imaginary parts of AICs.

Methods for DLM correction and computational tools have been developed and already implemented in the LAD aeroelastic process.

6.1 Downwash Correction On The Basis Of Wing Geometry And Other Effects

One of the characteristics of DLM is that the aerodynamic model is simplified, reducing the wing to a plain surface, without section profile thickness and camber. Also the spanwise twist effect is neglected. However, this are typical geometrical characteristics of a wing and correcting the DLM model to take some of them into account is feasible with MSC NASTRAN and can help to improve the accuracy of the prediction.
Another characteristic of DLM is that, being the aerodynamic surface flat, the C_{L0} is obviously null. The analysis of WT TA data have instead shown that this is not the case, owing to a certain number of potential effects, among which the most likely seems to be the effect of WT walls. The left plot in Figure 11 shows how the normal displacement at marker point S1 changes with the AoA. Model prediction (red line) and WT measurements (black dashed line) are plotted in the same picture. As expected, for a null AoA DLM predicts null aerodynamic forces and therefore the displacements are null too. On the contrary, the measured curve does not pass through the origin and, at AoA = 0, the displacement is not null.

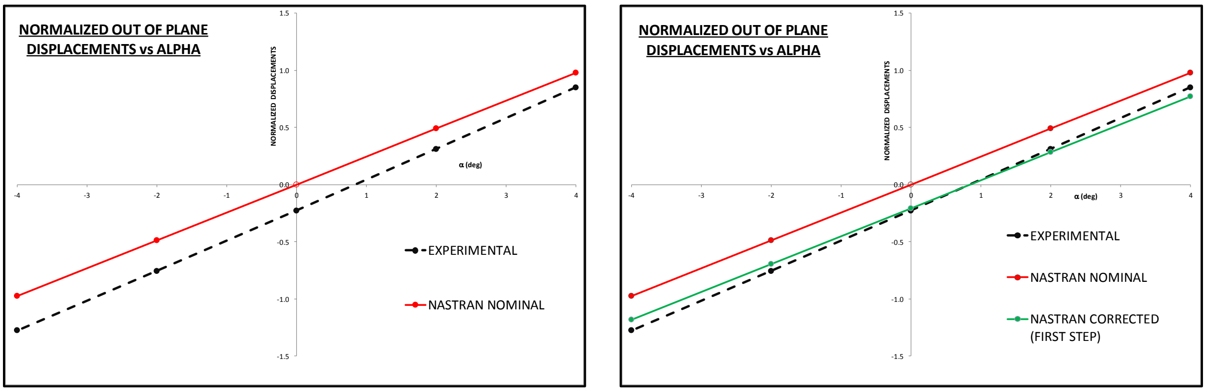

Figure 11 – Static aereolasticity. Experimental out of plane displacements vs theoretical (left) and first step of correction of theoretical results (right)

This discrepancy can be corrected by a proper manipulation of the local downwash at each DLM box. For this specific case a constant value has been applied to all boxes, determined after having verified that the percentage error of displacements at various locations on the wing was nearly the same. A trial approach led to the definition of the corrective downwash. The right plot of Figure 11 shows the effect of the correction, that is shifting the prediction towards the experimental curve. As a consequence, the displacement at null AoA is now matched. There is still an error on the slope of the line (the ±4 deg AoA range guarantees the aerodynamic behaviour can still be considered linear), but this will be object of a further correction, following the method described at the second point of the process.

6.2 Correction Of Aerodynamic Coefficients Of Influence

The technique that is presented here can be applied for improving the DLM steady and unsteady aerodynamic predictions computed by MSC NASTRAN. It is an additional correction step with respect to the downwash upgrade for the static case, the only way to improve the LFM for dynamic aeroelasticity. The method applied by LAD has been developed starting from work presented in [7]. The objective was to modify the theoretical pressures associated to the boxes of the DLM mesh in order to match the aerodynamic coefficients that are available from WT steady measurements, like C_L, C_m, etc. Usually these coefficients are the result of total forces and moments measurements carried out in steady conditions on a rigid WT model and by a balance. The correction is accomplished by means of an optimization process that generates a Premultiplying Correction Factor Matrix (PCFM). The constraint of the optimization process is that of generating a realistic pressure distribution, and this can be achieved using weighting functions and weighted least-squares conditions. In fact, one of the characteristics of this method is that the number of unknown factors (one for each box) is much larger than the number of equations available and the problem would be undetermined. The method of the least squares provides the solution, adding equations that imply that changes in the theoretical aerodynamic load distribution shall be as uniform as possible. This can be achieved imposing the weighted sum of the squares of the deviations shall be a minimum, where the deviation is defined as the difference between the correction factors and unity, the latter representing the no correction case. The PCFM matrix is diagonal and will multiply the vector of the areas of the DLM boxes, thus affecting the forces applied to each box by a specific factor. This choice makes quite easy the application of the correction within the NASTRAN aeroelastic solutions.
Giving here further detail on the theory behind the method, reporting the matrix formulations and the least squares theory on which it is based, is not considered useful to understand the correction approach followed and the reasons that have determined this choice. Any detail can be found in [7]. It is, instead, considered important to highlight the difficulties encountered for the application to the JRP case and how they have been overtaken.
A very quick and simple way for applying the PCFM method is to find, by a trial process, a corrective factor common for all boxes of the mesh. Figure 12 is an example of how it was possible to improve also the slope of the displacement vs AoA line applying a common factor to all boxes.

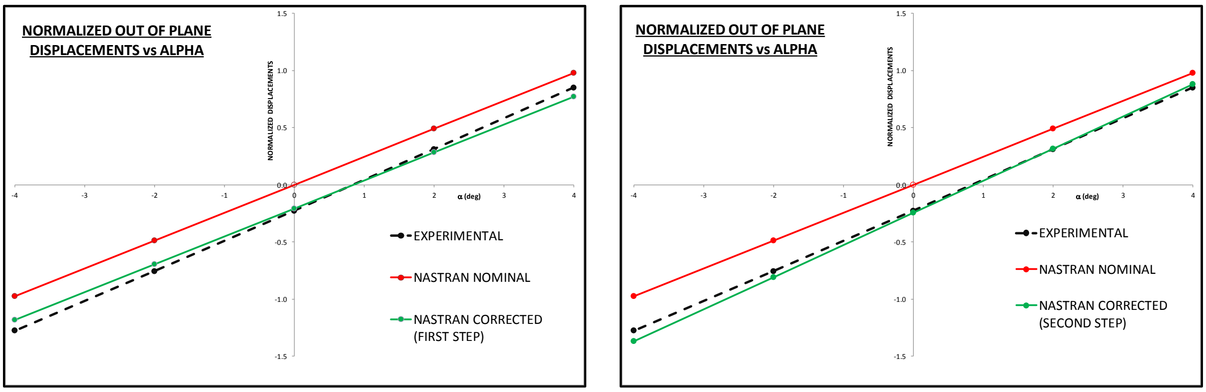

Figure 12 – Static aeroelasticity. Experimental out of plane displacements vs theoretical 1st step (left) and second step of correction of theoretical results (right)

The method reported in [7] is much more sophisticated and has the objective to use WT measurements for the matching of the DLM model. At that time, computational power and time required for computations were an issue even for DLM, leading to aerodynamic meshes quite coarse in terms of number of boxes. Modern multiprocessor computers have dramatically changed the situation and finer meshes are designed to improve the accuracy. However, when the PCFM method is applied to a mesh with a lot of boxes, this can lead to severe numerical issues. In fact, the system of equations is undetermined and the degree of under determination increases with the number of boxes of the mesh. This is one of the reasons that can explain why not completely satisfactory results have been obtained when the optimization method has been applied to the LFM, as it will be better explained later. But the most complex aspect has been that available WT measurements from WT trials are displacements and accelerations instead of aerodynamic coefficients, that are considered the most appropriate input of the PCFM method. Quite a significant effort has been spent by LAD to find a solution for the application of the PCFM when an aeroelastic model is tested in the WT and no pressure or balance measurements are available. Of course, this is not an issue when CFD is used, as the simplest solution could be that of validating the CFD by WT aeroelastic measurements and then use it to generate all required inputs for the correction method. Actually CFD is the key of the solution adopted by LAD, that is a combination of WT measurements and validated CFD predictions. Another aspect that cannot be neglected for a correct understanding of the method is to consider how the generic NASTRAN aeroelastic solution works. In fact, the deformed shape is generated in the structural domain, applying a loading condition and then, by a proper transformation, the deformed shape is computed in the aerodynamic domain, transferring displacements from the structural grids to the reference grids of DLM boxes. Aerodynamic forces are calculated in the aerodynamic domain (for each box, a normal force and a pitch moment) and then, by another transformation, loads at structural grids are computed. Vice versa, it is not possible to transform a set of loads from the structural environment to the aerodynamic one.

What follows is the description of the steps of the process that should allow to accomplish the DLM correction. It is here illustrated for a static aeroelastic case, but a similar method could be followed also for the dynamic case.

- It is assumed that the CFD aeroelastic model is validated by WT trials and so it can be considered reliable for the generation of realistic pressure distribution when the shape is deformed under the action of aerodynamic loads. This model is used to generate the aerodynamic coefficients that will be the target of the optimization process at the basis of the PCFM method. The same WT condition that has generated the deformed shape to be matched by the LFM is thus simulated by the CFD model and the aerodynamic coefficients computed. In case of availability of a balance the WT test is directly used as source of data for evaluating the aerodynamic coefficients.
- The deformed shape measured in the WT is defined by displacements at a limited set of points. The first problem is to generate a deformed shape of the FEM that matches these displacements. The static NASTRAN solution allows to use enforced displacements instead of forces and it is used to compute elastic reaction loads at grids after the deformation is enforced. These loads will be used to constrain the optimization process to realistic solutions through the least squares approach. In case of use of CFD, the displacements at each structural grid are directly provided and so no other analysis is required.
- The PCFM optimization is performed, aerodynamic loads are computed after the correction and then transformed from the aerodynamic set of grids to the structural grids.

- A new deformed shape is calculated in the structural domain, under the action of loads generated by the corrected aerodynamic, and compared with the initial one, obtained by the experimental displacements enforcement or by CFD.

The loop is repeated until a satisfactory result is obtained.

The overall method has been implemented combining MATLAB scripts and NASTRAN DMAPs, including the optimization by the PCFM method. An application has been carried out using the CFD as a reference case. The application has been successful (Figure 13), however further improvements are deemed necessary to overcome some issues due to the high level of under determination of the LFM case (very fine DLM mesh) and to other aspects. In particular, referring to Figure 13, where black point represent experimental values and purple ones the model output:

- The corrected deformed shape follows a correct trend, with larger displacements that in the original model were under predicted. However, a sort of overshoot effect has been noticed, since the new deformed shape is now over estimated with respect to CFD (see figure below).
- At this stage only an optimization run has been performed. A loop process should be put up, using the corrected solution as input to a new correction loop, until a convergence is achieved.
- A different approach should be tried, as an alternative to the generation of the aerodynamic coefficients by an aeroelastic CFD solution, using instead the deformed shape generated by the NASTRAN enforcement static analysis as a rigid mesh for the calculation of pressures by CFD. This should avoid to include in the process the CFD error in the prediction of the deformed shape and of consequent loads, owing to errors in the FSI interpolation.

PRE-CORRECTION	POST-CORRECTION

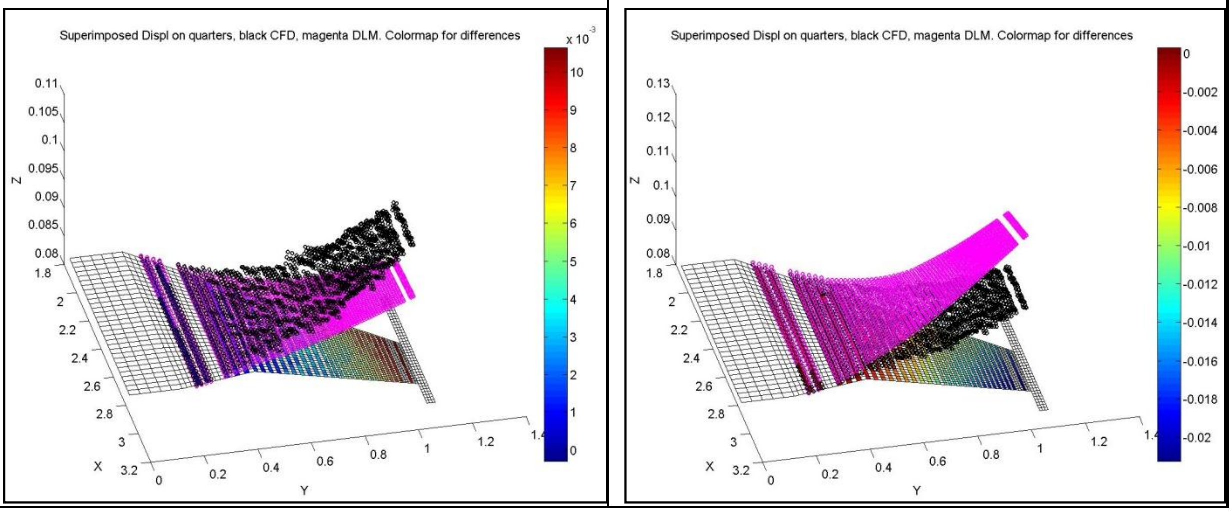

Figure 13 – Static aeroelasticity. Automatic process for correction of out of plane displacements. Pre correction (left), post correction (right)

Nowadays, CFD can be a valid alternative to WT and in some cases it represents the only way for the generation of more realistic pressure distributions in an affordable way. In conclusion, the process is implemented and working but it is clear that further work is necessary to achieve a higher level of maturity in terms of accuracy of the correction and efficiency of the process itself. The application has been verified for the static case and it can be extended to the dynamic aeroelasticity as well. Owing to the complexity of the process itself and the necessity to design and develop a significant number of scripts, this result could not be achieved within the JRP time frame.

7 CONCLUSIONS

During the JRP between Italy and Sweden some important achievements have been reached, both for static and dynamic aeroelasticity model correction. Notwithstanding this, some points are still open and could be treated more deeply, together with further improvements to the correction process. Concerning the static aeroelasticity, an ad-hoc approach has been followed owing to the type of data coming from the WT test (out of plane displacements in a set of WT model points). This approach contemplates two main steps. The first one is to make the theoretical model more adequate to replicate better the WT model behaviour for a null angle of attack. Exploiting a NASTRAN facility, this operation is straight forward and consists in applying a single correction factor, that acts on the local downwash, to the whole aerodynamic mesh. It is however important to remark that WT test have been performed at low dynamic pressure and number of Mach. In other conditions, where the assumption of linear aerodynamics is not applicable, the “single factor approach” could not be applicable and a more substantial approach would be required. The second step regards the adjustment of forces and moments applied to the theoretical aerodynamic model. For this issue, a specific method has been followed and a specific tool developed. The method has been modified to match the type of data available from WT test and applied. The results are promising but a deeper activity would be required to reach an higher level of maturity. Coming to the dynamic aeroelasticity, a good match, in terms of FRF, has been obtained between the theoretical model and the WT one. Further improvements have been achieved by performing a proper tuning. Moreover, to detect the quality of obtained results, proper indicators have been introduced for the first time in the LAD aeroelastic process. These indicators confirmed the conclusions already done and gave indication for improving the quality of the model.

8 REFERENCES

[1] A. Karlsson and Ulf Ringertz. *Experimental and analytical investigations of a fighter-like wind tunnel model with external stores.* International Forum of Aeroelasticity and Structural Dynamics, 2017.

[2] A. Manes, A. Gilioli, M. Giglio. *An Investigation In Hi-Fi Finite Element Modelling Aimed To Improve LCO Prediction*. International Forum on Aeroelasticity and Structural Dynamics, 2017

[3] D. Fotsch and D.J. Ewins. *Application of MAC in The Frequency Domain*

[4] Randall J. Allemang. *The Modal Assurance Criterion - Twenty Years of Use and Abuse*

[5] R. Pascual, J. C. Golinval, M. Razeto. *A Frequency Domain Correlation Technique for Model Correlation and Updating*

[6] C. Zang, H. Grafe and M. Imregun. *Frequency Domain Criteria for Correlating and Updating Dynamic Finite Element Models*.

[7] J.P. Giesing, T.P. Kalman and W.P. Rodden. *Correction Factor Techniques For Improving Aerodynamic Prediction Methods*

COPYRIGHT STATEMENT