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LOADS MODEL FLIGHT TEST VALIDATION BY MEANS OF INNOVATIVE, PHOTOGRAMMETRY BASED, DEFORMATION MEASUREMENT TECHNIQUE.

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Abstract

Airbus Defense and Space (Airbus DS) is working on the definition of a new methodology for the validation of the theoretic static loads model by implementing an innovative wing deformation measurement system based on photogrammetry on a medium transport aircraft (C295MW). The measured deformations are compared to those calculated by means of a high fidelity structural model subject to the loads derived from the theoretic loads model. This technique is expected to be as accurate as current strain gauges methods being at the same time far more flexible and economical.

1 General Introduction

A proper characterization of both flight and ground loads is of primary importance to any airframer company, as it is a requirement to achieve the certification of the aircraft design, as stated in international regulations, e.g. CS-25 25.301(b) and related AMC (AMC No. 1 & 2 to CS 25.301(b)). [1]. This implies performing a validation of the loads model used to certify the aircraft, ensuring that the loads calculated are conservative or otherwise reinforcing the aircraft's (A/C's) structure or limiting the A/C's operation.

In this context, the Aeronautic Industry has been demanding for a long time new, more flexible, accurate and economical methodologies to measure loads in flight, to move away from the current strain gauge based ones.

This paper succinctly describes the overall load calculation procedure (section 2), the standard model validation procedure (section 3) and proposes an innovative photogrammetry based, deformation measurement technique and loads model validation methodology (section 4). Preliminary results on the C295MW + AEW (Fig.1) prototype are presented in section 5, along with a number of lessons learned and conclusions. Airbus DS is confident that the continuation of this investigation will result in a robust and reliable method to measure in flight loads and to validate the loads model, significantly reducing the cost and complexity of the task when compared to the current standard methods based on strain gauges.

Fig. 1 C295MW with AEW radar

2 Loads Calculation

The calculation of aircraft loads, i.e. the definition of a set of load distributions over the entire aircraft structure representative of all possible flight & ground conditions, in accordance with the requirements held in the regulations, is performed by means of a loads model. The loads model, as defined at Airbus DS Static Loads Domain, is a dataset of linear and/or non-linear equations that relate loads at different aircraft stations, called Monitor Stations (MS), with the variables and parameters used to describe the A/C's state (flight angles, configuration, speed, acceleration etc…), whether in flight or on the ground.

The loads model accounts for every possible effect affecting loads, and is structured in three main parts, namely the aerodynamic model, the inertia model and the miscellaneous model.

The aerodynamic model relates loads at MS with those variables and parameters affecting it, such as Mach, angle of attack (α), side-slip (β), control surface deflections (δ's), configuration parameters etc… It is usually formulated as panel pressure distributions, calculated by means of CFD and/or wind tunnel test data (WTT) and finally tuned to flight test data.

The inertia model relates loads at MS with the inertial variables, i.e. load factors (Nx, Ny, Nz), angular accelerations (dp/dt, dq/dt, dr/dt) and products of angular rates (p^2, q^2, r^2, pq, qr, pr). To set it up the A/C is modelled as a distribution of mass points, including its inertia moments. The model is verified by weighing main components separately and finally weighing the final A/C before flight.

The so called miscellaneous loads model accounts for any other effect that may influence loads on the A/C, such as engine loads (thrust, torque, propeller 1P loads) or loads introduced by the landing gear.

The classic approach to load calculation is generally based on maneuver simulation, by means of an engineering flight simulator, to obtain the variation of the A/C variables and parameters in the time domain. This allows calculating via loads model the evolution of loads at all MS (i.e. load distributions over the structure). Simulations must cover all maneuvers required by the certification standards or the high level design requirements. The engineering flight simulator has to be as representative as possible of the real A/C, including its flight control system, whether a direct mechanic linkage system or a sophisticated electronic fly-by-wire, including flight control laws, travel limiters or any other logic.

It is evident that defining load distributions to size the structure is a complex process, associated to many uncertainties at the time of structural design; hence the need of in-flight measurement of loads and the validation of the loads model before reaching A/C certification.

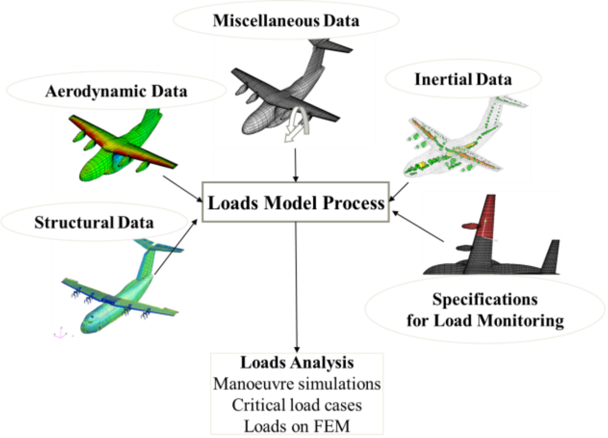

Fig. 2 Loads model & analysis summary

3 Standard Loads Model Validation

Standard loads model validation is performed by evaluating predicted load distributions against measured ones. The current methodology at Airbus DS is based on measuring micro deformations of the structure at given locations by means of arrays of strain gauges. In the case of the C295MW project (standard C295 equipped with winglets), the latest Airbus DS aircraft to undergo a model validation, the loads measurement has been performed by means of stain gauges installed along the outer wing of the test aircraft (C295-P1 test A/C equipped with AEW radar and winglets). These strain gauges, when properly calibrated, give an electric signal that can be related to loads at its position.

Even if this technique has been in service for many years, it still presents important challenges and disadvantages, as the signal coming from the strain gauges, even if properly calibrated, is severely affected by atmospheric changes, mainly temperature, the presence of contaminants, possible defects in the adherent layer and many other issues. Recording accurately the flight variables is also a non-trivial matter, which requires a very well equipped aircraft, with sufficient redundant sensors to properly filter the data. This all implies a significant post-process effort, analyzing the data carefully, evaluating its quality, the goodness of the sensor calibration and the possible presence of offsets.

Measuring loads by means of strain gauges is also a rather costly technique, as installing and calibrating the strain gauges requires grounding the aircraft for a significant period. Another major issue is managing the installation of these devices and its associated wiring in aircraft areas with little or no access, meaning that the gauges in these areas have to be installed when the components are manufactured, with no possibility of repairing, exchanging or evaluating them on a later date.

On board of the C295-P1 test A/C, the strain gauges shown in Fig.4 were available. As can be seen, some of the torsion bridges had fallen out, with no opportunity for repairing mainly due to cost and the A/C's tight test schedule.

The following image (Fig.3) shows an example of the time histories recorded for some of the main flight variables during a single manoeuver.

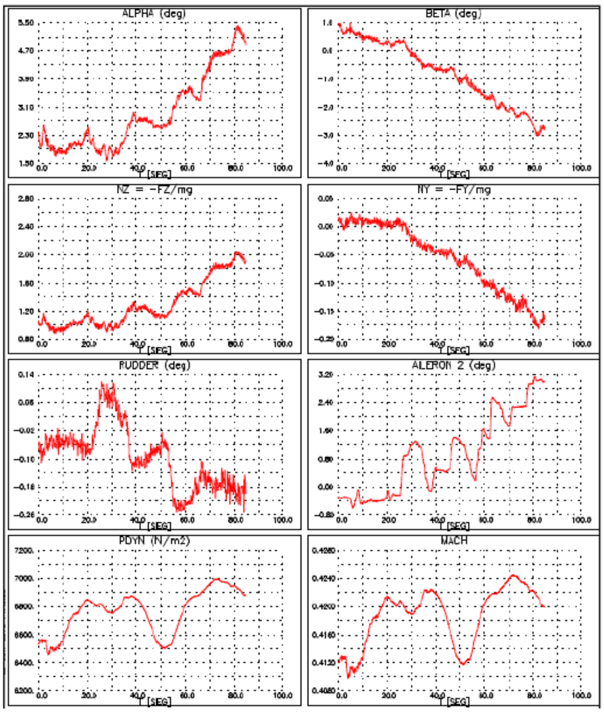

Fig.3: Example of recorded flight parameter time histories

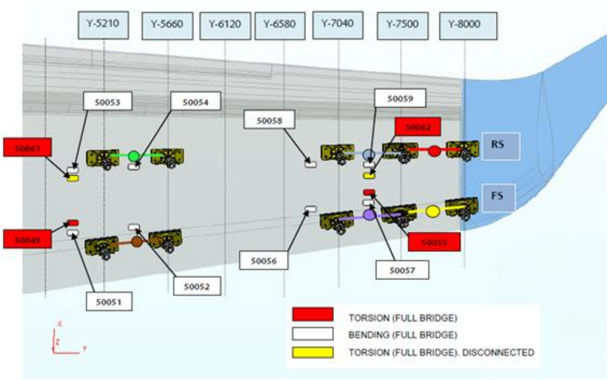

Fig. 4 Loads Model & Analysis summary

Fig.5 shows an example of the load results (bending moment at the indicated monitoring stations) obtained both in flight (black line) as well as through simulation with the loads model. As can be seen, there was a need of tuning either the loads model (mainly when there are differences in slopes or shapes, or repeating errors in off-sets) or the calibration of the measurement system (mainly when there are offsets that only appear at certain conditions).

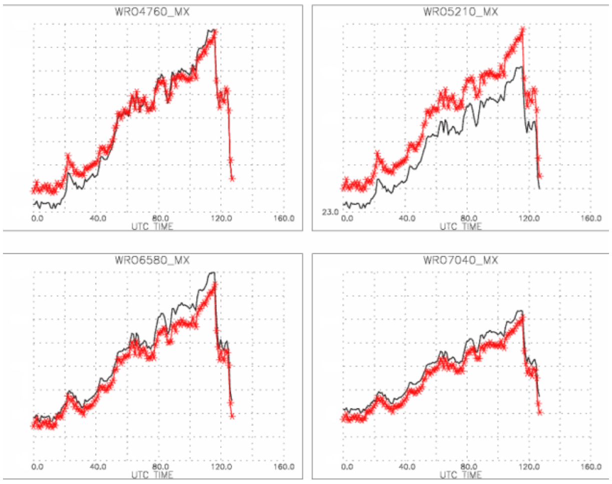

Fig.5: Examples of recorded load time histories (black) vs calculated loads (red dotted)

These images give only a glimpse of the enormous post-process task associated to performing a validation of the loads model, given the intrinsic complexities and the vast amount of data that is recorded during the flight campaign. In fact, a significant effort had to be dedicated to select a set of time instants (less than a hundred) or very short time histories, where there was certainty on the quality and validity of the results. Of course this implied a great analysis effort in terms of selecting and statistically validating the chosen time instants.

The new model validation technique currently being evaluated targets to reduce the effort and cost of this task addressing some of the main draw-backs of the traditional approach, as described in the next section.

4 Photogrammetry Based Loads Model Validation; Method Description

The new methodology that Airbus DS is developing and evaluating to validate the theoretic static loads model is based on direct, non-invasive measurement of wing deformation using photogrammetry.

The overall methodology consists of three main parts. The first one is dedicated to in flight data gathering, including the setup of the measurement instruments (cameras and reference stickers), the calibration of these instruments, the performance of the necessary flights and the post-process of the images to obtain wing deformations.

The second and third parts are dedicated to establishing an adequate mathematic procedure to estimate wing deformations at the same locations where deformation is measured. The second part, see section 4.2, focuses on the definition of a set of deformation matrices which will render unitary displacements at the points of interest as a function of unitary loads, addressing issues like the selection of the most representative model boundary conditions. The third and last part is the actual loads model validation. In many ways the procedure is similar to the one described in section 3, but benefitting from what is expected to be more reliable, less calibration error affected flight data. This should reduce the analysis cost of the procedure.

4.1 Photogrammetry Technique

Photogrammetry is a well-known deformation and displacement measurement technique that has been used for multiple applications in several fields, including aeronautics. Examples would be measurement of thermal deformation (satellite components) or monitoring aircraft store release, among others. Airbus DS is now applying it to inflight deformation measurement, taking advantage of one of its main qualities, i.e. its non-intrusiveness. Other main advantages of this new measurement technique based on photogrammetry algorithms are the simplicity of the installation, calibration and repair, the robustness of the measurements, which are far less affected by atmospheric changes than stain gauges, and the relative inexpensiveness of the techniques.

In this first evaluation of the methodology the focus is set on vertical displacements of the right outer wing sections. Displacements are measured as increments of the Z coordinate of the target locations along the wing with respect to the 0g theoretical model.

4.1.1 Measuring equipment & Setup

The measuring equipment consists of two video cameras synchronized with the flight parameters recording system of the test A/C. It is of primary importance to locate a place of installation free of deformation and vibration and with sufficient field of view to cover the target wing area where deformations will be measured. Of course, due to cost and simplicity constraints, it is required that a location for installation meeting all requirements is found on the fuselage, with no impact on the A/C's aerodynamics, discarding other options like pods mounted on booms or the vertical tail plane. After preliminary analysis it has been determined that the optimum area for installation on the C295 is the starboard landing gear fairing, as shown in Fig.6.

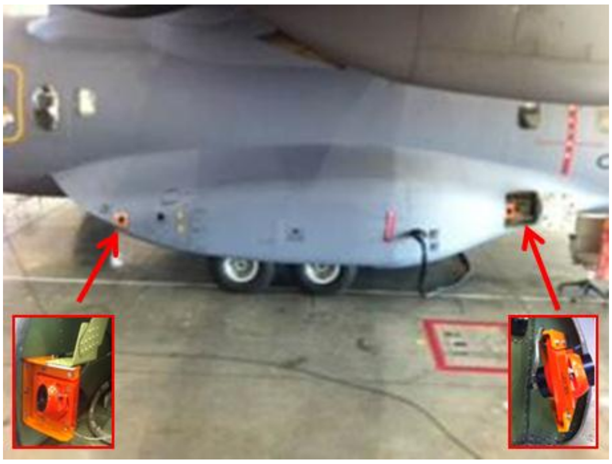

Fig.6: Camera location inside landing gear fairing

4.1.2 Calibration & Camera Positioning

This process is divided in three steps; system calibration, camera spatial alignment and identification of the target points where the deformations will be measured.

The aim of the calibration process is to obtain the intrinsic optical parameters of the cameras, more specifically of its lenses, like focal length, principal point and distortion of the lens. This has been done by means of Jean-Yves Bouguet's calibration toolbox [2], taking pictures of a checked board of known dimensions in different positions, varying distances and angles.

The position (x,y,z coordinates) and spatial alignment (roll, pitch and yaw angles) of the cameras has to be determined accurately with respect to the A/C's basic reference system. To calculate both camera position and orientation, a set of stickers is used as reference marks (Fig.7), placing them inside the cameras' visible field. With the aid of a tachymeter, the positions of the marks are measured in tachymeter coordinates, and then transformed to the aircraft reference system. Then, the 2D coordinates of the stickers on the picture are measured, and with the intrinsic parameters of the camera and with the 3D coordinates of the stickers the position and orientation of the cameras are calculated.

Fig.7: Determination of camera alignment

The last step in the preparation of the system is to paste measurement stickers on the spots where displacements are to be determined. These stickers are squares divided in yellow and black triangles, thought to signalize the target point with its center, simplifying the post-process of the images. As the magnitude of interest is the displacement (mainly in Z axis) of the right outer wing with respect to the 0g theoretical model, it was agreed to take measures at the nine most outward ribs of the wing structure. The sticker centers were placed over the bolts at the junction of ribs and wing stringers, which is a location easily identifiable both on the A/C and in the structural model. A total of 45 stickers were placed, four to six per rib (Fig.8), from section (Rib) Y=4310mm to Y=8000mm of the outer wing.

Fig.8: Sticker array on the outer wing's lower surface

4.1.3 Data post-process

The post-process of the inflight recorded images procedure includes a) extracting the image 2D coordinates of the sticker centers for both cameras; b) applying the camera calibration to these coordinates; c) calculation of the director vectors from camera to calibrated 2D sticker coordinates; d) calculation of each camera's 3D lines of sight, using the director vectors previously mentioned (Fig.9); e) calculation of final position of target point by determining the minimum distance between both lines of sight; f) calculation of absolute displacement with respect to 0g theoretical model.

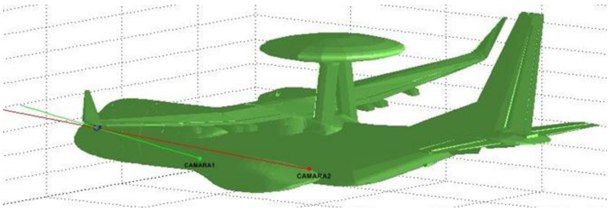

Fig.9: Measurement concept on C295 test A/C

4.2 Structural Model

The structural model of the aircraft is necessary to translate loads into displacements, and therefore allow checking calculated loads against measured displacements.

For this initial development of the methodology, loads are applied at each rib of the right wing, on the middle point between front and rear spar, which means a total of 27 load entry points. At each point forces and moments in all three axes can be entered. The target is to attain the displacement of each of the 45 target points using the structural model, as described in 4.1.2. As an additional check the displacements suffered by the camera locations are also calculated, in case it happens to be significant. This means that a total of 47 displacement matrices are calculated, describing the influence of each of the 6x27 unitary forces and moments on the displacement of each target point. In the end this will allow establishing a displacement model equivalent to the loads model.

The calculation of the deformation matrices has been done using the C295 P1 test A/C Nastran finite element model (FEM), equipped with both aerial early warning radar (AEW) and winglets.

A question that may arise is the overall representativeness of this structural model with respect to the test A/C. The availability of a representative, high fidelity structural model of the A/C is of primary importance to the project, as whatever error in it will be directly reflected on the results. The C295-P1 prototype was the first A/C of its class, the wing being a reinforced CN235 one. It has suffered a number of modifications later on, as it has been used to test several devices attached to the wing. Although the structural model has been updated with all these changes and its modal response adjusted to ground vibrational test (GVT), it is likely that the static response is not exactly the expected one. Nonetheless Airbus DS understands that for the current development phase the model is representative enough. Whatever errors may occur due to the mentioned reasons, they are expected to be small with respect to the uncertainties in this first approach.

Also the model boundary conditions have been identified as a considerable source of uncertainty. Simulating a flying condition with sufficient fidelity implies loading the structure with a balanced load case, reacting the forces and moments on the entire structure at a time, with no need to limit the rigid body motion. This is not the case in this exercise, as load will be entered only on the right wing, which means that these loads have to be reacted at some specific point, thus restricting the rigid body motion. Choosing the appropriate position to apply this reaction would have needed of a specific, detailed study. For this first phase of the study it has been decided to proceed with a simplified model, reacting the load at fuselage-wing joints. This choice means that the fuselage goes close to unaffected by the loads on the wing, with no displacement at the camera locations at all, i.e. the wing is treated like a simply supported beam. Nevertheless an action has been started to define the best possible boundary conditions to calculate the displacement matrices for the next development phase.

A last lesson derived from the model and boundary conditions selected is the importance of taking into account the effect of loading both half-wings, i.e. even if only the displacements of the right half-wing are being monitored, both right and left half-wings have to be loaded. Loads on one side of the wing cause about a 10 to 15% of the deformation on the opposite half-wing, as shown in Fig.10, where a vertical load at the right wing tip causes a vertical displacement of 1.6mm of its point of appliance, but also 0.19mm displacement at the opposite tip. To simplify the calculations both on the structural as on the loads side in this first evaluation phase, the hypothesis of considering the aircraft symmetrically loaded at whatever flight condition has been accepted, something that will not always be the case.

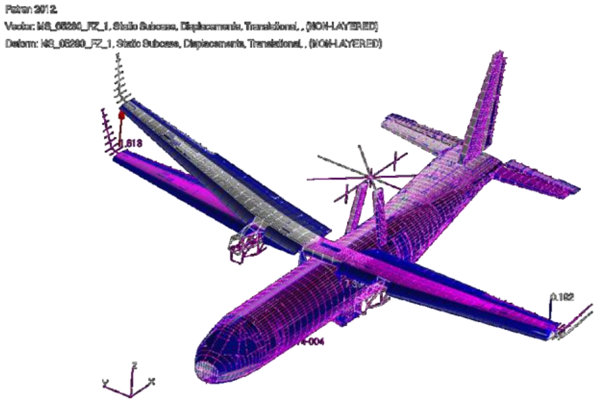

Fig.10: Importance of loading both half-wings

4.3 Loads Model Validation

4.3.1 From loads to displacements

The loads model validation is done in terms of wing monitor station displacement, each monitor station being assigned to one of the wing ribs. As mentioned, the photogrammetry system measures the displacements of four to six points on nine rib sections of the outer wing, where the stickers have been attached. By means of the displacement matrices described in 4.2 loads over the wing are to be translated into displacements at these 45 sticker positions.

For this first approach, it has been agreed that wing loads are to be discretized as forces and moments on 27 monitor stations (one MS located at each wing rib). In consequence the wing loads model, which is formulated as integrated loads at each MS, is reshaped to obtain distributed loads along these 27 monitor stations, one load vector per model variable. These load vectors are transformed into displacement vectors by means of the displacement matrices, obtaining a displacement model. Now the total displacement of each sticker can be calculated as a summation of displacement model coefficients times the load variable values, taking into account the same efficiencies or non-linearities the loads model considers.

Transforming loads into displacements is a linear operation; therefore whatever conclusions are reached in terms of displacement comparisons can be projected on the loads model, given the structural model is accurate enough.

4.3.2 Model simplifications

Regarding the loads model, a number of simplifications have been undertaken, mainly oriented to focus the task on those effects that may play a principal role in vertical wing displacements. For example only the main aerodynamic variables have been taken into account, such as angle of attack, side slip, aileron deflection etc...

The inertial model depends on the fuel quantity present in both the inboard and the outboard fuel tanks. Both the total fuel quantity at take-off and the approximated burned fuel quantity at the time the test is conducted are recorded in flight. An approximated inertial model, interpolating as a function of total onboard fuel between empty wing, full inboard tank and full fuel (both tanks) is setup, in accordance with the A/C’s fuel sequence (gravitational). This simplification avoids having to define a specific mass state for each flight condition, deeming the error produced to be small.

A probably more significant simplification has been done regarding the miscellaneous model. To avoid entering the complexities of the powerplant loads, including 1P loads, only thrust has been considered. This simplification will no doubt have to be revised on a future date.

4.3.3 Loads Models and Flight Maneuvers

Usually two different aerodynamic loads models are generated for each C295 aircraft, one for flap retracted and one for flap fully extended (23º), as flaps positions are treated as different A/C configurations.

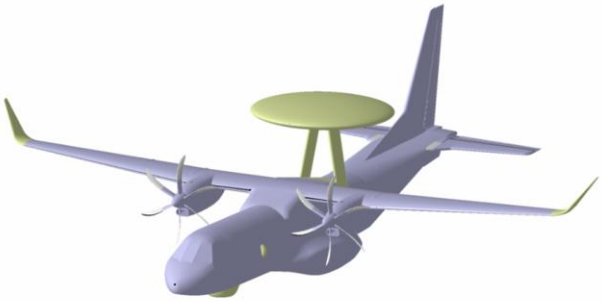

Fig.11: C295MW + AEW aero model.

To perform the Loads Model validation it is usual to request data of three types of maneuvers, namely 1g trimmed conditions, wind up turns (WUT) and steady heading side slips (SHSS). The WUT is a coordinated turn, starting from 1g trimmed condition, slowly increasing the angle of attack (AOA) and the load factor (Nz). This maneuver is especially useful to check the evolution of wing loads with respect to its two main drivers, i.e. angle of attack and load factor. The SHSS is a yaw maneuver, which if properly performed should keep Nz constant and close to one, at more or less steady values of angle of attack, while the side slip angle (SDP) increases. SHSS are usually relevant to validate the model associated to vertical tail and rear fuselage, but in this case, due to the presence of the winglets, these maneuvers are relevant for wing loads as well. The 1g trims are used as checks at fixed conditions.

5 Results, First Evaluation and Future Work

This section tries to give a first impression on some of the results obtained, keeping in mind that the developers are already aware of a number of corrections and improvements that have to be implemented in the future, i.e. any evaluation done in this section is a mere qualitative impression and will have to be thoroughly investigated in the future.

Summarizing the learned lessons before coming to the results, the first known improvement that has to be pointed out is the need of developing an automatic image post-process tool to be able to attain deformation time histories at a high sampling rate. Currently this work has to be done manually, processing image by image. In the meanwhile a number of discrete time instants have been processed, the focus being set on the most outer wing sections (stickers 1 to 19, sections Y=6580mm to Y=8000mm of the outer wing), as they were considered of greater interest. For some flights it happened that due to resolution problems displacements at the last section (Y=8000mm) could not be captured. The availability of deformation time histories will also contribute to identify possible oscillations of measurements.

A second issue to be taken into account, as described in 4.2, is the sensitivity of the calculated deformation results with respect to the structural model used. There is already an action ongoing to improve the structural model as well as the boundary conditions it is subject to, increasing the level of confidence in it.

In this exercise Airbus DS is performing the loads model validation by means of photogrammetry on the original A/C design loads model. In the meanwhile Airbus DS has already performed a standard, strain gauge based, loads model validation for the C295MW, which has led to changes in the aerodynamic model to be used for certification of the aircraft. The idea is to verify that similar conclusions are reached with the new technique.

Following images show, respectively, several instants of two different WUT maneuvers, (Fig.12 & Fig.13), both at flaps up conditions, and several instants of a SHSS at flap down conditions (Fig.14). All images have the same format, measured displacements in Z axis being marked in blue, while the estimated displacements are marked in red, in both cases using the same marker symbol.

This first figure (Fig.12) shows that there is clearly an overestimation of displacements at low Nz and small angle of attack, which grows smaller as both load factor and angle of attack increase. This behavior is confirmed by Fig.13 with a somewhat smaller ratio of gap reduction between measured and calculated displacements. It has to be pointed out that flight 864 was performed after having removed the AEW structure. This has an impact on the inboard wing aerodynamics, which has been considered in the loads model, and no significant impact on the structural model. Both flights took place at similar dynamic pressure ranges, the first from 6500Pa to 6900Pa and the second from 6300Pa to 6700Pa, which allows comparing absolute displacement values. The differences between measured and theoretic deformations could be indicative of an error in the structural model, causing an offset in displacements, and possibly a too small derivative of displacement with angle of attack, which in the end is the lift to angle of attack derivative in the loads model ($C_{L\alpha}$), which seems to be more significant in Fig.12.

Surprising is also that at one instant in Fig.12 (Nz=1.81, AOA=4.57) measured displacement is greater than the theoretic one. If some credibility is granted to what has been explained just above, this might be indicative of an oscillation in measured data. This of course couldn't be checked yet.

The last example of measured versus calculated displacement is Fig.14. It shows the evolution of displacements during a SHSS at flap down condition and A/C with AEW structure. All measurement have been taken at Nz values close to one (range 0.8 to 1.1). The dynamic pressure ranges from 1700Pa to 2250Pa. A first evaluation of this figure shows that there is an offset in the displacement calculations, the approximate offset values scaling properly with the dynamic pressure and the fact that now flaps are deployed, as expected. At the same time, while measured displacements suffer small variations with side slip and attack angles, the calculated ones suffer greater ones, apparently related to both effects at the same time. This last argument is substantiated by looking at the same time at the evolution of AOA and Nz with respect to SDP. This may point in the direction of the existence of a cross-effect between angle of attack and side slip that had not been properly captured in the original model. This has already been incorporated into the standard loads model for A/C certification.

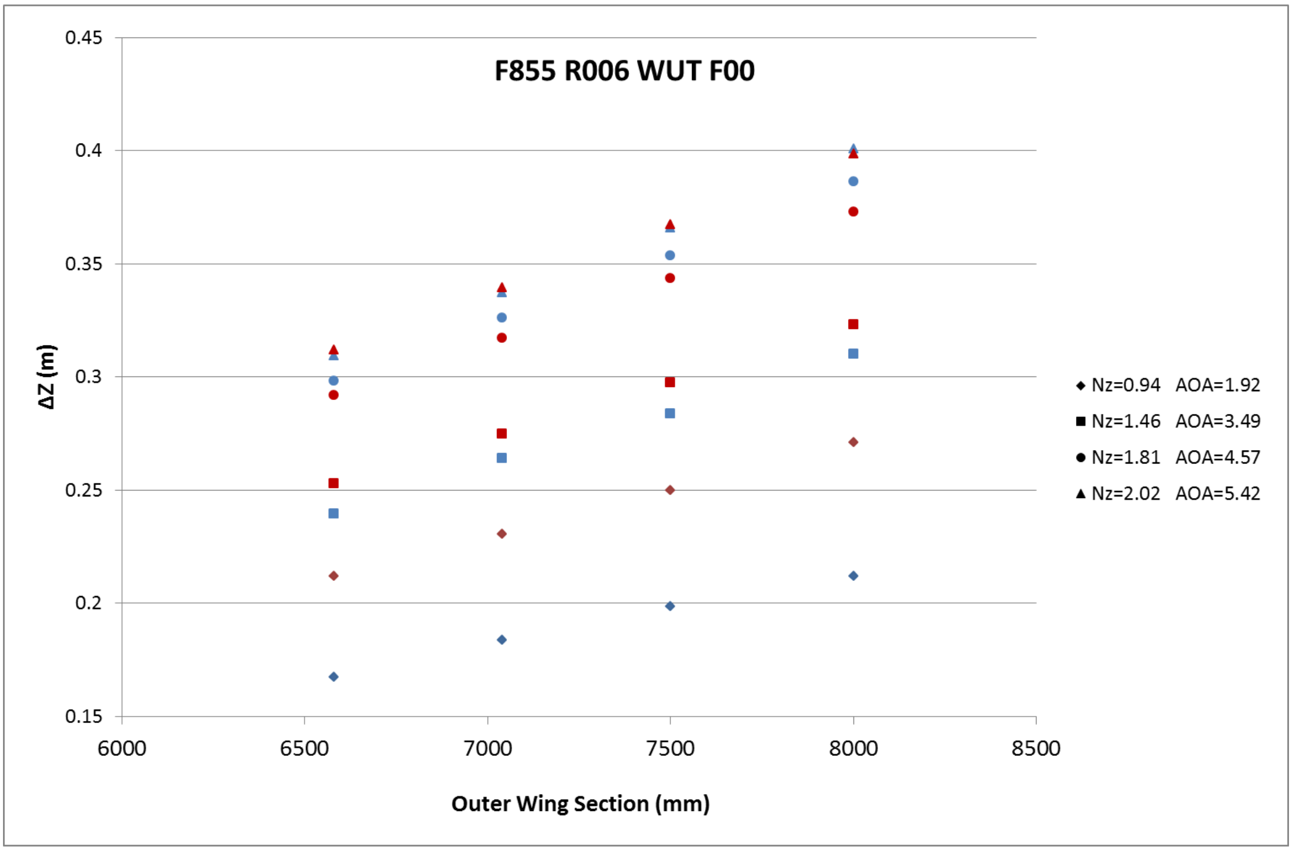

Fig.12: C295 AEW+Winglets test A/C, Flight 855 Run 006 Flap 0, theoretic (red) vs. measured (blue) displacement at each section. Legend indicates load factor (Nz) and angle of attack (AOA) at each of the four time instants.

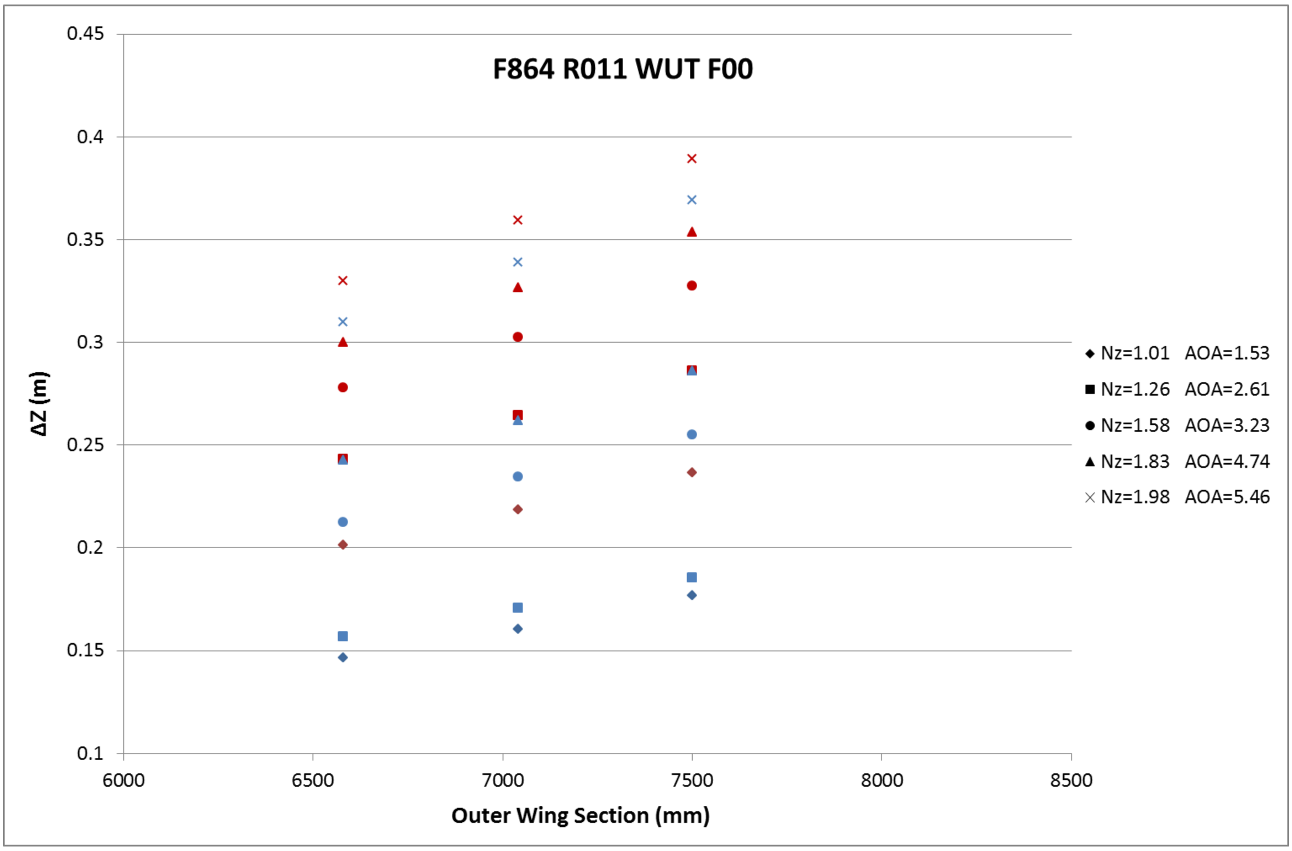

Fig.13: C295 Winglets test A/C, Flight 864 Run 011 Flap 0, theoretic (red) vs. measured (blue) displacement at each section. Legend indicates load factor (Nz) and angle of attack (AOA) at each of the five time instants.

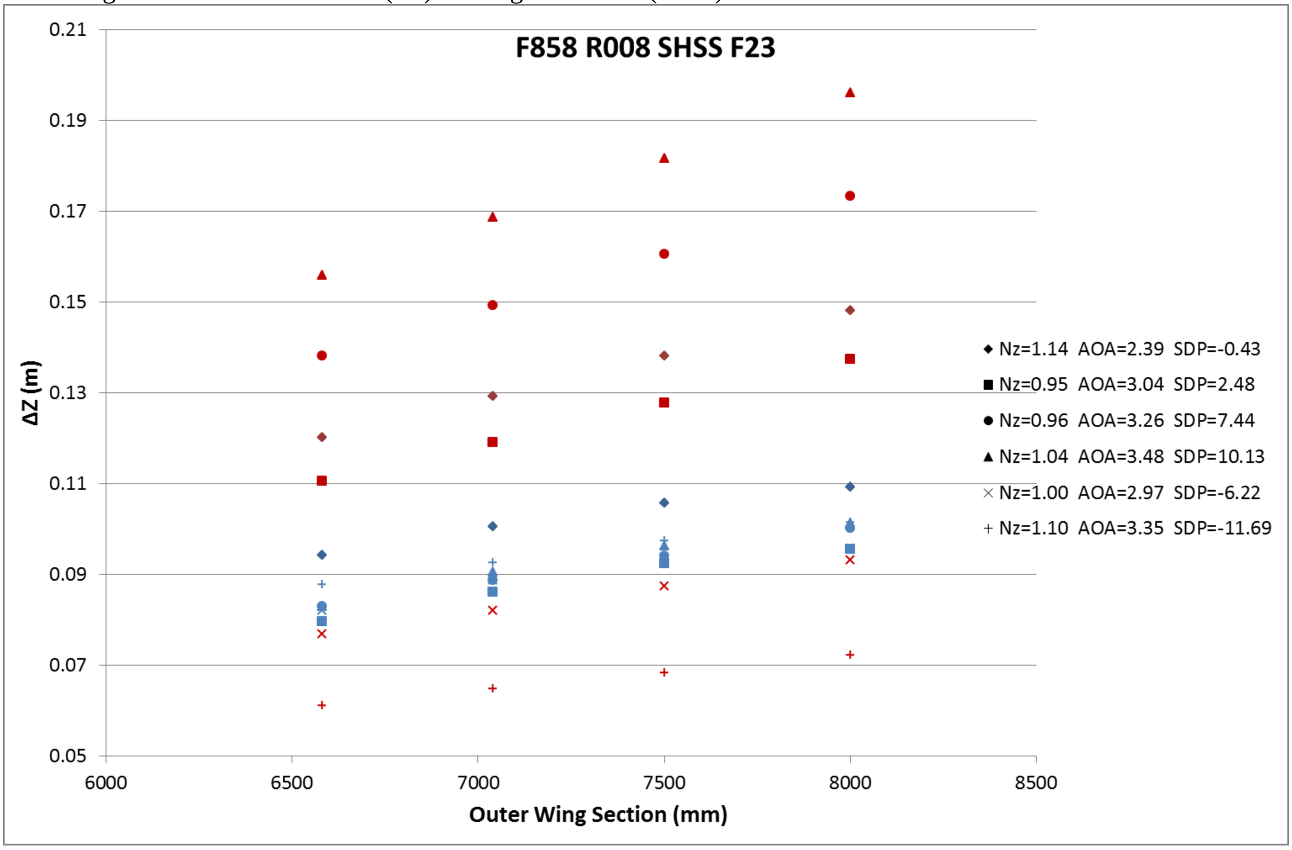

Fig.14: C295 AEW+Winglets test A/C, Flight 858 Run 008 Flap 23, theoretic (red) vs. measured (blue) displacement at each section. Legend indicates angle of attack (AOA) and side slip (SDP) at each of the six time instants.

As a final comment on the current status of the development, one could state that a lot has been progressed in the definition and evaluation of the methodology proposed in this paper. The availability of flight test data has led to the detection of some misconceptions and the identification of several potential improvements, some of which will have to be necessarily implemented during the next development phases.

Nonetheless the results are encouraging, and Airbus DS has the firm believe that this methodology is worth the effort dedicated to it, offering a good, simple and economic way to determine in flight loads. This may possibly also lead to a reduction of the current effort dedicated to the post-process of data.

In the near future, and while some technologies like the automatic image treatment tools are ripened, Airbus DS intends to continue working on the evaluation of the methodology, addressing the problems related to the structural model and validating the loads model using photogrammetry measurements for the same flight instants as used for the validation performed by means of extensometers.

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