PROGRESS IN THE PREDICTION OF AEROSERVOELASTIC INSTABILITIES ON LARGE CIVIL TRANSPORT AIRCRAFT

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Abstract

The civil aircraft manufacturers are developing and studying very large transport aircraft capable of seating more than 500 passengers. Some typical characteristics of these aircraft (overall size, mass, number of engines, large diameter engine fan, …), associated with flight conditions in the transonic regime and implementation of Flight Control Systems (FCS) require to improve the models for the prediction of aeroelastic instabilities.

The paper shows that progress made by Airbus partners in the field of aeroservoelasticity have been initiated by remarkable technical events coming with the development of Airbus aircraft family. It reviews the progress which have been made in the structural dynamic and in the unsteady aerodynamic models, as well as in the prediction of interaction with the Flight Control Systems .

1 Background of progress in aeroservoelasticity

Progress in industrial activities is a continuous process, but it is also triggered by special events which can be technical or economical. Since the launch of the first Airbus A300 in May 1969, large progress have been made in many fields by all Airbus partners.

The field of aeroservoelasticity is one of the technical fields for which noticeable technical progress has been made. The paper reviews some technical events which were important for the progress in aeroservoelasticity and explains with examples the progress over the last twenty years. Economical reasons can also explain the need for progress, but they are not considered here.

Four milestones linked with the development of Airbus aircraft are essential to understand the progress in aeroservoelasticity:

a) in the early 1980s, the use of a new supercritical wing and the application to primary structures of composite materials technology on A310, a shortened version of A300.

b) in the late 1980s, the implementation on A320, in addition to a), of fly by wire technology and the extended use of composites on horizontal and vertical tails.

c) in the early 1990s, the a) and b) events, in conjunction with the large size and four engines powered aircraft for the A340 series.

d) in the early 2000, the a), b) and c) features are there, in the perspective of A3XX development, but are enhanced due to the aircraft size. This size effect, which is of utmost importance for aeroservoelasticity is illustrated by some figures. The A3XX Max Take Off Weight will be 540 tons, the number of passengers 555, the engine thrust 69000 lbs and the fan diameter 110”. For these parameters, the ratios A3XX versus A340 range between 1.57 and 2, which gives an indication of the expected difficulties in the field of aeroservoelasticity.

The technical challenges to be taken up at each milestone were a source of progress. The paper reviews the progress made or still to be made for the aeroelastic models and for the prediction of FCS- aerodynamic and structural interaction. This review will address, as far as possible, the progress according to the above milestones.

2 Progress in the aeroelastic models

The aeroelastic models have been improved thanks to progress both on the dynamic structural model and on the unsteady aerodynamic model. The influence of the improved representation can be judged on the frequencies and damping of the aeroelastic model, and on the dynamic responses.

2.1 On the dynamic structural model

In the early 1980s, the state of the art for the dynamic models is a structural Finite Element Model coupled with a lumped masses representation. The aircraft FEM is composed of detailed FEM for some sections which are considered to be influent on the aeroelastic behavior and of equivalent beams representing a suitable stiffness for other sections(e.g., front and rear fuselage sections). A progress was made in the mid 1980s, when composite sections were introduced on A310. The A310-300 vertical tail plane and elevator were the first candidates. From this time, the aircraft FEM incorporates composite FEM. The quality of composite dynamic models is calibrated versus static and dynamic tests.

An important concern for the dynamic model is the representation of engines. The need for a flexible representation of the engine coupled with the aircraft appeared in the mid 1990s for the dynamic loads prediction after a fan blade release, for the continuation of flight in windmilling conditions. For the aeroelastic aspects, it was usually assumed that the representation of the rigid body movements of the engines was sufficient in order to properly assess the low frequency dynamic behavior. However, the influence of a FEM with several thousands of degrees of freedom versus a 6 degrees of freedom engine model has been studied on a four engines aircraft model. The usual 6 dof outer engine model was replaced by a detailed engine model on both sides of the aircraft (figure 1). The aircraft low frequencies up to 5 Hz are nearly unchanged. The maximum frequency shift of these modes is 0.5%, but the frequency of the so called outer engine roll and yaw mode at 5.5 Hz is increased by 20 %. It shows that the assumption of rigid body movements of the engine cannot be considered as valid, even if the frequency is very low (about 5 Hz). The influence of the several thousands dof engine model can also be judged on the flutter behavior and on the dynamic response in the case of aileron excitation (figures 2 and 3). This example shows that the influence of a detailed engine model is not negligeable, even at low frequency, in terms of frequency, damping and response, especially for some modes with engine movements.

Another factor to consider, especially with an outer engine installation and a large diameter fan, is the gyroscopic effect. The system of equations governing the response of the aircraft is:

$$[m]\{\ddot{q}\}+\left([b]+[\Psi]^T[G]\,[\Psi]\right)\{\dot{q}\}+[g]\,\{q\}$$

$$=[\Psi]^T\{F_{aero}(t)\}+[\Psi]^T\{F_{other}(t)\}$$

with :

- $[m]$, $[b]$ and $[g]$, diagonal matrices, representing the modal mass, damping and stiffness.
- $[\Psi]$ the mode shape matrix.
- $[G]$ the antisymmetric matrix of the gyroscopic effects.
- $[\Psi]^T\{F_{aero}(t)\}+[\Psi]^T\{F_{other}(t)\}$ is the sum of generalized aerodynamic forces and other forces.

The influence of the gyroscopic effect cannot be neglected, because the gyroscopic terms couple symmetrical and anti symmetrical modes. This influence is usually small on the damping of modes (figure 4), although it can be larger according to the payload and fuel configuration. But the key point is the modification of responses, especially on the engines. Figure 5 shows the non symmetry of an engine lateral response in turbulence and the comparison with the response obtained without gyroscopic effect.

The large deflections of wings on large civil transport aircraft can also impact the dynamic behavior (Ref. 4). A comparison of normal modes frequencies for two different wing shapes, the first one being the jig shape and the second one the gravity loaded shape, shows that the wing deflection of large aircraft has a real impact on the structural modes. A 5 % frequency shift can be obtained on the outer engine vertical mode.

2.2 On the unsteady aerodynamic model

For many years, the unsteady aerodynamic model used for the prediction of the aeroelastic behavior was obtained from the unsteady lifting surfaces theory. The Doublet Lattice Method allows to solve the linear aerodynamic equations and provides aerodynamic influence coefficients, function of Mach number and reduced frequency. The main limitation of this method comes from the impossibility to capture non linear phenomena like shocks, which appear during the transonic flight.

However, the DLM has been widely used by the aeroelasticians, trying to improve the model by scaling the aerodynamic influence coefficients versus wind tunnel measurements or CFD computations (Ref 2). In the early 1980s, in spite of the introduction of a new supercritical wing on A310, the aeroelastic analysis was performed with the above approach.

At this time, it had been shown by analysis and tests conducted in research works, that DLM was usually not conservative in the transonic conditions. It means that the flutter speed predicted with DLM is higher than the measured flutter speed. This feature of supercritical wings was called the "transonic dip". For this reason, unsteady Computational Fluid Dynamics codes have been implemented by Airbus partners in order to improve the capability to predict potential flutter cases in the transonic regime. The first step in the mid 1980s was the solution of Transonic Small Perturbations equations, then in the early 1990s, the solution of Euler equations. But, it was shown that the TSP method was not robust enough to properly predict well known flutter cases of two engines civil aircraft.

The development of four engines aircraft with high performance wings and with large deflections has enhanced the need for a better prediction of unsteady aerodynamics. The unsteady Euler CFD with a boundary layer coupling is today the candidate to complement the aeroelastic analysis performed with DLM. Figure 6 compares, for two different cases of aeroelastic coupling, the damping of a low frequency engine mode calculated from the DLM and Euler based methods on a four engines aircraft. The unsteady Euler method which allows to capture the position ant the intensity of shocks in 3D gives the aeroelastician a powerful tool to improve its capability to assess the strength of potential aeroelastic couplings in the transonic conditions. However, the need for a calibration of the unsteady CFD methods versus tests remains, due to the different applications and to the variants in the implementation of CFD methods (Ref 1 and 3).

3 Progress in the prediction of FCS and structure interactions

The introduction of FCS on A320 in the 1980s has opened the way for civil aircraft applications of aeroservoelasticity. The Interaction of Control with Aerodynamic and Structure (ICAS) was not a real difficulty for the aeroelasticians, because simple design precautions like the low pass filtering of structural modes was sufficient to avoid any ICAS. But, the so called "two actuators" design, for which a control surface is driven by two actuators, with one driving the surface and the other one acting as a damper, was much more challenging. Indeed, it was necessary to demonstrate that, without mass balance of the control surface, the aircraft had a safe behavior in configurations for which the surface was damped by only one actuator.

The next step, in the early 1990s, was reached with the A340 series aircraft, for which the increased flexibility made the ICAS more difficult to prevent. To check the absence of ICAS, once the FCS had been designed, was an important aeroservoelastic task on A320. Now, the current practice for the FCS design (Ref.5) is to consider handling criteria, but also aeroservoelastic and loads criteria. The issue of the aeroelastic model to the FCS designers allows to prevent the ICAS problem from the early stage of aircraft development. The aeroservoelastic instabilities are therefore avoided thanks to an integrated FCS design process (Ref. 6). This process considerably reduces the risk to discover late in the development an ICAS problem. Another means to manage the risk is to monitor the robustness of FCS design. Figure 7 shows the robustness of the damping versus phase variations for different loading configurations.

Another type of aeroservoelastic instability is the Aircraft Pilot Coupling (APC). The APC is characterized by a coupling of the pilot with the structural frequencies. Like for ICAS, the high structural flexibility is an aggravating factor for APC, because the number of modes within the actuator frequency band increases, and because they come closer the handling modes. The aeroelastic model which is distributed to the FCS designers and the use of flight mechanics simulators including the representation of in flight structural modes should help to anticipate the APC risks.

4 Conclusions

Over the last twenty years, large progress have been made by Airbus partners in the field of aero and aeroservoelasticity. The progress were pushed by the introduction of technologies as supercritical wings, composite structures, Flight Control Systems and by the development of large four engines aircraft which enhance the difficulties. Some of them have been reviewed in the paper. However, there is still a need for research in order to prevent adverse aeroservoelastic phenomena on the next generation highly flexible aircraft. The research should aim the improvement of aeroservoelastic prediction methods, but also the scope of ground, flight tests methods and identification of the aeroelastic model versus tests (Ref. 7) which were not developed in this paper.

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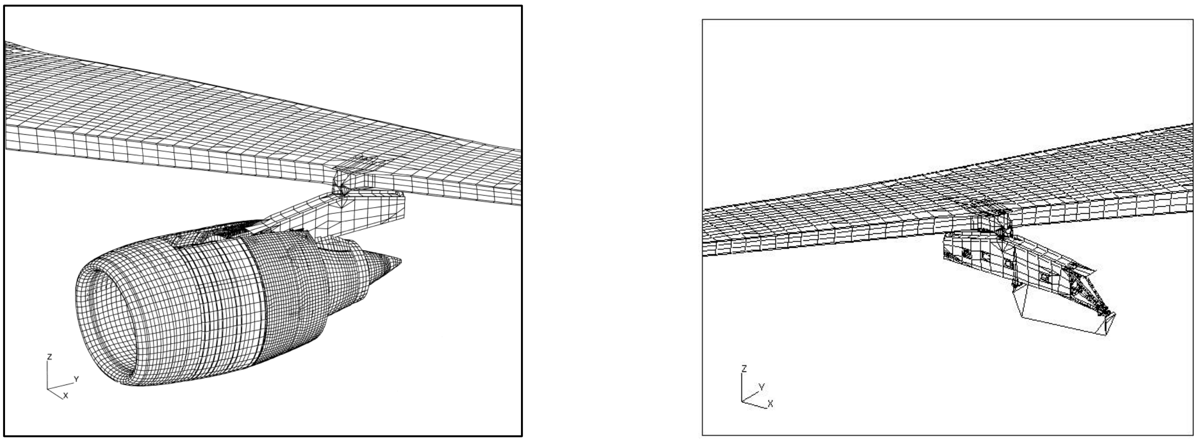

Fig 1 : Typical wing, pylon and engines FEM with 6 dof and several thousands dof engine representation

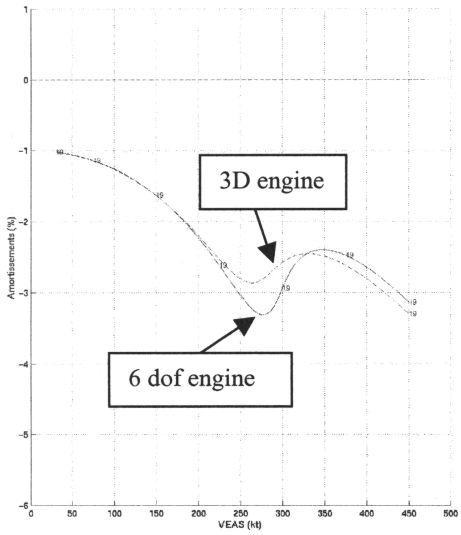

Fig 2 : Damping with 6 dof and detailed engine FEM

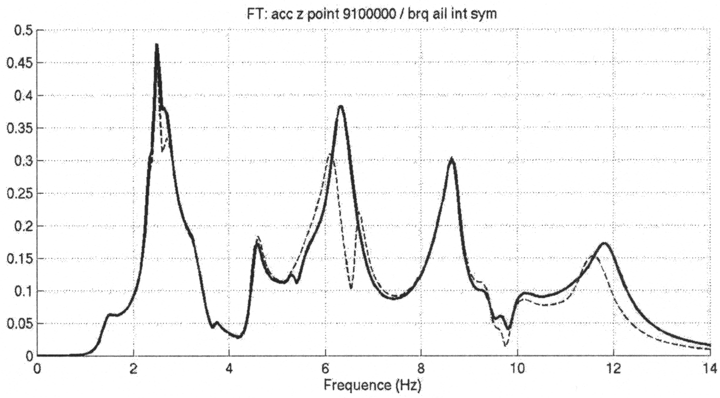

Fig 3 : Dynamic response with 6 dof and 3D engines

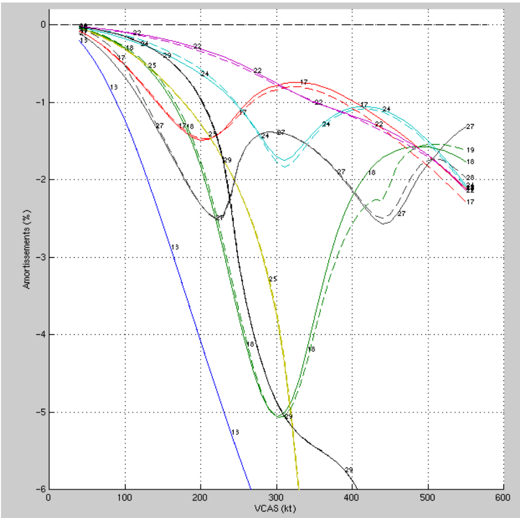

Fig 4 : Influence of gyroscopic effect on damping

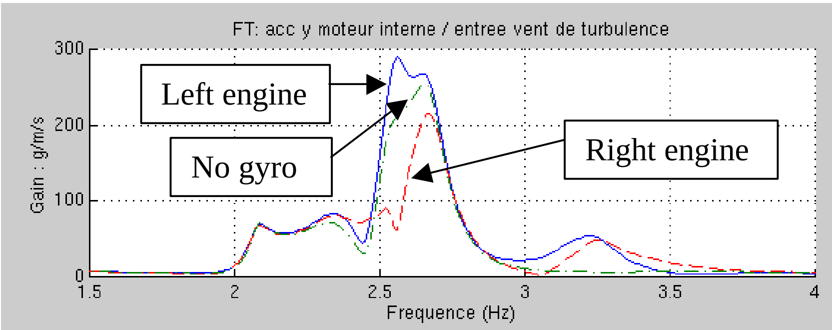

Fig 5 : Influence of gyroscopic effect on engine lateral response

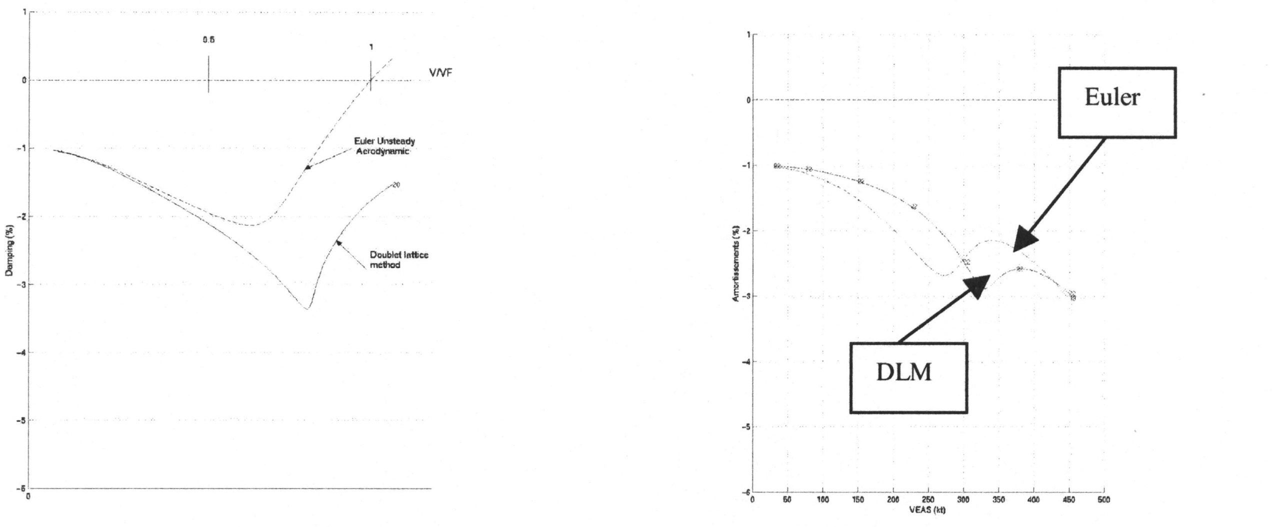

Fig 6 : Damping with DLM and Euler unsteady aerodynamic

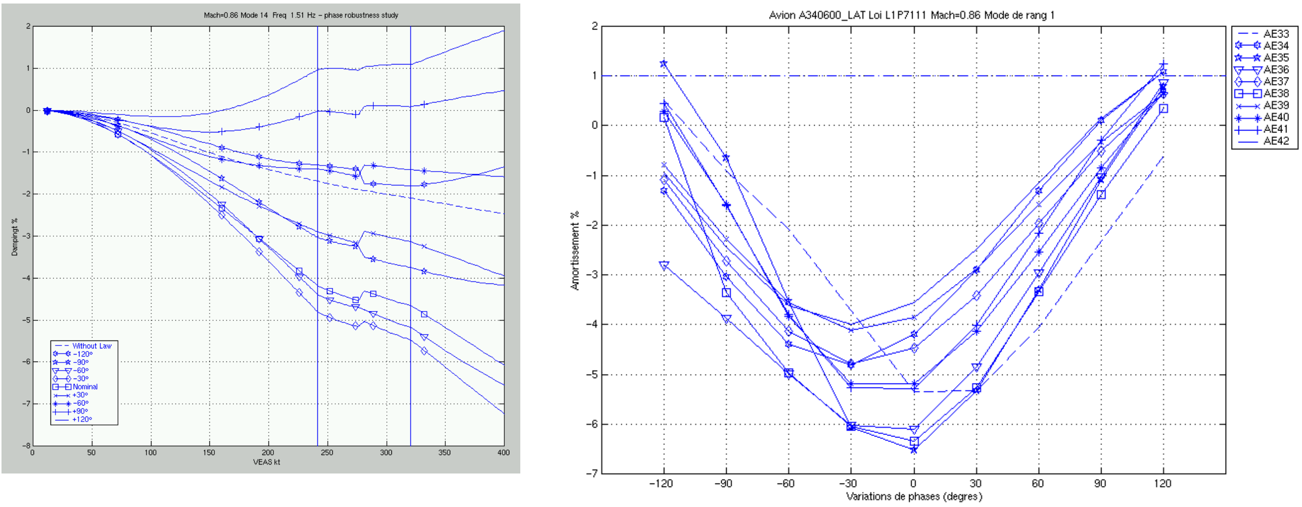

Fig 7 : FCS robustness study versus phase variations for different loading configurations