Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-30153

AEROELASTIC RESPONSE TO GUST USING CFD TECHNIQUES

Cédric Liauzun
Aeroelasticity and Structural Dynamics Department
ONERA
29 avenue de la Division Leclerc, BP 72, 92322 Chatillon cedex France
Email: cedric.liauzun@onera.fr

ABSTRACT

A numerical method to predict the aeroelastic response of an aircraft to a gust is assessed. It is based on the use of CFD techniques to compute accurately the aerodynamic fields. Gust models are then implemented as a field of grid deformation speed, that depends on both space and time. The numerical method has been first validated for a 2D Naca12 airfoil embedded in an inviscid flow and submitted to a sharp edged gust, by comparisons with results presented by Zaide et al. It has afterwards been validated in the case of a 3D wing submitted to a harmonic gust in the subsonic domain by comparisons with computations using the Doublet Lattice Method. After the validation step, the method has been used first to investigate the influence of the aerodynamic nonlinearities that occurs in the transonic domain, and at last to compute the aeroelastic responses of wings to gust excitations.

NOMENCLATURE

$\mathbf{X}$ vector of nodes coordinates
Ω elementary volume
t time variables
$\mathbf{W}$ vector of fluid conservative variables
$\mathbf{f}, \mathbf{g}, \mathbf{h}$ vectors of aerodynamic fluxes
$\mathbf{n}$ normal vector which components are n_x n_y n_z
$\mathbf{T}$ vector of fluid sources
$\mathbf{s}$ vector of the time derivative of the mesh deformation
$\mathbf{V}_G$ vector of the gust velocity
$\mathbf{u}_G$ direction vector of the gust velocity
λ_G gust wave length
$\mathbf{u}$ flight direction vector
U flight speed

INTRODUCTION

An aircraft design project has today to take into account wind loads due to gusts or to the atmospheric turbulence, at least for the certification of the aircraft (e.g. FAR/JAR 25 for commercial aircrafts [1]). Therefore numerous analysis methods have been developped in order to be able to predict gust effects earlier in the project process. The first methods are able to compute the responses to discrete gusts, and statistical treatments are then applied in a post processing step, to handle continuous gusts [2, 3]. Such analyses are most often studied in the frequency domain using linear aerodynamics. In particular, the Double Lattice Methods ([4]) or the Vortex Lattice Methods ([5, 6]) are used to compute aerodynamic forces due to a harmonic gust at a specified frequency. Time analysis can also be performed using the latter methods by applying a Fourier transform to the known gust time-law, by computing then the aerodynamics forces using the DLM, and by applying at last an inverse Fourier transform to the aerodynamic forces to get their time evolution. Such analyses are at least available in commercial softwares like NASTRAN [4]. Nevertheless, with increasing computing ressources, numerical methods based on CFD have appeared quite recently. Such methods are thus able to handle with non linear aerodynamics [7, 8]. All these techniques to compute gust loads have also been used to build aerodynamic or aeroelastic reduced order model for parametric studies [5, 9].

This paper is focused on the use of CFD techniques to compute the aeroelastic gust response of an aircraft in the time domain. Gust models are then implemented into a multi purpose CFD code with aeroelastic capabilities, according to the field velocity approach developped by Sitaraman et al [10]. Discrete gusts are thus modeled as a field of velocities depending on both space and time, field that is implemented as a grid deformation speed, whereas the Navier Stockes equations are solved using an ALE formulation to take into account grid motions or deformations. Such a technique allows to check the geometric conservation law, that is of most importance to get accurate solutions as Sitaraman et al have shown [10]. The first part of the paper gives a brief description of the gust models implemented in the CFD code. The second part is focused on the validation of these models by comparisons with DLM methods. And the last part is dedicated to the aeroelastic responses to gusts.

GUST MODELS DESCRIPTION

ONERA has been developing, since 1997, a software platform called *elsA* in order to be able to carry out all kind of aerodynamic numerical simulations that can be of interest in the aeronautic world (aircraft, turbomachinery, missile, space launcher, helicopter). It gathers all the ONERA's experience in the development of high accuracy algorithms (steady/unsteady RANS, DES, LES) for aerodynamic flow computations [11]. Aeroelasticity capabilities have also been implemented in order to perform fluid-structure coupling simulations in the time domain [12–14]. The four additional operators needed by the coupling process (i.e. the mesh deformation module, the structural solver, and the module performing the transfers from fluid to structure and from structure to fluid) have thus been developed within *elsA*. Furthermore, to make the fluid domain "follow" the structure during the simulation, i.e., the fluid mesh update to match the structure deformations or displacements, the Navier-Stokes equations are solved using an Arbitrary Lagrangian Eulerian (ALE) formulation :

$$\frac{d}{dt}\int_{\Omega(t)} \mathbf{W} d\Omega + \int_{\partial\Omega(t)} \Big[\mathbf{f}(\mathbf{W})n_x + \mathbf{g}(\mathbf{W})n_y + \mathbf{h}(\mathbf{W})n_z - \mathbf{W}\mathbf{s}\cdot\mathbf{n}\Big] d\sigma = \int_{\partial\Omega(t)} \mathbf{T}(\mathbf{W},\Omega,t) d\Omega \tag{1}$$

with the Geometric Conservation Law (GCL) condition

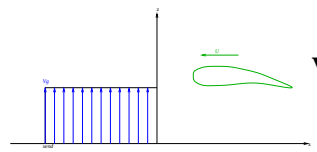
$$\frac{d}{dt}\int_{\Omega(t)} d\Omega - \int_{\partial\Omega(t)} \mathbf{s}\cdot\mathbf{n} d\sigma = 0 \tag{2}$$

where $\mathbf{s}$ denotes the grid deformation speed. This formulation leads naturally to introduce the gust velocity $\mathbf{V}_G(\mathbf{X},t)$ depending on both the spatial coordinates ($\mathbf{X}$) and the time variable (t) as a part of the grid deformation speed:

$$\mathbf{s} = \mathbf{s}_{Grid} + \mathbf{V}_G \tag{3}$$

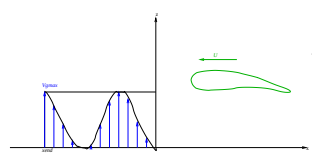
where $\mathbf{s}_{Grid}$ denotes the velocity of the grid deformation due to the structure or wall motion. This formulation allows to check the GCL even taking into account the gust velocity.

Three models of discrete gust have been implemented into the aeroelastic code: the first and simplest one is the "sharp edged gust" [2] (see figure 1). The second model called "One Minus Cosine" is often used for the certifications [1] (figure 2), and the last model is a simple "sine" one. The latter can be used to compute the response to a harmonic gust.



$$\mathbf{V}_G = V_{max}\mathbf{u}_G \quad if\ x_{end} + Ut \le \mathbf{X}\cdot\mathbf{u} \le Ut \qquad = 0 \quad else$$

FIGURE 1. SHARP EDGED GUST



$$\mathbf{V}_G = \frac{V_{max}}{2}\left[1-\cos\left(\frac{2\pi(\mathbf{X}\cdot\mathbf{u}-Ut)}{\lambda_G}\right)\right]\mathbf{u}_G \quad if\ x_{end} + Ut \le \mathbf{X}\cdot\mathbf{u} \le Ut \qquad = 0 \quad else$$

FIGURE 2. ONE MINUS COSINE GUST

AERODYNAMIC RESPONSES TO GUSTS

The first step consists of the validation of the numerical method for the computation of the gust response. Since few experiments are available, it has been decided to carry out comparisons with data provided by other authors or resulting from other numerical methods.

Numerical simulations have been first performed with the Naca12 airfoil submitted to a sharp edged vertical gust, which is defined to get an angle of attack jump of 2°, the fluid being inviscid. It has then been checked that after a long simulated

duration, the computed flowfield matches to the one providing from a steady simulation with an angle of attack of 2°. Furthermore, the transient aerodynamic behaviours, presented by Zaide et al [9] at Mach 0.2 and 0.7, have been reproduced (see figure 3 for Mach = 0.11).

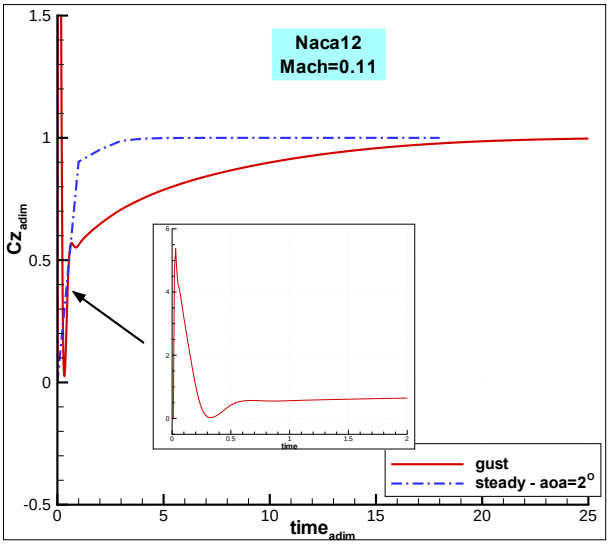


FIGURE 3. NACA12 - MACH=0.11 - SHARP EDGED GUST

The second validation consists of the comparisons between the CFD and the Doublet Lattice Method (DLM) for the aerodynamic response to a harmonic gust. They are performed with a 3D clean wing configuration (called "AMP wing") to which is applied a gust whose wavelength (λ_G) is 25 times the mean chord and whose amplitude is $1/40^{th}$ the flight speed ($U/40$, what is equivalent to an angle of attack jump of 1.43°). The gust frequency is then derived from the flight speed ($f_G = U/\lambda_G$). In order to better compare with the DLM method and to determine the effects due to the 3D geometry, two kind of meshes are built for the use of CFD techniques: a first 3D mesh modelling the wing with a flat plate that matches to the plan-form used with the DLM code, and a second mesh respecting the 3D geometry of the wing. Simulations are carried out for subsonic Mach numbers using the DLM and the Euler code with both meshes. A first set of simulations are performed at Mach 0.4 for a gust frequency of 19.83 Hz and an amplitude of 3.4 m/s. It can be noticed that a very good agreement has been obtained between the DLM and the CFD Euler with the plate mesh (see figure 4 that shows the distribution of the upper-lower surfaces variation of the unsteady Cp). Moreover taking into account the real 3D wing geometry has a very small impact on the unsteady pressure. A second set of simulations have been carried out at Mach 0.6 and for a gust frequency of 29.19 Hz and an amplitude of 5 m/s. Again a good agreement has been achieved between the three simulations (see figure 5). Nevertheless, discrepencies between the ΔCp distributions computed taking into account the 3D geometry and computed by the other simulations appear close to the wing root (top of figure 6). They can be explained by the fact that unsteady simulations are initialized with steady ones. The geometry of the wing being not symmetric, the steady solution obtained with the mesh matching to the 3D geometry of the wing is not symmetric and a weak shock occurs close to the wing root on the upper surface (figure 7), whereas the steady flow field computed with a plate is symmetric without any shock. The unsteady pressure distribution is then slightly non symmetric as can been seen on the unsteady pressure distributions along four slices on the bottom of the figure 6.

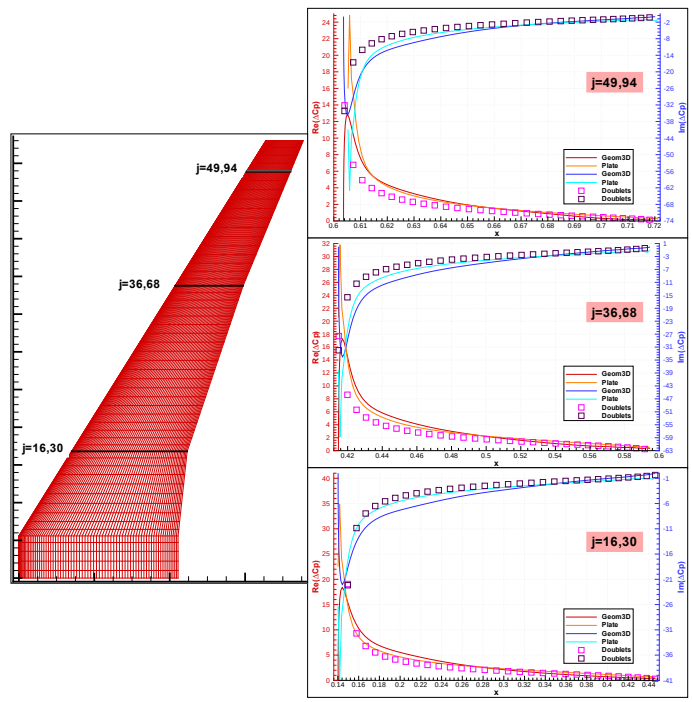


FIGURE 4. AMP WING - MACH=0.4 - UNSTEADY ΔCp DISTRIBUTION

Simulations have afterwards been performed in the transonic domain (Mach 0.8) with a gust whose frequency and amplitude are 37.94 Hz and 6.5 m/s, domain where the assumptions underlying the DLM formulation are a priori not valid anymore. As expected, the structure of the unsteady flow fields computed using the DLM and the Euler solver are greatly different (figure 8). A non linearity occurs at about 50% chord from the root quite to the tip, non linearity that is not captured by the DLM nor the Euler simulation with the plate geometry (see ΔCp distributions on figure 9). This shows a strong impact of taking into account

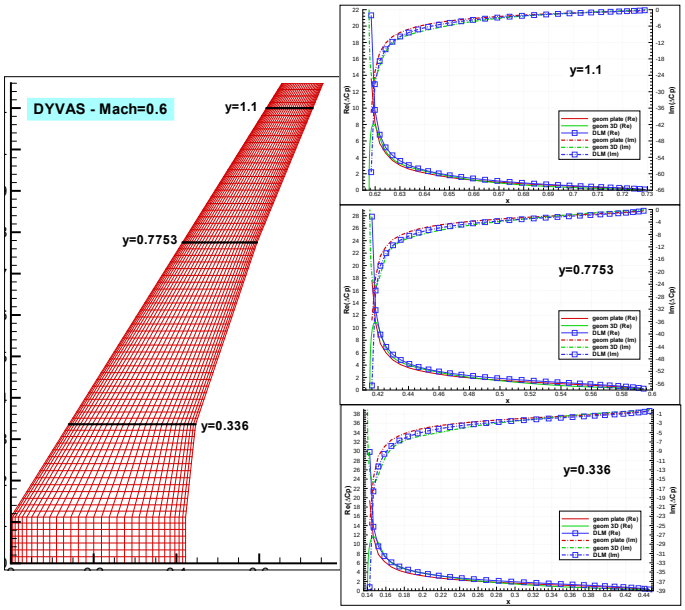


FIGURE 5. AMP WING - MACH=0.6 - UNSTEADY ΔCp DISTRIBUTION

the 3D geometry for such aerodynamic conditions. Indeed, the initializing steady solution shows a strong shock on the upper surface (figure 10), whereas the latter shock does not occur when the wing is modeled as a plate. The application of a harmonic gust induces a shock motion on the upper surface, producing then the sharp gradients that can be seen in the ΔCp distributions. A second point is that Figure 8 and 9 show ΔCp discrepencies between the DLM computation and the Euler simulation with the plate representation of the wing. These discrepencies are larger than the ones obtained at lower Mach numbers. That shows the impact of the fluid equation formulation (Euler vs DLM) itself.

To investigate further the influence of the fluid modelling, simulations have been equally performed taking into account the fluid viscosity (URANS computation with the Spalart-Allmaras turbulence model). As could be expected, the steady solution shows a weaker and upstream shock on the upper surface. The unsteady pressure distributions are also slightly different than the ones gotten using an Euler solver, with less sharp gradients (figure 11). All these simulations show that for such transonic conditions, the unsteady gust response is highly non linear with siginificant effects of the fluid viscosity.

AEROELASTIC GUST RESPONSE

The numerical method based on CFD to compute gust responses is now assessed in the case of fluid-structure coupling in the time domain.

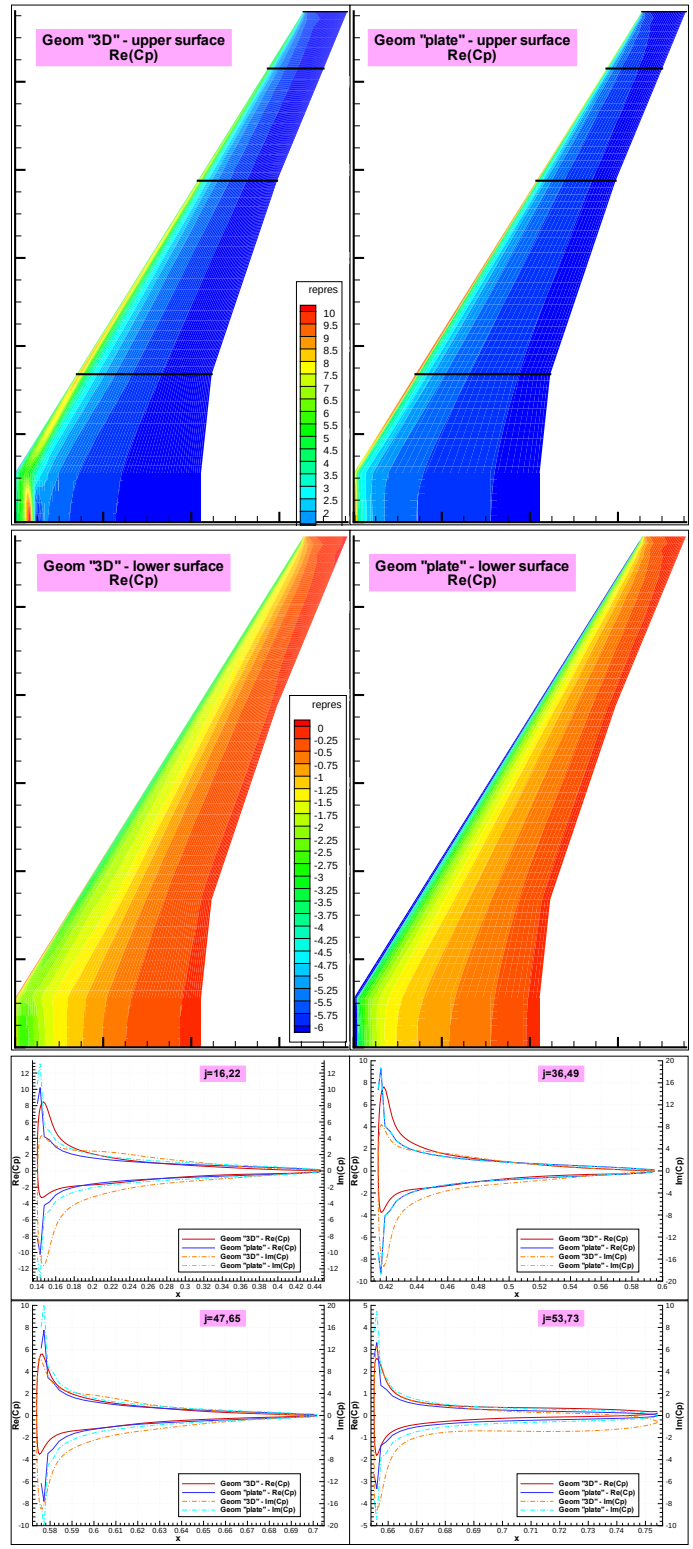


FIGURE 6. AMP WING - MACH=0.6 - UNSTEADY Cp DISTRIBUTION: GEOMETRIES 3D VS PLATE

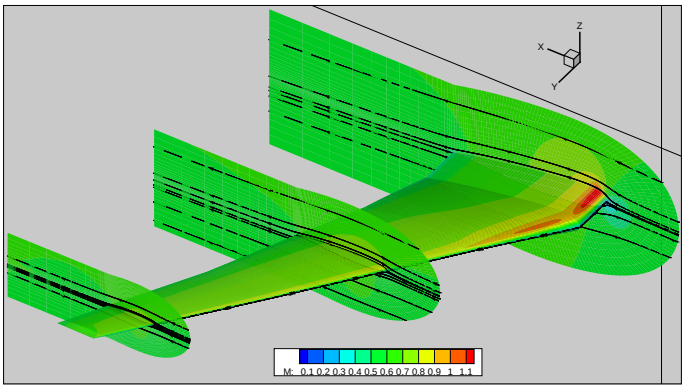


FIGURE 7. AMP WING - MACH=0.6 - STEADY SOLUTION (3D GEOMETRY)

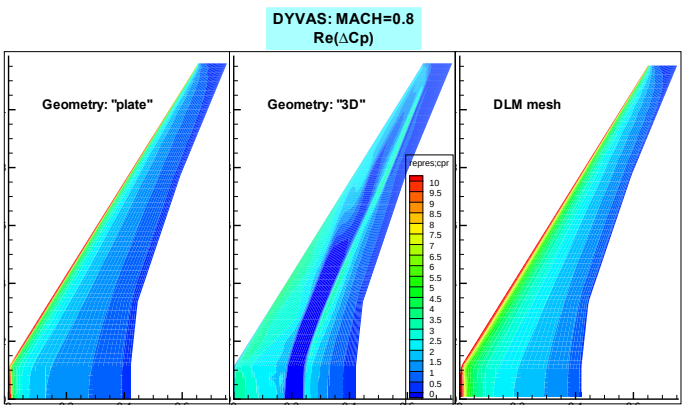


FIGURE 8. AMP WING - MACH=0.8 - UNSTEADY ΔCp DISTRIBUTION

Response of a 2D airfoil

The first case is about the 2D NLR7301 airfoil for which a wind tunnel model has been built to carry out LCO experiments [15]. It has been widely used to evaluate numerical method aiming at predicting LCOs [14]. A 2D numerical structural model has then been designed to reproduce well the heave (32.88 Hz) and pitch (43.27 Hz) modes, and an aerodynamic mesh has been built (structured C-block of 385x97 nodes and 273 on the airfoil) for Navier Stokes simulations with the Kok's $k-\omega$ turbulence model. Aeroelastic simulations are then performed at Mach 0.7 for a periodic "one minus cosine" gust whose characteristics are: amplitude equal to the flight speed over 20 (incidence jump of 2.86°), and wavelength equal to 10 and 25 times the chord length (gust frequency of respectively 78.55 Hz and 31.42 Hz). On figure 12 are drawn the time evolutions of the lift coefficient for those two gust response simulations and also for an unsteady simulation without any excitation to check the natural stability of the airfoil for these aerodynamic conditions. In the case of the highest gust frequency (i.e. the lowest wave length), the lat-

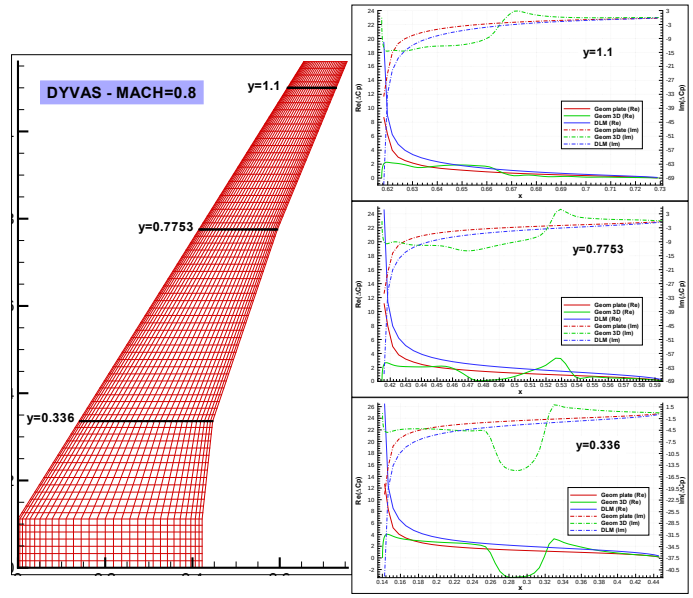


FIGURE 9. AMP WING - MACH=0.8 - UNSTEADY ΔCp DISTRIBUTION

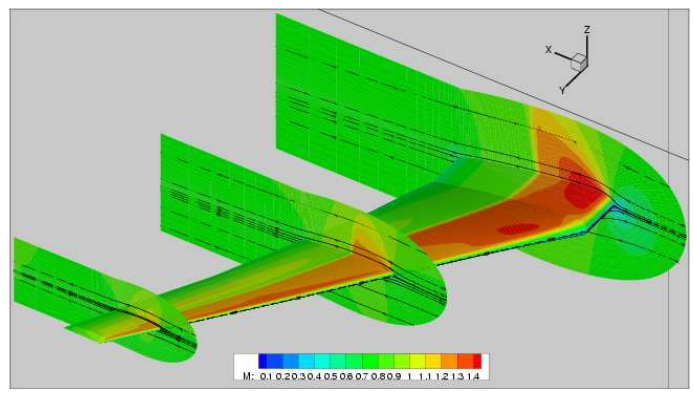


FIGURE 10. AMP WING - MACH=0.8 - STEADY SOLUTION

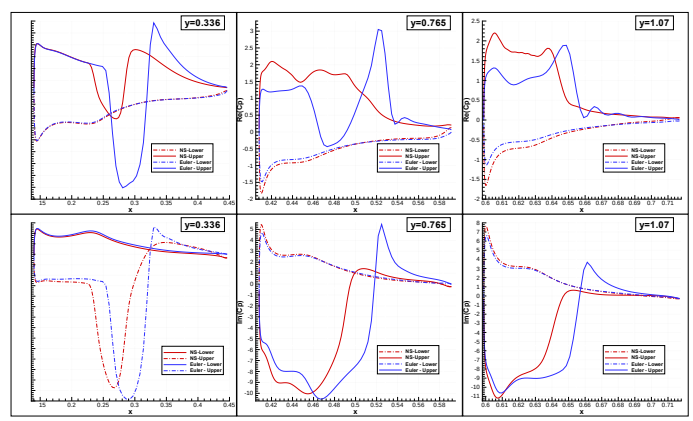


FIGURE 11. AMP WING - MACH=0.8 - UNSTEADY PRESSURE DISTRIBUTION (EULER VS URANS)

ter is higher and quite far from the structural eigen ones. The Fourier transform of the aeroelastic response shows then 3 distinct peaks matching to the structural eigen frequencies and to the gust one. In the case of the highest gust wavelength, the excitation frequency is very close to the heave eigen one. The time response is then periodic of a high amplitude with a long transient part. Furthermore, its Fourier Transform reveals 3 peaks, with 2 very close matching to the gust and the heave frequencies. The response of the second eigen mode (pitch mode) is then very damped, and the third peak at a very low frequency (1.8 Hz, visible on figure 12) could be interpreted as a beat frequency between the first mode and the excitation. Such behaviour can of course not be simulated considering the wing rigid (in that case of a pure aerodynamic response, only a periodic phenomenon with only one fundamental frequency can be captured, as is illustrated in figure 13).

A last set of two unsteady simulations with the NLR7301 airfoil have been performed: the structure is first submitted to a one period "one minus cosine" gust, period that matches again to a frequency of 31.42 Hz. For the second simulation, the airfoil is submitted only to initial velocities on both modes, velocities being equal to the maximal ones if a gust were applied. The resulting time evolutions of the heave generalized coordinate and the gust profile are plotted in figure 14. The time evolutions of the two generalized coordinates (heave and pitch) resulting from the application of an initial velocity are periodic and weakly damped. Their frequency analyses have indeed shown a first peak at 33.15 Hz close to the first eigen frequency with a small damping coefficient of 1.56×10^{-4}, and a second peak at 46.04 Hz close to the second eigen mode with a higher damping coefficient of 4.23×10^{-2}. On the other hand, the time evolutions of the generalized coordinates resulting from the one period gust excitation seems to present a LCO of higher amplitude. The Fourier analyses of the signals have indeed shown a first frequency peak at 33.17 Hz with a negative damping coefficient of -9.44×10^{-5} and a second peak of very small amplitude at 45.7 Hz with a damping coefficient of 4.67×10^{-2}. The difference of amplitude between the two simulations can be explained by the fact that more energy is brought to the system when the latter is excited by a gust (energy is brought for a whole period). The second point is that the simulated duration of the response to the one period gust is too small to be able to compute accurately damping coefficients and then to predict LCO. Nevertheless, the numerical method have shown its ability to predict a vibratory behaviour of a structure submitted to different kind of gusts (one period or periodic in time).

Response of a 3D clean wing conf guration

The numerical method to get aeroelastic gust responses is now assessed in the 3D case of the AMP wing, for wich a wind tunnel model had been designed for flutter experiments [16]. A

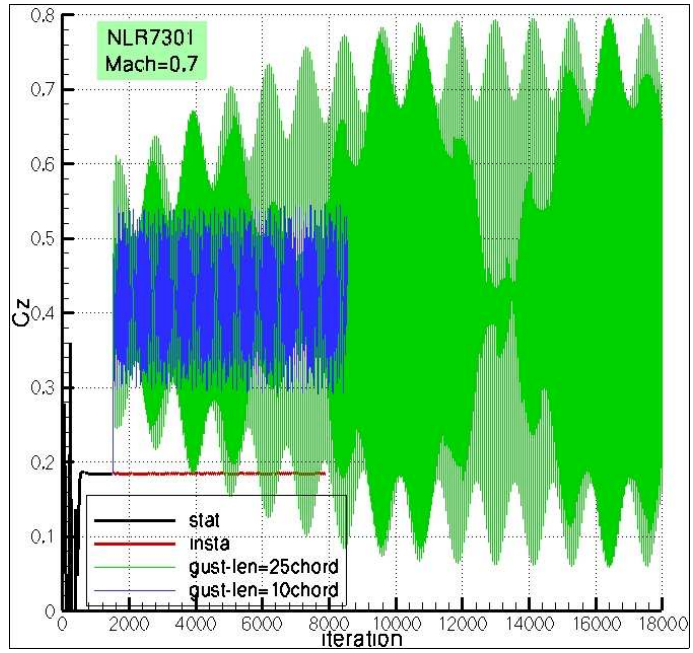


FIGURE 12. NLR7301 AIRFOIL - MACH=0.7 - TIME EVOLUTION OF THE LIFT COEFFICIENT

structural finite element model has been built to reproduce the first two modes of the wind tunnel model (first bending mode at 23.39 Hz and the first torsion mode at 31.85 Hz), modes that are involved in flutter. An aerodynamic model has also been built with a structured C-block of 305x61x69 nodes and 241x41 on the wing in order to perform Navier Stokes computations with the Spalart-Allmaras turbulence model. A static coupling simulation is performed for a Mach number of 0.8 and taking into account the fluid viscosity (figure 15). This simulation is used to initialize the unsteady ones. The wing is then submitted to a harmonic gust of frequency 37.94 Hz (matching to a wavelength of 25 times the mean chord). A first unsteady simulation is carried out from the statically deformed wing ("flight shape") considering the wing rigid (aerodynamic response). A second dynamic simulation is performed taking into account the structure. Those simulations are compared with the aerodynamic response computed from the undeformed shape ("jig shape") and presented in the previous part. A first remark is about the influence of the static solution on the aerodynamic unsteady response. The dynamic behaviours are similar (figure 16), even if the mean values are different and if the amplitude of the oscillations is slightly smaller when the static wing deformations are taken into account. On the other hand, the dynamic aeroelastic behaviour (taking into account the mass and the stiffness of the wing) is different than the rigid wing ones. The amplitude of the oscillations are similar, but the aeroelastic response is periodic with several fundamental frequencies. A Fourier transform of the signal has shown at least 3 frequencies

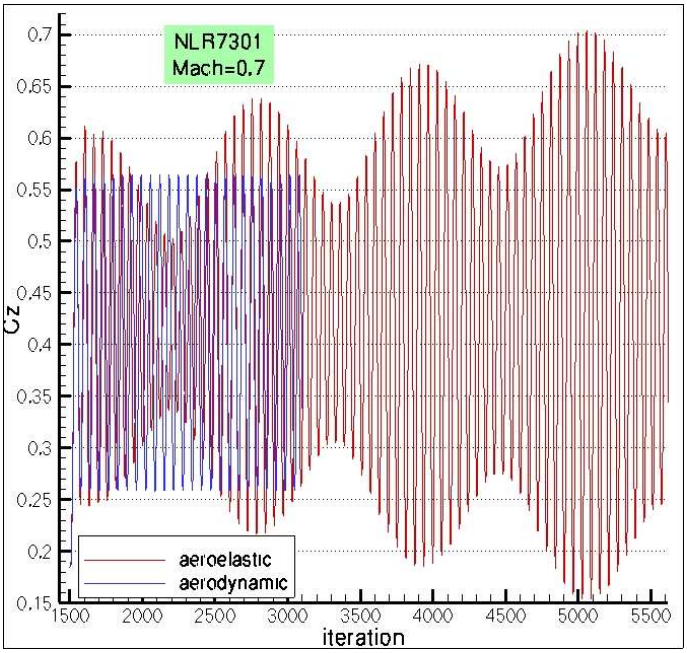


FIGURE 13. NLR7301 AIRFOIL - MACH=0.7 - TIME EVOLUTION OF THE LIFT COEFFICIENT (FLEXIBLE VS RIGID WING)

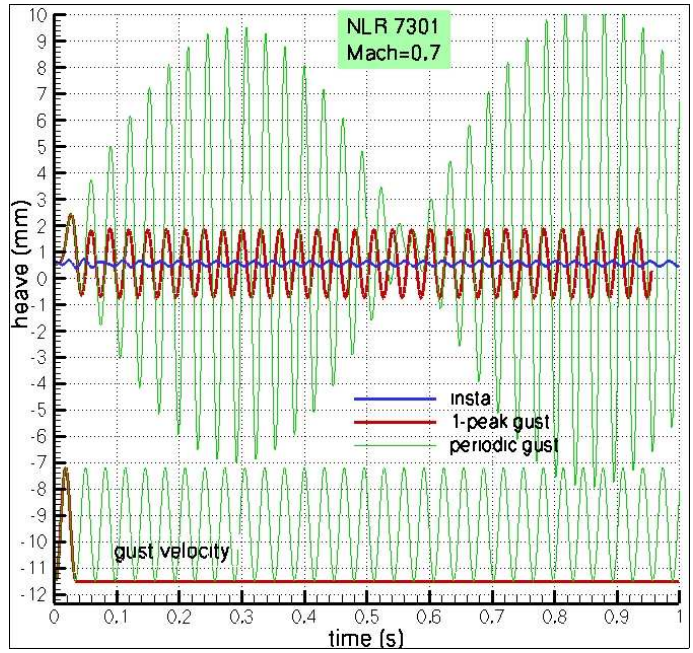


FIGURE 14. NLR7301 AIRFOIL - MACH=0.7 - TIME EVOLUTION OF THE HEAVE GENERALIZED COORDINATE

matching to the ones of the two eigen modes and to the gust frequency. But the simulated duration is too weak to postprocess the signal with a good frequency definition.

CONCLUSIONS

A numerical simulation tool have been developed for years at ONERA to compute the time aeroelastic response of an aircraft (the *elsA* code). It is based on the resolution of the coupled fluid-structure equations, using non linear CFD techniques to compute the aerodynamic forces, and coupling techniques that are usually used for the aeroelasticity (mesh deformation, fluid-structure and structure-fluid data transfer, linear structure solver, coupling time driver). Three gust models have been implemented into the latter code in order to compute aeroelastic responses to gust excitations: a sharp edged gust, a "one minus cosine" model, and a simple "sine" model to simulate harmonic gusts. These gust models have been implemented as a velocity field depending on both space and time, added to the field of the grid deformation speed, and being thus taken into account in the GCL (as suggested by Sitaraman et al [10]). A first validation step has consisted of the comparisons of the computed aerodynamic responses to gusts in the subsonic domain, with available data in the litterature and with data resulting from computations using the DLM. Such comparisons have been achieved for a inviscid flow over the Naca12 airfoil, for which the results from Zaide et al [9] have been well reproduced. They have also been in a second step performed for 3D inviscid flows over a clean wing configuration. For that case, very good agreements have been found between data resulting from DLM and CFD computations. Simulations have also been carried out in the transonic domain where aerodynamics is no more linear. Non linear gust responses have thus been computed and have revealed a significant influence of both the geometry and the fluid viscosity. The nonlinear numerical method has afterwards been assessed for the computations of the aeroelastic response to gusts. This has been achieved for the 2D NLR7301 airfoil and a 3D clean wing, for which taking into account the structure flexibility has also a significant impact on the dynamic response to gusts. Furthermore the method has

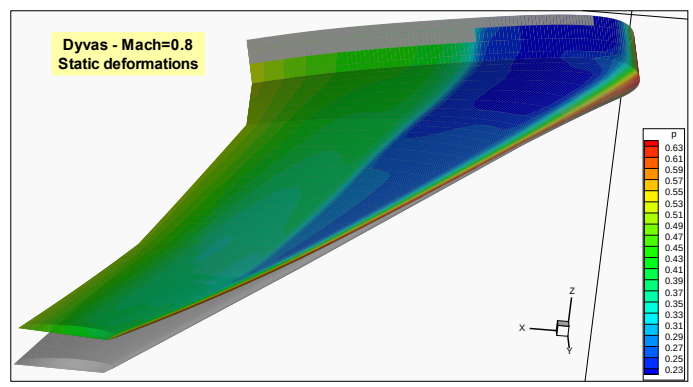


FIGURE 15. AMP WING - MACH=0.8 - STATIC COUPLING

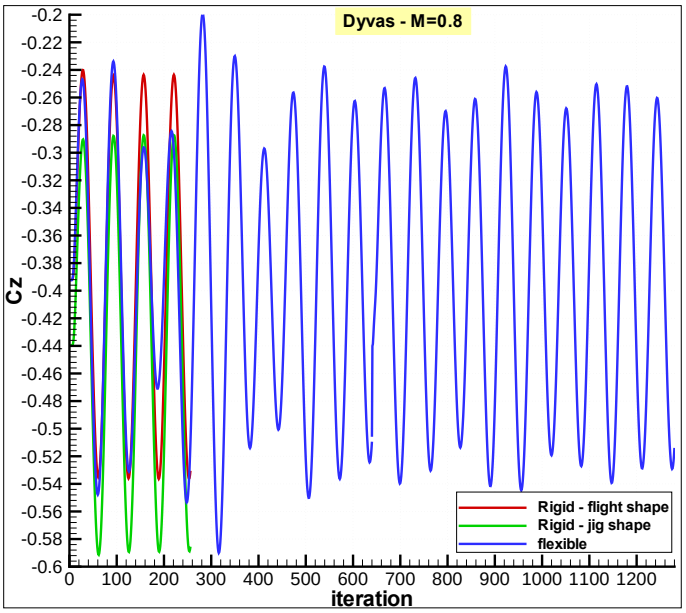


FIGURE 16. AMP WING - MACH=0.8 - TIME EVOLUTION OF THE LIFT COEFFICIENT

equally shown its ability to compute a vibratory behaviour (resonance and beat phenomena) of an airfoil excited by a periodic gust or by a one period gust (induced LCO).

The numerical method to compute the response of an aircraft to a gust has shown its capability to take into account aerodynamic non linearites, but it has still to be validated in the transonic domain with experiments. An other perspective is that this method can be easily coupled with a simple flight mechanics 6 dof solver, what will make possible the computation of the stability of a free flexible aircraft submitted to a gust. Gust control functions can also be implemented in order to simulate their effects taking into account the non linear behaviour of the coupled fluid-structure system.

REFERENCES

[1] *Joint Aviation Regulations - 25, Airworthiness Standards: Transport Category Airplanes*, Vol. Subpart C- Structure.

[2] Dowell, E. H., Crawley, E. F., Jr, H. C. C., Peters, D. A., Scanlan, R. H., and Sisto, F., 1995. *A Modern Course in Aeroelasticity*. Kluwer Academic Publishers.

[3] Coupry, G., 1970. "Problèmes du vol d'un avion en turbulence". *Progress in Aerospace Sciences*, ***11***.

[4] Corporation, M. *MSC.Nastran Version 68 Aeroelastic Analysis User's Guide*.

[5] Tang, D., Henry, J. K., and Dowell, E. H., 2006. "Effects of steady angle of attack on nonlinear gust response of a delta wing model". *Journal of Fluids and Structures*, ***16***(8), pp. 1093–1110.

[6] Tang, D., and Dowell, E. H., 2006. "Experimental and theoretical study of gust response for a wing-store model with freeplay". *Journal of Sound and Vibration*, ***295***, pp. 659–684.

[7] Yang, G., and Obayashi, S., 2004. "Numerical analysis of discrete gust response for an aircraft". *Journal of Aircraft*, ***41***(6).

[8] Golubev, V. V., and Rhode, A., 2003. "Application of space-time mapping analysis method to unsteady flow simulations". In 33rd AIAA Fluid Dynamics Conference and Exhibit, Orlando FL.

[9] Zaide, A., and Raveh, D., 2006. "Numerical simulation and reduced-order modeling of airfoil gust response". *AIAA Journal of Aircraft*, ***44***(8), August, pp. 1826–1834.

[10] Sitaraman, J., Iyengar, V. S., and Baeder, J. D., 2003. "On field velocity approach and geometric conservation law for unsteady flow simulations". In 16th AIAA Computational Fluid Dynamics Conference, Orlando FL.

[11] Cambier, L., and Gazaix, M., 2002. "elsa: An efficient object-oriented solution to cfd complexity". In 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno NV.

[12] Lavigne, P. G., and Dugeai, A., 2003. "Transonic aeroelastic computations using navier-stokes equations". In International Forum on Aeroelasticity and Structural Dynamics (IFASD), Amsterdam (NL).

[13] Dugeai, A., 2008. "Nonlinear numerical aeroelasticity with the onera elsa solver". In NATO-AVT 152 Limit-Cycle Oscillations and Other Amplitude-Limited, Self-Excited Vibrations, Loen (Norway).

[14] Lavigne, P. G., 2008. "Prediction of limit cycle-oscillations induced by aerodynamic non-linearities". In NATO-AVT 152 Limit-Cycle Oscillations and Other Amplitude-Limited, Self-Excited Vibrations, Loen (Norway).

[15] Knipfer, A., and Schewe, G., 1999. "Investigation of an oscillating supercritical 2d wing section in a transonic flow". In 37th Aerospace Sciences Meeting and Exhibition, AIAA-99-0653G, Reno (NV).

[16] Zingel, H., 1991. "Measurement of steady and unsteady airloads on a stiffness scaled model of a modern transport aircraft wing". In International Forum on Aeroelasticity and Structural Dynamics, Aachen (Germany), pp. 120–131.