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INVESTIGATION OF LIMIT CYCLE OSCILLATIONS OF TRANSPORT AIRCRAFT

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Abstract--- The Limit Cycle Oscillations (LCO) produced at the time of cruising flight segment is a serious concern in the large airplanes. The three dimensional fully coupled Fluid-Structural Interaction (FSI) analysis on a swept back wing with control surface is a challenge due to many uncertainties. To measure nonlinear aeroelastic phenomena like LCO caused by fluid-structure interaction in transonic range, Computational Fluid Dynamics (CFD)/ Computational Structure Dynamics (CSD) coupled simulations is proposed. It reveals the specific properties of the wing with control surface modal and allows the investigation of unstable behavior using experimental or numerical solution at transonic flow conditions. The simulation is done using Reynolds Averaged Navier Stokes (RANS) equations coupled with Spalart–Allmaras one- equation turbulence model. The obtained LCO frequency, amplitudes, mean lift and moment values are used to analyze the nonlinear aerodynamic effects. The solutions are reliant on the initial fields or perturbation. The LCO with very small amplitudes are determined by the developed (CFD)/ (CSD) simulation. This is endorsed to the fully coupled FSI turbulence model of higher order low diffusion schemes.

Keywords: Aeroelasticity, Limit Cycle Oscillation, Uncertainties, Coupled FSI Analysis, Frequency Response, Nonlinear aerodynamics, CFD/CSD, Navier-Stokes equations, Transonic region, Simple design framework methodology

INTRODUCTION

Aeroelasticity is the interaction of inertial, structural and forces on an airplane. Determination of the aeroelastic behavior of a Transport airplane wing with control surface with interior structure is an aspect of research in transport wing design and is a historical starting point for complex airframe analysis

The complete structural and aerodynamic transient loads of the wing is given by airflow structure interaction model. [1] and [2] describe the steady FSI problem and also analysis the validation of applicability of the structural model with influences of various turbulence models. The low diffusion of the analytical scheme is essential to accurately determine flow damping, which may specifically affect the structure displacement [3]. Though, the prediction of structural failure is difficult due to lack of advanced computational tools to capture the physics, It helps to study the vibrations due to steady and unsteady aerodynamic forces [4]. Reduced order models which are popular in many different disciplines are suggested and applied to the linear and nonlinear systems [5].

The aero elastic limit cycle vibrations of a two-degree-of-freedom supercritical airfoil linear structural model with impact of nonlinear aerodynamics at transonic speeds are analyzed in [6]. A dominantly linear one-domain approach for flow conditions and the way to enhance the sequential coupling between the aerodynamic and structural dynamic equations are essential to analyze the limit cycle vibration problems [7]. [8] presents the results of experiments where the boundary layer transition is mainly considered for the investigation. A control s made to control the oscillations amplitude, since it has nonlinearity within the system [9]. Instead, transient behavior is captured by the time domain aerodynamic approximations with the equations of structural states and second order aerodynamic equations. These non-linear equations are solved by Newton–Raphson, and Newmark methods [10]. The aerodynamic uncertainty and stochastic uncertainty at a hypersonic aspeed has been estimated and validated with the effects of heat and temperature change in flow and the body [11].

The novel purpose of this research is to produce a research tool for the application of the FEM and easy lifting load prediction to aeroelastic analysis. Basic knowledge of flight mechanics is assumed since such a discussion is a related but independent field. This paper will focus on the structural dynamic response of a wing with the control surface, in particular, Limit cycle oscillations.

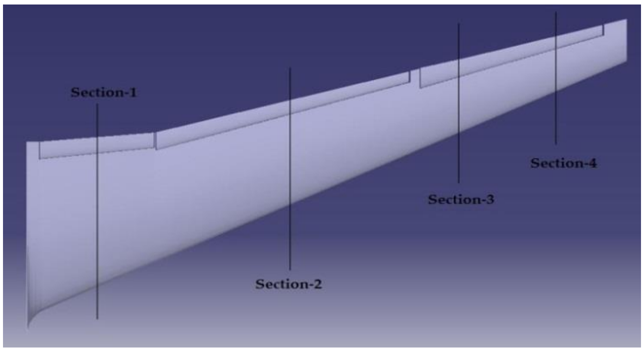

Figure 1. Wing sectioned model

WING CONFIGURATION - DESIGN

A transport airplane A340-200 wing configuration is used for design purposes with the support of Airbus technical

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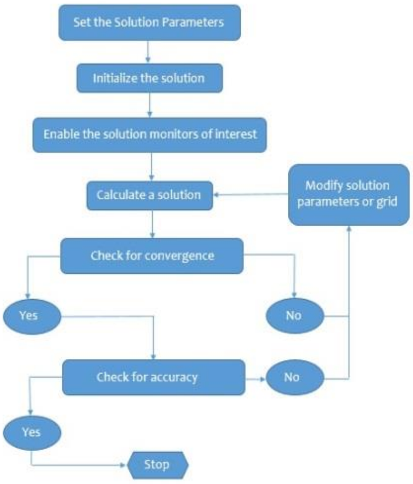
manual. The chosen wing for the simulation is a swept backward wing with quarter-chord sweep angle of 32 degrees. The wing has NACA cambered airfoil cross section. The wing model designed by CATIA V5 as shown in Figure 1

To ease the computational time, the design was separated into four sections considered to the structured grid evolving for the 2D sectioned grid for four sections. The mapped mesh developing for quad cells future it requirements to relate to the turbulence model therefore the orthogonal quality and aspect ratio is considered to developed the following Multi-block C-type of grid.

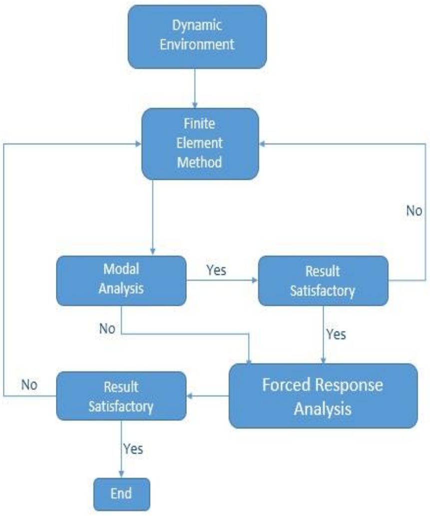
NUMERICAL SIMULATION

CFD & CSD Analysis – Methodology:

The present CFD solver that is used to obtain LCO simulations with the transport airplane wing with the control surface. It is used to simulate airflow around moving or non-moving two-dimensional airfoils, generating time-dependent CFD results of the aerodynamic properties of the flow field.The detailed CFD simulation process as shown in flowchart 1./A dynamic analysis, the formulation of the analysis prior to the finite element model as shown in flow chat 2.



Flow chart: 1



Flow chart: 2

Mathematical Model:

The turbulence model used for the simulation is Reynolds Averaged Navier–Stokes equation with Spalart-Allmaras model. Conservative form of the above mensioned equations in a generalized coordinate system is given as

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial \varepsilon}+\frac{\partial F}{\partial \eta}+\frac{\partial G}{\partial \zeta}=\frac{1}{\mathrm{Re}}\frac{\partial R}{\partial \varepsilon}+\frac{\partial S}{\partial \eta}+\frac{\partial T}{\partial \zeta}+D \quad [1]$$

The structural dynamic analysis includes determination of the natural mode shapes and natural frequencies of an elastic structure with free or unforced vibration. The classical cubic beam element and linear torsion element are a natural foundation of the comparison and will direct to the relation of quantic beam element and cubic torsion element capable of directly incorporating stress-free conditions.

Mesh Generation:

A CFD mesh is generated around the wing by placing the wing in the middle of the computational domain. Surface mesh was created with QUAD-4 kind cell to make the structured mesh easier and efficient. For the present study, the C-type topology is used, and the boundary conditions of this topology are schematically depicted. This particular mesh of C-type topology consists of six block, which is the terminology used to name a topology region.

Fluid - Structure coupling:

The compatibility of the displacements and forces between the nodes of the structural mesh elements and the corresponding nodes of the CFD mesh elements have to be performed to get the time-accuracy, airflow-structure coupling, and Eigen mode interpolation in the frequency analysis process. Hence, scattered data interpolation is mainly used with the application of Radial Basis Function (RBF) interpolation (see Bernd Stickan 2012).

Computation of Aerodynamic Load:

The above validation analysis notified clearly that the k-omega turbulence modal predicts the better result. So future more, the different match no region = 0.7-0.8 will calculate. The net lift force for various angle of attack is calculated and also compare with the other match no, are showed below,

On the upper surface, the flow is nearly transonic and gets decelerated to subsonic speed near the trailing edge due to the presence of a shock wave. Since a shockwave present on the upper surface, the lift produced is rapidly decreased. And also the flow separation at the bottom of the shockwave is noticeable. The proper result is obtained for the free stream Mach number of 0.8, when the shock waves on upper and lower surfaces have reached the rear end.

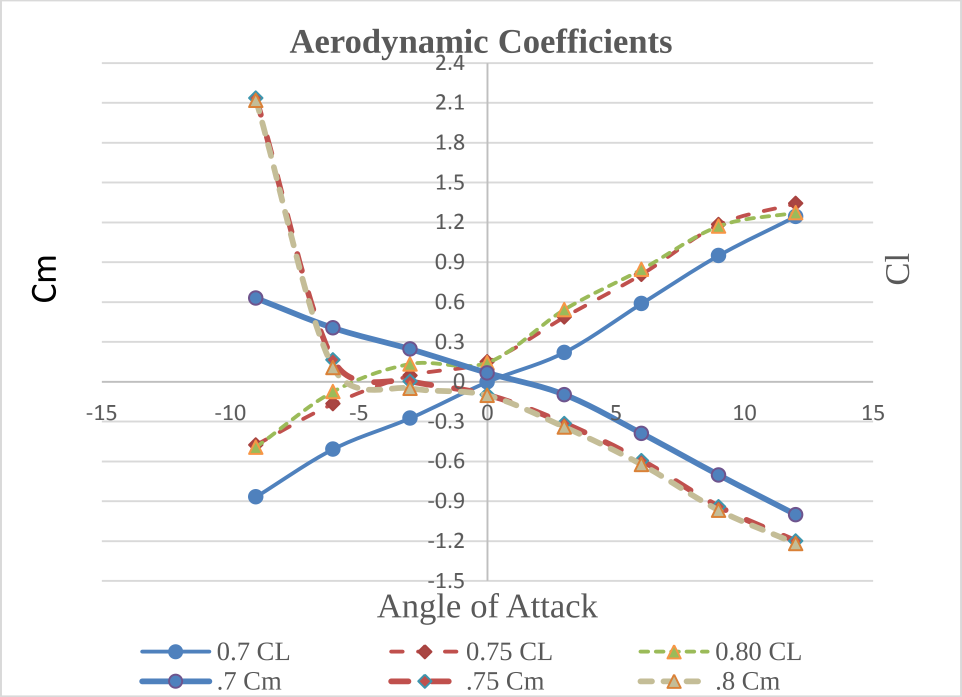


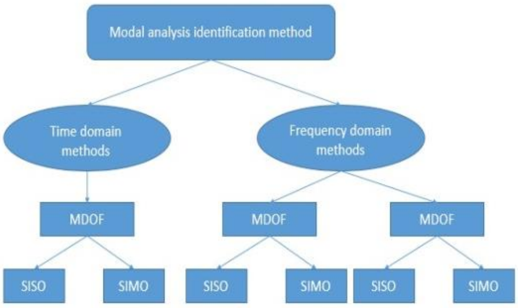
Figure 2: Net aerodynamic Coefficient of Moment of SST k-omega method at M=0.7-0.8 range and Re-6.0367e6 for transport wing

From the lift slope, good agreement of results will be presented in the k-omega turbulence model.

The pressure distribution on the airfoil is integrated and the overall forces and moments were generated. This was done primarily to map the 2D airfoil solution to meet the 3D flow fields and the force distribution. In the Mach number range of interest, this mapping is reasonably accurate and is an elegant and simple method for engineering accuracies

Structural Results:

This section covers the recent applications of the ROM and POD to problems in computational aeroelasticity. It includes LCO analyses of the transport airplane wing with a nonlinearity in structures. And the figure 3 shows the methods of modal analysis identification.



Flow chart: 3

The results from the LCO test gives a good initial point to validate the computational results, even it exhibits a weak non-linear behavior. The first 10 mode shapes for this wing are computed for various modes like bending, torsion, and combined loading. The corresponding modal frequencies are 1.27, 4.16, 9.3, 10.68, 14.01, 16.7, 24.84, 26.49, 32.66 and 36.38 Hz. To validate the results with LCO predictions at various Mach number and decreased velocities, the model was simulated numerically. Hence, the two dimensional airfoil model is well enough to validate the provisions of the new NPOD/ROM.

The responses for lift coefficient, drag coefficient and moment coefficient of various models are very close. It confirms that this model is sufficient to analyze the transient aerodynamics accurately at slight disturbance. It also point out that the essence of first order POD/ROM which can be used to analyses aeroelastic problems such as flutter, LCO, and gust response since these are all with slight disturbances.

Then, the aerodynamics response for magnified amplitudes which are ten times more than large disturbance, is analyzed. While comparing the results, the snapshot equation which is in linear form, gives apparent errors in amplitude and slight shift in frequency. And the snapshot equation which is in nonlinear form, gives good performance against the CFD solver. At last, it shows that the conventional time domain POD/ROM is very sensitive to the flow parameters.

Limit Cycle Oscillations – Prediction:

At Ma=0.7 - 0.8 with α= -9 to 12°, step response is obtained with the time step of 10sec and 1000 s for each mode of displacement and velocity. The consistent response shows the capability and accuracy of NPOD/ROM for LCO prediction. The flutter response of the transport aircraft was analyzed at transonic speed with LCO phenomenon. From experiments, linear p-k method and high-precision aeroelastic model, flutter dynamic pressure variation were reported.

The structure, aerodynamics and its interaction were captured as the LCO response dependent in the present work. Earlier work shows the considerable impacts that the geometric nonlinear terms have on the computed LCO of the model. The CSD analysis carrying through the transonic region of different match number 0.7-0.8 has been studied. The CFD aerodynamic load has been given through the CSD input boundary condition this analysis for both with and without damping conditions of a structural geometry nonlinearity, the material damping value of Al-T015-T6 = 0.05. at the different angle of attack -9to12o has been agreed with results.

RESULTS & DISCUSSIONS

The results given in this section are obtained using Roe scheme. The CFD results associated with these flow behaviors are post-processed in order to obtain the pressure coefficient distribution and Dynamic pressure distribution. These plots help to demonstrate the physics behind the limit cycle oscillations, flutter, and damping vibrations. In the following sections, the flow and structural parameters that are used to run the CFD simulations of each airfoil are provided in the below. The results of the CFD simulations, using the Roe upwind scheme, are provided for transport airplane wing with a control surface in the sections.

At transonic speeds, due to the presence of shockwaves and the variations of cross section, angle of attack, and Reynolds number, the flow becomes undesirable. At Ma = 0.7, the presence of low frequency Limited Cyclic Oscillation (LCO) is observed. At Ma = 0.8, It is being converted as a strong oscillation and finally vanished.

Two viscous computations are then performed on a Multiblock C-type grid. One uses the K-omega turbulence model and the other uses the Spalart–Allmaras turbulence model. Both the case simulated at the transonic region of 0.7-0.8 free stream Mach no condition at 6000 altitudes and Reynolds no 6.0367e6 done based on the Chord length, with the simulation results mention at a different angle of attack -12 to 15 degree respectively.

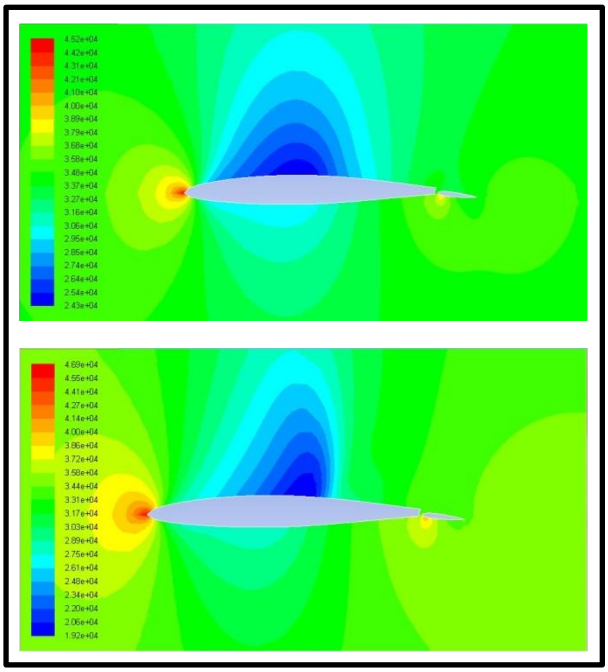


Figure 2. Static Pressure of SST k-omega for M=0.75 & 0.8 and Re-6.0367e6 For Section-2 at α =6 ^{0}

From the analysis results, Static pressure decreases as altitude increases because their air density is low. At 19685.03ft altitude, the static pressure value is 0.5 times the value at the standard sea level condition. As the angle of attack increases, the flow has a stagnation point just under the leading edge and hence producing lift as there is a low-pressure region on the upper surface of the foil. From the observations of contours states that Bernoulli's principle is holding true; the velocity is high (denoted by the red contours) at the low-pressure region and vice-versa.

CONCLUSIONS

The limit cycle oscillations of a transport wing were investigated by means of coupled fluid-structure simulations applying a detailed structural model and a finite-volume RANS CFD code. The nonlinear aeroelastic phenomena like Limit cycle oscillation caused by fluid-structure interaction in the transonic range is proposed. It reveals the specific properties of the wing with control surface model and allows the investigation of unstable behavior using numerical solutions at transonic conditions. Numerical analysis has been carried out by Partially Coupled simulation is done using RANS coupled with Spalart-Allmaras model. The full Multi-Grid technique is used in order to accelerate the convergence of the solution. The aerodynamic loads for the configuration at a various angle of attack is calculated and also compared with the K-ω model. It can be noticed clearly that the K-ω model predicts better results than the SA model.

This LCO analyses depicts its capacity in simulating the aeroelastic problem at transonic speed. The simulation of fluid structure interaction helps to solve the problem in the earlier stages of design process. This will lead to reduce the time and cost of experimental tests.

This paper result demonstrates that the simple design framework technique using the structure model, is capable of capturing the LCO phenomenon of the transport airplane wing and it also reduces the computation time and power required. It has been proven that the efficiency and reliability are more based on a comparison of the results the previous research.

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