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FINITE ELEMENT METHOD COMPUTATIONAL FLUID DYNAMIC ANALYSIS OF AEROELASTICITY IN POLYMER COMPOSITE AIRPLANE WING

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Abstract

Aero elasticity has been a widely studied phenomenon during the past few years in the aircraft industry. It has a major implication on the structural design and reliability of the aircraft structure. It is two field phenomenon which is dependent on each other. The difficulty lies in coupling both the domains due to the fact that the structural equations are solved in the material coordinates whereas the fluid equations are solved in the spatial coordinates. In this paper Carbon T300/ Epoxy resin and NACA 0012 were considered for the design of the polymer composite airplane wing. An attempt has been made to model the polymer composite airplane wing by Finite Element Method, using the Multiphysics capabilities of ANSYS. SOLID 45 element type with 11560 elements and 13735 nodes for structural analysis and FLUID 142 element type with 186990 elements 196546 nodes for computational fluid dynamics were is considered. Fluid Analysis results and Transient dynamic response plots obtained from Transient Structural Analysis gives a clear indication of existence of aero dynamic instability cruising airplane wing. From the results it can be observed that in actual practice the wing would fail catastrophically or would fail in fatigue.

Keywords: Aeroelasticity, CFD Analysis, Polymer Composite, Finite Element Analysis, ANSYS.

I. Introduction

Aero elasticity has been a subject of increasing concern among aircraft industries in the wake of increasing speeds and maneuverability. The analysis involves the twin domains of structure and fluid. Both analyses are interdependent on each other. The change in the geometry due to the aerodynamic pressures in turn effects the aerodynamic pressure distributions. The CFD module in ANSYS can effectively compute the pressure distribution on the wing. The Multiphysics capability in ANSYS can simulate the dual effect of fluid and structure by data exchange, pressure in the case of CFD and deformations in the case of structure.

Aeroelasticity is a discipline focusing on problems concerning the deformations of elasto-mechanic bodies (elasticity) in an air flow (aero). Deformations interact with flow through change in angle of attack of an air foil, leading to change in the aerodynamic loads and these loads in turn affect functioning of elasto-mechanic bodies.

Aero elasticity involves substantial interaction among the aerodynamic, inertial, and structural forces that act upon and within the aero body. The relation among these can be clearly shown using following diagram.

Static aeroelasticity involves the interaction of aerodynamic and elastic forces as shown in Figure 1. In an aircraft, following significant static aeroelastic effects may occur.

- DIVERGENCE: Deformation dependent aerodynamic forces exceed the elastic restoring capability of the structure [4][5]
- CONTROL SURFACE REVERSAL: Controls or reversal of expected response due to structural deformation (stiffness) of the primary surface
- LIFT EFFECTIVENESS: Change in magnitude and distribution of aerodynamic loads due to the structural stiffness of the aerodynamic surface

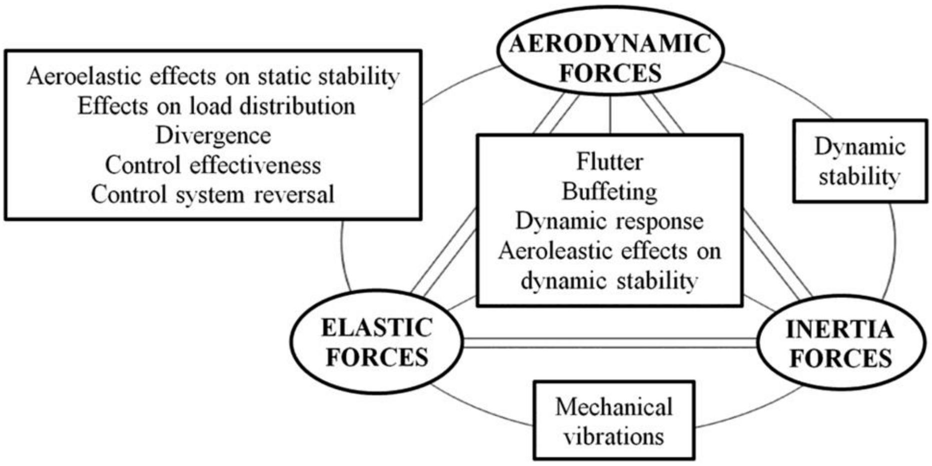


Figure 1: Aeroelasticity

Dynamic aeroelasticity involves the interaction of aerodynamic and elastic and inertial forces as shown in Figure 1. Examples of dynamic aeroelastic phenomena are:

- FLUTTER: An oscillatory instability where one mode of motion is driven to resonance by a second mode. Both modes have coalesced to the same frequency (includes ‘bending-torsion’, propeller whirl and panel flutter)
- ‘BUZZ’ and ‘BUFFET’: High frequency instabilities caused by flow separations, wakes from forward structures, shock wave oscillations [6]
- ‘DYNAMIC RESPONSE’: Due to gusts, turbulence and other such atmospheric disturbances that affect air craft performance.

II. Literature

Samuel Langley created the first tandem-wing aircraft in aviation history, featuring an aft-mounted tail unit for control and stability [1] [3] [5]. Langley gave these aircraft the name Aerodromes. As Figure. 2 shows, to offer lateral stability, the wings had a sizable dihedral angle. In fact, the goal of Langley's design was to give the airframe inherent stability without requiring pilot input. It was fired from a catapult mounted on a houseboat, just like the scale models.

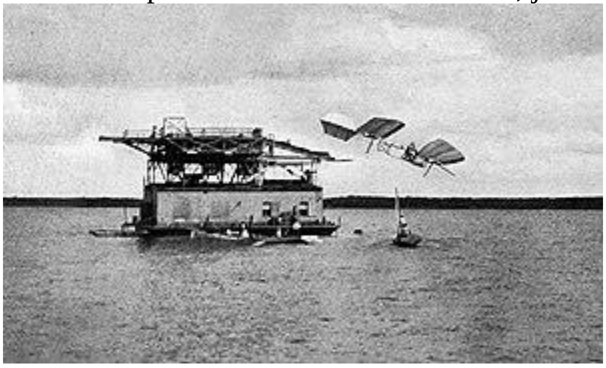


Figure 2: Langley’s Aerodrome

However, the aerodrome plunged rapidly into the river, without any successful flight. With advancements in aviation technology, such as the comprehension of aeroelastic effects, the belief that wing torsional divergence was the cause of the Great Aerodrome's collapse expanded. Langley's pursuit of flight came to an end on December 17, 1903, nine days after the Wright brothers' first flight (Figure. 3). Curtis successfully completed a flight at Langley's aerodrome in 1914 after making minor modifications.

Figure 3: Wright brother's Bi-plane aircraft

Although the Fokker D-8 performed admirably, it had wing problems during steep dives. Aileron efficacy was lost and wing flutter and wing-aileron flutter were caused by the early monoplanes' inadequate torsional stiffness. Mass balancing and torsional stiffness were discovered to be the answers [2]. The O/400 Bomber Biplane (Figure 4) owned by Hadley Page experienced the first documented flutter occurrence in 1915 [3][4]. Torsion of the fuselage combined with elevators caused "violent oscillations" in the tail flutter problem. Von Schlippe conducted the first official flutter test in 1935 in Germany. The test involved vibrating the aircraft at resonant frequencies at increasing speeds and plotting the amplitude as a function of speed. The aforementioned concept was used on numerous German aircraft up until 1938, when a Junkers JU 90 flapped and crashed during flight testing.

Figure 4: Bomber Bi-plane

The basic aeroelastic equation is given by

$$M\ddot{u} + C\dot{u} + Ku = f(u, \dot{u}, t)$$

The righthand side of the equation denotes the unsteady aerodynamic forces varying with respect to time. The CFD code solves for the aerodynamic pressures at different velocities (Mach no’s). These pressures are aerodynamic loads for a time marching structural solution. The wing has an inherent damping force (courtesy, the hysteresis damping) and inertial force which acts opposite to the applied aerodynamic force. The mass and damping matrices are superimposed on the structure. Ideally parallel solution in a tight coupled approach would involve solving for both the fluid and structural equations simultaneously. In the present analysis this has been approximated by conducting a fluid run for a given velocity and then conducting a structural run for discrete time steps to capture the transient behavior of the system. In present work an attempt has been made to simulate the dynamic aero elastic behavior at a lower angle of attack (fixed initially). Due to the inherent limitation in the code only one mode of deformation (1F Mode) could be taken. Structures usually exhibit nonlinear behavior at larger amplitudes. The possibility of nonlinearity arising from geometrical aspects has been avoided in the present analysis.

2.1 MATERIALS & RESEARCH

Polymers are materials made of lengthy chains or networks that are built from tiny reactive molecules linked together repeatedly. With a thorough understanding of the chemistry and physics of plastics, rubber, adhesives, coatings, and fibers, it is now conceivable to combine these materials with fibers to create a vast array of unknown compounds that are colloquially referred to as "advanced composites." Carbon T300/ Epoxy resin is considered for the design of the polymer composite airplane wing. Table 1 lists the mechanical characteristics that were taken into consideration when designing the polymer composite airplane wing.

Table: 1. Material characterizations of Carbon T300/ Epoxy resin composite material [7].

S.No	Property	Experimental values of Carbon T300/Epoxy for V_f =0.51
1	Longitudinal Tensile Modulus(E_1)	144000 Mpa
2	Transverse tensile modulus (E_2)	6500 Mpa
3	In plane shear modulus (G_{12})	5600 Mpa
4	Major poison's ratio (ν_{12})	0.21
5	Tensile strength (NOL ring) (S_{1T})	1361Mpa
6	Longitudinal Tensile Strength (S_{LT})	1224 MPa
6	Transverse tensile strength(S_{2T})	17MPa
7	Longitudinal Compressive strength (S_{1C})	600MPa
8	Transverse compressive strength (S_{2C})	55MPa
9	Density (ρ)	1.35gm/cc

The National Advisory Committee for Aeronautics (NACA) created the NACA airfoils, which are airfoil shapes for aircraft wings. The sequence of numbers that comes after the word "NACA" describes the form of the NACA airfoils. The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil as shown in Figure. 5.

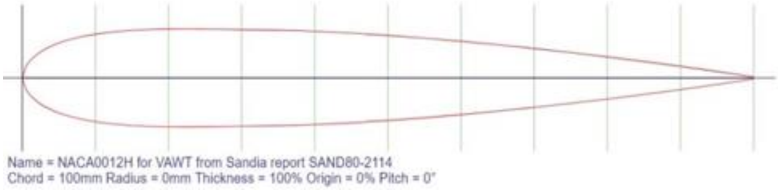


Figure 5. Plot of a NACA 0012 foil generated for polymer composite airplane wing

The analysis's technique is depicted in the flowchart that follows in Figure 6. Initially a vibration analysis was carried out to determine the salient mode shapes that are usually known to affect from a flutter point of view. In the literature surveyed, researchers who have used wind tunnel testing methods have adopted the method of weakening the wing structurally to adjust the frequencies to the desired level.

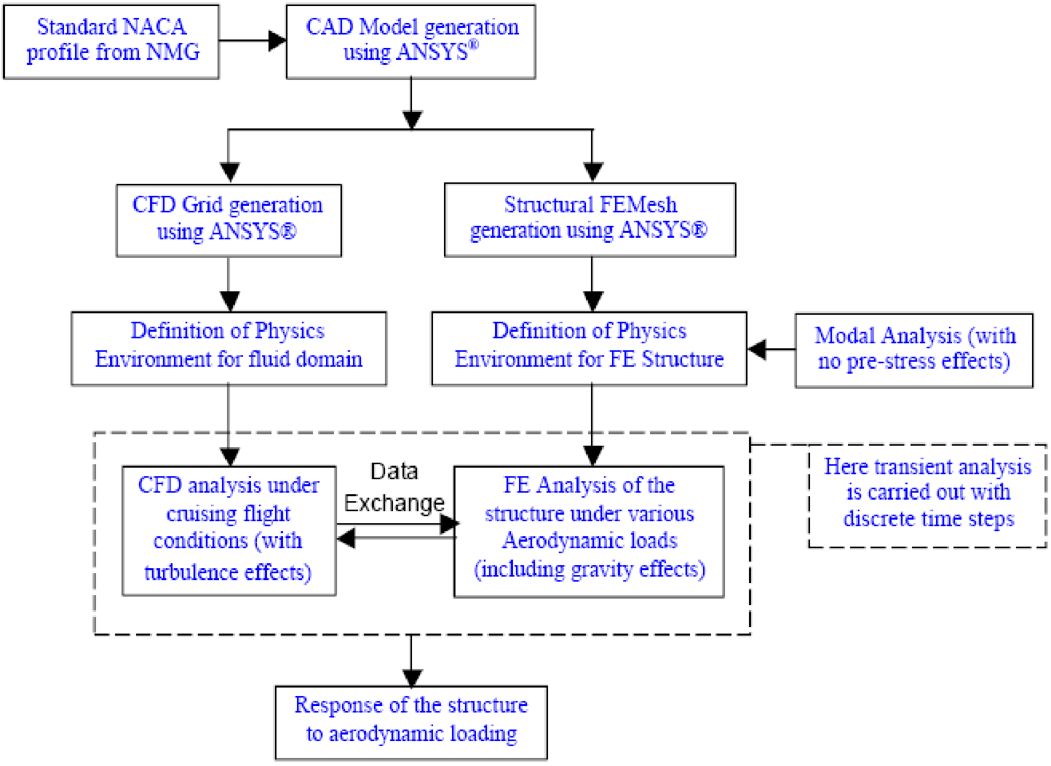


Figure 6: Flow chart representation of the computation

In the computational approach it is done by adjusting the material properties. The first flap mode frequency was maintained at 16 Hz. Ansys/Multiphysics provide an option of carrying out both CFD as well as structural analysis in tandem [9][10].

A novel technique which can be used to simulate the physics of various problems is the mesh morphing technique used in Ansys/Multiphysics. The morphing mesh mechanism can be described using the spring analogy. The fluid domain is assumed to be like numerous springs attached to the structure. The springs are able to take up the deformation of the structure by deforming themselves. Likewise, in Multiphysics the grid of the computational domain adjusts itself to the deformation by suitably deforming itself according to the structural deformation. This would be dependent on the mode of deformation of the structure. This particular aspect imposes a serious constraint on the mesh deformation as there could be chances of a negative Jacobian value for the mesh. This is indicated as negative volume of the hexahedral element. It is in this aspect that ANSYS imposes serious constraints on aeroelastic analysis. A static run using the ANSYS feature of applying the accelerations on the structural model was used to keep the deformations within the limits permitted by the deterioration of the element aspect ratio [7][8]. The effect of gravity is also included in the coupled field analysis to take care of inertial effects. During the actual Multiphysics run the fluid pressures are calculated using the standard k-e model of turbulence. The k- e model of turbulence has two parameters in it. One is the kinetic energy which is direct property in the fluid space and the other one is the turbulence dissipation which although is not a direct property is derived term to adjust the viscosity factor in the flow field. The calculated pressures are transferred directly as structural loads on the wing through the use of Multiphysics code. An interesting point to be noted here is that when the code does the fluid flow simulation around the airfoil the solid part is made as null element. When the code solves the structural analysis the fluid elements are made as null. By doing this, the coordinate system's lack of conflict is verified. After the pressures are applied as structural loads by transfer of physics on the wing, a transient structural dynamics run is carried out to determine the structural response of the wing. The iterations are carried out at different inlet speeds.

2.1.1. ASSUMPTIONS:

- Aero body (Airplane wing) is moving (cruising or traveling) at a uniform speed.
- Wing is modeled with solid elements of SOLID 45 with 11560 elements and 13735 nodes as shown in Figure. 7 and accordingly material properties have been tweaked to provide adequate strength and mass.
- 3D model is used for transient structural analysis and has sufficient stiffness and behaves as a real model or working model of wing.
- Fluid domain for CFD Analysis of FLUID 142 element type with 186990 elements 196546 nodes were considered as shown in Figure 8.
- Structural Boundary conditions shown in Figure. 9 are acceleration in vertical direction, fixed structural boundary conditions in all directions at fixed end.
- Fluid Boundary conditions shown in Figure. 9 are three side zero absolute pressure, one side x directional velocity of 150 or 325 m/s and zero velocity in all directions was considered to act as wall.

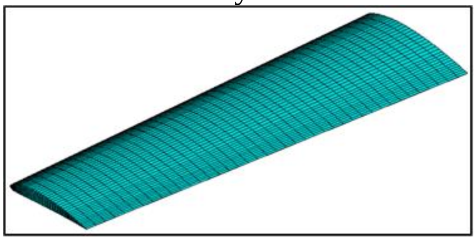


Figure 7: SOLID 45 element type airplane wing with 11560 elements and 13735 nodes.

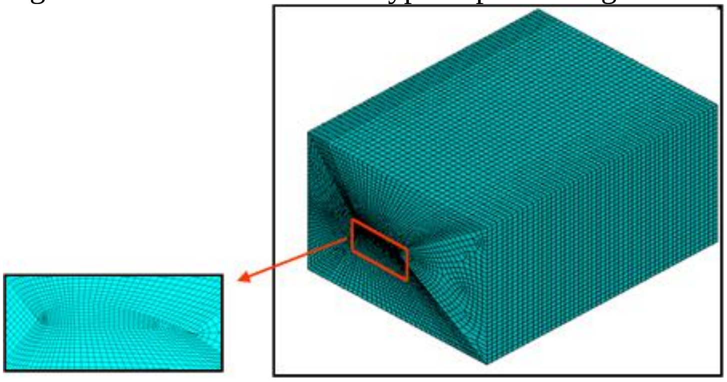


Figure 8: Fluid domain for CFD Analysis of FLUID 142 element type with 186990 elements 196546 nodes.

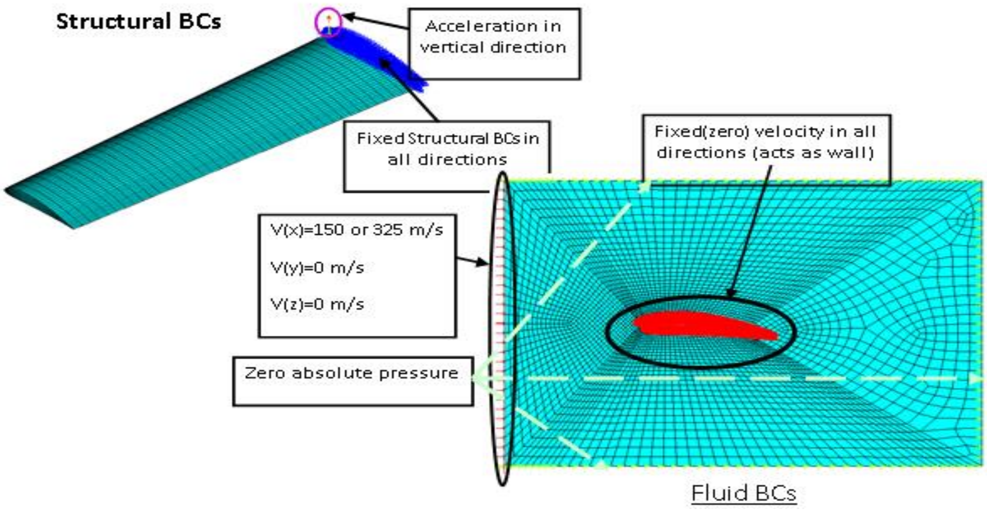


Figure 9: Boundary Conditions

2.2 RESULTS AND DISCUSSIONS

From the vertical displacement plot from analysis, it can be seen that the maximum deformation of the wing under its own weight is 0.00156 m (1.56 mm) as shown in Figure 10. This ensures the wing is sufficiently stiff enough and SAG produced under its self-weight is very less.

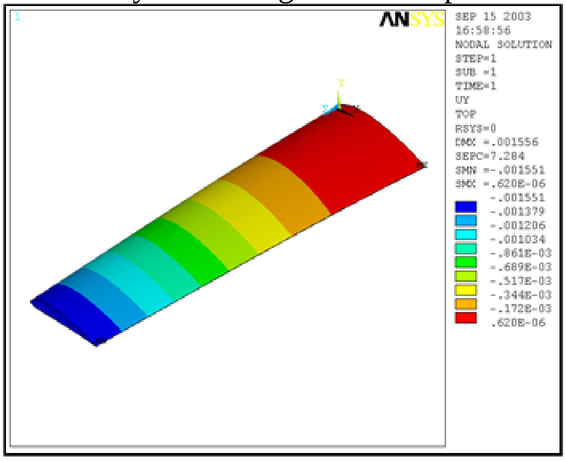
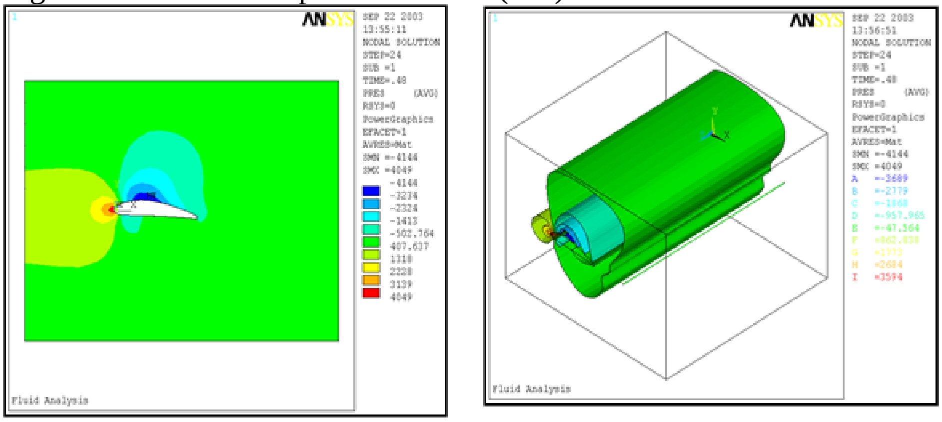


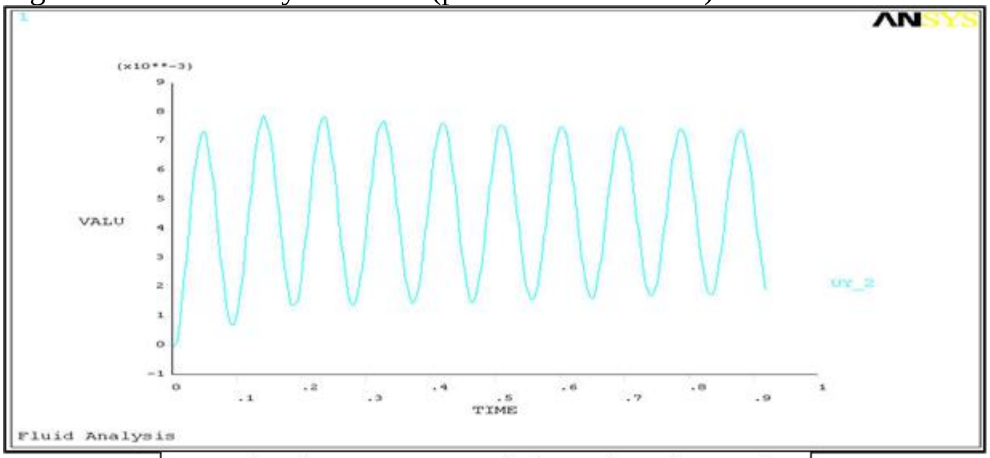
Figure 10: Vertical Displacement Plot (UY)



Pressure Contours at 150 m/s

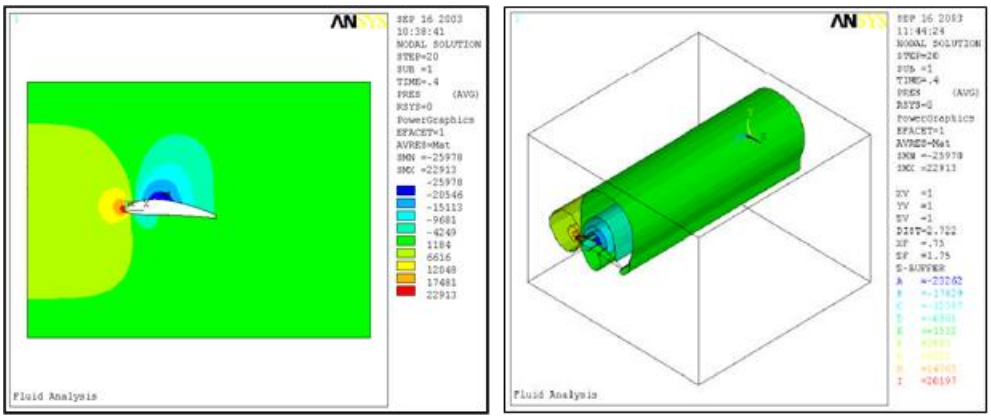
Isosurface pressure contours at 150m/s

Figure 11: Fluid Analysis results (pressure distribution) at 150 m/s



Vertical Displacement Vs. Time Plot for Leading edge tip node

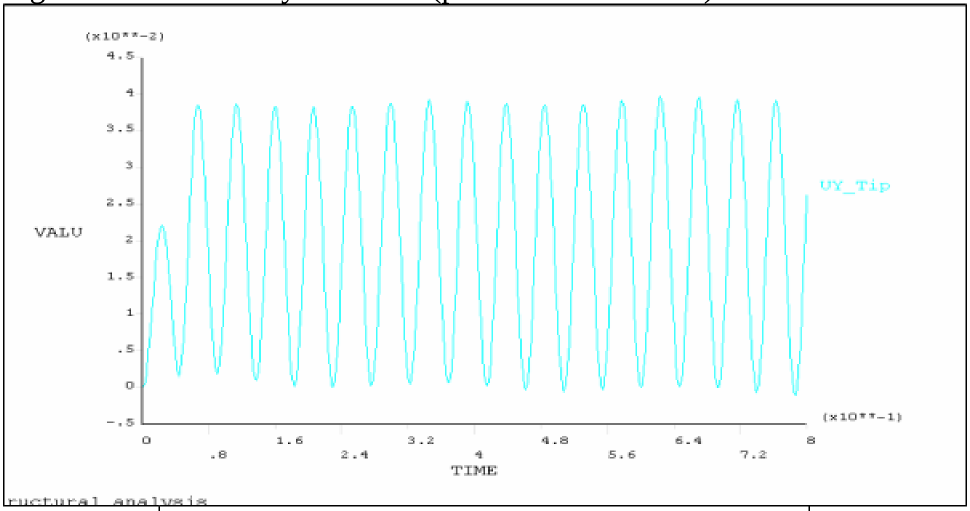
Figure 12: Transient Dynamic structural response at 150m/s



Pressure Contours at 325m/s

Isosurface pressure contours at 325m/s

Figure 13: Fluid Analysis results (pressure distribution) at 325m/s



Vertical Displacement Vs. Time Plot for Leading edge tip node

Figure 14: Transient Dynamic structural response at 325m/s

Fluid Analysis results and Transient dynamic response plots for the structure as shown in Figure. 11 to Figure 14 are obtained from Transient Structural Analysis, which gives a clear indication of existence of aero dynamic instability cruising airplane wing.

In dynamic aeroelasticity the behavior is characterized by violent oscillations of the wing which are termed as ‘Limit Cycle oscillations. Increase in amplitudes can be clearly seen in the graph. In actual practice the wing would fail catastrophically or would fail in fatigue.

III. Conclusion

An attempt has been made in this paper to simulate and capture the effects of fluid structure interaction in an airplane wing. A methodology has been proposed using ANSYS. The results have been compared favorably with numerous research papers. However, due to the inherent limitations in the technique used to simulate the aeroelastic phenomenon the breadth of the problem has been limited.

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