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Dynamic Aero elastic (Flutter) Instability Characteristics of an Aircraft Wing

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Abstract*— Aerospace structures which are subjected to aero elastic problems deals with the interaction between aerodynamic, elastic and inertial forces acting on atmospheric flight vehicles such as wing, tail units and control surfaces. Wing Flutter is one of the dynamic aero elastic problems, it mainly occurs at lifting. In order to maintain the airplane stability in high-speed, wings can be designed to minimize the distance between aerodynamic centre and shear centre (on the elastic axis). The main focus of this thesis is to calculate the frequency of an aircraft wing performance and need to study both structural deformation and flow distribution over a wing during ultimate condition as the aircraft wing is going to deform at esteem condition to sustained while it is subjected to dynamic aero elastic (flutter) instability. The geometry of the tapered wing 3D model is created with designing software CATIA is imported in ANSYS workbench. The detailed analysis process carried out in ANSYS workbench tool. At critical or flutter speed, the structure sustains oscillations following some initial disturbance and the amplitude of vibration will increase, resulting in self exciting oscillation so that to eliminate the possibility of the occurrence of the flutter.

***Index Terms*—Flutter, dynamic, aero elasticity, instability, oscillations, frequency**

I. INTRODUCTION

Concept of Fluid-Structure Interaction

In Fluid-structure interaction (FSI) problems, solid structures interact with an internal or surrounding fluid flow. FSI problems play prominent roles in many scientific and engineering fields, yet a comprehensive study of such problems remains a challenge due to their strong nonlinearity and multidisciplinary nature. Fluid-structure interaction (FSI) occurs when a fluid interacts with a solid structure, exerting pressure on it which may cause deformation in the structure. As a return, the deformed structure alters the flow field. The altered flowing fluid, in turn exerts another form of pressure on the structure with repeat of the process. This kind of interaction is called Fluid-Structure Interaction (FSI). Such interactions may be stable or oscillatory, and are a crucial consideration in the design of many engineering systems, especially aircraft. Failing to consider the effects of FSI can be catastrophic, especially in large scale structures and those comprising materials susceptible to fatigue. One of the typical problems, the fluid flow in either inside or outside of pipe or vessels exerts steady or oscillatory pressure on the wetted surface of pipes or vessels which may deform or vibrate them. Another one is that the flow of air around an Airplane wing causes the wing to deform, and as the wing deforms it causes the air pattern around it to change. In application of, Fluid-Structure interaction covers such subjects as Aero-elasticity, hydro-elasticity, flow induced vibration, thermal deformations. Aero-elasticity can be defined as the phenomena associated with the interaction of aerodynamic forces and inertial forces within elastic structural systems. There are also aero-elastic phenomena associated with interaction between aerodynamic and elastic forces alone. Aero-elastic problems mainly arise from the flexible nature of the structure. In other words, rigid structures do not experience aero-elasticity of any sort. It is well known that external forces acting on a flexible structural system (such as a wing) lead to a deformation in the wing geometry, and this structural deformation thereby leads to additional aerodynamic loads. Fluid-Structure Interaction problems in general are often too complex to solve analytically and so they have to be analyzed by the means of experiments or numerical simulation. Many approaches in computational aero-elasticity seek to synthesize independent computational approaches for the aerodynamic and structural dynamic systems. This strategy is known to be fraught with complications associated with the interaction between the two simulation modules.

Brief History of Fluid-Structure Interaction

In 1828, the concept of hydrodynamic mass (or added mass) was proposed first by Friedrich Bessel who investigated the motion of a pendulum in a fluid. He found out that a pendulum moving in a fluid had longer period than in a vacuum even though the buoyancy effects were taken into account. This finding meant that the surrounding fluid increased the effective mass of the system. Thereafter, in 1843 Stokes performed a study on the uniform acceleration of an infinite cylinder moving in an infinite fluid medium and concluded that the effective mass of the cylinder moving in the fluid increased due to the effect of surrounding fluid by the amount of hydrodynamic mass equal to the mass of the fluid displaced. It was known that this finding proposed the concept of fluid-structure interaction. In 1960's some designers of nuclear reactor systems found that the hydrodynamic mass of a structure in a confined fluid medium resulting from the fluid-structure interaction was much larger than that for the structure in an infinite fluid medium which was equal to the mass of fluid displaced by the structure.

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ADVANTAGES

Practical uses fluid film interaction

- FSI is responsible for countless useful effects in engineering.
- It allows fans and propellers to function.
- Sails on marine vehicles to provide thrust.
- Aerofoil's on racecars to produce down force.

Problem Definition

The 3D tapered wing is widely used benchmark in computational Aero-elasticity. FSI arises in transient flow experiments are highly expensive and can be destructive. 3D tapered wing is selected as it is regarded as benchmark in dynamic aero-elastic analysis. The transient flow in subsonic regime (M= 0.9) over the 3D tapered wing will be simulated and the results will be validated by comparing the computational results with the previously published results. The stresses induced corresponding to the flow will be computed using the ANSYS Workbench.

II. LITERATURE SURVEY

This chapter includes description of cases that are studied for static aero-elasticity of 3D tapered wing. this wing is being chosen because the experimental results are available and various aspects and modules related to the field of computational aero-elasticity are reviewed. To understand the fluid-structure interaction problem, we need to model both the structure and the fluid efficiently, and then we review various classes of CAE models.

Aircraft aero elastic instabilities

Aerodynamic forces act on the aircraft structure which, being flexible deforms. The interaction of the aerodynamic forces with the flexible structure is termed aero elasticity. Figure 1 shows the classical Collar's triangle whose three vertices are aerodynamic, elastic and inertial forces. The interaction of the aerodynamic and elastic forces results in static deformations. The interaction of all the three forces gives rise to dynamic instabilities and is shown in the centre of the triangle. The interactions of inertial and aerodynamic forces are usually associated with flight mechanics problems, whereas the study of the interaction of the elastic and the inertial forces is known as structural dynamics. The classical Collar's triangle has been extended to include heating effects at high Mach numbers and the effect of control systems, termed aero servo elasticity.

Aero elasticity Triangle

All structures deform when external loads are applied although the deflections may be barely discernible. In most cases, the external and internal loads do not depend on the structural deformation.

From an analysis perspective this means we can compute the internal loads and the external deflections independently. These structural analysis problems are called statically determinate and include structural stability problems such as column buckling. However, if the loads and structural deflection interact the structural analysis problem becomes very different, both physically and computationally, because the problem is statically indeterminate. Both loads and deflections must be determined simultaneously. This load/deflection interaction is represented graphically by the Venn diagram in figure .2 in which the overlapping orange area represents the statically indeterminate problem area. The purpose of this chapter is to illustrate the effect of aerodynamic load/structural deflection interactions on aircraft operation and performance. These problems are statically indeterminate and also involve considerations of structural stability. We will use simple models to reveal the causes of the aero elastic phenomena and suggest cures for these problems.

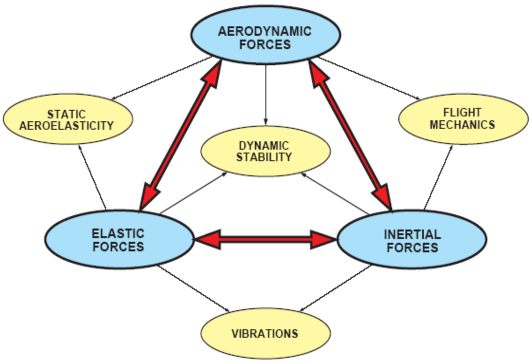

Fig 1: the Collar's aero elasticity Triangle

DYNAMIC AEROELASTICITY

In dynamic aero elasticity flutter, buffeting and dynamic response are the three problems identified. A brief coverage will be given here to show how this interaction leads to aero elasticity phenomena.

Aero elastic flutter

One of the interesting problems in aero elasticity is the stability (or rather instability) of structure in wind. Since, for a given configuration of the elastic body, the aerodynamic force increases rapidly with the wind speed, while elastic stiffness is independent of the wind, there may exist a critical wind speed at which the structure becomes dynamically unstable. Such dynamic instability may cause excessive oscillatory deformations that increase in amplitude exponentially with time, and may lead to the destruction of the structure. A major problem is the flutter of structures such as airplanes or suspension bridges, when small disturbances of an incidental nature induce more or less violent oscillations. It is characterized by the interplay of aerodynamic, elastic and inertia forces and is called a problem of dynamic aero elastic instability. The particular case of an oscillation with zero frequency, in which in general the inertia force is neglected, is called the steady state, or static aero elastic instability.

Flutter Speed

In modern aircraft, the flutter speed (the air speed at which flutter, a dynamic aero elastic instability, occurs) is usually reached before the divergence speed (the air speed at which divergence occurs) so divergence is not normally a problem. Because of this problem, flutter speed is a useful measure of the aircraft structure and must be considered as part of the

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certification process

Flutter Response

The determination of flutter boundary can provide valuable information about the stability condition within the airspeed range. As the aircraft becomes more complex and design requirement increases, flutter prediction is not enough. Now, flutter analysis result should include the time history deflection or response. Flutter response is capable of revealing many flutter characteristics such as non-linear effects, limit cycle oscillation, catastrophic or benign flutter as well as the condition which undamped oscillation might appear at velocities below critical speed. The response for an arbitrary input can be constructed by integrating the nonlinear function or convoluted for linear system. In addition, the non-linear effect such as limit cycle oscillation can only be shown through response and it is not possible to predict the LCO using a purely linear analysis .For two degrees of freedom flutter, the response will be in two modes, plunging or bending and pitching. Heave mode response shows the wing section's translational motion with time while the pitch mode response shows the wing section's rotational motion with respect to the elastic axis.

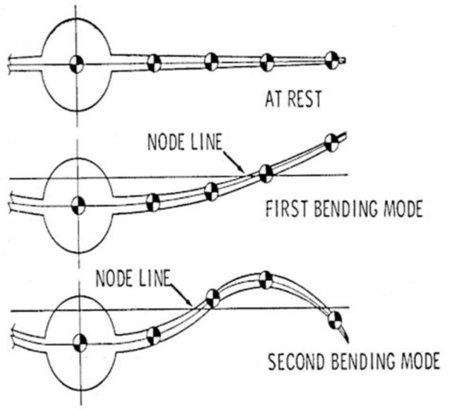

Fig 2 Wing vibration mode shapes

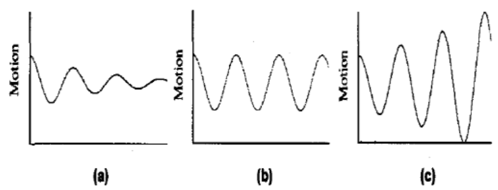

Fig 3: (a)Stability, (b) Marginal Stability and (c) Instability

Range of Computational aero-elastic model

Computational aero-elasticity can be classified broadly under three major categories: fully coupled, closely coupled, and loosely coupled analyses. Before looking at the various CAE models in detail, it is useful to look at the generalized equations of motion [1] to explain CAE methodologies better.

[M]{q (t)}+[C] {q(t) +[K]{q(t)}={F(t)}………. (1)

Here, {w(x, y, z, t)} is the structural displacement at any time instant and position and {q(t)} is the generalized displacement vector. The matrices *[M], [C], [K]* are the generalized mass, damping, and stiffness matrices; respectively and Φ_i are the normal modes of the structure, with N being the total number of modes of the structure. The term on the right-hand side of Eq. (1), *{F (t)}* is the generalized force vector, which is responsible for linking the unsteady aerodynamic and inertial loads with the structural dynamics. Eq. (1) shows that there are distinct terms representing the structures, aerodynamics, and dynamics disciplines.

III. PROBLEM DESCRIPTION

This section includes description of Tapered wing model and its airfoil series, model specifications and operating conditions that are to be conducted on the wing and the coupling definition and techniques.

Model Description

Tapered wing is widely used for much aero-elastic analysis. It is an experimental wing that has NACA64215 airfoil and an aspect ratio of 4, sweep of 30˚ and taper 0.5. This model is homogeneous and orthotropic in nature. Figure below shows the plan form of the Tapered wing used in the experiment. Material properties of the wing are shown below. The material use here is laminated mahogany as considered in previously available results.

Wing Specifications

- Aerofoil used in model is NACA64215
- Root Chord length Cr = 2000 mm
- Tip chord length Ct =1000mm
- Wing Span L=5000mm

Material Properties

The material used was aluminum alloy.

- Density **ρ** = 2700 kg/m^3.
- Parallel young's modulus $\mathbf{E_p}$ = 3.151e9 pa.
- Orthogonal young's modulus $\mathbf{E_o}$ = 4.162e8 pa.
- Tangential modulus **G** = 4.392e8 pa.
- Poisson's coefficient **η** = 0.3.

Operating conditions

Domain of this dimension is generated around the wing, Flow property such as that of air at 25deg is considered in the domain. Steady state is conducted for better accuracy and boundary conditions such as inlet, outlet, wall and opening has to be assign, k-epsilon turbulence model is selected as it has proven stable and numerically robust and has well established regime of predictive capability. Subsonic flow regime (M=0.9) over the wing will be simulated.

IV. EXPERIMENTAL PROGRAM

Structural Dynamic Capabilities of ANSYS

The finite element method (FEM) is the most popular simulation method to predict the physical behavior of systems

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and structures. Since analytical solutions are in general not available for most daily problems in engineering sciences numerical methods have been evolved to find a solution for the governing equations of the individual problem. Although the finite element method was originally developed to find a solution for problems of structural mechanics it can nowadays be applied to a large number of engineering disciplines in which the physical description results in a mathematical formulation with some typical differential equations that can be solved numerically. Much research work has been done in the field of numerical modeling during the last twenty years which enables engineers today to perform simulations close to reality. Nonlinear phenomena in structural mechanics such as nonlinear material behavior, large deformations or contact problems have become standard modeling tasks. Because of a rapid development in the hardware sector resulting in more and more powerful processors together with decreasing costs of memory it is nowadays possible to perform simulations even for models with millions of degrees of freedom.

Modeling

STEP-1: The taper wing is generated in CATIA by importing the point data in to the software using swept back wing with root chord as 5000mm and wing tip as 2000mm. The geometry of the wing model is created with designing software (CATIA). The aerofoil used in this model is NACA64215.The wing model is given below with dimensions. Geometry wing in CATIA is shown in figure below.

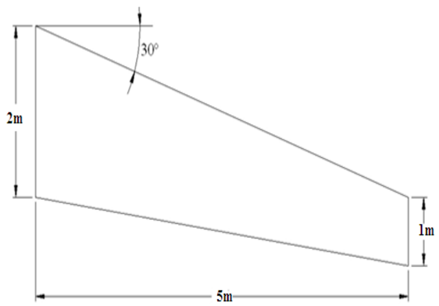

Fig 4.: taper wing dimensions

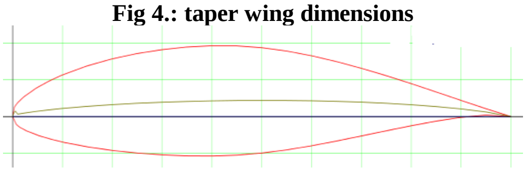

Fig 5: NACA 64215 Airfoil

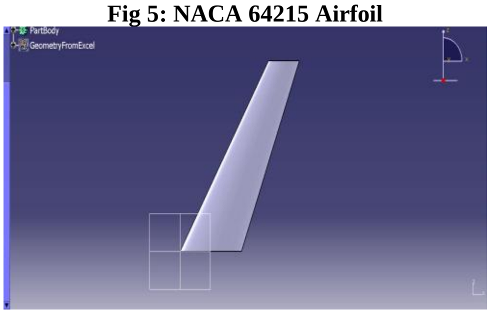

Fig 6: Design taper wing in CATIA top view

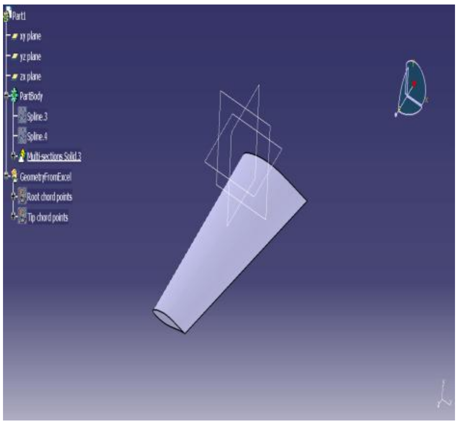

Fig 7: Design taper wing in CATIA 3D view

This designed wing should be save in .igs format in order to import the file in ANSYS workbench. This generated wing is imported to the custom systems in ANSYS WORKBENCH i.e. FSI: fluid flow (FLUENT) □static structural. The link shown below between solutions of fluent and setup of static structure is used to import the pressure load on the wing from fluent to the static structural as shown in figure

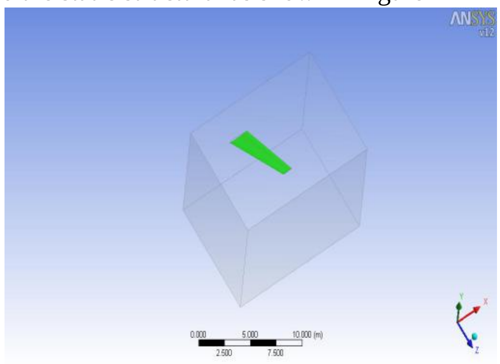

Fig 8: wing with Domain

Meshing

STEP 2: CFX-mesh method is used for meshing; Mesh is generated on the domain with the wing as wall-solid.

Mesh – select mesh method – CFX-mesh method- generated

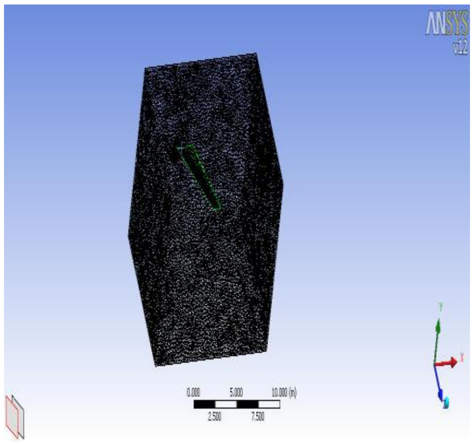

Fig 9: representing mesh on the fluid domain

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V. EXPERIMENTAL RESULTS

Structural deformation due to fluid (air) pressure

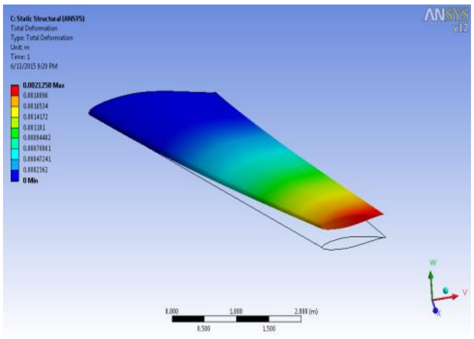

Fig 10: Contour of total deformation on wing

Stresses due to fluid pressure

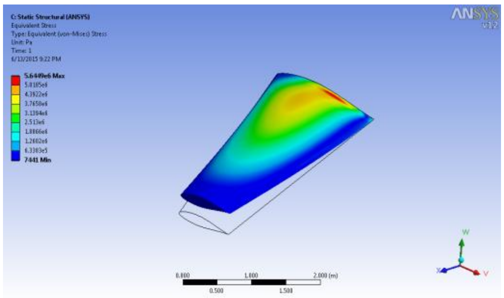

Fig 11: Contour of Von-mises stress

Computational fluid dynamics

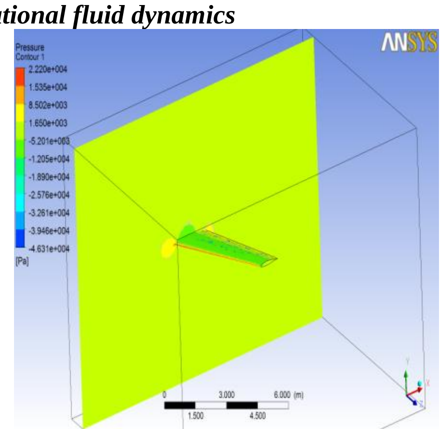

Fig 12: Contour of Fluid pressure contour -1

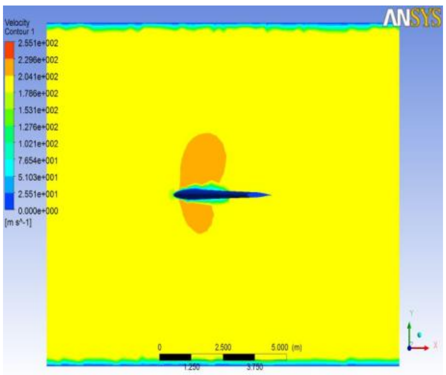

Fig 13: Contour of velocity contour -1

Mode shapes due to free vibration of the structure

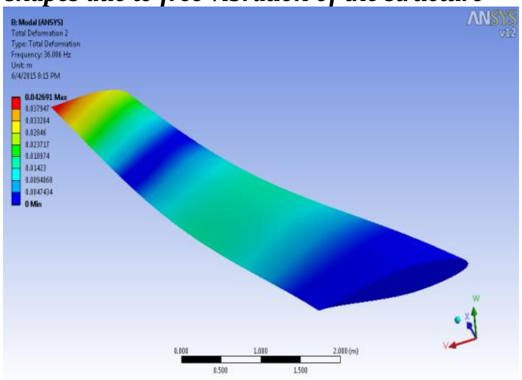

Fig 14: Contour of Mode shape 2

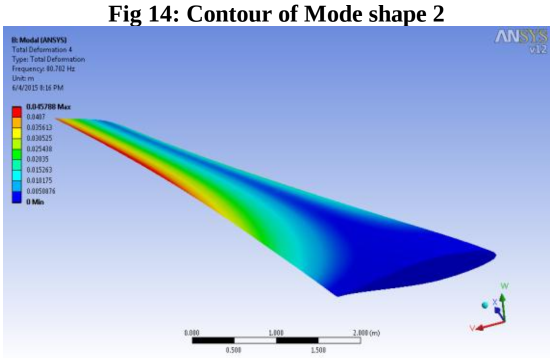

Fig 15: Contour of Mode shape 4

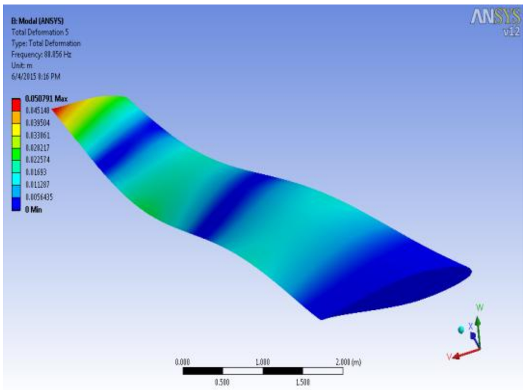

Fig 16: Contour of Mode shape 5

The objective of the project is successfully achieved. One-way FSI has been demonstrated in ANSYS-WORKBENCH. The object of this test is to show deflection of the wing due to pressure due to aerodynamic loads and resulting change in frequency due to deflection of wing. Taper wing is a benchmark for Aero-elastic analysis as its experimental flutter results are available in open literature. This wing is to be checked for dynamic structural stability by carrying out dynamic Aero-elastic study and then validate the results with experimental results. The wing is tested for flutter at Mach=0.9 and dynamic pressure is varied and resulting tip motion is noted. At each Mach number there is a dynamic pressure at which the tip displacement maintains its amplitude, i.e. it is neither increasing nor decreasing, is called Flutter Boundary for that Mach. The region above flutter boundary is unstable i.e. amplitude of deformation increases;

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while the region below flutter boundary is stable region i.e. deformation decreases. Material properties of the wing are not fully specified in the NASA's paper so these properties are picked because using these properties we get the modal frequencies very close to those that were found experimentally.

PROPERTY	VALUE
E_x	3.1511E9
E_y	4.162E8
E_z	4.162E8
Poison's Ratio XY	0.3
Poison's ratio YZ	0.3
Poison's Ratio XZ	0.3
GXY	4.392E8
GYZ	4.392E8
GXZ	4.392E8

Table 1 Material Properties

The following results show the Natural Frequency and modal shapes obtained in ANSYS.

SI NO	Fluent (flow analysis) Results	
1	Velocity	255.149m/s
2	Pressure	23187.1N/m^2
3	Lift	21041.6N
4	Drag	2356.32N

Table 2: Fluent (flow analysis) Results

SL NO	Computational static structural Results	
1	Deformation	2.21258 mm
2	Von Mises Stress	Max (5.6N/mm^2) Min (0.07 N/mm^2)
3	Maximum shear stress	Max (3.17N/mm^2) Min (0.041 N/mm^2)

Table 3: Computational static structural Results

SL NO	Computational modal analysis Results	
	Modes shapes	Natural Frequency
1	1	8.5826 Hz
2	2	36.006 Hz
3	3	47.259 Hz
4	4	80.702 Hz
5	5	88.056 Hz

Table 4: Computational modal analysis Results

Validation

Modes	Value from reference thesis	Computed value	%age error
1	7.0018 Hz	8.5826 Hz	0.012
2	35.717 Hz	36.006 Hz	0.002
3	45.671 Hz	47.259 Hz	0.015

Table 5 Flutter frequency comparison

VI. CONCLUSION

This project was largely aimed at gaining a basic understanding and better overview of the fundamental structural behavior of the tapered wing under practical load conditions, As from the previously discussed chapter we can say that Fluid-structure interaction plays prominent roles in many ways in the engineering fields. These problems are often too complex. In this project the FSI problem was successfully solved using the wing. The computations were performed for tapered wing by considering the transonic flow at subsonic mach numbers. The stresses induced corresponding to the flow has been successfully computed using the ANSYS Workbench. Validation of flutter frequency also accomplished by comparing it with the previously published thesis. This project provides the complete exposure to the FSI problem and gives the complete study of fluid on structure and vice-versa. A larger quantum of work has been done to make the study more meaningful.

VII. FUTURE DIRECTIONS

The current project can be extended in the following direction:

➢ Extend the methodology to investigate nonlinear structural dynamics models to address issues related to larger and more complicated deformation characteristics.

➢ Issues such as limit cycle oscillations, buffeting, etc, can be investigated in detail.

➢ Refine both spatial and temporal resolutions, including possibly adopting higher order time marching schemes. Coupled fluid and structure simulations are very time consuming. Priority should be given to help reduce the computational cost, including higher order schemes, parallel computational capabilities, and adaptively updated grid distributions.

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