Vibrational Analysis of an Aircraft wing model using ANSYS Workbench

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Abstract - **The wing of an aircraft is the most critical part of an aircraft structure as it greatly influences the aerodynamic performance of the aircraft. Maintaining aircraft stability involves a lot of factors including the control of vibrations in an aircraft wing. It is paramount that the structural integrity of the aircraft body and the wing is maintained to avoid structural failure. The interaction of aerodynamic forces and elastic forces in a structure leads to aeroelasticity problems and the most important dynamic aeroelastic problem is Flutter. Flutter is a dynamic, oscillatory structural instability enabled by interactions between unsteady aerodynamic forces and moments created by vibratory motion of lifting surfaces and the vehicles to which these surfaces are attached. In this paper, an aircraft wing is designed and modeled using CATIA whose material is Aluminium Alloy. The vibrational analysis is carried out using Modal analysis in ANSYS Workbench to determine the bending modes and torsional modes of the wing which gives us the mode shapes of the classical flutter of the chosen wing.**

keywords - **Aircraft wing, ANSYS, CATIA, Flutter, Frequency, Mode, Vibrations.**

I. INTRODUCTION

Vibrations are the periodic motion in a rigid body or an elastic body to which an external force is applied or in the state of equilibrium. These periodic motions are oscillating and reciprocating that causes vibrations. Generally, Vibrations in a body can be classified into two namely Harmonic and Random. Harmonic vibrations are the periodic motions whose frequency and magnitude of the vibrations remain constant. On the other hand, Random vibrations are vibrations whose frequency and the magnitude are varying with time.

A. *Types of Vibration on an aircraft*

In the aerospace and aeronautics field of study, vibrations are the crucial phenomenon in maintaining the structural integrity and stability of the structure used in any aerospace or aircraft structures. The different form of vibrations studied in this area are:

Buffet, a type of vibration that is generally caused by aerodynamic excitation. This type of vibrations is generally associated with separation in airflow. The extension of the speed brakes or during air turbulence on an aircraft leads to the causes of a buffet.

Flutter is a condition that is usually caused due to the aerodynamic excitation in an aircraft structure that leads to excitation of natural frequencies of the same structure over which the air flows, mostly wing structure. These vibrations in higher magnitude that causes the structure to fail.

Noise is a type of vibration that excites the airflow and is audible. Noise can be musical when they are produced by vibrations excited by musical instruments. But this noise is unmusical, unpleasant, and damaging to human ears.

B. *Aeroelastic Instability*

Many factors are influencing the causes and effects of vibrations on an aircraft structure. They include Aerodynamic flow fluctuations, mechanical malfunctions, structural integrity, and other external factors such as atmospheric turbulence. The vibrations are the oscillatory motions that have associated frequencies and magnitudes that can be detected by engineering practices and can be made reliable for a flight crew and passengers. There are practices already available to measure the magnitude of the vibration such as a dedicated measuring instrument to detect the vibrations with engine operation. On the other hand, other unmeasured vibrations are detected by sight and sound and depend on the flight crew for analysis.

Aeroelastic instability mainly flutter causes abnormal vibration in rare cases. Commercial jet airplanes are made with configurations free from flutter by thorough design, extensive tests, and analysis to ensure that the structure lies within aeroelastic stability envelope. This envelope determines the permissible operating speeds but it extends well beyond the boundary in cases of situations like failures and malfunctions. When an airplane is operated beyond this envelope, it led to severe cases of flutter.

Even though both flutter and buffet have similar cases of causes of vibration, flutter can also occur in smooth air condition. It is mainly because the flutter is originated from the airplane and not the atmosphere. Limited Cycle oscillations are also associated with Flutter. During an LCO, the vibration is self-excited, but the amplitude of the vibration is limited due to nonlinear effects like friction, clearances, and backlash. They are usually caused in Control surfaces of a wing structure.

C. *Flutter*

Flutter is an oscillatory structural instability that is caused by interactions between unsteady aerodynamic forces and elastic forces. The moments exerted by the vibratory motion of control surfaces on an aircraft wing is one of the main causes for this dynamic instability. Flutter is one of the rare cases of mechanical problems associated with the structural integrity of an aircraft structure. The mechanism of flutter depends on an aircraft flying at or above the allowed airspeed and altitude during which any two or more modes of the vibrations tend to couple with each other. Flutter is categorized into at least five different areas, depending on the characteristic modes of motion:

- Classical flutter: wing bending and torsion
- Control surface flutter: wing bending and surface rotation
- Empennage flutter: fuselage and tail torsion
- Stall flutter: wing torsion
- Body freedom flutter: fuselage pitch and wing bending

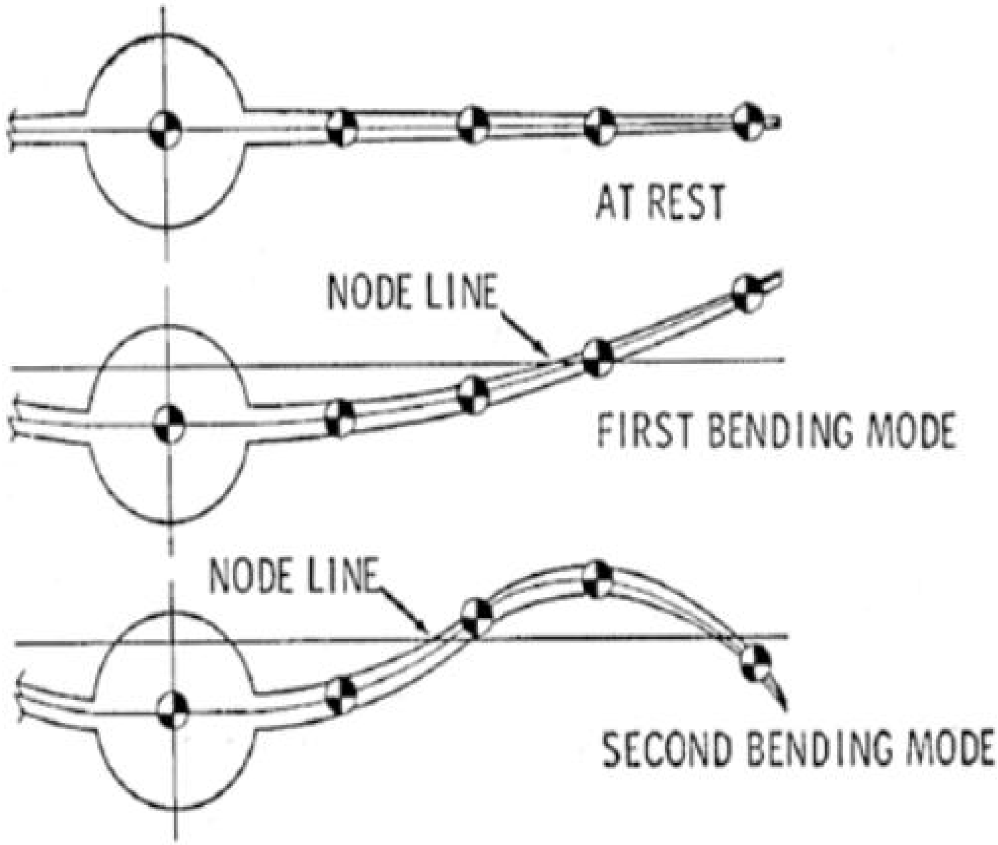


Fig. 1 Mode shapes in an aircraft wing

The effects of such airplane vibrations cause passenger and crew discomfort with flight safety issues. In commercial flights, the crew is made responsible for continuing the flight in such situations by avoiding the vibration and identifying the cause and rectify the problem. The flight crews' knowledge and understanding of airplane vibration and response procedures are very crucial because it can prevent events that may cause airframe/ structural damage and proper awareness can provide valuable information to facilitate maintenance troubleshooting. In these cases, flight safety takes precedence over any in-flight vibration analysis.

Thus, vibrations are an important aspect of aircraft stability and it is crucial in designing a stable aircraft structure. This paper deals with the analysis of a simplified wing structure and determining the bending modes and torsional modes acting on the chosen wing. The first six bending modes and the first six torsional modes are identified and discussed in this paper.

II. Literature review

Xiangying Chen, Ge-Cheng Zha, Ming-Ta Yang (2007) The authors have developed a numerical methodology with fully coupled fluid-structural interaction for determining the flutter characteristics in a 3-D transonic wing. It involves coupling Navier–Stokes equations and structural modal equations. They have employed the dual-time step implicit unfactored Gauss-Seidel iteration with the Roe scheme in the flow solver. A modal approach structure solver is used to simulate the wing's response. The flow and structure solvers are fully coupled via successive iterations within each physical time step. They have used ANSYS Workbench for this method of approach and have verified the accuracy of the solver. They obtained the first 5 modes of the chosen wing to study the modal response with the coupled system. They have done the study on the flutter boundary of AGARD wing 445.6 with free-stream Mach numbers ranging from 0.499 to 1.141 and their results are proved to be compared well with the experimental data.

Han Jinglong, Cui Peng (2011) This paper involves the study of aeroelastic behavior of the subject wing model using numerical simulation and comparing the results with experimental results. The wing used was the MAVRIC wing. They have adapted a high-fidelity method of approach to solve the structural and aerodynamic factors of the wing. They have used the CFD approach derived from Euler equations to solve the aerodynamic properties and CSD for structure. Also, since the aeroelastic behavior requires both the factors, they have developed a coupling solver to solve the aeroelastic phenomenon. Flutter and limit cycle oscillation (LCO) behavior of the basic transport wing was predicted first, and the results were compared with the existing experiment. It was found that large-amplitude shock-wave motion provided the proper physical mechanism for the LCO. Then, flutter analyses of winglet transport wing and C-wing were sequentially conducted.

Bocheng Zhang, Weilong Ding, Shengcheng Ji & Jiazhen Zhang (2016) In this paper, the authors have proposed a method based on Euler equations for predicting transonic flutter boundary in this paper. Euler equations are considered for the fluid field and boundary layer equations are considered inside the boundary layers, taking viscosity into account. The prediction of the transonic flutter boundary is performed based on the traditional method in the frequency domain using generalized aerodynamic coefficients matrices. Also, the simulation results are compared with the experimental results in this paper. The comparisons between the simulation and experimental results of the AGARD 445.6 wing show that the simulation results are following the experiment results for Mach numbers less than 1. They have encountered a transonic dip of the flutter boundary of the AGARD 445.6 wing which is located at a Mach number of around 0.954, which is also the Mach number when the shock wave appears on the wing surface. Also, they have proved that this frequency-domain is efficient than the time-domain method.

J S Chaitanya, Arun Prasad, B Pradeep, P L N Sri Harsha, S Shali, and S R Nagaraja (2017) The main objective of this paper is to use the application of CFD in determining the vibrational characteristics of an aircraft wing. The analysis has been performed in ANSYS Workbench to obtain the vibrational characteristics of the AGARD 445.6 wing. The wing was studied under transonic flow conditions. CFD analysis is performed on the wing to have a basic understanding of the pressure variations on the surface of the wing. The transient analysis gives the time domain solution for the wing which is utilized to extract the structural frequency. The plot of Mach number and its corresponding flutter index is used to observe the behavior of the wing when it is in the transition zone between subsonic and supersonic speeds. From the flutter index diagram, a dip is observed in the transonic regime and at a certain Mach number, the wing is most unstable.

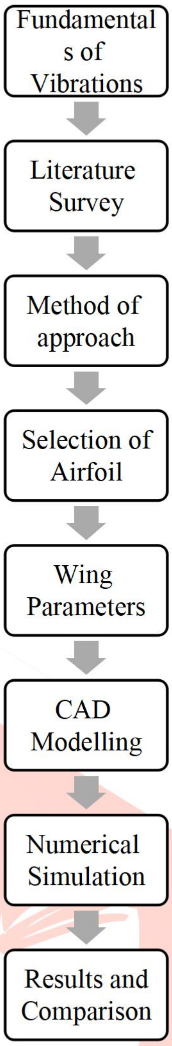
Ali Demirtaş and Meral Bayraktar (2018) The paper presents the modal analysis of an aircraft wing with the NACA 4415 airfoil profile. Both the theoretical and numerical calculations are performed by considering the aircraft wing as a cantilever beam and the values are compared. The wing model is designed and modeled using SolidWorks and the numerical simulation is carried out using ANSYS. The natural frequencies and the related mode shapes are obtained using Modal Analysis. The results of theoretical calculations are compared with the numerical modal analyses. The study has a conclusion that an aircraft wing can be considered as a cantilever beam by ignoring the whole forces on the aircraft. In this study, the wings of aircraft were considered as a cantilever beam to perform modal analysis. The results of the numerical modal analysis and theoretical approach method of cantilever beam were compared. It was observed that the natural frequency obtained from numerical and theoretical approaches are in good agreement. The validation of the modal analysis of the cantilever beam proved that the procedure opted for numerical modal analysis of aircraft wing is correct.

Nataraj Kuntoji, Dr. Vinay, and V. Kuppast (2017) The design of the aircraft wing using NACA standards has been discussed in this work. The wing analysis is carried out by using computer numerical analysis tools including CAD/CAE and CFD. The necessary inputs for carrying out the structural analysis with emphasis on the vibration are obtained by CFD analysis. The deformation of the wing structures is investigated concerning the standard airflow velocity. The Computer-Aided Design Tools and NACA standards have been accomplished to design the wing structure. The vibration characteristics of the wing structures are studied by modal analysis to find the natural frequency of the wing structures. The CFD results revealed that the pressure on the upper surface of the wing for all the wing section planes is less, about -4.97e3N/mm2, as compared to the pressure on the lower surface, about 1.08e4 N/mm2, which satisfy the theory of lift generation. The pre-stressed modal analysis shows the correlation of the stress, deformation, and the corresponding mode of vibration.

Kakumani Sureka and R Satya Meher (2015) this paper deals with finding suitable material for a given wing ode which is the A300 wing since it is one of the most widely used aircraft wings. The main purpose of this project is to find out which material either AL alloy or Al alloy 7068 is best suited for making the wing of flight. The CAD model of the A300 wing with spares and ribs using is modeled using the software CATIA V5 R20 and the structural analysis is carried out using ANSYS WORKBENCH. From the obtained results they have concluded that the difference between the values of deformation, equivalent stress, max principle stress, stress intensity, and shear stress with Al alloy and Aluminum alloy7068 is minimal, and the results obtained are validated and verified. Since the difference in values was minimal, they have proposed that Aluminum Alloy 7068 should be used in the place of Aluminium alloy for the better structural integrity of the wing structure.

Ramindla Praveen, Elumagandla Surendar, and K Shyam Kumar (2018) The main objective of this paper is to achieve a reduction in the weight of an aircraft by using different materials including some composite materials, in which Aluminium as base material and mixed with some other materials at different proportions. A suitable wing profile NACA 4412 is selected and modeled in CATIAV5 R20. The generated wing profile is imported to ANSYS WORKBENCH. To examine the structural effectiveness of the designed wing, 3-D finite element analysis was performed using ANSYS software to compute the critical stresses, displacements, strains and to test the wings against Von- Misses failure criterion. The conditions are given based on the inputs obtained from experimental examinations on the selected wing. The materials were assigned differently and the results were compared. The first 6 order natural frequency and the vibration modes are obtained. The results are used to study the structural performance of the wing with different materials.

III. METHODOLOGY



Flowchart 1 Overview of Approach of method

IV. Modeling of Wing

The performance and operation of any aircraft are fundamentally dependent upon the type of wing, its parameters, and characteristics. Hence, the wing of an aircraft is the most important part of an aircraft structure. The aircraft wing is modeled using CATIA V5 wherein the airfoil coordinates are imported through Microsoft Office Excel Macros. The wing model used in this paper is a tapered wing and the angle of attack maintained with the wing model is 10 degrees. The specifications of the wing model used are as follows.

A. *Airfoil*

An airfoil is the 2D representation of the aircraft wing or in other words, it is the cross-sectional view of the wing. It is a fluid determined body and responds to movement by aerodynamic forces. The front of the airfoil is named the leading edge and the rear of the trailing edge.

Airfoil used: NACA a65112
Maximum thickness ratio is 12% at 40% of the chord
Maximum camber is at 1.1% at 50% of the chord

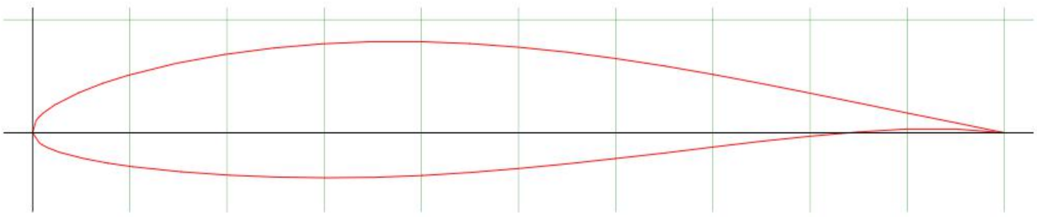


Fig. 2 Airfoil Plot

B. *Wing Dimensions*

The wing used for this project is inspired by the AGARD wing. However, the dimensions are changed for research purposes. The dimensions of the wing used in this paper are as follows.

Root Length = 559 mm
Tip Length = 356 mm
Wing Span = 1542 mm

C. ***CAD Model***

The airfoil data imported into the CATIA Software is displayed in the below figure. The points seen in Fig.2 are the coordinates of the above-mentioned airfoil and they are connected to form the curve of an airfoil.

Fig. 3 Airfoil Plot imported in CATIA

The above figure displays the airfoil curve for the Root of the wing structure used in this project. Similarly, the airfoil coordinates for the tip are also generated by altering the data and dimensions of the coordinates and are generated using MS Excel macros. Once both the airfoil curves of Root and Tip are generated, the curves are joined using the Multi-Section method to generate the Wing Surface. The isometric view of the wing used is displayed in Fig. 3.

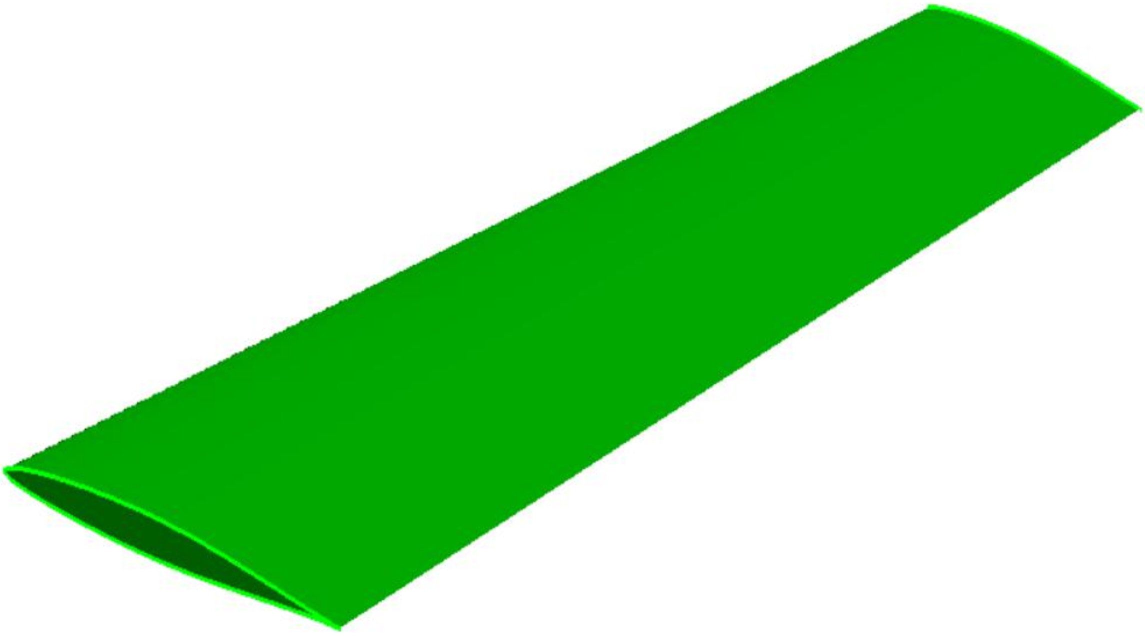


Fig. 4 CAD Model of the wing

D. ***Material Used***

The material properties of a structure or fluid have a great influence on the results of both structural and fluid simulations. The material of the wing structure is defined with **Aluminum Alloy**. Aluminum is the most common material used in the aerospace field due to its lightweight structural property and high strength. Aluminum Alloy constitutes mixtures of materials including Copper, Iron, Manganese, Silicon, Magnesium, Zinc, and Lithium. The Mechanical Properties of the chosen Aluminium allow exhibits lower weigh or density than any other high strength materials. The Aluminium is much reliable for aerospace applications, especially for the high strength low weight property. The properties of the Aluminum material used in this project are represented in Table 1.

TABLE 1

MATERIAL PROPERTIES

Density (g/cm3)	2.6898
Modulus of Elasticity (GPa)	68.3
Poisson's Ratio	0.34

V. FINITE ELEMENT ANALYSIS

Finite Element Analysis is a numerical simulation method in which a mathematical representation of a physical system is produced. A structural model is created by applying material properties, and applicable boundary conditions which collectively are referred to as PRE-PROCESSING of the analysis. It is followed by the solution of that mathematical representation, which is referred to as SOLVING. Finally, the study of the results of that solution and plotting virtual representations of the results are collectively referred to as POST- PROCESSING. On the other hand, Computational structural and solid dynamics (CSD) is one of the classical core disciplines in FEA that deals with the problems involving vibrations, transient problems, and harmonic problems. The vibrational analysis for the given objective of this project is carried out using ANSYS Workbench. ANSYS is an analysis systems software that performs structural thermal, vibrational, and fluid analysis. In this project, a Modal Analysis solver is used for the vibration study required for this paper.

A. ***Ansys Modal***

The modal analysis component calculates the natural frequencies of the given system. Modal Analysis in ANSYS Workbench is the solver that determines the resonant frequencies of any given geometry under defined conditions. Resonance frequencies are the results of the shape and constraints of the geometry. The modal analysis also provides us the representation of different modes of the caused vibration. In other words, it shows the different mode shapes a structure exerts during vibration. This shape during different modes is called mode shape and all mode shapes have their corresponding natural frequency. The mode shapes of both Torsional and Bending, also other mode shapes of any structure can be visualized with the modal analysis with ANSYS Solver.

In this project, the vibrations are determined to study the flutter of the chosen wing. The mode shapes give the flutter behavior of the chosen wing. The 1st 20 modes of the Wing structure are analyzed and the bending modes and torsional modes are identified from the results obtained.

VI. ANALYSIS

The Modal analysis is performed under the Pre-Stress environment. The ANSYS Workbench performs the simulation on the provided structural model and provides the results. The structural model is imported from CATIA to ANSYS in the format of IGES.

A. *Meshing*

The primary part of the model setup in any numerical simulations is meshing and the wing model is meshed using the Setup component in ANSYS Workbench. Meshing is an important part of the simulation as the elements discretized contribute integrally to the final results. A fine mesh is required for good results, the default mesh provided by ANSYS may not be uniform and proper in many cases. Especially for a structure with airfoil and wing parameters, the meshing is complicated.

A structured mesh is necessary for better results in such numerical simulations. ANSYS Workbench provides a default unstructured mesh for any geometry that is defined in the solver. So, a meshing method is introduced to form a structured mesh for this analysis. The meshing method used in our problem is the automatic method with the 2nd order quadratic elements. The whole body is uniformly discretized as 10mm elements in size and the mesh is solved as shown in Fig.6.

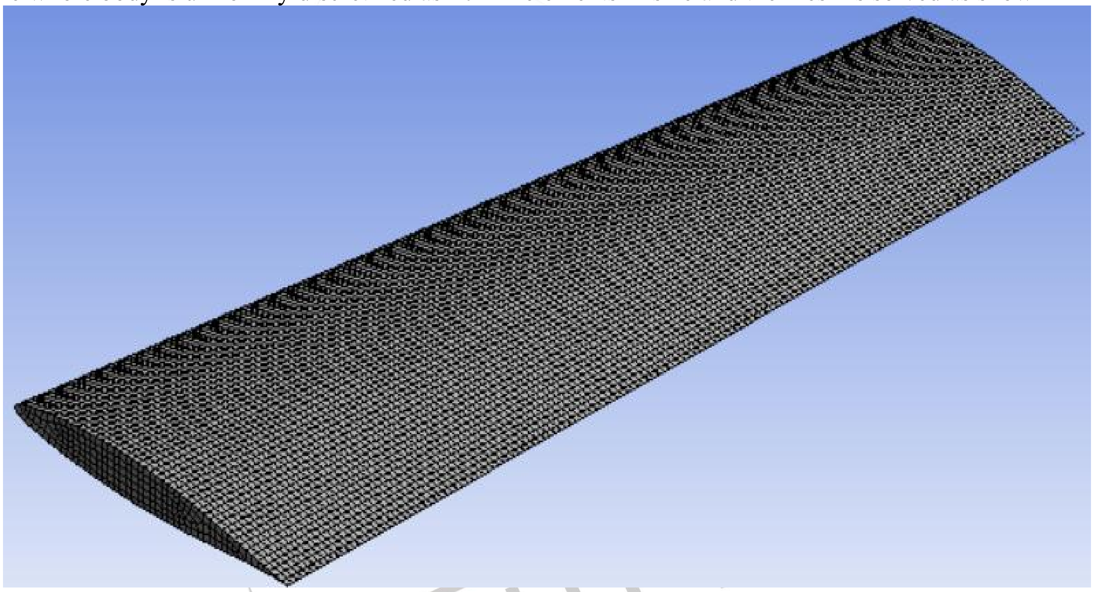


Fig. 5 Mesh of the model

The growth rate and smoothing of the above model are defined as high to attain a smooth mesh of the model. The statistics of this particular mesh are as follows,

Number of Nodes : 141894
Number of Elements : 30030

B. *Boundary Conditions*

In this project, the wing model is set up at Cantilever Beam's condition. The condition is based on the objective that the Root of the wing structure is attached to the body of the fuselage in an aircraft and hence it is fixed. The fixed support in the ANSYS is applied to the face of the Wing Root.

C. *Solver Setup*

The analysis is carried out under Pre-Stress Environment. The number of modes to be obtained was set to 20 to obtain the first six mode shapes of bending modes of the wing as well as the torsional modes of the given wing structure. The total deformations in all these modes respectively will give us the required mode shapes and the vibrational behavior of the wing structure. Based on the mode shape, the bending modes and torsional modes are identified and observed.

VII. SOLUTION

The ANSYS Solver solves the modal component for the 20 modes of the given wing structure and produces the solutions under the cantilever beam condition. The solution includes the natural frequencies of the wing structure corresponding to the respective mode shapes. The total deformations for all the 20 modes are observed and the required bending modes and torsional modes are distinguished. Although the default mode numbers in ANSYS are different, the first six bending modes and the first 6 torsional modes are represented below.

A. *Natural Frequencies*

The ANSYS Solver system performs the numerical simulation with the given conditions and produces the results. In Modal simulation, the natural frequencies are produced for the defined number of modes. Since the first 20 modes are required for this project, the frequencies of all the respective mode shapes are obtained and are tabulated below in Table 2.

TABLE 2
MODES AND FREQUENCIES

Mode	Frequency [Hz]
1.	23.231
2.	110.43
3.	168.73
4.	186.76
5.	281.1
6.	432.13
7.	525.86
8.	685.91
9.	704.99
10.	832.35
11.	981.11
12.	993.43
13.	1175.8
14.	1302.2
15.	1483.5
16.	1513.4
17.	1645.5
18.	1776.2
19.	1823.5
20.	1981.4

B. ***Bending Modes***

Bending modes are the type of normal modes of vibration occurring in a system. Generally, bending mode in a cantilever beam occurs along the longitudinal axis producing a deflection of the structure. Such modes are studied in this paper for the given wing structure. The ANSYS Workbench solves the numerical simulation and provides the results with the harmonic response and natural frequencies with respective mode shapes. The main objective of this paper is to obtain the bending modes and Torsional modes for the given aircraft wing. The bending modes in the aircraft wing model produce a deflection with respect to the root of the wing. With various mode shapes, the deflection along the longitudinal axis of the structure varies, and also the natural frequency of the structure increase with the mode shapes. The deformation of the wing structure varies from 9.5 mm in the first bending mode to 26 mm in the observed sixth bending mode. This deformation is along the root of the wing. The first six bending mode shapes are obtained and they are illustrated in the following figures. This bending mode shapes are the illustration of how the bending modes of a flutter in an aircraft wing will cause.

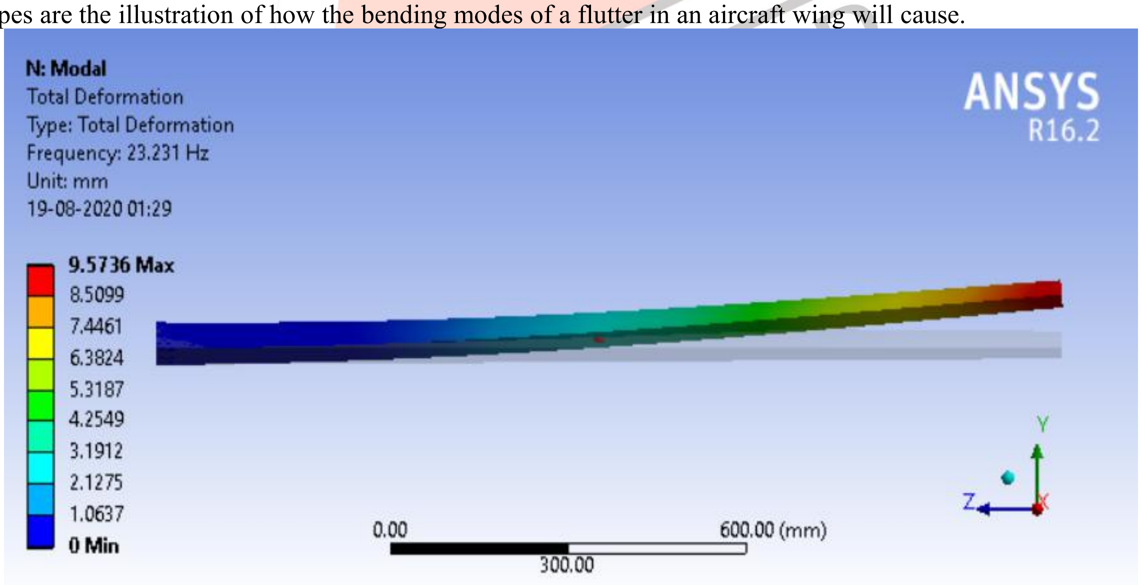


Fig. 6 Bending Mode 1

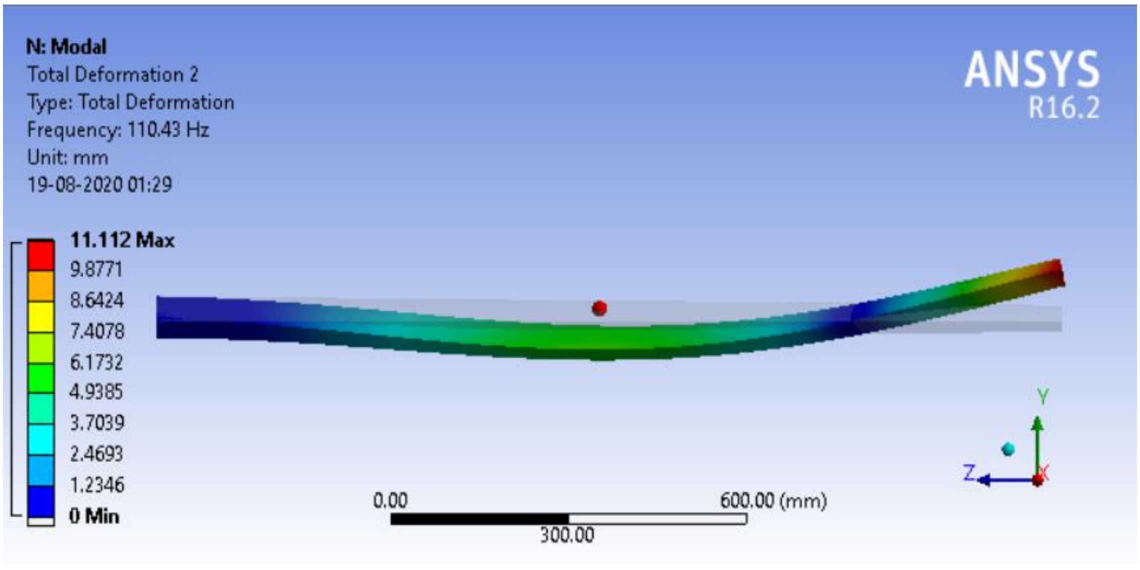


Fig. 7 Bending Mode 2

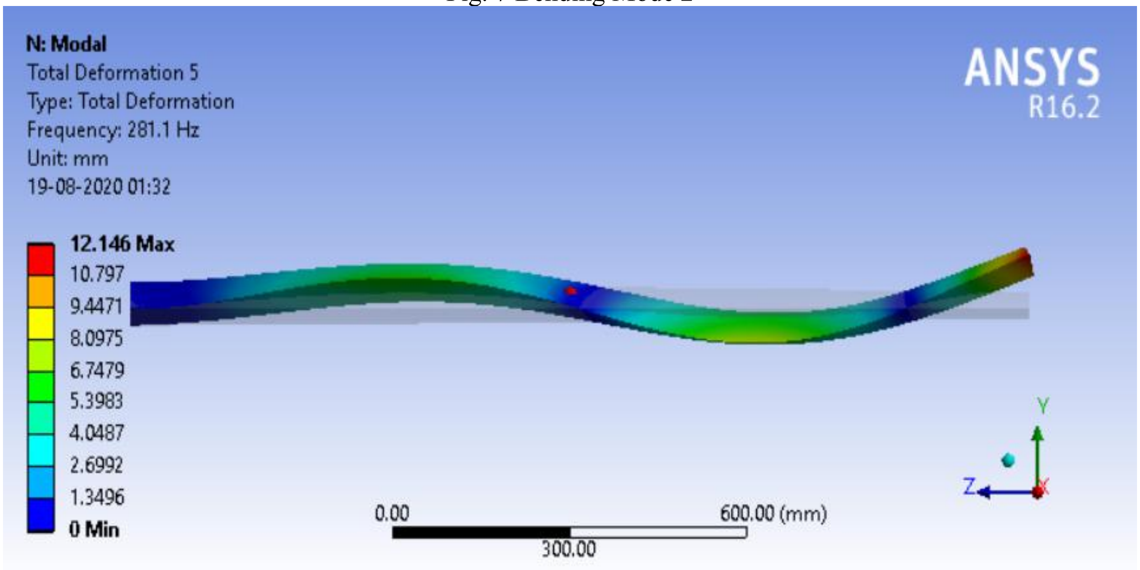


Fig. 8 Bending Mode 3

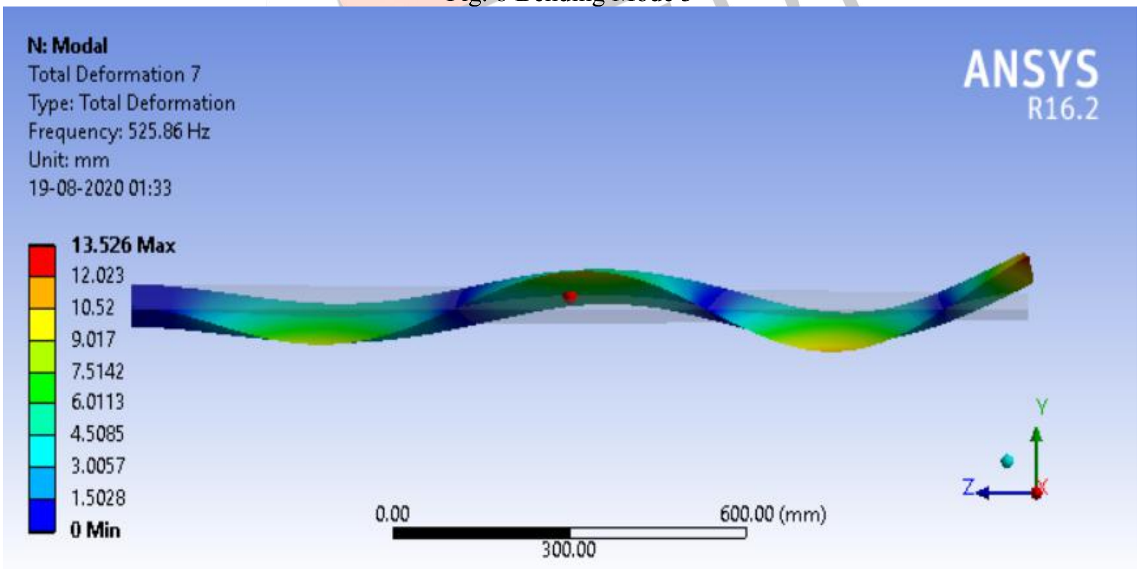


Fig. 9 Bending Mode 4

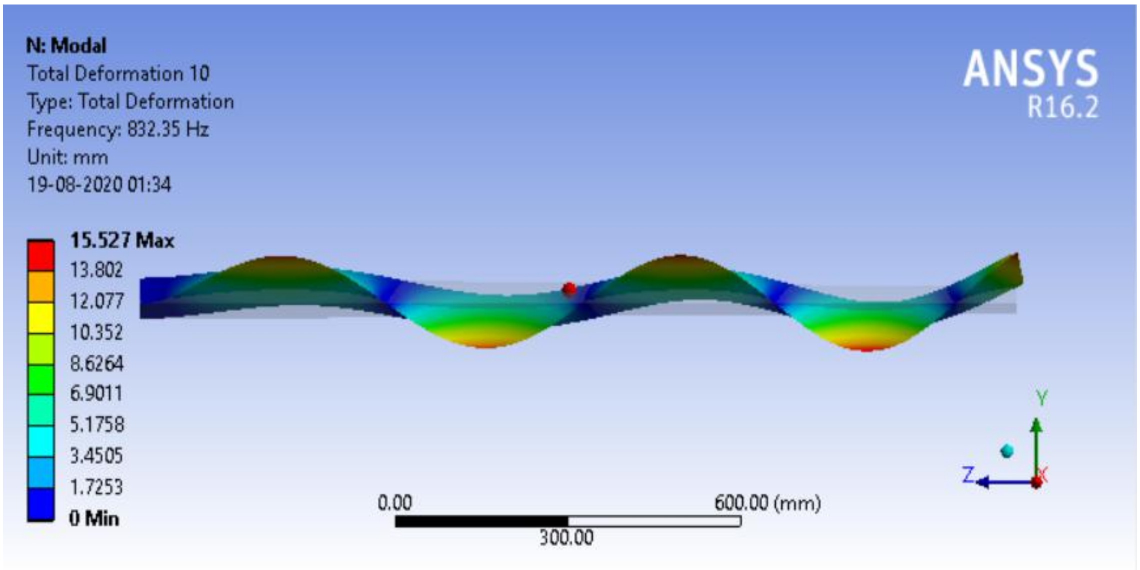


Fig. 10 Bending Mode 5

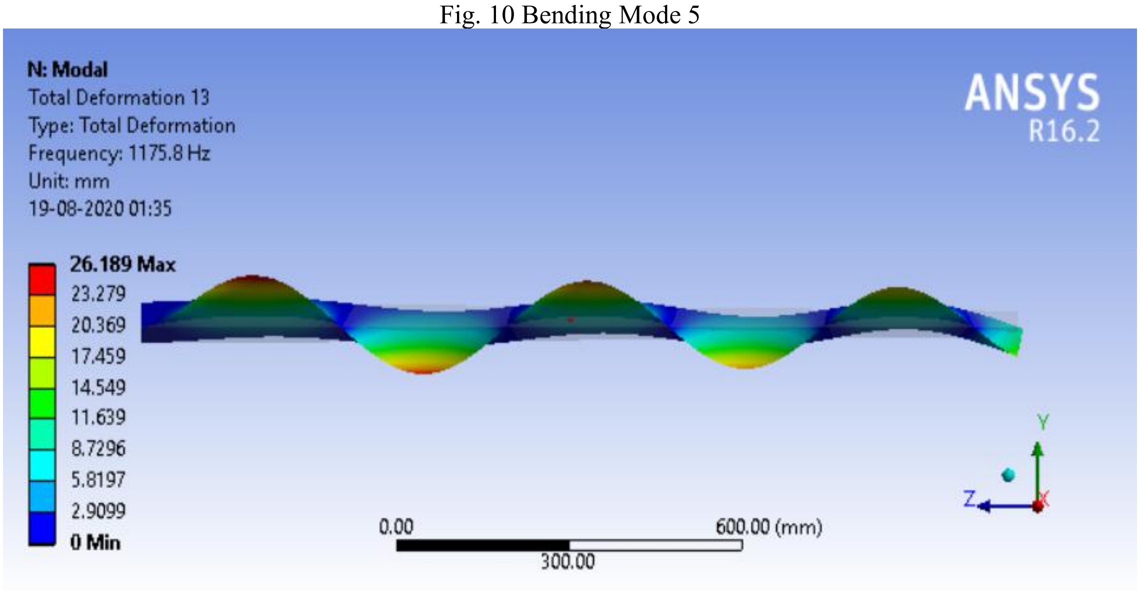


Fig. 11 Bending Mode 6

C. ***Torsional Modes***

Torsional modes of vibrations are the mode shapes that fall under this category when there is a twisted deformation in the structure. While bending mode shapes lead to deflection along the longitudinal axis, torsional mode shapes cause deformation in the transverse axis as well. Torsional modes are nothing but the twisted deformation occurring in a structure due to harmonic vibrations. Both the deformation and frequency of vibration in torsional modes are higher than that of bending modes. The first torsional mode causes deformation at the trailing edge of the wing of about 15 mm whereas the values increase up to 70 mm in higher modes. Since all the first 20 mode shapes are solved for the given aircraft wing under the assigned Cantilever Beam Condition, bending modes and torsional modes are identified and are represented in this paper. The previous section illustrates the first 6 bending modes from the view of the XZ Plane for better picturization. However, the torsional modes are illustrated from the isometric view, so the deformation can be viewed in all three directions. Unlike the bending mode deformations, deformations due to torsional mode account for deflection along two or more axis. The higher the mode, the higher the twisted deformations can be viewed. The following six figures represent the first six torsional modes observed for the given wing structure under cantilever beam condition using ANSYS Modal analysis. This illustration is also a representation of how torsional mods occur on an aircraft wing that can lead o severe flutter issues. The natural frequencies of these modes range from 186 Hz to 1981 Hz.

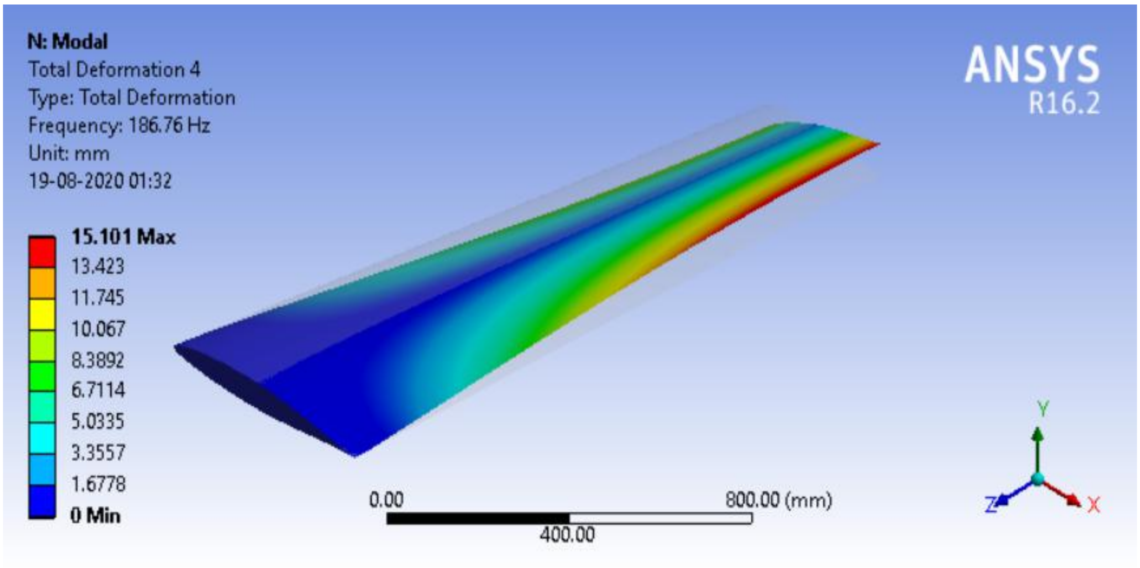


Fig. 12 Torsional Mode 1

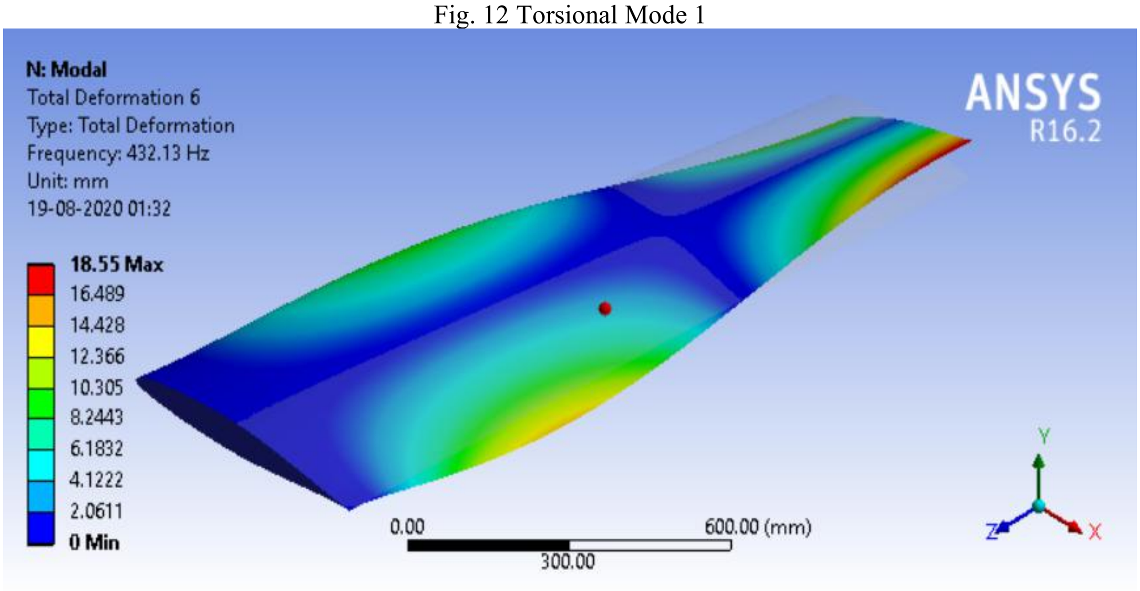


Fig. 13 Torsional Mode 2

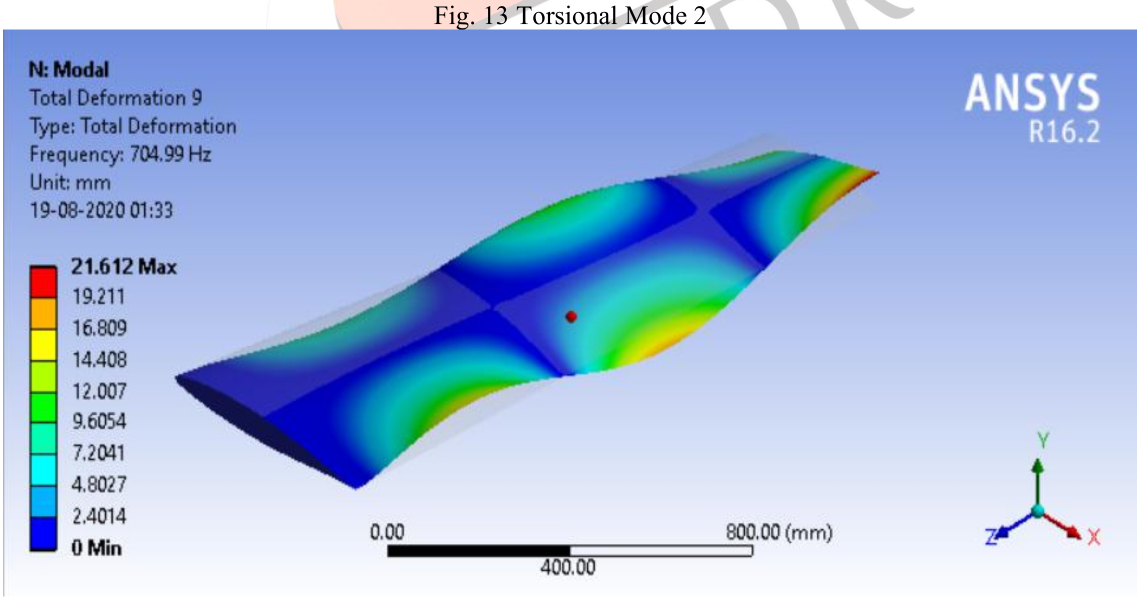


Fig. 14 Torsional Mode 3

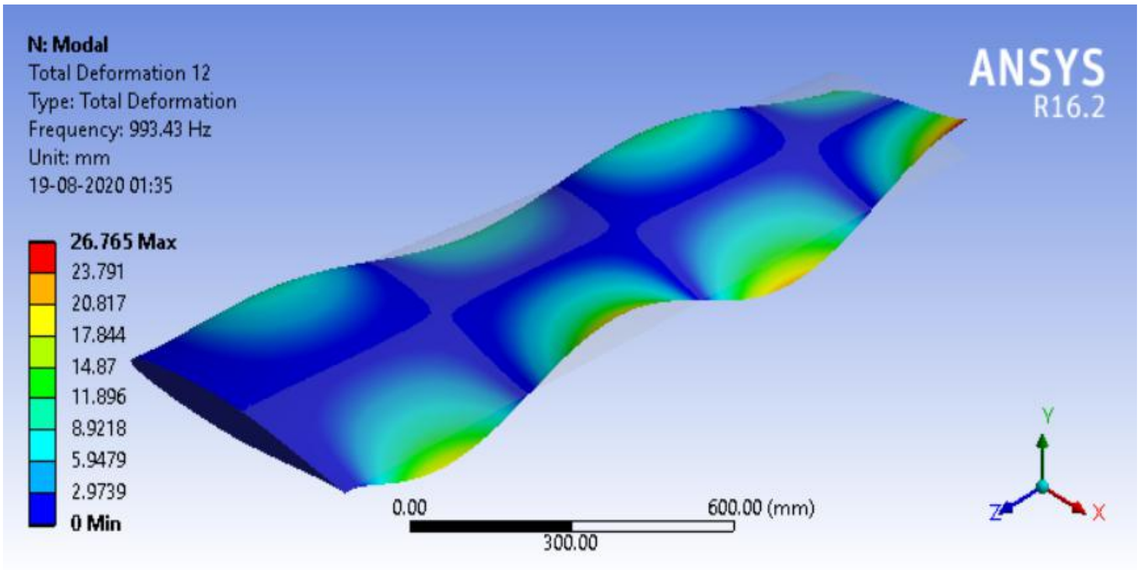


Fig. 15 Torsional Mode 4

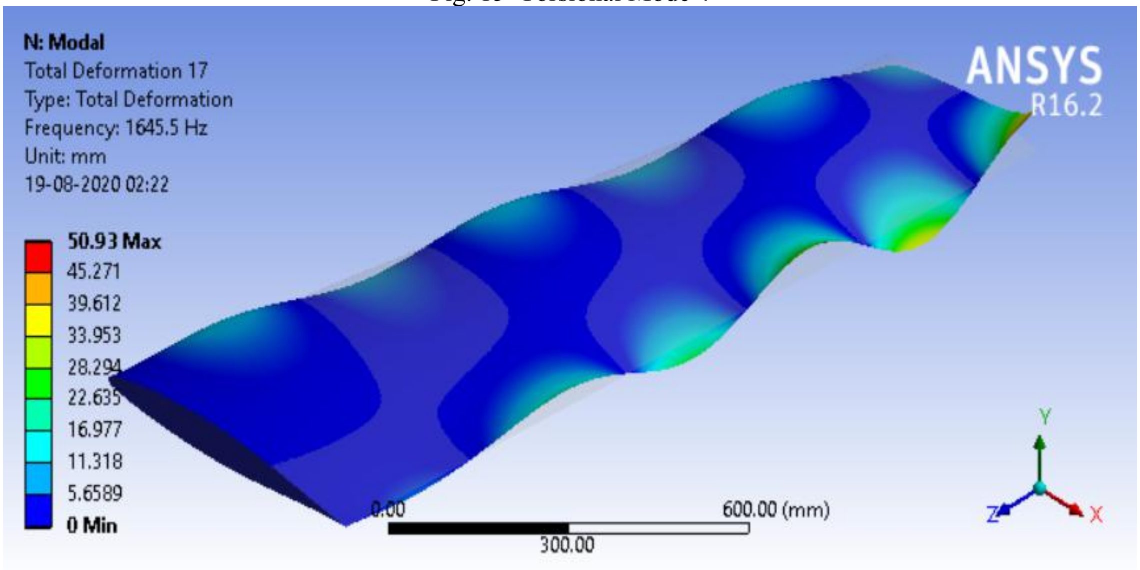


Fig. 16 Torsional Mode 5

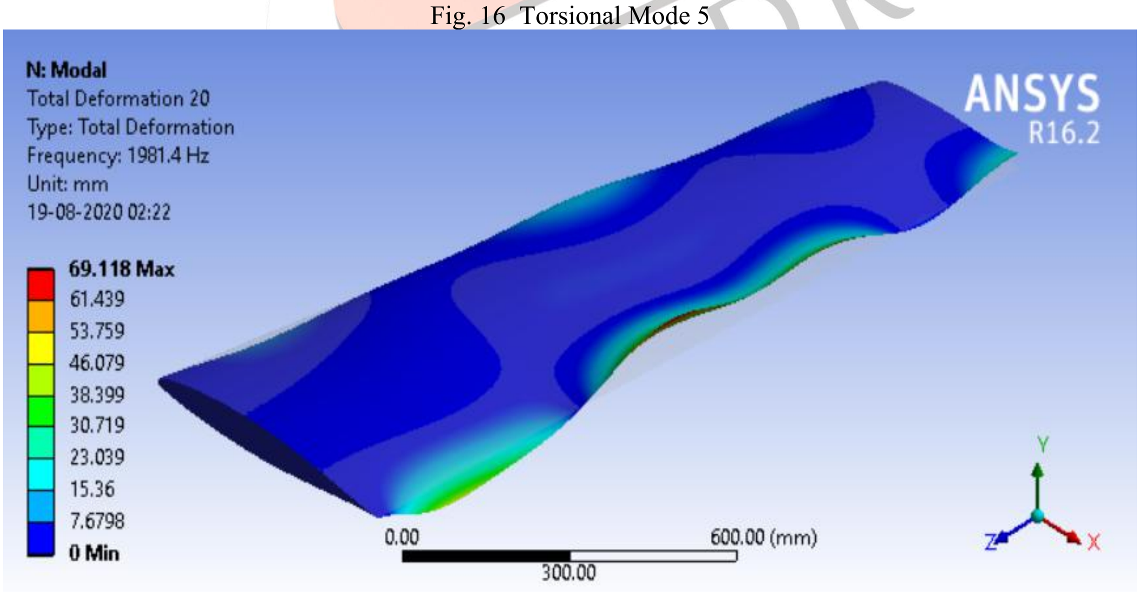


Fig. 17 Torsional Mode 6

VIII. RESULTS

The mode shapes for the bending modes and torsional modes of the given wing structure is determined using the ANSYS Workbench Modal analysis component. The natural frequencies for the 20 modes of the model are obtained. However, the natural frequencies of the bending modes and torsional modes determined above are ordered differently and they are tabulated in Table 3 and Table 4.

TABLE 3
NATURAL FREQUENCIES OF BENDING MODES

Bending Mode	Frequency [Hz]
1.	23.231
2.	110.43
3.	281.1
4.	525.86
5.	832.35
6.	1175.8

TABLE 4
NATURAL FREQUENCIES OF TORSIONAL MODES

Torsional Mode	Frequency [Hz]
1.	186.76
2.	432.13
3.	704.99
4.	993.43
5.	1645.5
6.	1981.4

The values of the natural frequencies are obtained by identifying their respective modal shapes and sorted out from all the 20 Mode vales that are given in Table 3 and Table 4. The first six bending modes have natural frequencies ranging from 23 Hz to 1175 Hz. The deflection of the structure during these modes range from 11 mm to 26 mm. The first six torsional modes have natural frequencies ranging from 186 Hz to 1981 Hz. The deflection of the structure during these modes range from 15 mm to 69 mm. These are the natural frequencies of the classic flutter modes for the given aircraft wing structure. The values obtained are only for the first six modes in both conditions. Both bending modes and Torsional modes occur more than six that are observed in this paper.

IX. CONCLUSION

In this Vibrational study, the aircraft wing is modelled using CATIA V5 CAD software and is imported into ANSYS Mechanical Workbench. The vibrational study is carried using the Modal Analysis component in the ANSYS Solver. The boundary condition is applied under the Cantilever Beam condition according to the assumption that the wing is attached to the fuselage body in a fixed condition. The first 20 mode shapes of the wing structure under this condition are solved under this numerical simulation and the results are obtained. The first six bending modes and torsional modes are observed, identified, and determined from the results produced by the ANSYS Solver. The deflection of the wing structure is also studied and the varying behaviors in different modes are noted. Thus, the mode shapes of vibrations occurring in this wing structure than can lead to classic flutter characteristics in this wing are studied.

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