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# Comparative Modal Analysis of NACA 4412 Airfoil Air-Wings Using Multiple Composite Materials

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**ABSTRACT**

This study presents a comprehensive modal analysis of NACA 4412 airfoil-based air-wings constructed from various composite materials, aiming to evaluate their dynamic performance characteristics. The NACA 4412 airfoil is widely recognized for its aerodynamic efficiency, making it a popular choice in aerospace applications. The modal analysis focuses on identifying natural frequencies, mode shapes, and damping ratios of the air-wings, which are critical parameters for assessing structural integrity and performance during flight operations. Different composite materials, including carbon fiber, glass fiber, and aramid fiber, are employed to investigate their effects on the vibrational behavior of the air-wings. Utilizing advanced finite element analysis (FEA) techniques, this research reveals significant variations in modal properties based on material selection, highlighting the influence of stiffness, mass distribution, and damping characteristics on the overall dynamic response. The findings underscore the importance of optimizing material choices to enhance the performance and reliability of air-wing designs in aerospace engineering. Furthermore, the insights gained from this study can inform future developments in lightweight and high-performance airfoil structures, contributing to advancements in aircraft efficiency and safety.

## I. INTRODUCTION TO NACA 4412 AEROFOIL:

The NACA 4412 airfoil is a well-established airfoil shape renowned for its favorable aerodynamic characteristics, making it a popular choice in various aerospace applications, including aircraft wings and wind turbine blades. Understanding the dynamic behavior of airfoil-based structures is essential for ensuring their performance, stability, and longevity during operation. Modal analysis, a critical aspect of structural engineering, focuses on identifying the natural frequencies, mode shapes, and damping characteristics of structures under vibrational loads. These parameters are vital for predicting how an airfoil will respond to aerodynamic forces, vibrations, and potential structural failures.

The integration of composite materials in the design of air-wings has gained significant traction due to their superior strength-to-weight ratio, corrosion resistance, and tailorability of mechanical properties. Composites such as carbon fiber, glass fiber, and aramid fiber offer unique advantages over traditional materials like aluminum and steel, enabling the development of lighter and more efficient airfoil structures. However, the specific impact of different composite materials on the modal behavior of airfoil designs remains an area of active research.

This study aims to conduct a modal analysis of NACA 4412 airfoil-based air-wings constructed from various composite materials. By employing advanced finite element analysis (FEA) techniques, this research will explore how different composites influence the dynamic properties of the air-wings, including their natural frequencies and mode shapes. The analysis will also consider how factors such as material stiffness, density, and damping characteristics contribute to the vibrational response of the airfoils.

Through this investigation, the study seeks to provide valuable insights into optimizing composite material selection for airfoil designs, enhancing their performance and reliability in aerospace applications. By understanding the relationships between material properties and dynamic behavior, engineers can make informed decisions when designing air-wings, ultimately leading to advancements in aircraft efficiency and safety. The findings of this research will contribute to the broader field of aerospace engineering, promoting the use of innovative materials and design methodologies in the pursuit of more efficient and sustainable flight technologies.

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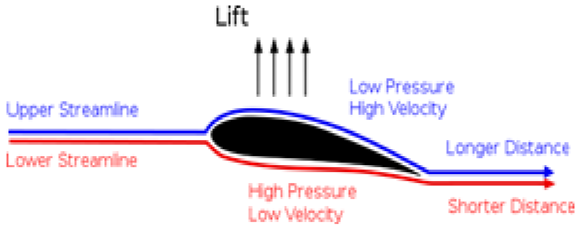


**Fig.1 Forces Acting on Airfoil**

The airs flowing below the wing moves in a comparatively straighter line, so its speed and air pressure remain the same. Since high air pressure always moves toward low air pressure, the air below the wing pushes upward toward the air above the wing. The wing

is in the middle, and the whole wing is "lifted." The faster an airplane moves, the more lift there is. And when the force of lift is greater than the force of gravity, the airplane is able to fly.

Aerodynamic is a study of the powers and moments vital to possess a sustainable aerial movement. The aerodynamic force functioning on the flying vehicle can be described as "lift indirection normal to the flight" with "drag in the same direction". Hence, various factors such as aircrafts' load, size, rate of climb, and required landing speed need to be heavily considered to design wings. With that, this study aims to find drag and lift contribution in wing's aircraft by analysis approach by investigating the better performance of the wing at various wing aspect ratio and its aerodynamic achievement; which can be analyzed by observing not just the coefficients of drag and lift, but also the lift drag ratio. It is a reality of general expertise that body in moving through a fluid covering with a resultant force that by and hugged in a very primarily movement of the resistance. A category of the body exists, regardless, that the fragment of the resultant force ordinarily to the orientation of the event is sometimes additional clear than the contradicting the event to boost the likelihood of the flight of a plane depends upon the usage of the body of this category for wing structure. The approach is that the purpose between the approach air or relative breeze and a reference line on the plane or wings. As this nose of the wing turns up, approach increments and raise a force in addition increased. Drag goes up, however, additionally not as fast as a raise. Within the interior of activity, a briefing creates a specific speed and after the pilot flips the plane, that's the pilot controls with the controls that the nose of the plane returns up and, at some approach, the wings create enough to raise to bring the plane into the air. An airfoil is the shape of a wing, blade of a propeller, rotor, or turbine, or sail as seen in cross-section to generate aerodynamic force.

**HISTORY OF AIRFOIL:**

The historical evolution of airfoil sections, 1908-1944. The last two shapes are low-drag sections designed to have laminar flow over 60 to 70 percent of chord on both the upper and lower surface. The Wright brothers had done some of the earliest research on the most effectivecurvature, or camber, of a wing, known as an airfoil. But during the early years of powered flight, airfoils for aircraft were essentially hand-built for each airplane. Before World War I, there had been little research to develop a standardized airfoil section for use on more than one aircraft. The British government had performed some work at the National Physical Laboratory (NPL) that led to a series of Royal Aircraft Factory (RAF—not to be confused with the Royal Air Force) airfoils. Airfoils such as the RAF 6 were used on World War I airplanes.

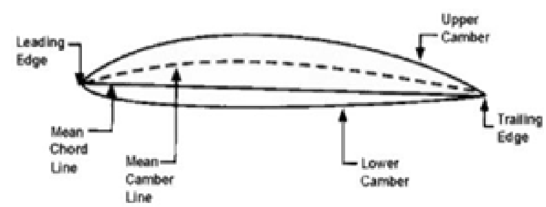


**Fig. 2 NACA Airfoil**

When the National Advisory Committee on Aeronautics (NACA) was established in 1915, its members immediately recognized the need for better airfoils. The first NACA Annual Report stated the need for "the evolution of more efficient wing sections of practical form, embodying suitable dimensions for an economical structure, with moderate travel of the center of pressure and still affording a large angle of attack combined with efficient action." NACA explained its first work with airfoils in 1917 NACA Technical Report No. 18, "Aero foils and Aero foil Structural Combinations

**NOMENCLATURE OF AN AIRFOIL:**

An airfoil is a body of such a shape that when it is placed in an airstream, it produces an aerodynamic force. This force is used for different purposes such as the cross sections of wings, propeller blades, windmill blades, compressor and turbine blades in a jet engine, and hydrofoils are examples of airfoils. The basic geometry of an airfoil is shown in Figure Basic nomenclatureof an airfoil The leading edge is the point at the front of the airfoil that has maximum curvature. The trailing edge is defined similarly as the point of maximum curvature at the rear of the airfoil. The chord line is a straight line connecting the leading and trailing edges of the airfoil.

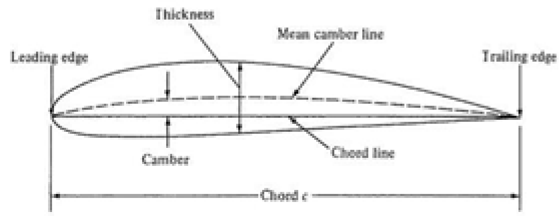

**Fig. 3 Nomenclature of Air Foil**

**NACA 4412 SYMMETRIC AEROFOIL:**

The reason to choose the NACA 4412 symmetric aerofoil is that it produces a more lift-to-drag ratio at low wind speed and is the most common kind used for research purposes in most cases. Symmetrical aerofoil reduces the complexity of design and imparts easiness in the design modifications of the aerofoil. The center of pressure remains at a constant position as the upper and lower surfaces are identical in a symmetrical aerofoil. This reduces problems of Cp variations with varying angles of attack of airflow over the aerofoil. With changes in the positions of maximum thickness in percentages of chord and along the chord, the following profiles have been named as per their specification criteria. It is to be noted that the amount of maximum thickness is not disturbed in this research content.

## II. LITEREATURE REVIEW

Energy is essential to human civilization development. With the progress of economics and socialization, there's an expanding demand for renewable energy resources to secure energy supply, like solar energy, wind generation, tide and wave power, etc. As a clean natural resource, wind generation plays a more and more important role in modern life. according to Wikipedia Wind power accounts for nearly 10% of India's total installed power generation capacity and generated.

[1] Computational investigation of inviscid flow over an airfoil. The drag and lift forces can be determined through experiments using wind tunnel testing, in which the design model has to beplaced in the test section. The experimental data is taken from Theory of Wing Sections by Abbott et al., This work presents a computational method to deduce the lift and drag properties, which can reduce the dependency on wind tunnel testing. The study is done on air flow over a two-dimensional NACA 4412 Airfoil using ANSYS FLUENT (version 12.0.16), to obtain the surface pressure distribution, from which drag and lift were calculated using integral equationsof pressure over finite surface areas. In addition the drag and lift coefficients were also determined. The fluid used for this purpose is air. The CFD simulation results show close agreement with those of the experiments, thus suggesting a reliable alternative to experimental method in determining drag and lift.

[2] Aerodynamics — as an engineering discipline involved deeply in the aircraft development process — always have been and will continue to be essential for the commercial success of any aircraft programme. Past developments in computing methods and tools as well as in wind tunnel testing technologies have produced clear cost and performance benefits. For this reason it is absolutely justified to invest in further improvements concerning development of tools and methods including experimental technologies and facilities, taking advantage of the enormous leverage on both total programme costs and aircraft performance.

[3] Micro air vehicles (MAVs) have the potential to revolutionize our sensing and information gathering capabilities in areas such as environmental monitoring and homeland security. Flapping wings with suitable wing kinematics, wing shapes, and flexible structures can enhance lift as well as thrust by exploiting large-scale vortical flow structures under various conditions. However, the scaling invariance of both fluid dynamics and structural dynamics as the size changes is fundamentally difficult. The focus of this review is to assess the recent progress in flapping wing aerodynamics and aeroelasticity. It is realized that a variation of the Reynolds number (wing sizing, flapping frequency, etc.) leads to a change in the leading edge vortex (LEV) and spanwise flow structures, which impacts the aerodynamic force generation. While in classical stationary wing theory, the tip vortices (TiVs) are seen as wasted energy, in flapping flight, they can interact with the LEV to enhance lift without increasing the power requirements. Surrogate modeling techniques can assess the aerodynamic outcomes between two- and three- dimensional wing. The combined effect of the TiVs, the LEV, and jet can improve the aerodynamics of a flapping wing. Regarding aeroelasticity, chordwise flexibility in the forward flight can substantially adjust the projected area normal to the flight trajectory via shape deformation, hence redistributing thrust and lift. Spanwise flexibility in the forward flight creates shape deformation from the wing root to the wing tip resulting in varied phase shift and effective angle of attack distribution along the wing span. Numerous open issues in flapping wing aerodynamics are highlighted.

[4] In the present study, a general aviation airplane is designed and analyzed. The design processstarts with a sketch of how the airplane is envisioned. Weight is estimated based on the sketch and a chosen design mission profile. A more refined method is conducted based on calculated performance parameters to achieve a more accurate weight estimate which is used to acquire the external geometry of the airplane. A three-dimensional layout of the airplane is created usingRDS

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software based on conic lofting, then placed in a simulation environment in Matlab which proved the designs adherence to the design goals. In addition, static stress analysis is also performed for wing design purposes. Using the finite element software package COMSOL, thecalculated aerodynamic loads are applied to the wing to check the wing reliability. It is shown that the designed wing could be a good candidate for similar general aviation airplane implementation.

**SPECIFIC OBJECTIVES:**

- General evaluation of mechanical reliability for NACA 4412 blade in terms of stressconcentration.
- Determining the proper material using FEM.
- Analyzing the stress concentration on NACA 4412 blade geometry.
- Finally find out stress, total deformation, shear stress and modal analysis.
- Recommending the geometry and the suitable material we should be using in futureNACA 4412 blade material.

## III. METHODOLOGY:

**Step 1:** Collecting information and data related to wind turbine blade.

**Step 2:** A fully parametric model of the wind turbine blade created in solid works software.

**Step 3:** Model obtained in igs. Analyzed using ANSYS 18.0 (workbench), to obtain stresses, deformation, Shear stress and mode shapes etc.

**Step 4:** Taking boundary conditions.

**Step5:** Finally, we compare the results obtained from ANSYS and compared geometry with different materials.

**MATERIALUSED:**

- **Carbon Fiber**
- **Alpha-Beta Titanium Alloy**
- **Al-Zn-Mg Alloy**

**MODAL AND ANALYSIS OF NACA 4412 AIRFOIL**

The blade profile was chosen as NACA 4412. The profiles were obtained from Design Foil Workshop Software and were exported directly to Solid Works. The modeling was done inSolid Works and shown in figure.

**NACA 4412 Data File:**

| X CORDINATE | Y CORDINATE | Z CORDINATE |
|---|---|---|
| 100.0167 | 0.1249 | 0 |
| 99.8653 | 0.1668 | 0 |
| 99.4122 | 0.2919 | 0 |
| 98.6596 | 0.4976 | 0 |
| 97.6117 | 0.7801 | 0 |
| 96.2742 | 1.1341 | 0 |
| 94.6545 | 1.5531 | 0 |
| 92.7615 | 2.0294 | 0 |
| 90.6059 | 2.5547 | 0 |
| 88.1998 | 3.1197 | 0 |
| 85.557 | 3.7149 | 0 |
| 82.6928 | 4.3305 | 0 |
| 79.6239 | 4.9564 | 0 |
| 76.3684 | 5.5826 | 0 |
| 72.9457 | 6.1992 | 0 |
| 69.3763 | 6.7967 | 0 |
| 65.6819 | 7.3655 | 0 |
| 61.8851 | 7.8967 | 0 |
| 58.0092 | 8.3817 | 0 |

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| | | |
|---|---|---|
| 54.0785 | 8.8125 | 0 |
| 50.1176 | 9.1816 | 0 |
| 46.1516 | 9.4825 | 0 |
| 42.2059 | 9.7095 | 0 |
| 38.2787 | 9.8537 | 0 |
| 34.3868 | 9.881 | 0 |
| 30.5921 | 9.7852 | 0 |
| 26.9212 | 9.5696 | 0 |
| 23.4002 | 9.24 | 0 |
| 20.0538 | 8.8046 | 0 |
| 16.9056 | 8.2736 | 0 |
| 13.977 | 7.6589 | 0 |
| 11.288 | 6.9743 | 0 |

| | | |
|---|---|---|
| 11.288 | 6.9743 | 0 |
| 8.856 | 6.2343 | 0 |
| 6.6964 | 5.454 | 0 |
| 4.8221 | 4.6485 | 0 |
| 3.2437 | 3.8325 | 0 |
| 1.9693 | 3.0193 | 0 |
| 1.0051 | 2.2209 | 0 |
| 0.3547 | 1.4471 | 0 |
| 0.0198 | 0.7052 | 0 |
| 0 | 0 | 0 |
| 0.2885 | -0.6437 | 0 |
| 0.8765 | -1.2027 | 0 |
| 1.7579 | -1.6779 | 0 |
| 2.925 | -2.0704 | 0 |
| 4.3684 | -2.3825 | 0 |
| 6.0773 | -2.6172 | 0 |
| 8.0396 | -2.7782 | 0 |
| 10.2423 | -2.8706 | 0 |

| | | |
|---|---|---|
| 12.6714 | -2.9 | 0 |
| 15.3123 | -2.8734 | 0 |
| 18.1496 | -2.7986 | 0 |
| 21.1676 | -2.6843 | 0 |
| 24.35 | -2.5401 | 0 |
| 27.6797 | -2.376 | 0 |
| 31.1396 | -2.2023 | 0 |
| 34.7115 | -2.0295 | 0 |
| 38.3767 | -1.8677 | 0 |
| 42.1506 | -1.72 | 0 |
| 46.0025 | -1.5646 | 0 |
| 49.8824 | -1.4038 | 0 |
| 53.7674 | -1.2432 | 0 |
| 57.6342 | -1.0875 | 0 |
| 61.4595 | -0.9404 | 0 |
| 65.2198 | -0.8049 | 0 |
| 68.892 | -0.6829 | 0 |
| 72.4534 | -0.5754 | 0 |
| 75.8815 | -0.4826 | 0 |

| | | |
|---|---|---|
| 79.1547 | -0.4042 | 0 |
| 82.252 | -0.3392 | 0 |
| 85.1537 | -0.2863 | 0 |
| 87.8408 | -0.244 | 0 |
| 90.2958 | -0.2109 | 0 |
| 92.5025 | -0.1853 | 0 |
| 94.4461 | -0.1659 | 0 |
| 96.1137 | -0.1514 | 0 |
| 97.4939 | -0.1409 | 0 |
| 98.5774 | -0.1335 | 0 |
| 99.3567 | -0.1286 | 0 |

**Table. 1 NACA 4412 Data File**

Creating this NACA 4412 Aerofoil blade shape developed by using above XYZ through curve coordinates data file. By browsing the text data file on SOLIDWORKS to make a fully parametric aerofoil design as shown as follows.

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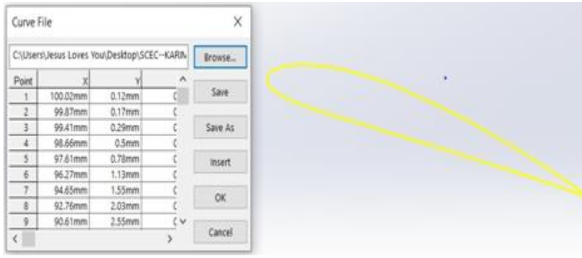


**Fig. 3 Aerofoil Blade Shape Developed By Using Above XYZ Through Curve**

After creating the NACA 4412 Aerofoil blade shape developed by using above XYZ through curve coordinates data file then apply a extruded boss/base of 1000mm or 1meter. Itslooks like as follows,

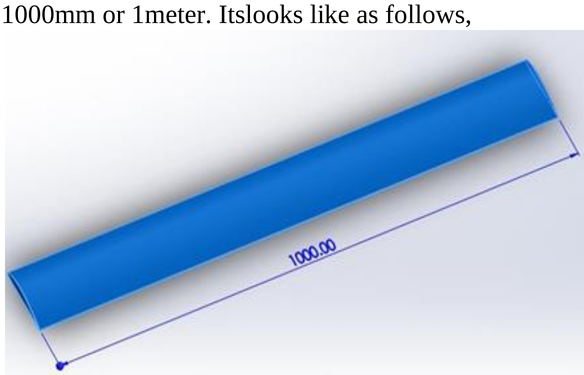



**Fig. 4After Creating the Aerofoil**

The file created by using NACA 4412 Aerofoil blade shape developed by using above XYZ through curve coordinates data file, after applying some features it should saved with an extension of SOLIDPART as **.sldprt** format.

Later it should be saved as **.igs** format for the ANSYS simulation.

**MESHING:**

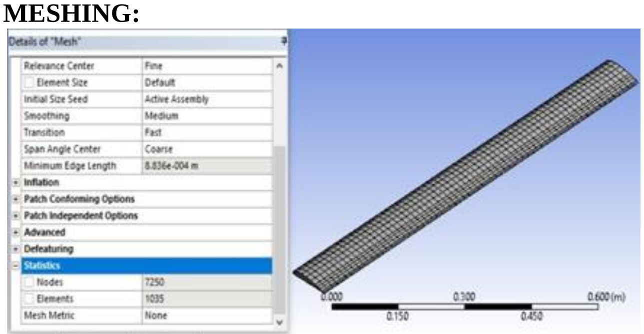



**Fig.6 Meshing (Nodes: 7250, Elements: 1035)**

**BOUNDARY CONDITIONS:**

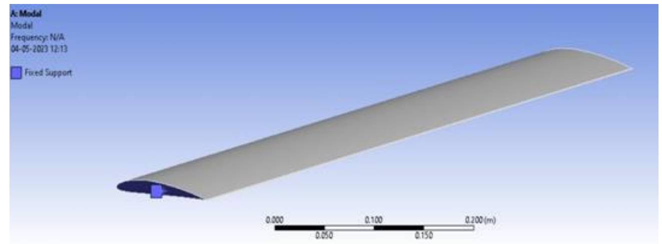


**Fig. 7 Fixed Support Indicated with Blue Tag**

## IV. RESULTS AND DISCUSSION

The following are the modal analysis results obtained by conducting simulation on ANSYS workbench at six different nodes with three different materials like Carbon fiber, Al- Zn-Mg alloy and Alpha-beta titanium alloys are used.

**MODAL ANALYSIS ON CARBON FIBER MATERIAL:**

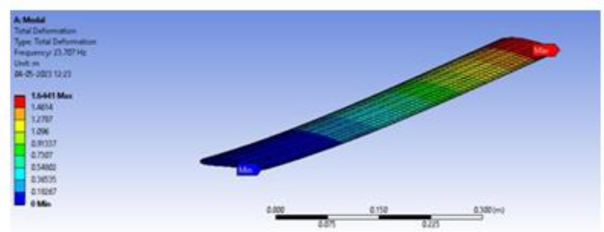


**Fig.8 Carbon Fiber Material Total Deformation at Mode 1**

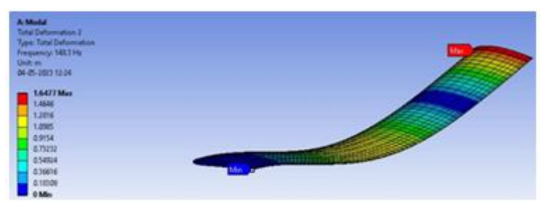


**Fig.9 Carbon Fiber Material Total Deformation at Mode 2**

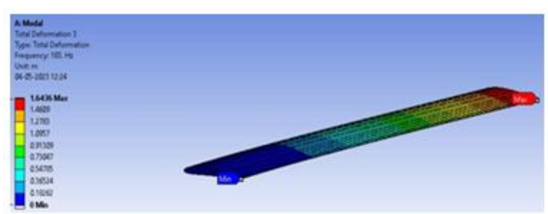


**Fig.10 Carbon Fiber Material Total Deformation at Mode 3**

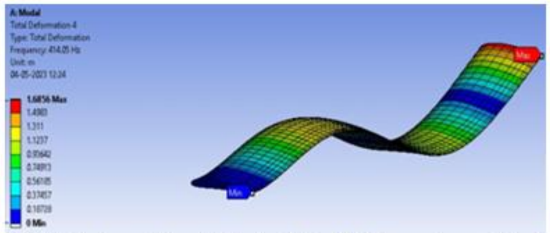


**Fig.11 Carbon Fiber Material Total Deformation at Mode 4**

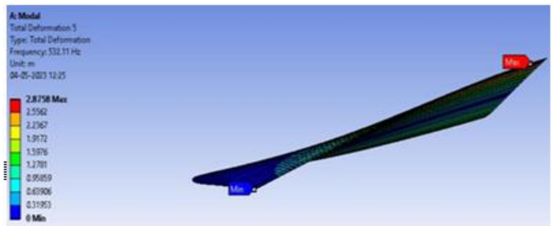


**Fig.12 Carbon Fiber Material Total Deformation at Mode 5**

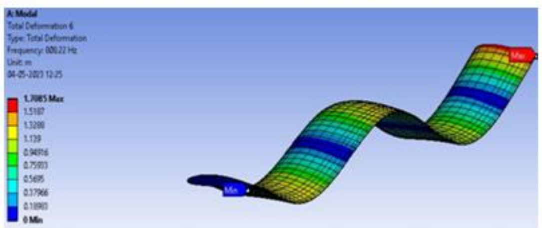
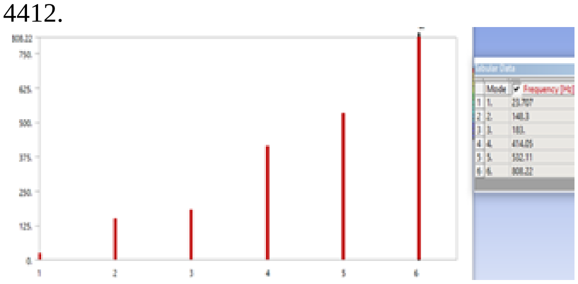


**Fig.13 Carbon Fiber Material Total Deformation at Mode 6**

The figures 8 to 13 show the distribution of equivalent stress, equivalent strain, total deformation on Carbon Fiber material under the load of 100N respectively. The maximumvalue is labeled in red color and minimum value is labeled is blue color. The following graph despites the MODE VS FREQUENCY on carbon fiber material total deformation at six different modes. On each direction of mode, the frequency parameters are changed as per profile NACA 4412.



**Graph 1 Mode Vs Frequency**

| MODE | FREQUENCY |
|---|---|
| 1. | 23.707 |
| 2. | 148.3 |
| 3. | 183. |
| 4. | 414.05 |
| 5. | 532.11 |
| 6. | 808.22 |

**Table 2 Mode Vs Frequency for Carbon Fiber Material**

**MODAL ANALYSIS ON ALPHA-BETA TITANIUM ALLOY:**

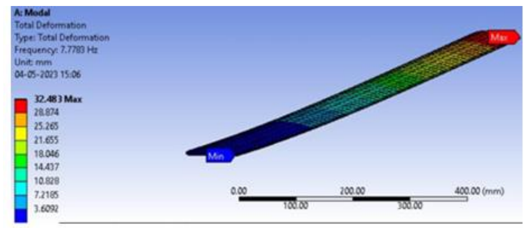


**Fig.14 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 1**

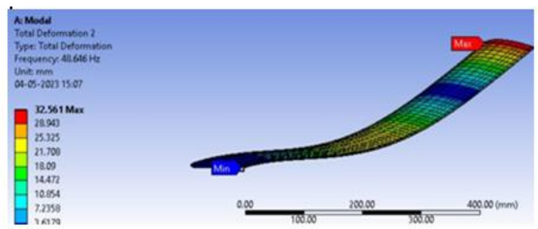


**Fig.15 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 2**

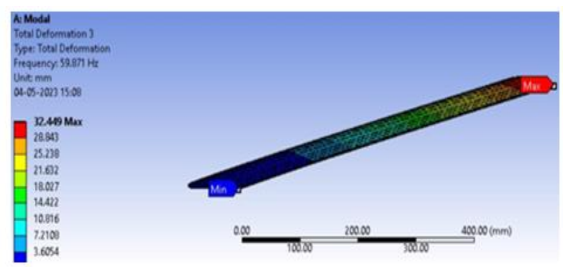


**Fig.16 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 3**

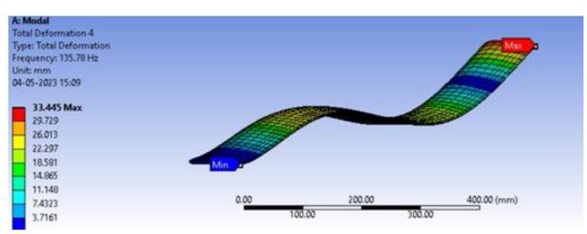


**Fig.17 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 4**

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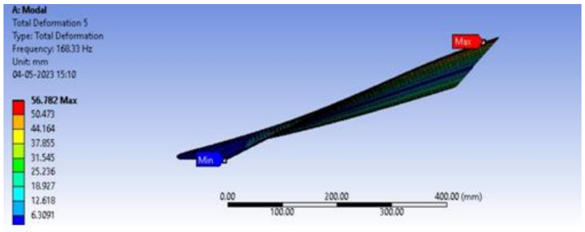



Fig.18 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 5

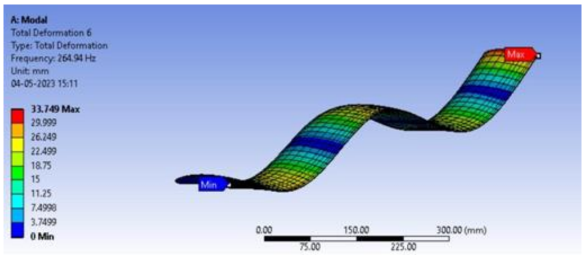
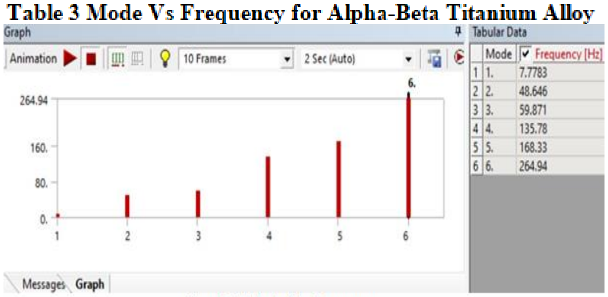



Fig. 19 Alpha-Beta Titanium Alloy Material Total Deformation at Mode 6

The figure 14 to 19 shows the distribution of equivalent stress, equivalent strain, total deformation on Alpha-Beta Titanium Alloy material under the load of 100N respectively.The maximum value is labeled in red color and minimum value is labeled is blue color.

| MODE | FREQUENCY |
|---|---|
| 1. | 7.7783 |
| 2. | 48.646 |
| 3. | 59.871 |
| 4. | 135.78 |
| 5. | 168.33 |
| 6. | 264.94 |

Table 3 Mode Vs Frequency for Alpha-Beta Titanium Alloy




Graph 2 Mode Vs Frequency

## Modal Analysis on Al-Zn-Mg Alloy:

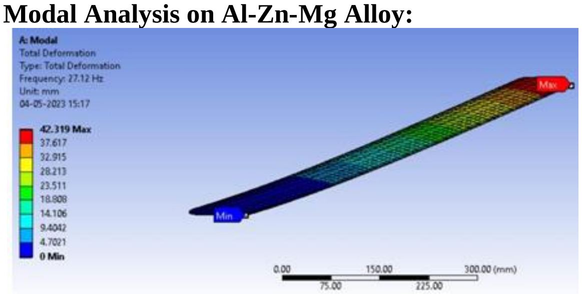



Fig. 20 Al-Zn-Mg Alloy Material Total Deformation at Mode 1

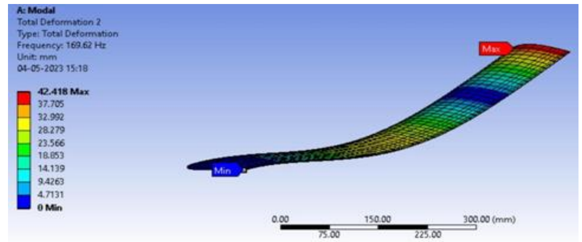



Fig. 21 Al-Zn-Mg Alloy Material Total Deformation at Mode 2

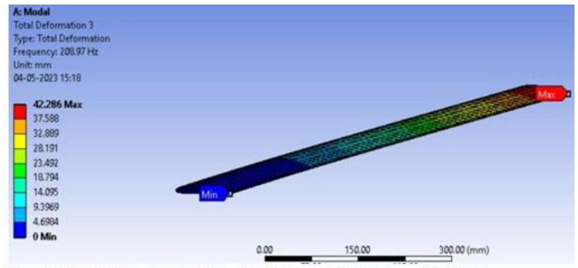



Fig. 22 Al-Zn-Mg Alloy Material Total Deformation at Mode 3

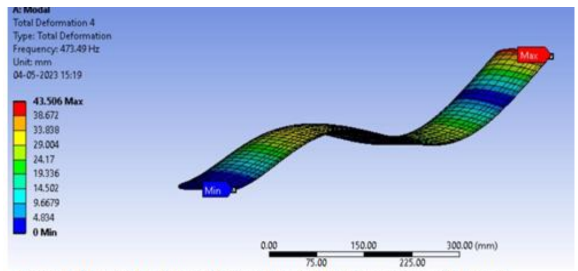



Fig. 23 Al-Zn-Mg Alloy Material Total Deformation at Mode 4

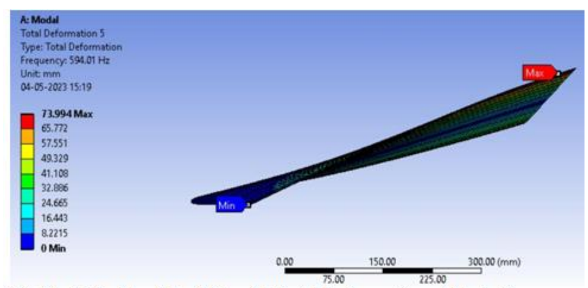



Fig.24 Al-Zn-Mg Alloy Material Total Deformation at Mode 5

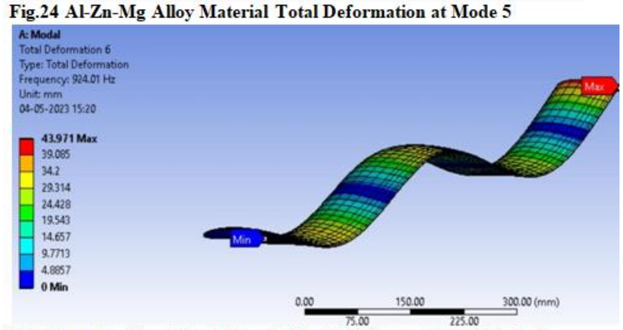



Fig.25 Al-Zn-Mg Alloy Material Total Deformation at Mode 6

The figures 20 to 25 show the distribution of equivalent stress, equivalent strain, total deformation on Al-Zn-Mg Alloy material under the load of 100N respectively. The maximum value is labeled in red color and minimum value is labeled is blue color.

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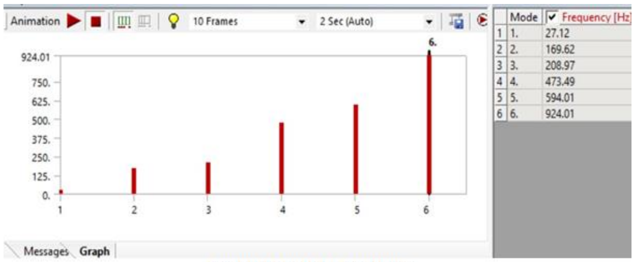


Graph 3 Mode Vs Frequency

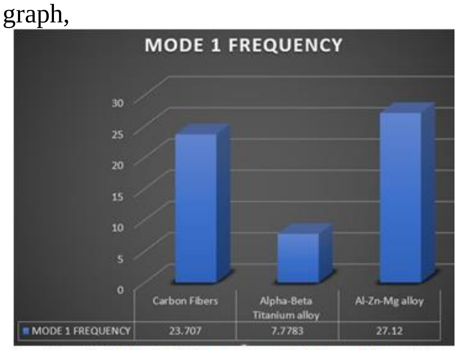
| MODE | FREQUENCY |
|---|---|
| 1. | 27.12 |
| 2. | 169.62 |
| 3. | 208.97 |
| 4. | 473.49 |
| 5. | 594.01 |
| 6. | 924.01 |

Table 4 Mode Vs Frequency for Al-Zn-Mg Alloy

**GRAPHS:**

**MODE 1 FREQUENCY:**

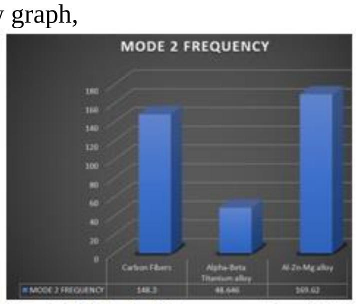
The frequency of mode 1 modal shapes are illustrated in below graph with having maximum frequency obtained by Al-Zn-Mg alloy of 27.12 and lesser frequency obtained by 7.7783 are shown in the below graph,



Graph 4 Mode 1 Frequency of Three Materials

**MODE 2 FREQUENCY:**

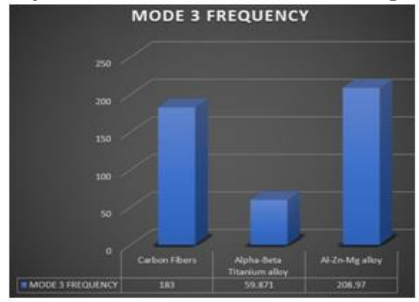
The frequency of mode 2 modal shapes are illustrated in below graph with having maximum frequency obtained by Al-Zn-Mg alloy of 169.62 and lesser frequency obtained by 48.646 are shown in the below graph,



Graph 5 Mode 2 Frequencies of Three Materials

**MODE 3 FREQUENCY:**

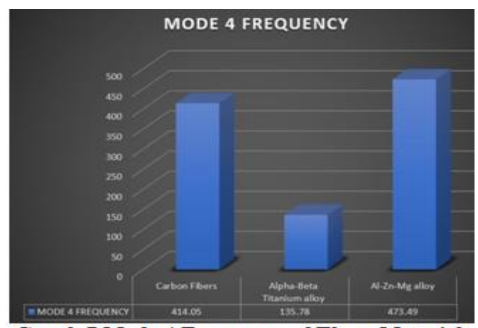
The frequency of mode 3 modal shapes are illustrated in below graph with having maximum frequency obtained by Al-Zn-Mg alloy of 208.97 and lesser frequency obtained by 59.871 are shown in the below graph,



Graph 6 Mode 3 Frequencies of Three Materials

**MODE 4 FREQUENCY:**

The frequency of mode 4 modal shapes are illustrated in below graph with havingmaximum frequency obtained by Al-Zn-Mg alloy of 473.49 and lesser frequency obtained by 135.78 are shown in the below graph,



Graph 7 Mode 4 Frequency of Three Materials

**MODE 5 FREQUENCY:**

The frequency of mode 5 modal shapes are illustrated in below graph with having maximum frequency obtained by Al-Zn-Mg alloy of 594.01 and lesser frequency obtained by 168.33 are shown in the below graph,

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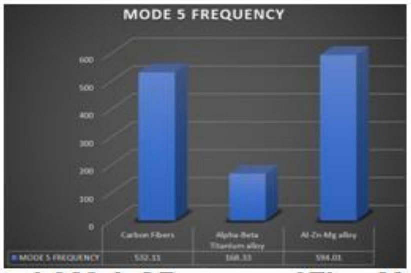
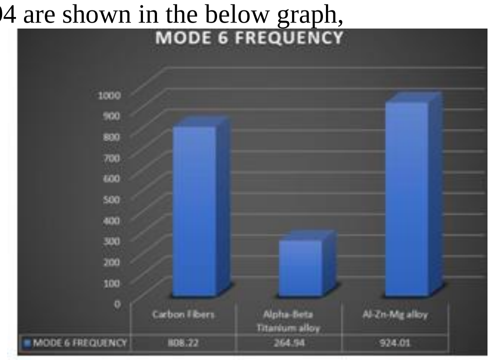


**Graph 8 Mode 5 Frequency of Three Materials**

**MODE 6 FREQUENCY:**

The frequency of mode 6 modal shapes are illustrated in below graph with havingmaximum frequency obtained by Al-Zn-Mg alloy of 924.01 and lesser frequency obtained by
264.94 are shown in the below graph,



**Graph 9 Mode 6 Frequency of Three Materials**

## V. CONCLUSION

In conclusion, this study successfully conducted a modal analysis of NACA 4412 airfoil-based air-wings constructed from various composite materials, providing critical insights into their dynamic performance characteristics. The results demonstrated that the choice of composite material significantly influences the natural frequencies, mode shapes, and overall vibrational response of the air-wings. Notably, materials such as carbon fiber exhibited superior stiffness and lower weight, resulting in enhanced vibrational performance compared to glass and aramid fibers. These findings underscore the importance of material selection in the design of airfoil structures, as it directly impacts their stability and structural integrity during operation. By employing advanced finite element analysis (FEA) techniques, this research not only contributes to the understanding of dynamic behavior in composite airfoils but also offers practical guidelines for optimizing air-wing designs in aerospace applications. Future work should explore the effects of environmental factors, such as temperature and humidity, on the modal properties of composite airfoils, as well as the potential for hybrid composite materials to further enhance performance. Overall, the insights gained from this study pave the way for advancements in lightweight, efficient, and reliable airfoil designs, promoting the development of next-generation aircraft and renewable energy technologies.

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