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RESEARCH ARTICLE

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# DESIGN AND ANALYSIS OF A COMPOSITE PROPELLER

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**ABSTRACT**

This work was carried out in one of the leading Automotive Component Manufacturing Company (Automotive Composite Systems International ACSI). At present they are manufacturing composite parts like front panel, engine hood, side panel, sill cover etc; and supplying to various Original Equipment Manufacturers like TATA MOTORS, Ashok Leyland, JOHN DHERE etc. Now they are looking at expansion of their business to under water and aerospace vehicles. Hence this project deals with composite material application to propeller which is the basic and the most important element for propelling the underwater vehicles like submarines and ships. Ships and underwater vehicles like submarines use propeller for propulsion. In general, propellers are used for propulsion and they are also used to develop significant thrust to propel the vehicle at its operational speed. The blade geometry and design are more complex involving many controlling parameters. Propeller with conventional isotropic materials creates more vibration and noise in its rotation which is undesirable from stealth point of view. In current years the increased need for light weight structural element with acoustic insulation has led to the use of fiber reinforced multi layered composite propeller. The present work is to carry out the static and dynamic analysis of aluminum, composite propeller which is GFRP (Glass Fiber Reinforced Plastics).The present work deals with modeling and analyzing the propeller blade of an underwater vehicle for its strength. A propeller is a complex geometry which requires high end modeling software. The solid model of propeller is developed in CATIA-V5 R17 and the tetrahedral mesh is generated for the model using HYPER MESH. Static, Eigen and Frequency response analysis of both aluminum and composite propeller are carried out using ANSYS. Inter-laminar shear stresses are calculated for composite propeller by varying the number of layers. The stresses obtained are well within the limit of elastic property of materials. The results were compared with Tsai-Wu failure theory and found they were within the safe limits.

Keywords: GFRP (Glass Fiber Reinforced Plastics), Static, Eigen and Frequency response analysis ,aluminum and composite propeller, ANSYS

Ships and under water vehicles like submarines and submersibles etc., uses propeller for propulsion. The blade geometry and its design are more complex involving many controlling parameters. The strength analysis of such a complex 3 Dimensional blades with conventional formulas will give less accurate values. In such cases numerical analysis (Finite Element Analysis) gives comparable results with experimental values. In the present project the propeller blade material is changed from aluminum metal to fiber

**OVERVIEW OF PROPELLER**

**PROPELLER TYPES**

Depending on the type of application different propellers are to be used

(1) Nozzle propeller
(2) Voith Schneider Propeller
(3) Contra rotating Propeller
(4) Super cavitating Propeller
(5) Jet propeller

**PROPELLER AND ITS MATERIAL**

For underwater vehicles the main criteria in selection of the material depends on its strength, stiffness, weight, thermal expansion and corrosion resistant to seawater. The material used for the manufacturing of propeller depends upon the strength, ease of manufacturing, production methods, environment, weight etc,.

The material used for propellers must be light, strong and ductile, easy to cast and machine, and resistant to erosion and corrosion. The Ship propeller may be manufactured from commercially available material like gray cast iron, carbon and low-alloy steels, chromium stainless steels, chromium-nickel stainless steel, manganese bronze, nickel- manganese bronze, nickel-aluminum bronze, Naval brass etc. Some model propellers are manufactured with non-metallic materials like wood, polyamide resins (Nylon). Thermosetting plastics and Fiber reinforced composite materials (GFRP and CFRP) etc.

**Aluminum**

The first step is to understand the effect of different alloying elements to choose the best grade of Aluminum to meet the design requirements. Copper, Zinc and Magnesium boost the strength of Aluminum to that approaching mild steel. Lead, Bismuth and Tin are favored for applications where Aluminum stock will be machined. Silicon and Bismuth improves wear resistance by preventing galling in Aluminum components used for High-wear applications. Chromium and stantinum help to refine grains, which improve the properties of Aluminum components.

**Chemical composition: (in %)**

Copper: 0.1
Magnesium: 0.2 to 0.65
Silicon: 6.5 to 7.5
Iron: 0.5 max
Manganese: 0.3 max
Nickel: 0.1 max
Zinc: 0.1 max
Lead: 0.lmax
Tin: 0.05 max
Titanium: 0.2 max
Aluminum: rest of abve

**Mechanical Properties:**

Casting Condition: Chill Cast
Proof stress: 230 N/sq.mm
Tensile strength: 280 N/sq.mm
Young's modulus: 7.OOx $10^4$ N/sq.mm
Rigidity modulus: 2.71 x $10^4$N/sq.mm
Poisson's ratio: 0.29
Density: 2.7g/cc
%Elongation: 2
Hardness: 105 BHN
Melting point: 650°c

**FIBER REINFORCED PLASTIC MATERIALS**

**OVERVIEW**

Fiber reinforced composite material consists of fibers of high strength and modulus embedded in or bonded with matrix. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. In general, fibers are the principal load carrying members while the surrounding matrix keep them in desired location and orientation, acts as a load transfer medium between them and protects them from environmental damages due to elevated temperatures and humidity.

**FIBERS**

Fibers are the principal constituents in a fiber reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Proper selection of the type, amount and orientation of fibers is very important since it influences the following characteristics of a laminate. For the flange under consideration carbon fiber is chosen. Carbon fibers are commercially available with a variety of tensile modulus ranging from 207 Gpa on the low side to 1035 GPa on the high side.

**MATRIX**

The role of matrix in a fiber reinforced composite material is

a) To transfer stresses between the fiber

b) To provide a barrier against an adverse environment

c) To protect the surface of the fiber from mechanical abrasion

The matrix plays a minor role in load carrying capacity. The matrix has a major influence on inter laminar shear as well as in plane shear properties of the composite. Inter laminar shear strength is important in design under bending loads. The plane shear strength is important under torsion loads. The matrix provides support against the possibility of fiber buckling under compressive loads.

**ELASTIC PROPERTIES OF A LAMINA**

(a) Unidirectional continuous fiber 0° lamina

*Longitudinal modulus* $= E_{11} = E_f V_f + E_m V_m$

Major Poisson's ratio $= \mu_{12} = \mu_f V_f + \mu_m V_m$

Transverse Modulu= $E_{22} = \dfrac{E_f E_m}{E_f V_M + E_M V_F}$

Minor Poisson's ratio $= \mu_{12} = \dfrac{E_{22}}{E_{11}} \mu_{12}$

Shear Modulus = $G_{12} = \dfrac{G_f G_m}{G_f \mu_m + G_m \mu_f}$

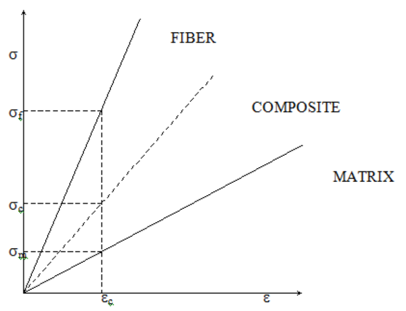


Figure.3.1 stress –strain diagram for a hypothetical composite material

(a) Unidirectional Continuous Fiber Angle-Ply Lamina

$$\frac{1}{E_{XX}} = \frac{\cos^4\theta}{E_{11}} + \frac{\sin^4\theta}{E_{22}}\left[\frac{1}{G_{12}} - \frac{2\mu}{E_{11}}\right]\sin^2\theta\cos^2\theta$$

$$\frac{1}{E_{yy}} = \frac{\sin^4\theta}{E_{11}} + \frac{\cos^4\theta}{E_{22}}\left[\frac{1}{G_{12}} - \frac{2\mu}{E_{11}}\right]\sin^2\theta\cos^2\theta$$

$$\mu_{xy} = E_{xy}\left[\frac{\mu_{12}}{E_{11}}\left(\sin^4\theta + \cos^4\theta\right)\right] - \left[\frac{1}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}}\right]\sin\theta\cos\theta$$

$$\frac{1}{G_{xy}} = 2\left[\frac{2}{E_{11}} + \frac{2}{E_{22}} + \frac{4\mu_{12}}{E_{11}} - \frac{1}{G_{12}}\right]\sin^2\theta\cos^2\theta + \frac{1}{G_{12}}\left[\sin^4\theta + \cos^4\theta\right]$$

**MODELING OF PROPELLER**

Modeling of the propeller is done using CATIA V5 R 17. In order to model the blade, it is necessary to have sections of the propeller at various radii. These sections are drawn and rotated through their respective pitch angles. Then all rotated sections are projected onto right circular cylinders of respective radii as shown in figure below. Now by using multi section surface option, the blade is modeled.

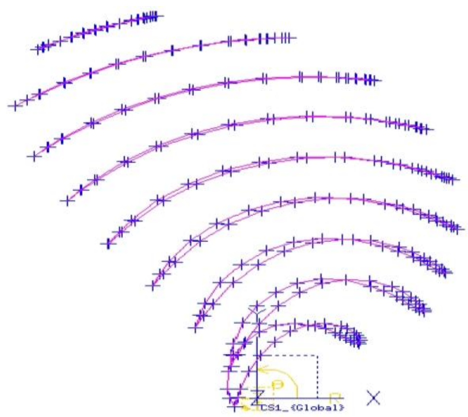

Figure 3. construction of hydrofoils by joining of points on surface of the blade

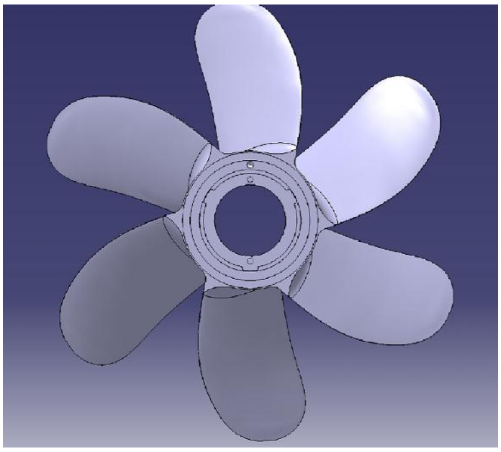

Figure 4: final solid model of propeller

**MESH GENERATION USING HYPERMESH**

The solid model is imported to HYPERMESH 7.0 and tetrahedron mesh is generated for the same. The meshed model is shown in figure 4.7. Boundary conditions are applied to meshed model. The contact surface between hub and shaft is fixed in all degrees of freedom. Thrust of 4000 N is uniformly distributed in the region between the sections at 0.7R and 0.75R on face side of blade, since it is the maximum loading condition zone on each blade as per the George [7] work. The loading condition is as shown in figure 4.8. The number of elements created are 1,60,455. Number of nodes created are 2,83,553. Quality checks are verified for the meshed model. Jacobian, warpage and aspect ratio are within permissible limits.

Power=50 Kw

velocity=12.5 m/s

Thrust = power/velocity

=50000/12.5

=4000 N

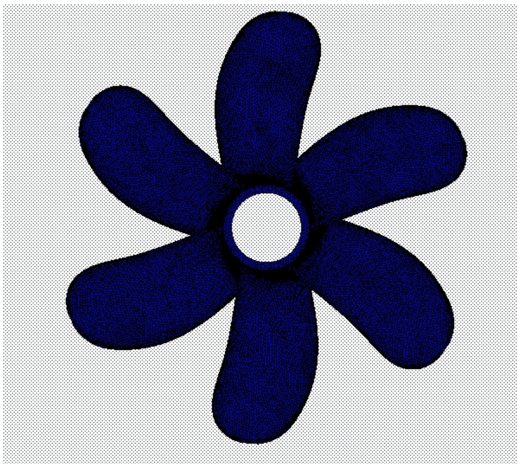

Figure 5.1: meshed model

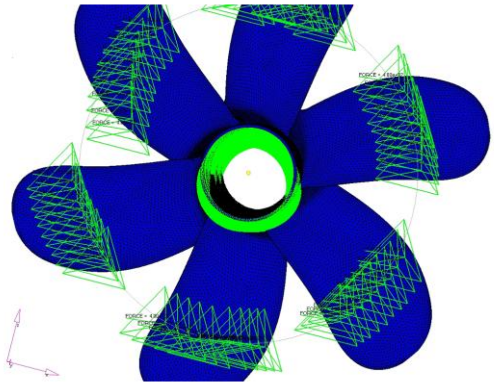

Figure 5.2 loading on meshed model.

**RESULTS AND DISSCUSSIONS**

**LINEAR STATIC ANALYSIS**

Linear static analysis is concerned with the behavior of elastic continuum under prescribed boundary conditions and statically applied loads. The applied load in this case is thrust acting on blades. Under water vehicle with contra rotating (aft) propeller is chosen for FE analysis. The FE analysis is carried out using ANSYS. The deformations and stresses are calculated for aluminum (isotropic) and composite propeller (orthotropic material). In composite propeller 4 cases are considered by varying, number of layers as 4, 8, 12, 16. For propeller blade analysis 3D solid element type 92(from ANSYS library) is considered for aluminum and solid 46(from ansys library) for composite propeller.

**Static analysis of aluminum propeller**

The thrust of 4000N is applied on face side of the blade in the region between 0.7R and 0.75R. The intersection of hub and shaft point's deformations in all directions are fixed. The thrust is produced because of the pressure difference between the face and back sides of propeller blades. This pressure difference also causes rolling movement of the under water vehicle. This rolling movement is nullified by the forward propeller which rotates in other direction (reverse direction of aft propeller). The propeller blade is considered as cantilever beam i.e. fixed at one end and free at other end. The deformation pattern for aluminum propeller is shown in figure 6.1. The maximum deflection was found as 6.883mm in y-direction. Similar to the cantilever beam the deflection is maximum at free end.

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Table 1 Static analysis of aluminum propeller

| Result | Aluminum propeller |
|---|---|
| Deflection in mm | 6.883 |
| Max. normal stress, N/mm$^2$ | 485.337 |
| Von mises, N/mm$^2$ | 525.918 |
| 1$^{st}$ principal stress, N/mm$^2$ | 518.775 |
| 2$^{nd}$ principal stress, N/mm$^2$ | 206.945 |

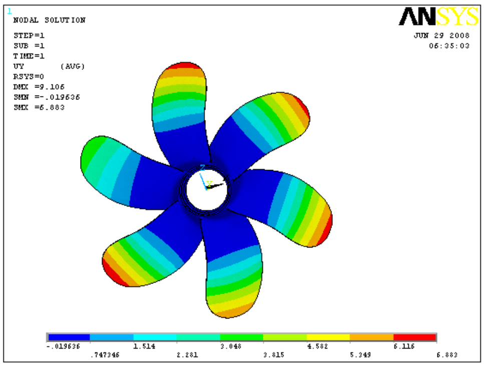


Figure 6.1: Max deflection of aluminum propeller, mm

**Static analysis of composite propeller**

Four cases are considered for static analysis of composite propeller by varying the number of layers to check the bonding strength. Interlaminar shear stresses are calculated for all cases.

**Case 1 :** 4 Layers
**Case2 :** 8 layers
**Case 3 :** 12 layers
**Case 4 :** 16 layers.

**Case1: Analysis results of 4 layers**

Maximum deflection for composite propeller with 4 layers was found to be 0.47939mm in Z-direction i.e perpendicular to fibers of the blade as shown in figure 4.2. The maximum normal stress was found to be 77.555 N/mm$^2$ as shown in figure 4.3.The maximum von mises stress was found to be 97.038 N/mm$^2$ as shown in figure 4.5. The maximum interlaminar shear stress was found to be 51.327 N/mm$^2$ as shown in figure 4.6 at top of 4$^{th}$ layer.

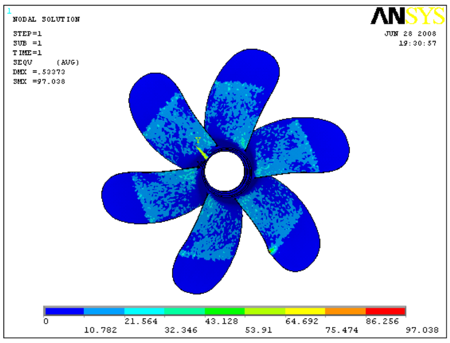


Figure 6.2 : Max. normal stress of composite propeller with 4 layers, MPa

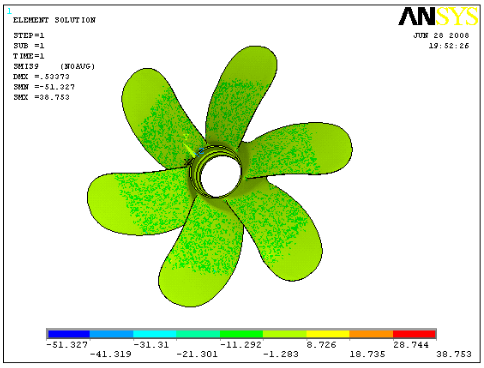


Figure 6.4: Max. von mises stress of composite propeller with 4 layers, MPa

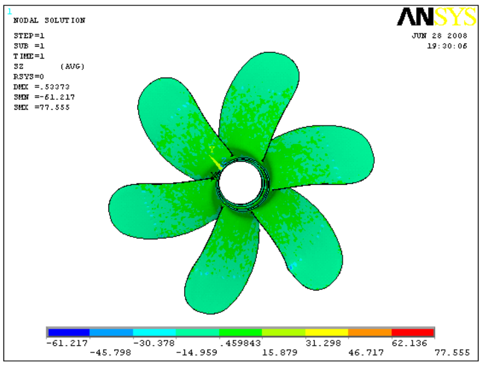


Figure 6.5:Max.inter laminar shear stress in composite propeller with 4 layers, MPa

**Case3: Analysis results of 12 layers**

Maximum deflection for composite propeller with 12 layers was found to be 0.4846mm in Z-direction i.e perpendicular to fibers of the blade as shown in figure 6.12. The maximum stress was found to be 78.784 N/mm$^2$ as shown in figure 6.13.The maximum von mises stress was found to be 101.099 N/mm$^2$ as shown in figure 6.14. The maximum interlaminar shear stress was found to be 52.744 N/mm$^2$ as shown in figure 6.15 in compression at top of 12$^{th}$ layer.

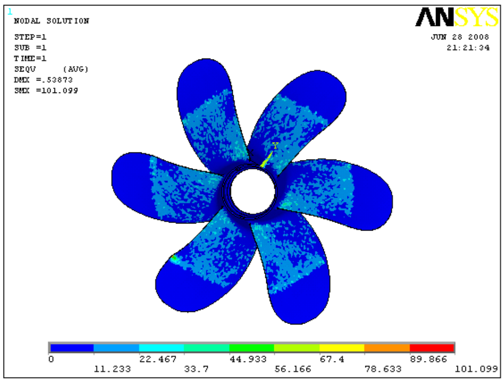

Fig 6.6: Max.von mises stress of composite propeller with 12 layers, MPa

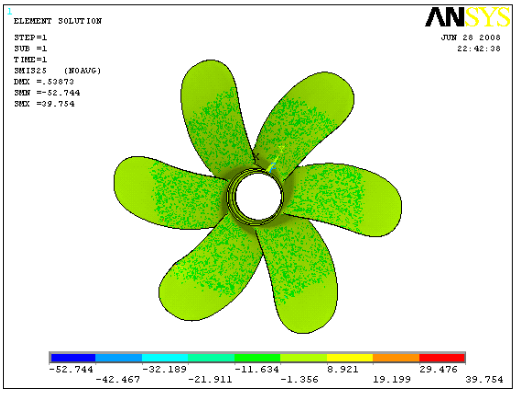

Figure:6.7 Max. Interlaminar shear stress of composite propeller with 12 layers, MPa

**Case 4: Analysis results of 16 layers**

Maximum deflection for composite propeller with 16 layers was found to be 0.488923m in Z-direction i.e perpendicular to fibers of the blade as shown in figure 6.16. The maximum stress was found to be 79.511 N/mm$^2$ as shown in figure 6.17.The maximum von mises stress was found to be 101.876 N/mm$^2$ as shown in figure 6.18. The aximum interlaminar shear stress was found to be 53.07 N/mm$^2$ as shown in figure 6.19 in compression at top of 16$^{th}$ layer.

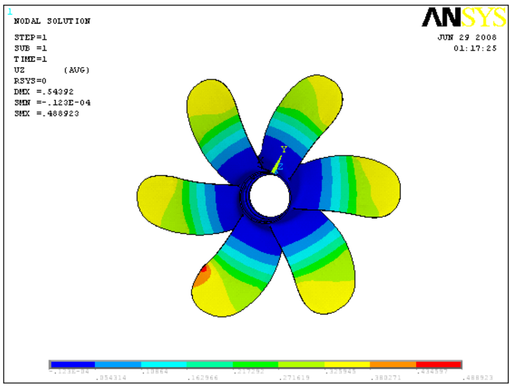

Figure 6.8: Max. deflection of composite propeller with 16 layers, mm

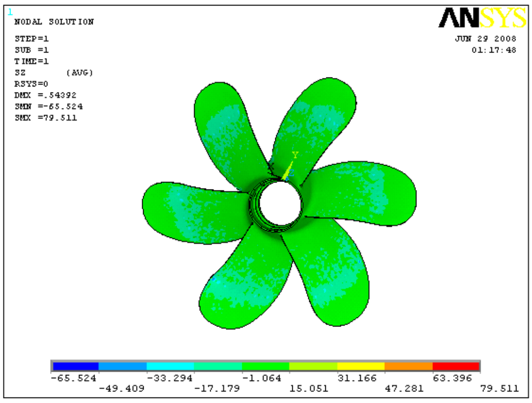

Figure 6.9: Max stress of composite propeller with 16 layers, MPa

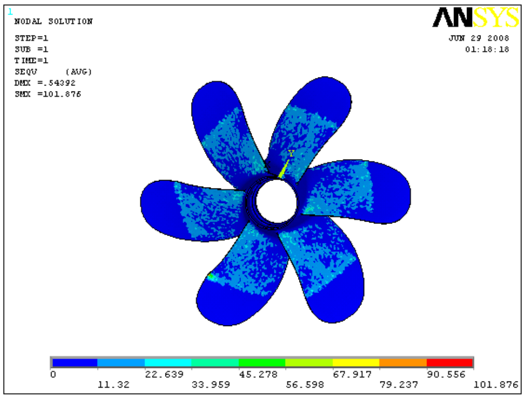

Figure 6.10: Max.von mises stress of composite propeller with 16 layers, MPa

Table 2 shows induced deflections and stresses in composite propeller for differrent layers. The variation of deflection, stress for different layers was not found to be of much difference. The variation of interlaminar shear stresses between 4 and 8 layers was found to 1.5705%. The variation of interlaminar shear stresses between 8 and 12 layers was found to 1.133%. The variation of interlaminar shear stresses between 12 and 16 layers was found to 0.5017%. The overall variation between 4 to 16 layers was found to be 3.147%.

Table 2 Static analysis results of composite propeller

| No. of layers | Max deflection in mm | Max. normal strss, N/mm$^2$ | von mises stress, N/mm$^2$ | Interlaminar shear stress, N/mm$^2$ |
|---|---|---|---|---|
| 4 | 0.479367 | 77.555 | 97.038 | 51.327 |
| 8 | 0.47721 | 77.611 | 99.276 | 52.146 |
| 12 | 0.4846 | 78.784 | 101.09 | 52.744 |
| 16 | 0.488923 | 79.511 | 101.86 | 53.01 |

**EIGEN VALUE ANALYSIS OF PROPELLER**

Eigen value analysis is carried out for aluminum propeller, composite propeller using Block Lanczos method. This analysis does not represents the response due to any loading but yields by natural frequencies and corresponding mode shapes in the form of Eigen vectors of the propeller blade when there is no dissipation of energy due to damping.

Table 3 Natural frequencies of aluminum propeller blade

| S.no | Eigen value analysis for aluminum in Hz | Eigen value analysis for composite propeller in Hz |
|---|---|---|
| 1 | 439.76 | 2257.4 |
| 2. | 439.77 | 2266.4 |
| 3. | 439.8 | 2268.6 |
| 4. | 439.86 | 2272.5 |
| 5. | 439.95 | 2275.3 |
| 6. | 439.96 | 2277.9 |
| 7. | 1178.4 | 3159.5 |
| 8. | 1178.5 | 3174.0 |
| 9. | 1178.5 | 3177.8 |
| 10. | 1178.5 | 3181.9 |

**HARMONIC ANALYSIS OF ALUMINUM PROPELLER**

Harmonic response analysis is a technique used to determine the steady-state response of a linear structure to loads that vary sinusoidally (*harmonically*) with time. The idea is to calculate the structure's response at several frequencies and obtain a graph of some response quantity (usually displacements) versus frequency. "Peak" responses are then identified on the graph and stresses reviewed at those peak frequencies. This analysis technique calculates only the steady-state, forced vibrations of a structure..

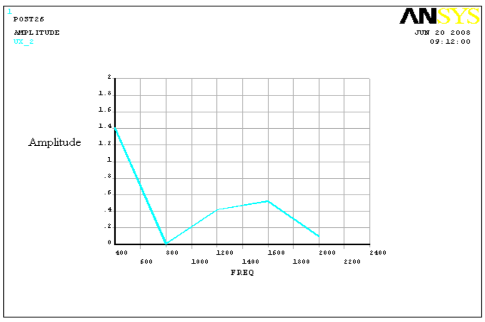


Figure 7: Frequency response of propeller made of aluminum material (in Ux direction)

**Harmonic analysis of composite propeller with 4 layers**

In this harmonic analysis with 4 layers, Amplitude vs. frequency graphs are plotted. It is observed that resonance occurs in the frequency range of 2000-2500 Hz in Ux direction as show in figure 6.23. and in Uy direction it is observed around 3000Hz.

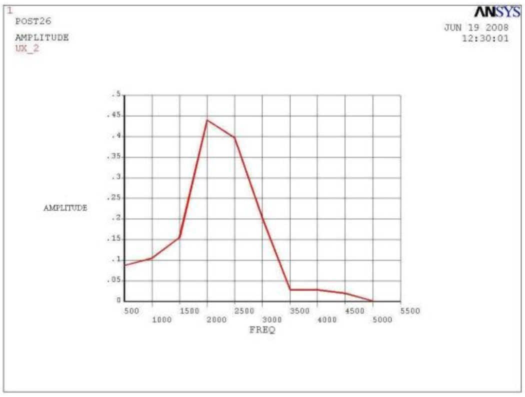


Figure 8: Frequency response of propeller made of composite material with 4 layers (in Ux direction)

**CONCLUSIONS AND FUTURE SCOPE OF WORK**

The following conclusions are drawn from the present work; The deflection for composite propeller blade was found to be around 0.5mm for all layers which is much less than that of aluminum propeller i.e 6.883mm, which shows composite propeller is much stiffer than aluminum propeller. Maximum induced von mises stress for aluminum was found to be 525.918 N/mm$^2$ which exceeds allowable strength of aluminum i.e 230 N/mm$^2$ that may cause failure. Interlaminar shear stresses were calculated for composite propeller by incorporating different number of layers viz. 4,8,12,16 and was found that the percentage variation was 1.5705% between 4 and 8 layers. The variation of interlaminar shear stresses between 8 and 12 layers was found to 1.133%. The variation of interlaminar shear stresses between 12 and 16 layers was found to 0.5017%. The overall variation between 4 to 16 layers was found to be 3.147%.which shows that there is strong bonding between the layers and there is no peel-off.

| Result | Aluminum propeller | Composite propeller |
|---|---|---|
| Deflection in mm | 6.883 | 0.479367 |
| Max. normal stress, $N/mm^2$ | 485.337 | 77.555 |
| Von mises stress, $N/mm^2$ | 525.918 | 97.038 |

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