MODELLING AND ANALYSIS OF PROPELLER BLADE FOR MARINE ENGINE BY FEA APPROACH

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Abstract: *Ships and underwater vehicles use propeller for propulsion. In general, propellers are used as propulsors and they are also used to develop significant thrust to propel the vehicle at its operational speed and RPM. The blade geometry and design are more complex involving many controlling parameters. In current years the increased need for light weight structural element with composite materials has led to use of S2 Glass fabric/epoxy to propeller. The present work is to carry out the model and static analysis of aluminum, composite material which is a combination of GFRP (Glass Fiber Reinforced Plastics) materials.*

The present work deals with modeling and analyzing the propeller blade of a underwater vehicle for their strength. A propeller is a complex geometry which requires high end modeling software. The solid model of propeller is developed in CATIA V5 R21. Static, model analysis of the propellers made of aluminum and composite materials are carried out in ANSYS (Advanced Numerical Simulation Systems). We applied thrust force at blade blend section and centrifugal force at the centre of gravity and found out Von Mises stresses, total deformation, directional deformation, principal and shear stresses of aluminum and composite propeller.

Keywords: **Propeller, S2 Glass Fiber Composites, Finite Element Analysis, Ansys, Catia, Von-Mises Stresses, Principle Stresses.**

1. Introduction

Ships and under water vehicles like submarines, torpedoes and submersibles etc., uses propeller as propulsion. The blade geometry and its design is more complex involving many controlling parameters. The strength analysis of such complex 3D 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 work the propeller blade material is converted from aluminum metal to fiber reinforced composite material for underwater vehicle propeller. Such complex analysis can be easily solved by finite element method techniques.

1.1 History

The force needed to propel a ship is obtained from the reaction against the water, causing a stream of water to move in the opposite direction. The devices like oars, paddle wheel, jets etc are used to propel ship. From this basic knowledge propellers came into existence.

Recording history indicates that the idea of a propeller was first suggested by Leonardo davinci in the 15th century. During the years that followed, a number of people experimented unsuccessfully with screw propulsion. Then in 1802, an American lawyer- turned -inventor, colonel john Stevens, constructed the first vessel to be powered by steam and a screw propeller.

The study of propeller action and design is complex especially the manufacturing of marine propellers is a highly specialized procedure. On The experimental side, Froude developed a method for studying the action of a propeller behind a ship. The conditions under which the model experiments can be used to determine ship performance and model propellers may be derived by dimensional analysis. It is not practicable to fulfill all these. Conditions exactly, and therefore some empirical corrections are necessary in determining ship performance and model propellers from experiments with models.

The experiments that are normally carried out with ship models and model propellers are:

- Resistance experiments
- Open water experiments
- Self propulsion experiments
- Wake measurements
- Cavitation experiments

1.2 Applications

Design of complex 3-Dimensional models like under water vehicle propellers, wings of air craft and helicopters, rotor and stator blades of the turbine, cam shaft, car bodies, ship model, marine and other commercial application ranging from mine hunting and intelligence gathering to oceanographic resources exploration and pollution monitoring etc.

1.3 Advantages and Disadvantages of Propeller

Propellers will be used as a propulsors where the speed is slow and the propeller has to be immersed completely in the water into a depth of minimum 2D. The efficiency of the propeller will be reduced and noise will increase and start cavitation as the speed increases. At high speeds the pump jet and water jet propellers will be used.

1.4 Problem Definition

Propeller being an important component for propulsion, more emphasis is done on design of the propeller. It has to withstand to the high pressure acting over on it. The metal propellers generally used cause vibration during its operation. In order to avoid it, conventional isotropic materials are replaced with composite materials. GFRP materials are woven with fiber orientation angles 45,-45. Strength analysis is carried out for composite propeller by using different number of layers for composite materials and inter laminar shear stresses are found out.

2. Literature Review

A literature survey was taken up to review present status of research in the field of theoretical analysis of stresses and deflection on propeller blades and identify great areas requiring focused attention focused specifically relevant to the project topic.

The papers collected could be broadly classified into theoretical study on propeller strength and experiential studies on propeller strength and a few on composite materials and their fem treatment. Many investigators discussed with the strength of the propeller blade and only a few of them are fitted in this report. To find out the stresses and deflections of a propeller blade subjected to hydrodynamic loading.

Strength of Propeller Blades: The strength requirements of propellers dictate that not only the blades be sufficiently robust to withstand long periods of arduous service without suffering failure or permanent distortion, but also that the elastic deflection under load should not alter the geometrical shape to such an extent as to modify the designed distribution of loading .A first approach to strength problem was made by Taylor[1] who considered a propeller blade as a cantilever rigidly fixed at the boss. The stresses were evaluated following the theory of simple bending using section of the blade by a cylinder. Such sections are having straight faces and curved backs. The greatest tensile stress was calculated to occur at the trailing edge and the greatest compressive stress at the center of the back. This method being the simplest of all is still widely used for simple and conventional propeller geometries, with narrow blades. But the method is suspect when used for propellers with wide blades and width comparable ton length.

J E Connolly [2] addresses the problem of wide blades, tried to combine both theoretical and experimental investigations. The author carried out the measurements of deflection and stresses on model blades subjected to simulated loads with an aim to develop a theoretical model calibrated against the laboratory experiments. This model was validated by measurements of pressure and stress distribution on the blades of a full scale ship propeller at sea based on the experimental results it was concluded that wide blades are subjected to tensile stress on the face and compressive stress of similar magnitude on back side. It was pointed out the accuracy of the predication from the model depends on the accuracy of working load determined.

Terje sont vedt [3] studied the application of finite element methods for frequency response and improve to the frozen type of hydrodynamic loading. The thin shell element of the triangular type and the super parametric shell element are used in the finite element model it presents the realistic and dynamic stresses in marine propeller blades. Stresses and deformation calculated for ordinary geometry and highly skewed propellers are compared with experimental results.

*Propeller blade failure***:** Chang suplee [4] et.al investigated the main sources of propeller blade failures and resolved the problem systematically. An FEM analysis is carried out to determine the blade strength in model and full scale condition and the range of safety factor for the propeller under study is determined.

M.Jourdain [5] recognized that the failure of un-numerous blades is due to fatigue, which cannot be taken into account in a conventional static strength calculation. When comparing to J E Connolly [2], improvements were taken on the structural model and also loading is taken into account the wake pattern. The feasibility of a dynamic analysis combined with an improved knowledge of fatigue resistance of the material will result in a reliable cure for this situation. General three dimensional solid elements of the results directly compared with the measured values. Correlation was made between model and full scale results. The radial stresses have been chosen as typical for the stress situation at each point.

Hub-blade interaction in propeller strength: The finite element method is generally used for calculating the stresses in propeller blade and hub separately. In the blade stress calculation, the hub is assumed to be rigid. On the other hand the blade is completely ignored if hub strength is considered. G.H.M.Beek [6] the interference between the stresses conditions in both parts. Strong tools are available to shift the disturbing boundary conditions fro the blade root to the hub-shaft interface and obtain reliable information about the blade root loading an its resolution in the hub. Detailed experimental data, obtained in strain gauge measurements on a full scale blade, proved the validity of the chosen element type and for application on propeller blades. Finite element calculations of propeller blade stresses for a blade clamped to an assumed rigid hub give reliable results over the whole blade except for the very close vicinity of the clamped section. Results of comparative calculations show the strong influence of the hub elastically on the stress distribution in the blade root section. It is noticed that special attention must be paid in hub blade transition for highly skewed blades.

Computer technique for propeller blade section design: Kevwin J.E [21] developed a numerical procedure and computer program for the lifting surface design of sub-cavitation propellers. The procedure includes careful treatment of the effect of radical-induced velocities on blade-section design and provides for independent specification of the pitch angle of trailing vorticity. Numerical results demonstrate the importance of including radial-induced velocities for propeller blades having significant skew, rake and/or a non- uniform radial pitch distribution.

CW Deckanelkj [22] et.al, generate a geometry for given operating conditions by using the partial differential equation (PDE) method approach. Standard techniques of surface representation, such as B-spline interpolation, require a large number of control points to achieve this. The PDE method approaches the representative of the blade as a boundary valued problem which ensures that a fair surface is generated and secondly that a small set of design parameters are needed. The small parameter set is of importance since it can firstly manipulate the propeller design with ease and secondly, use it to great advantage in the task of functional design

3. MODELIGN OF PROPELLER

3.1. OVERVIEW OF DESIGN OF PROPELLER

Modeling of the propeller is done using CATIA V5 R 19. 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. Propeller blade is modeled by using single section surface option

3.2. DETAILS OF DIESEL ENGINE

G8300/3000HP(2206KW) Marine Diesel Engines "AVESPEED" brand boat-purpose diesel engines have their power ranging from 184-4044KW and their speed 400-1200r/min, being widely used on the outside sea steel fishing boats, inner river and coastal sea transport vessels, engineering operation vessels, roll-on-roll-off ships and large-medium ships as main propelling power and auxiliaries. Of these the G-type diesel engine may burn the heavy fuel oil of HFO-18-CST/50 Max.

3.3. 4100C SERIES MARINE DIESEL ENGINE

Considered four cylinder diesel marine engine

Direct injection four stroke

Power: 29KW

Temperature of water: 30 ^{0}C

Dynamic viscosity μ (N s/m²) ×10-3 = 0.798

Kinematic viscosity v (m²/s) × 10-6 = 0.801

Reynolds number Re = 3400

Density of water ρ=1000kg/m3

Diameter of propeller D= 200 mm = 0.2 m

By using this formula velocity is calculated:

$$\mathrm{Re} = \frac{\rho v D_H}{\mu} = \frac{v D_H}{\nu} = \frac{Q D_H}{\nu A}$$

Velocity =13.49 m/s

3.4 DESIGN PARAMETERS

The design parameters are shown in the below figure 3.1

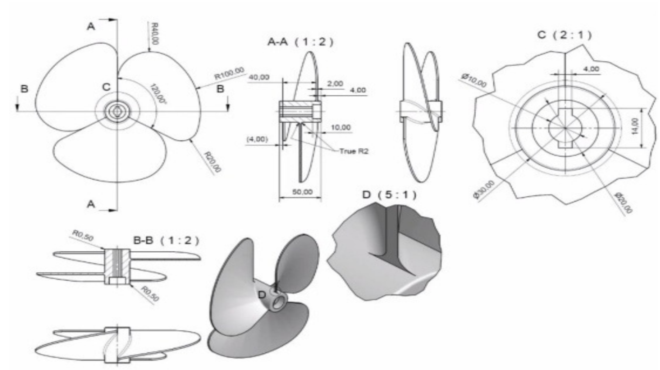

Figure3.1: Design parameters of propeller

3.5. MODELING OF PROPELLER

- Open Catia V5 R19.
- Click on start generative shape design in shape section
- Name the new part as propeller click ok
- Click on axis system Axis system type on and standard and click ok
- Hide all XY,YZ and ZX plane respectively
- Select the "Sketch" button and select YZ plane
- Draw a vertical line of 50 mm height at a distance of 15 mm from Z-axis.
- Now exit workbench.
- Select the "Revolution surface definition" and select the revolution axis as Z-axis.
- Select YZ-Plane and select the "Sketch button"
- Now put a point on the surface of the cylinder generated at a height of 4 mm from the bottom of the cylinder
- To Draw Helix
- Now exit work bench
- Select the Helix curve definition and select axis as Z-axis and given pitch=126 mm and revolution=1 and height=42mm and click ok

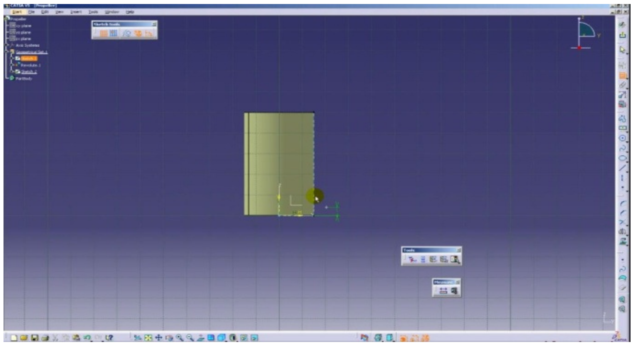

Figure 3.2: Cylinder is generated

To generate blade Profile:

- Click the “swept surface definition” button.
- In that select 2nd profile type

Sub type: With reference surface

Guide curve1: Helix 1

Reference Surface: Revolute.1

Angle: 90^0

Length 1:85 mm

Length 2:0 mm

Click ok

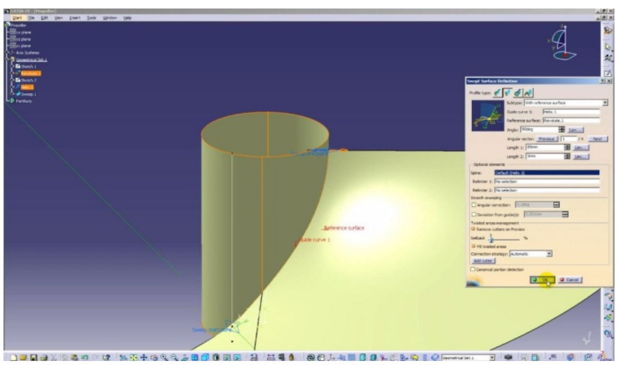

Figure 3.3: Helix is generated

- Now select XY plane
- Select “Project 3D Element ” option to project the edge of the blade
- Now select the “corner” icon to round off the one of corners
- Give the R=40 mm
- Now again do the step 5 with R=20 mm for another corner
- Exit work bench
- Now select extrude surface definition and drag the two green colored arrows to extend the shape.
- Now select “Split definition”

Element to cut: sweep.1

Cutting element: Entrude.1

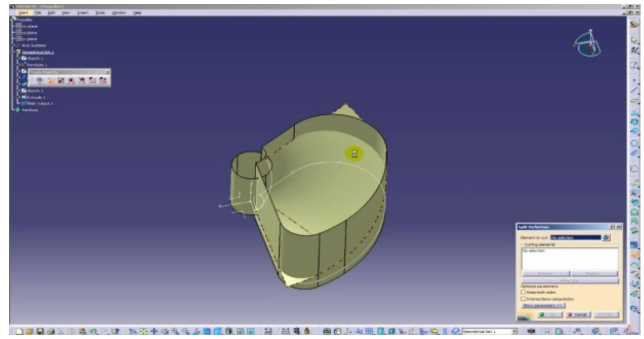

Figure3.4: After extrude command

- Now hide some unwanted swept area to get the blade profile.
- Now left click on part body to “Define in work object”.
- Click “part design” in mechanical Design in start.
- Click “Thick surface Definition” button.

First offset: 1

Second offset: 1

Object offset: Split

Click ok

- Select the “Circular pattern definition”

Parameters: Complete Crown

Instance: 3

Reference element: Revolute.1\face.1

Object: Current solid

Click ok

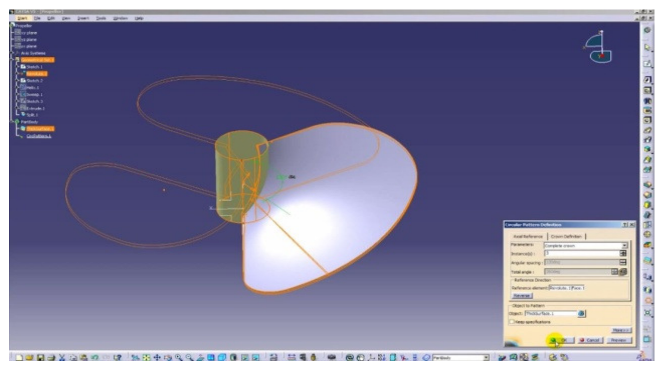

Figure3.5: Before revolute

- Select “Close surface Definition” and click the cylinder edge and click ok

Object of close: Revolute1

- Hole
- Click “Edge Fillet definition”

Radius =2mm

Object fillet=6

Click ok

3.6. FINAL MODELS OF PROPELLER

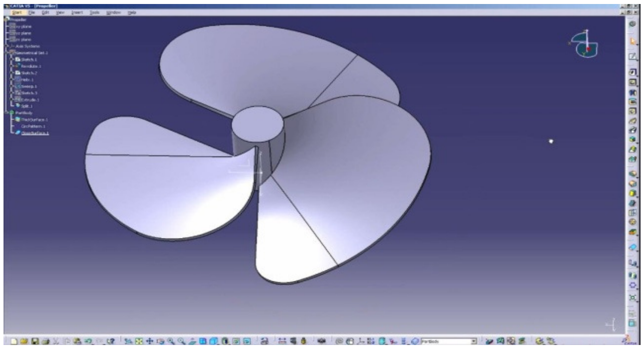

Figure 3.6: Final model before making groove for shaft

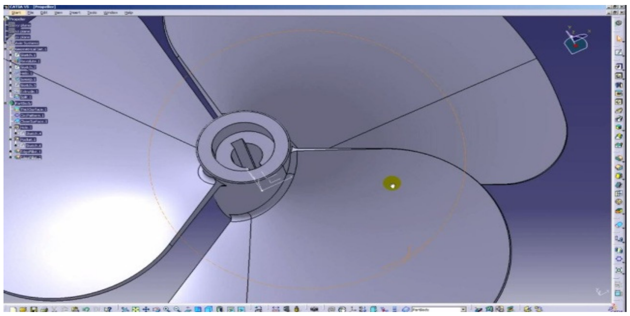

Figure 3.7: Final model after making groove for hole

Figure 3.8: Aluminum model

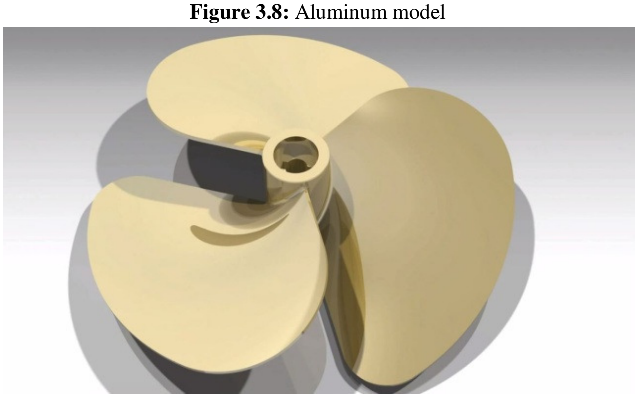

Figure 3.9: Aluminum alloy model

4. ALUMINUM PROPELLER ANALYSIS IN ANSYS

4.1. PROPERTIES OF ALUMINUM

Casting Condition: Chill Cast

Proof stress: 230 N/sq.mm

Tensile strength: 280 N/sq.mm

Young's modulus: 7.OOx 1 e4 N/sq.mm

Rigidity modulus: 2.71 x I 4 N/sq.mm

Poisson's ratio: 0.29

Density: 2.7g/cc

%Elongation: 2

Hardness: 105 BHN

Melting point: 650°c

4.2. MESHING

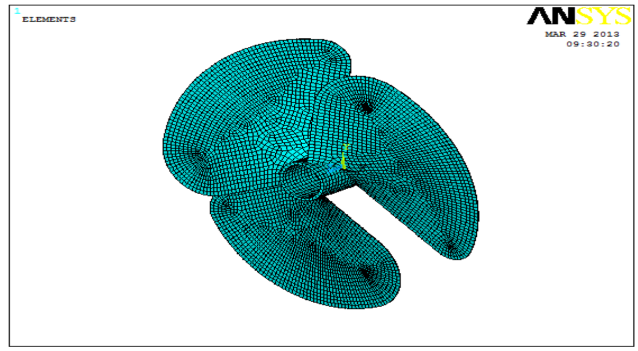

Figure4.1: Meshed model in ansys of aluminum propeller

4.3. MODAL ANALYSIS

When an elastic system free from external forces is disturbed from its equilibrium position it vibrates under the influence of inherent forces and is said to be in the state of free vibration. It will vibrate at its natural frequency and its amplitude will gradually become smaller with time due to energy being dissipated by motion. The main parameters of interest in free vibration are natural frequency and the amplitude. The natural frequencies and the mode shapes are important parameters in the design of a structure for dynamic loading conditions. Modal analysis is used to determine the vibration characteristics such as natural frequencies and mode shapes of a structure or a machine component while it is being designed. Modal analysis is used to determine the natural frequencies and mode shapes of a structure or a machine component.

The rotational speed is limited by lateral stability considerations. Most designs are sub critical, i.e. rotational speed must be lower than the first natural bending frequency of the propeller.

Number of revolutions per second

= fundamental frequency × 60

$$N = f \times 60$$

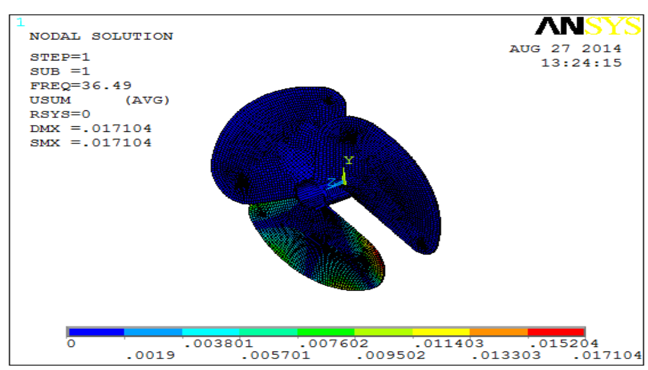

Figure 4.2: Modal Analysis of blade 1

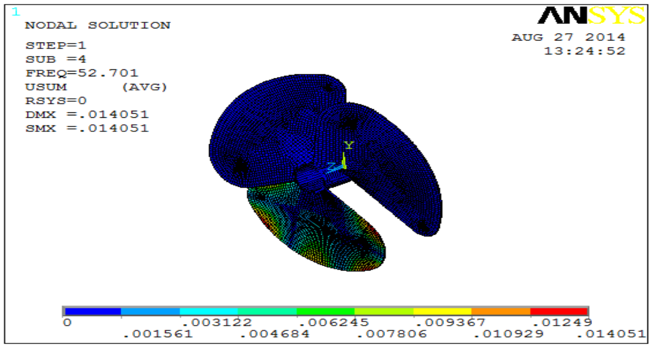

Figure 4.3: Modal Analysis of blade 2

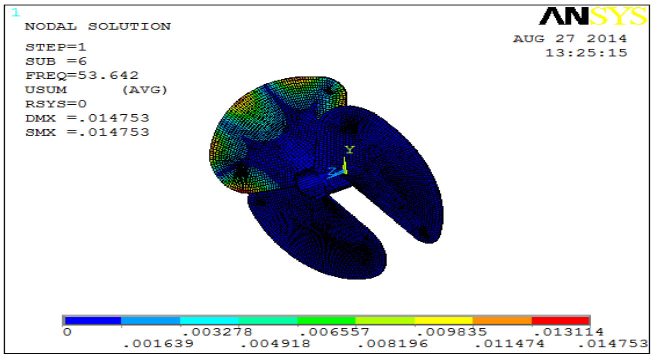

Figure 4.4: Modal Analysis of blade 3

4.4. Calculations of Stresses in a Propeller

The calculation of the stresses in a propeller is extremely complicated owing to a number of reasons: the loading fluctuates, its distribution over the propeller blade surface is difficult to calculate, and the geometry of the propeller is rather complex. It is therefore usual to use simplifies methods to calculate the stresses in the propeller blades and to adopt a large factor of safety based on experience.

The simple method described here is based on the following principal assumptions:

i) The propeller blade is assumed to be a cantilever fixed to the boss at the root. The critical radius is just outside the root fillets.

ii) The propeller thrust and torque, which arise from the hydrodynamic pressure distribution over the propeller blade surface, are replaced by single forces each acting at a point on the propeller blade.

iii) The centrifugal force on the propeller blade is assumed to act through the centroid of the blade, and the moment of the centrifugal force on the critical section can be obtained by multiplying the centrifugal force by the distance of the centroid of the critical section from the line of action of the centrifugal force.

iv) The geometrical properties of the radial section (expanded) at the critical radius may be used instead of a plane section of the propeller blade at that radius, and the neutral axes may be taken parallel and perpendicular to the base line of the expended section.

4.5 The Following Notation Is Adopted

Area of propeller A = 239.36 mm²

Power of engine P = 29000 Watts

Velocity V=13.49 m/sec

Outer radius of propeller R=100 mm

Hub radius r =15 mm

Mean radius r1=0.40R

Angular speed $\omega = \frac{2\pi N}{60}$

Thrust T = Power/Velocity

Acceleration due to gravity g = 9810 mm/sec²

Number of blades Z = 3

Torque $Q = P \times \frac{60}{2\pi N}$

Actual thrust acting = $0.85 \times T$

Actual torque transmitted to Propeller = $0.75 \times Q$

Thrust force per blade $Ft = \frac{1}{z} T$

Centrifugal force $Fc = \frac{w}{g} r (2\pi n)^2 = 4\pi^2 \frac{w}{g} n^2 r$

For Aluminum Propeller

Frequency f =36 Hz

Speed N = 36.5×60 = 2190 rpm

Thrust T = P/V = 29000/13.49 = 2149.74 N-m

Actual Thrust = 0.85 × T = 0.85 × 2149.74

= 1827.28 N-m

Actual Thrust per blade = 1827.28/3

= 609.1 N-m

Q = 29000 × 60 / (2×π×2190) = 126.51

Centrifugal force $= 4\pi^2 \frac{W}{g} n^2 r$

$$Fc = \frac{w}{g} r (2\pi n)^2$$

= 2.12(2π×2190)²*0.015/9.81

=95.780 KN

Angular speed $\omega = \frac{2\pi N}{60}$ = 229.22 rad/s

Weight W = 2.12 kg

4.6. Stress Analysis For Aluminum Propeller In Ansys

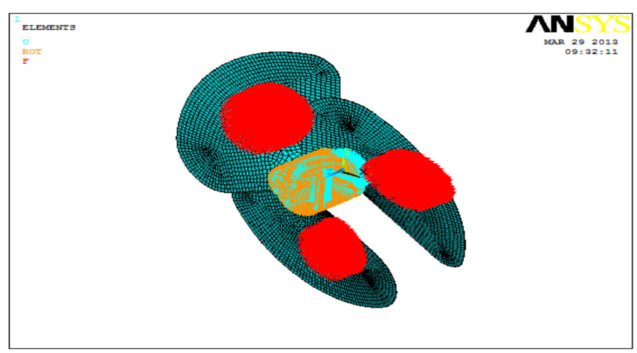

Figure 4.5: Thrust force applied on the blade

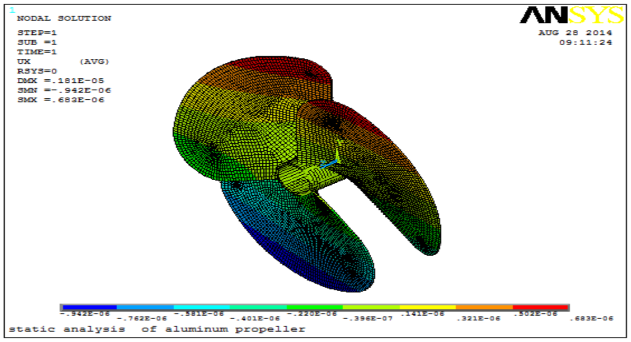

Figure 4.6: Deflection of aluminum propeller in X direction

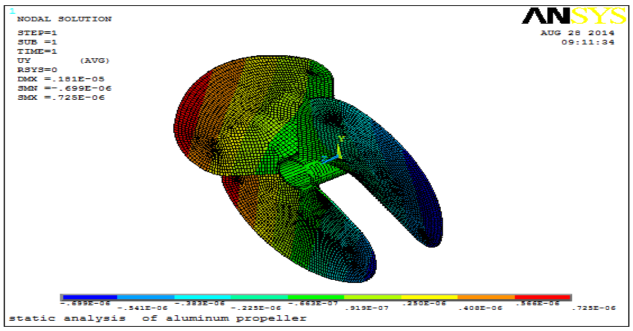

Figure 4.7: Deflection of aluminum propeller in Y direction

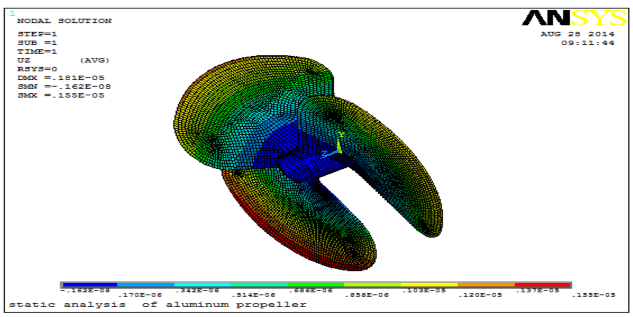

Figure 4.8: Deflection of aluminum propeller in Z direction

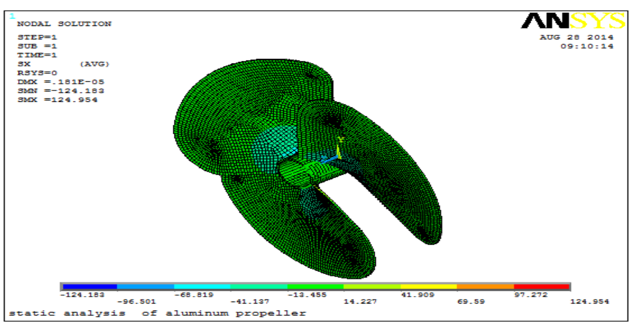

Figure 4.9: Normal stress of aluminum propeller in X direction

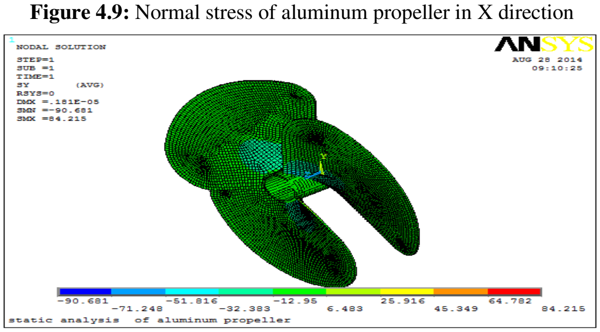

Figure 4.10: Normal stress of aluminum propeller in Y direction

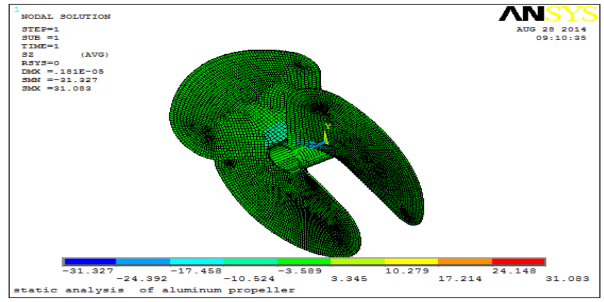

Figure4.11: Normal stress of aluminum propeller in Z direction

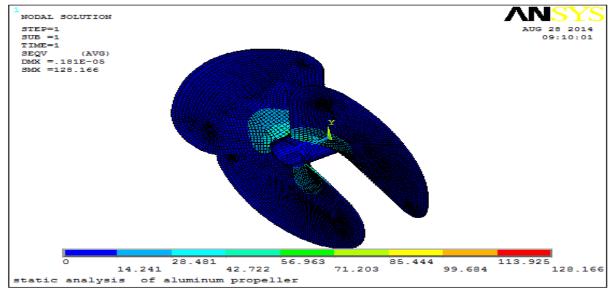

Figure 4.12: Von Mises stresses of aluminum propeller

5. Composite Propeller Analysis In Ansys

5.1. Properties Of S2glass Fabric/Epoxy

E_x = 22.925 GPa E_y = 22.925 GPa

E_z = 12.4 GPa NU_{xy}= 0.12

NU_{yz}= 0.2 Nu_{zx} = 0.2

G_{xy} = 4.7 GPa G_{yz} = 4.2 GPa

G_{zx} = 4.2 GPa Density = 1.8 gm/cc

5.2. Composite Material Layer Stacking

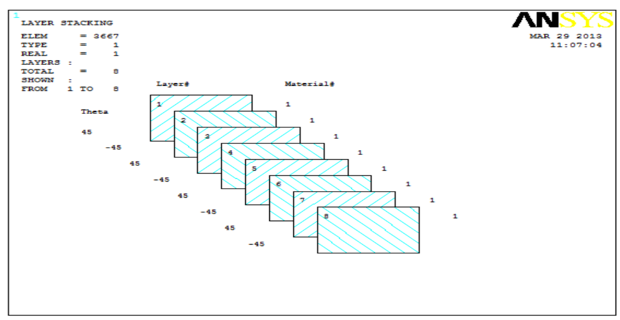

Figure5.1: Composite material layer stacking

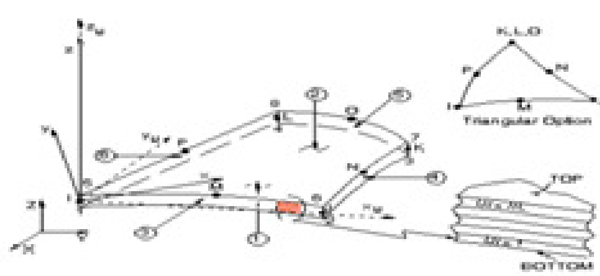

Figure: 5.2: SHELL 99 Linear layered structural shell.

Meshing: SHELL99 may be used for layered applications of a structural shell model as shown in Fig 5.1. SHELL99 allows up to 250 layers. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes.

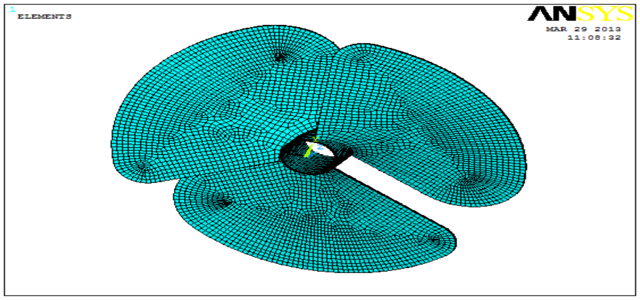

Figure5.3: Meshed model of composite propeller

5.3. Modal Analysis

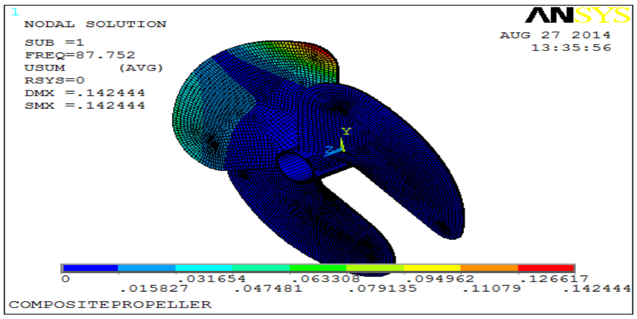

Figure5.4: Modal analysis on blade 1

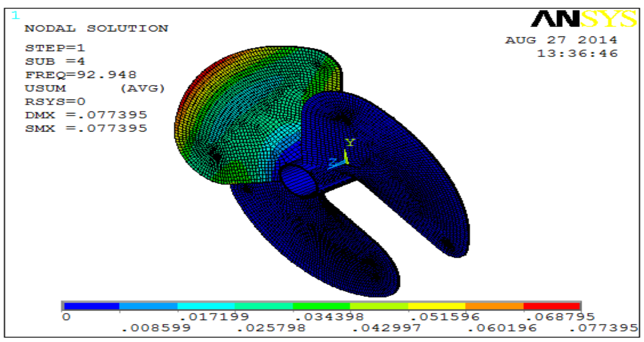

Figure5.5: Modal analysis on blade 2

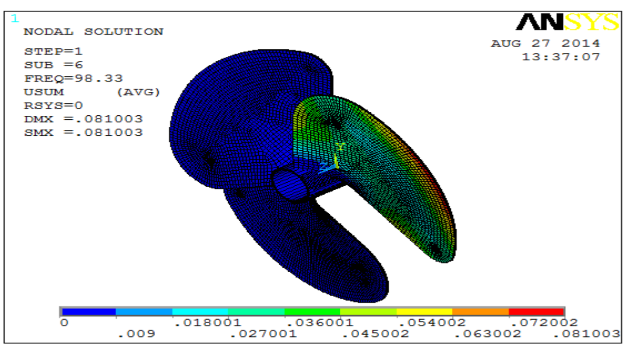

Figure5.6: Modal analysis on blade 3

5.4 Calculations Of Stresses In A Propeller

For Composite Propeller

Frequency, f =81 Hz

Speed, N = 88×60 =5280 rpm

Thrust, T = P/V =29000/13.49 = 2149.74 N-m

Actual Thrust = 0.85×T= 0.85 × 2149.74 = 1827.28 N-m

Actual Thrust per blade =1827.28/3 = 609.1 N-m

Q = 29000 × 60 / (2×π×5280) = 52.47

Centrifugal force $= 4\pi^2 \frac{W}{g} n^2 r$ $Fc = \frac{W}{g} r(2\pi n)^2$

= 1.2(2π×5280)² *0.015/9.81 = 315.137 KN

Angular speed, $\omega = \frac{2\pi N}{60}$ = 552.64 rad/s

Weight, W = 1.2 kg

5.5 Static Analysis of Composite Propeller

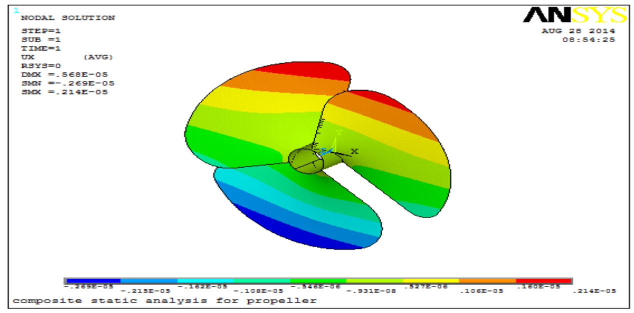

Figure5.7: Deflection of a composite propeller with 8 layers in X direction

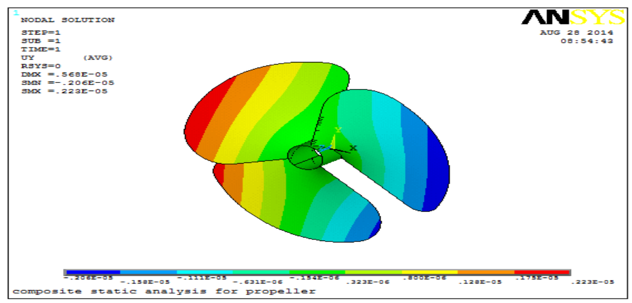

Figure5.8: Deflection of a composite propeller with 8 layers in Y direction

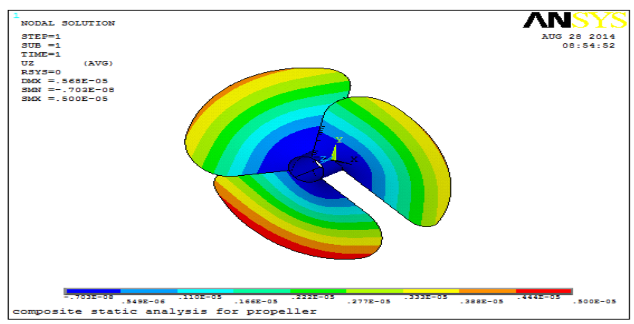

Figure5.9: Deflection of a composite propeller with 8 layers in Z direction

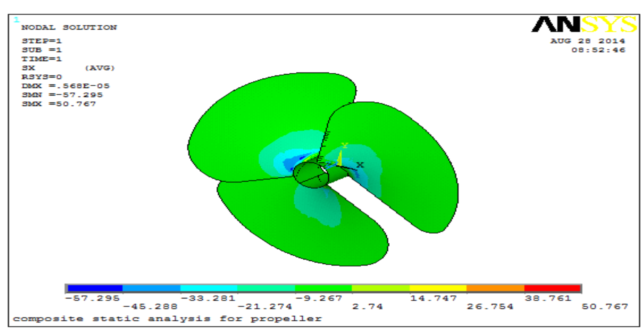

Figure5.10: Normal stress in composite propeller in X direction

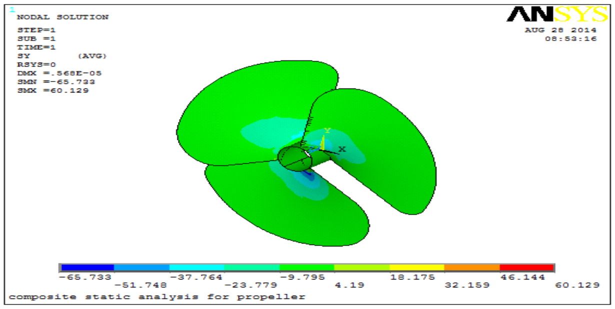

Figure5.11: Normal stress in composite propeller in Y direction

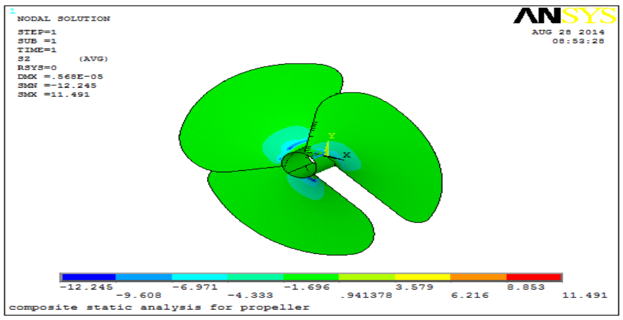

Figure5.12: Normal stress in composite propeller in Z direction

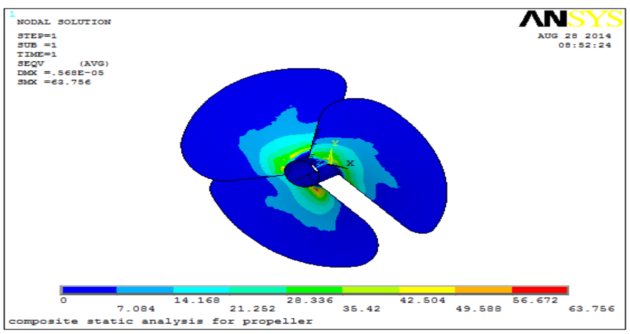

Figure5.13: Von mises stress of a composite propeller

6 Results And Discussion

6.1 Linear Static Analysis

Linear static analysis is concerned with the behavior of elastic continua 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 number of layers is taken as 8.

6.2. Static Analysis Of Aluminum Propeller: The thrust of 2150 N 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 underwater 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 4.6. The maximum deflection was found as 3.62 mm in y-direction. Similar to the cantilever beam the deflection is maximum at free end.

Maximum principal stress value for the aluminum propeller are shown in figure 4.9 .The Von mises stress on the basis of shear distortion energy theory also calculated in the present analysis. The maximum von mises stress induced for aluminum blade is 124.166 N/mm^2 as shown in figure 4.12.The stresses are greatest near to the mid chord of the blade-hub intersection with smaller stress magnitude toward the tip and edges of the blade.

Table 6.1: Static Analysis of Aluminum Propeller

Results	**Aluminum Propeller**
Deflection	0.181 mm
Max Normal Stress	124.954 N/mm^2
Von Mises	128.166 N/mm^2
1st Principal Stress	124.954 N/mm^2
2nd Principal Stress	84.215 N/mm^2
3rd Principal Stress	31.083 N/mm^2
Frequency	36.49

Table 6.2: Static Analysis of Composite Propeller with 8 Layers

Results	**Composite Propeller**
Deflection	0.142 mm
Max Normal Stress	50.767 N/mm^2
Von Mises	63.756 N/mm^2
1st Principal Stress	50.767 N/mm^2
2nd Principal Stress	60.129 N/mm^2
3rd Principal Stress	11.491 N/mm^2
Frequency	87.752

6.3. Conclusions And Future Scope Of Work

The following conclusions are drawn from the present work:

1. The deflection for composite propeller blade was found to be around 0.142mm for all layers which is much less than that of aluminum propeller i.e. 0.181mm, which shows composite materials is much stiffer than aluminum propeller.
2. Modal analysis results showed that the natural frequencies of composite propeller were 150% more than aluminum propeller, which indicates that the operation range of frequency is higher for composite propeller.
3. Static analysis results showed that the max normal stresses of aluminum propeller are 87% higher than the composite propeller and von mises stresses are 50% higher in aluminum propeller than that of the composite propeller.
4. Aluminum propeller can rotate at maximum speed of 2190 rpm without failing while composite propeller can rotate at a maximum speed of 5280 rpm. The weight of the propeller can also be significantly reduced by using composite materials without sacrificing the mechanical properties.

FUTURE SCOPE OF WORK: The present work only consists of static and modal analysis, which can be extended for Eigen value, harmonic, transient and spectrum analysis in case of both aluminum and composite materials.

There is also a scope of future work to be carried out for different types of materials. For present purpose only modeling and analysis of a propeller blade is carried only for GFRP materials.

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