Design and Analysis of A Aerfoil Shaped Propeller Blades Used In Ships Using FEA

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***Abstract**:*

Propeller design aims at achieving high propulsive efficiency at low levels of vibration and noise, usually with minimum cavitations. Achieving this aim is difficult with conventional propellers, as ships have become larger and faster propeller diameters have remained limited by draught and other factors. Surface piercing propeller offers an attractive alternative to high-speed crafts, which operate under limited draught. The performance of the vehicle depends upon the efficiency of the propeller. The geometric shape and its surface finish will decide the efficiency of the propeller. The material used is carbon UD and aluminum. The present project basically deals with the modeling, Analysis of the propeller using composite material of a marine vehicle having low draft. A propeller is complex 3D model geometry. CATIA modeling software is used for generating the blade model and tool path on the computer. Sectional data, pitch angle of the propeller are the inputs for the development of propeller model. Finite element analysis was carried out using ABAQUS. The propeller model developed in CATIA is converted in to IGES file and then imported to HYPERMESH for developing fine mesh of the model. As a part of the analysis static structural testing was conducted by varying material properties in pre-processing stage. Further fatigue analysis was performed to analyze the factor of safety. Based on the results obtained from both static analysis and dynamic analysis a better performing material is identified for the development of a propeller. The post processed results obtained from both analysis methods recommends carbon UD/ Epoxy for the fabrication of propeller.

Keywords: *Blade Angle, Catia, Hyper Mesh Pitch angle, Propeller Blades Surface piercing*

1. Introduction

A propeller is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and air or water is accelerated behind the blade. Propeller dynamics can be modeled by both Bernoulli's principle and law. A propeller is the most common propulsion on ships, imparting momentum to a fluid which causes a force to act on the ship. Three, four, or five blades are most common in marine propellers, although designs which are intended to operate at reduced noise will have more blades. The blades are attached to a boss (hub), which should be as small as the needs of strength allow - with fixed pitch propellers the blades and boss are usually a single casting.

A ship needs propulsion system to move in water, so by using a thrust – producing mechanism the ship moves. There are many thrust-producing devices called propellers like screw propellers, pump jet, water jet etc which producing by high speed crafts, ships, pleasure crafts and torpedoes. The speed of marine vehicle depends on the choice of propulsion system. The thrust from the propeller is transmitted to move the ship through a transmission system which consists of a rotational motion generated by the main engine crank shaft, intermediate shaft and its bearings, stern tube shaft and its bearing and finally by the propeller itself.

Surface piercing propeller has em1erged as an integrated solution for high-speed craft, to overcome the problems such as cavitations, low draught & shallow water restrictions that is prominent with these crafts. It is also easily adaptable for different operating speeds. These propellers operate in partially submerged condition, mostly in inclined position and draws in air bubble along the blade on the back surface. The air bubbles contract or expand on the surface all along its underwater operation and avoid cavitation's and its implied problems like vibration, erosion and thrust breakdown. This propeller eliminates the appendage drag due to the brackets, shafts including the drag due to Magnus effect of the rotating shaft. In is best suitable for small and high- speed crafts and has virtually no limit on size of propeller due to draught

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restrictions. These propellers are freely adoptable for large range of vehicle speeds by adjusting the immersion. It is suitable for very high craft to attain high speeds. Steering requirements also can be met partially by adjustment of the angles of the shaft.

II. PROPELLER MATERIALS

A. Materials:

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, nickel-manganese bronze, nickel- aluminum bronze, Naval brass, forged aluminum, composite materials etc.

A.1 Types of Composite Materials:

Composite materials are as follows

- Glass fiber
- Aramid fiber
- Carbon fiber (Standard Grade)
- Carbon fiber (Special Grade)
- Glass-reinforced plastic (GRP)
- Carbon UD/EPOXY

Carbon UD/Epoxy:

Carbon fiber reinforced polymer carbon reinforced plastic (CFRP or CRP), is a very strong, light, and expensive composite material or fiber-reinforced polymer. Similar to fiberglass (glass reinforced polymer), the composite material is commonly referred to by the name of its reinforcing fibers (carbon fiber). The polymer is most often epoxy, but other polymers, such as polyester, vinyl ester or nylon, are sometimes used. Some composites contain both carbon fiber and other fibers such as Kevlar, aluminum, and fiberglass reinforcement. The terms graphite-reinforced polymer or graphite fiber-reinforced polymer (GFRP) are also used, but less commonly, since glass-(fiber)-reinforced polymer can also be called GFRP. In product advertisements, it is sometimes referred to simply as graphite fiber (or graphite fiber), for short.

It has many applications in aerospace and automotive fields, as well as in sailboats, and notably in modern bicycles and motorcycles, where its high strength-to-weight ratio is of importance. Improved manufacturing techniques are reducing the costs and time to manufacture, making it increasingly common in small consumer goods as well, such as lap tops, tripods, fishing rods, paint ball equipment, archery equipment, racquet frames, bodies, classical strings, drum shells, golf clubs, and pool/billiards/ snooker cues.

TABLE: 1

Properties of Carbon Ud/Epoxy Material

S.No	Young's Modulus variables	Young's Modulus values
1	E_X (Gpa)	25
2	E_Y (Gpa)	10
3	E_Z (Gpa)	10
4	NU_{XY}	0.16
5	NU_{YZ}	0.48
6	NU_{ZX}	0.16
7	G_{XY} (Gpa)	5.2
8	G_{YZ} (Gpa)	3.8
9	G_{ZX} (Gpa)	6
10	Density Ns^2/mm^4	1.6×10^{-9}

III. PROPELLER MODELING USING CATIA

CATIA is used for modelling of propeller, it provides multiple surface and solids- based machining for a full range of parts, from 2-Axis work to complex 3-axis moulds, dies and prototypes.

A. Introduction to Propeller Geometry:

A propeller consists of a number of identical blades on a boss. The propeller is usually fitted at the aft end of the ship. The surface of a propeller blade, which faces aft is called its Face, the opposite surface being the Back of the blade. The junction of the blade to the boss is the blade root and the extremity of the blade (the point farthest from the center of the propeller) is the blade tip. The blades of a propeller; the sometimes inclined aft with respect to the axis of the rotating of the propeller; the propellers are then said to have rake. The inclination of the propeller blade in a plane normal to the propeller axis is called skew. When the propeller is rotating so as to cause the ship to move forward, the front edge (with respect to the motion) is called the leading edge of the propeller blade propeller blade, while the rear edge is called the trailing. The diameter of the circle traced out by the blade tips when the propeller is turning is called the propeller diameter (D).

CATIA allows for creation of complete three-dimensional models of parts. The part model can be used to (i) produce fully-dimensioned engineering drawings for manufacturing the part (ii) Generate the tool path (iii) Verify tool path (iv) Generate NC part program for NC machines (v) Generates inputs for analytical processes such as Finite element analysis. These components are modeled by using the geometric entities like Points, Curves, surface, etc.

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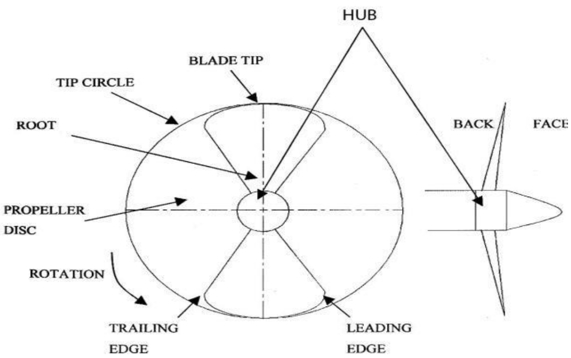

Fig: 1 Geometry of The Propeller

B. Generating Propeller Geometry in CATIA:

The blade is divided into fourteen sections over the blade radius. Since the coordinate point data for the blade sections are more, the sections data is converted into a machine code language file.

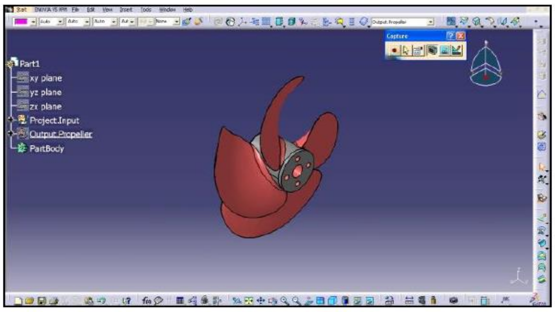

Figure:2 Project Input

Follow the same path as discussed below for all the fourteen section.

- Start the CATIA and select new
- Select start and then Modelling
- Select sketch and select the XY plane
- Draw a circle with 50mm diameter and finish sketch
- Select the circle and Extrude (-50,50) and ok
- Select splines, through points, points from file
- Select the splines and edit, transform and translate

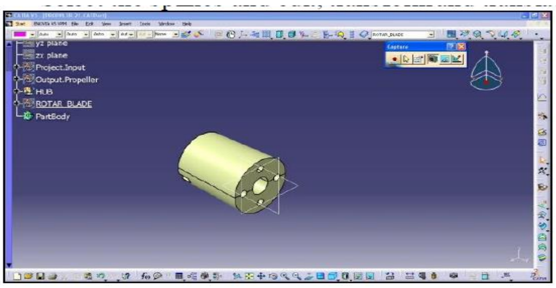

Figure: 3 Hub Model Developed In Catia

- Select delta and give XC value ,ok and move
- Rotate between two axes and select the YC and rotate 90
- Translate the splines in Y axis and give the value
- Rotate between two axes in X axis and give the value and ok
- Create a datum plane
- Wrap the splines into the circle.
- Join all the splines which forms the blade curvature and then ruled it.
- Using rotate option> select the blade and rotate it.

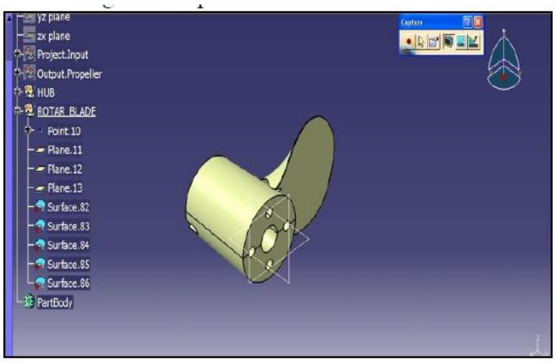

Figure: 4 One Blade of The Propeller

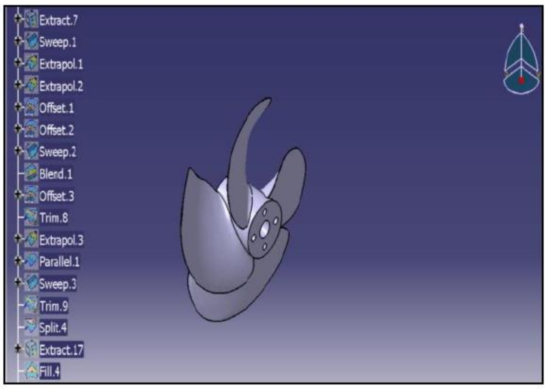

Figure: 5a Model Of Surface Piercing Propeller Developed

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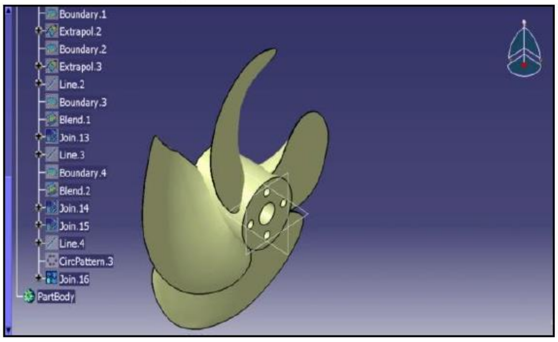

Figure: 5a Model of Surface Piercing Propeller Developed

IV. ANALYSIS OF PROPELLER USING ABAQUS

A. MESH THE GEOMETRY (USING HYPER MESH)
MESH SPECIFICATION:

Meshing is the procedure of applying a finite number of elements to the model. In order to conduct a finite element analysis the structure must be first idealized into some form of mesh. The art of successful application of the technique, so far as the user is concerned, lies in the combined choice of element types and associated mesh. As the method it approximates, it is necessary that the user have a good idea of the form of the solution, together with an understanding of the consequences of the assumptions made within the element types to be used.

B. ELEMENT TYPE:
ELEMENT TYPE FOR STRUCTURAL ANALYSIS:

Picking an element type from the large library of elements in ABAQUS can be an intimidating thing for a beginner. The following are the two types elements which are used for meshing.

- Hexa – C3D8
- Penta – C3D6
- Hexa C3d8/ Eight-Node Brick Element.

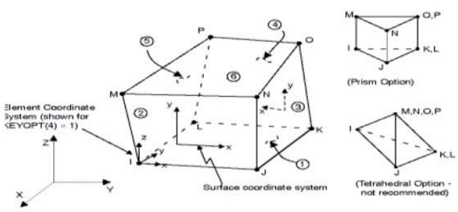

Figure: 6 hexa c3d8geometry Hexa c3d8 input summary:

Element Name C3D8
Nodes I, J, K, L, M, N, O, P
Degrees of Freedom UX, UY, UZ
Real constants None
Material Properties EX, EY, EZ, ALPX, ALPY, ALPZ, PRXY, PRYZ, PRXZ , DENS, GXY, GYZ,GXZ,DAMP
Surface Loads Pressures:
face 1 (J-I-L-K), face 2 (I-J-N-M), face 3 (J-K-O-N), face 4 (K-L-P-O), face 5 (L-I-M-P), face 6 (M-N-O-P)

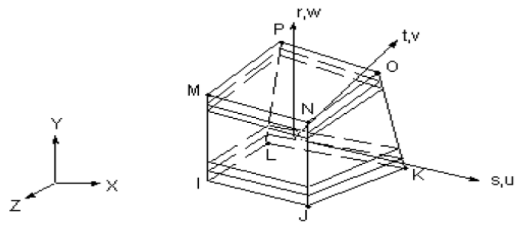

Fig: 7 Hexa - 3-D 8- Node Layered Structural Solid

ASSUMPTIONS AND RESTRICTIONS

All material orientations are assumed to be parallel to the reference plane, even if the element has nodes inferring warped layers. The numerical integration scheme for the thru-thickness effects are identical to that used in SHELL4 noded element. This may yield a slight numerical inaccuracy for elements having a significant change of size of layer area in the thru-thickness direction. The main reason for such discrepancy stems from the approximation of the variation of the determinant of the Jacobian in the thru-thickness direction. The error is usually insignificant

.However, users may want to try a patch-test problem to assess accuracy for their particular circumstances. Unlike shell elements, HEXA cannot assume a zero transverse shear stiffness at the top and bottom surfaces of the element. Hence the intern laminar shear stress must be computed without using this assumption, which leads to relatively constant values thru the element. The use of effective (“eff”) material
properties developed below is based on heuristic arguments and numerical experiences rather than on a rigorous theoretical formulation. The fundamental difficulty is that multi linear displacement fields are attempted to be modeled by a linear (or perhaps quadratic) displacement shape function since the number of DOF per element must be kept to a minimum. A more rigorous solution can always be obtained by using more elements in the thru-the-layer direction. Numerical experimentation across a variety of problems indicates that the techniques used with HEXA give reasonable answers in most cases.

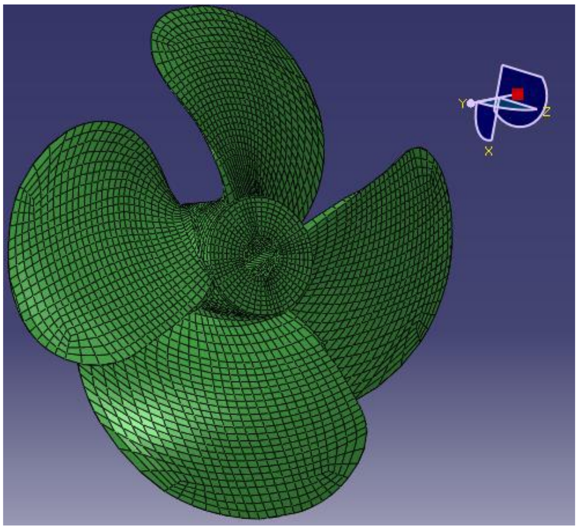

Figure: 8 Fe Model of Propeller

C. IMPORTING FILE TO ABAQUS:

The model created in CATIA is imported into ABAQUS using the IGES/IGS file.

By using the following procedure file can be imported:

STEP I : Select file option and import using part format.

STEP II : Browse the file from the selected location and open it.

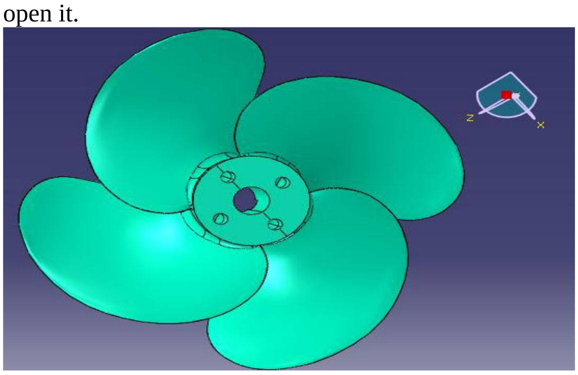

Figure:9 Propeller Geometry Imported To Abaqus

D. MATERIAL PROPERTIES:

Select the material module option and select material manager.

- After that we have to define the material properties.
- Select section manager and call material properties in this section.
- Assign the section by picking the part.

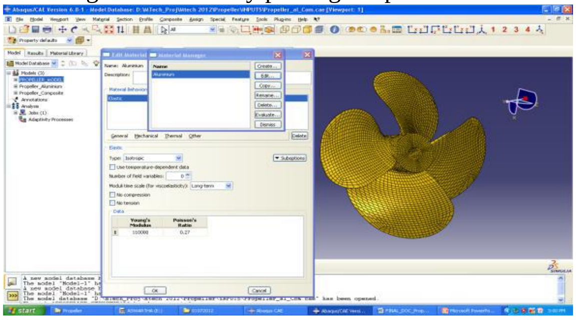

Figure:9 (a) Assigning The Material Properties

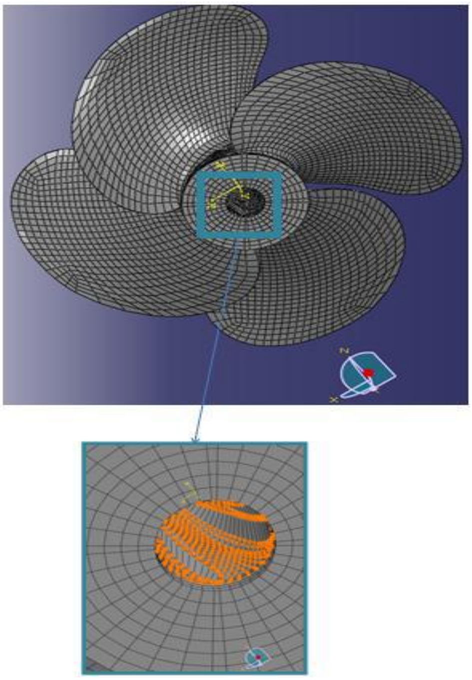

Figure: 10 Boundary Conditions Applied on The Nodes

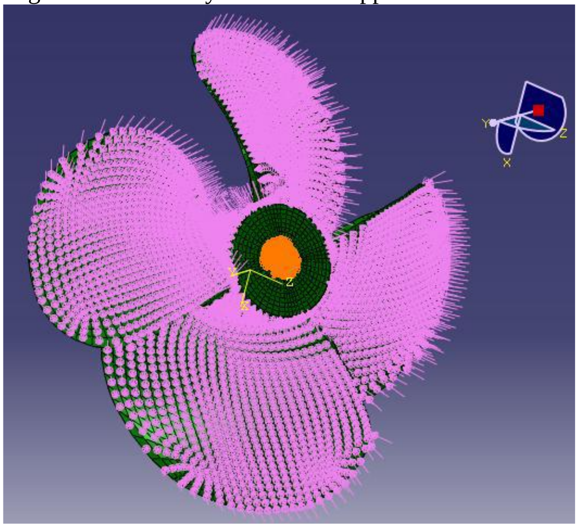

Figure: 11 Pressure Loads Applied on The Propeller Blades

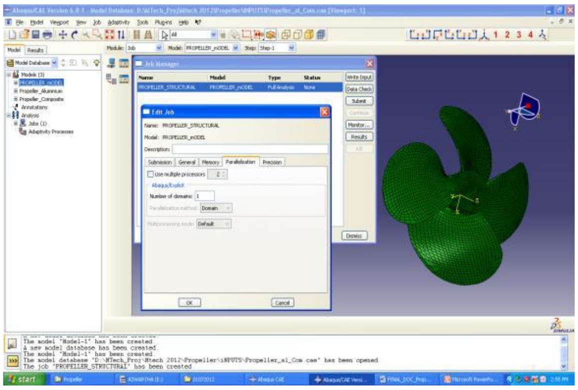

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Figure: 12 Solving Using Abaqus

V RESULTS

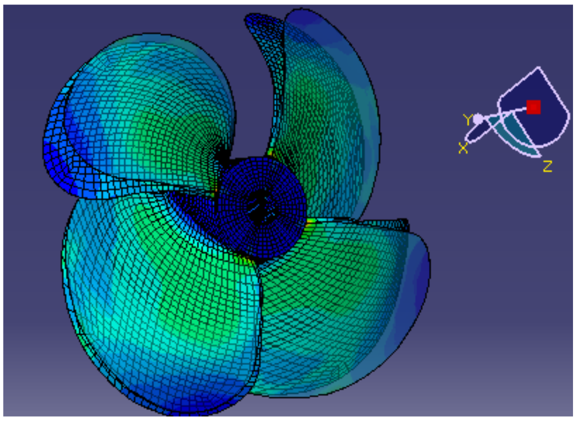

Figure: 13 Deformation of The Propeller

A. MATERIAL ALUMINUM
B. COMPOSITE MATERIAL

DISPLACEMMENT, STRESS X, Y, Z Directions

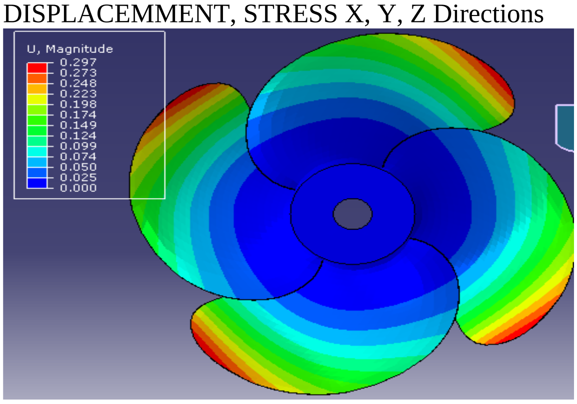

Figure 14: Displacement Vector Sum

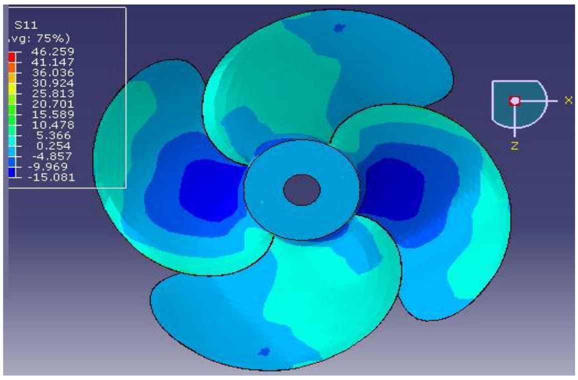

Figure 15: Stresses in X Direction

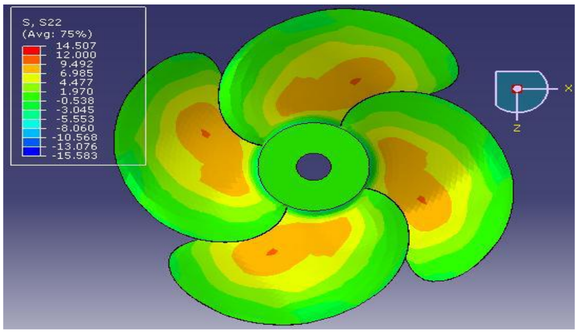

Figure 16: Stresses In Y-Direction

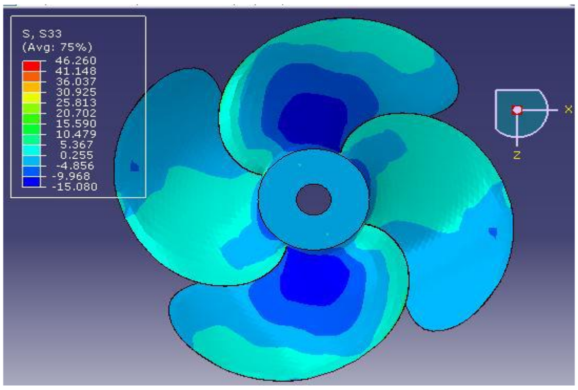

Figure 17: Stresses In Z-Direction

TABLE: 2
Results of Aluminum and Composite Materials

Element type	Displacement			Stresses(N/mm²)			Von misses stresses
	X	Y	Z	X	Y	Z	
Aluminum propeller	0.496	0.396	0.250	77.098	24.179	77.100	92.642
Carbon UD epoxy propeller	0.297	0.237	0.150	46.259	14.507	46.260	55.85

Composite material gives less deformation when the loads are applied. Therefore Composite material propeller is considered for the fatigue analysis of surface piercing propeller.

C. FATIGUE ANALYSIS OF SURFACE PIERCING PROPELLER:

When propellers are subjected to time varying loads, their behavior is unconditional and it requires a specific methodology to determine them. For example, a particular fiber on the surface of rotating propeller subjected to the action of pressure loads undergoes both tension and compression for each revolution of the shaft, is stressed in tension and compression N times each minute if the propeller is rotated at N rev/min.

Machine members are found to have failed under the action of repeated or fluctuating stresses, yet the most careful analysis reveals that the actual maximum stresses were well below the ultimate strength of the material, and quite frequently even below the yield strength. A fatigue failure has an appearance similar to a brittle fracture, as the fracture surfaces are flat and perpendicular to the stress axis with the absence of necking.

The fracture features of a fatigue failure, however, are quite different from a static brittle fracture arising from three stages of development. Fatigue failure is due to crack formation and propagation. A fatigue crack will typically initiate at a discontinuity in the material where the cyclic stress is a maximum.

Discontinuities can arise because of:

- Design of rapid changes in cross section, keyways, holes, etc.
- Elements that roll and/or slide against each other (bearings, gears, cams, etc.) under high contact pressure, developing concentrated subsurface contact pressure that can cause surface pitting (hole) or spalling after many cycles of the load.
- Carelessness (lack of care) in locations of stamp marks, tool marks, scratches, and burrs; poor joint design; improper assembly; and other fabrication faults.
- Composition of the material itself as processed by rolling, forging, casting, extrusion, drawing, heat treatment, etc.

D. FATIGUE LIFE METHODS:

There are three major fatigue life methods used in design and analysis:

1- Stress-Life Method

- It is based on stress levels.
- The least accurate approach, but most used method, since it is the easiest implement for a wide range of design applications.

2- Strain-Life Method

- Involves more detailed analysis of the plastic deformation at localized regions where the stresses and strains are considered for life estimates.

3- Linear-Elastic Fracture Mechanics Method

- It assumes a crack is already present and detected.
- It is then employed to predict crack growth with respect to stress intensity.
- It is most practical when applied to large structures in conjunction with computer codes and a periodic inspection program.

  In this study first method is used, i.e., Stress-Life Method.

E. FATIGUE LIFE METHODS:

To determine the strength of materials under the action of fatigue loads, four types of tests are performed: tension, torsion, bending, and combinations of these. In each test, specimens are subjected to repeated forces at specified

magnitudes while the cycles or stress reversals to rupture are counted. For the rotating-beam test, a constant bending load is applied, and the number of revolutions (stress reversals) of the beam required for failure is recorded. The first testis made at a stress that is somewhat under the ultimate strength of the material. The second test is made at a stress that is less than that used in the first.

F. CHARACTERIZING FLUCTUATING STRESSES:

Fluctuating stresses in machinery often take the form of a sinusoidal pattern because of the nature of some rotating machinery. It has been found that in periodic patterns exhibiting a single maximum and a single minimum of force, the shape of the wave is not important, but the peaks on both the high side (max.) and low side (min.) are important. Thus, F_{max} and F_{min} in a cycle of force can be used to characterize the force pattern.

$$F_m = \left|\frac{F_{max} + F_{min}}{2}\right|, \quad F_a = \left|\frac{F_{max} - F_{min}}{2}\right|$$

F_m: midrange component of force
F_a: amplitude component of force

Many time in design the stresses fluctuate without passing through zero. The following relationships and definitions are used when discussing mean andalternating stresses:

σ_{min}= minimum stress
σ_{max}= maximum stress
σ_r= stress range
σ_s= steady or static stress

$$\sigma_a = \text{amplitude stress} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\sigma_m = \text{midrange or mean stress} = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$R = \text{stress ratio} = \frac{\sigma_{min}}{\sigma_{max}}$$

$$A = \text{amplitude ratio} = \frac{\sigma_a}{\sigma_m}$$

Fatigue Failure Criteria for fluctuating Stress:

Varying both the midrange stress and the stress amplitude, or alternating component, will give some formation about the fatigue resistance of parts when subjected to such situations.

Modified Goodman Diagram:

- σ_m plotted along the x-axis.
- All other components of stress plotted on the y-axis.
- The modified Goodman diagram consists of the lines constructed to S_e (or S_f)above or below the origin.

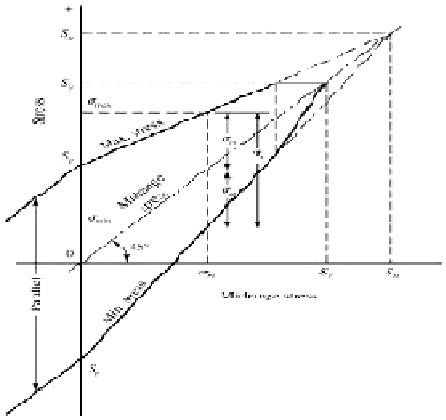

FIGURE 18 Modified Goodman's Diagram

- S_y is plotted on both axes, because S_y would be the criterion of failure if σ_{max} exceeded S_y.
- Useful for analysis when all dimension of the part are known and the stress components can be easily calculated. But it is difficult to use for design when the dimension are unknown.
- Modified Goodman's Equation is given by:

$$\frac{1}{n} = \frac{\sigma_e}{S_e} + \frac{\sigma_m}{S_{ut}}$$

The following results are obtained by conducting fatigue test on propeller model. Von -mises stresses, displacement contours are plotted by conducting the test. The results plotted are used to determine the factor of safety.

Figure 8.17 shows displacement contour for carbon UD/Epoxy material.

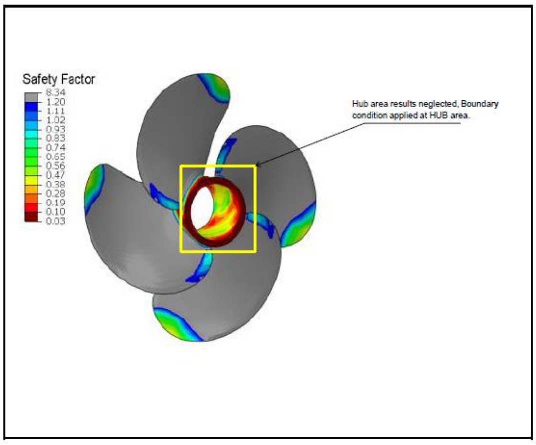

FIGURE: 19 Fatigue Analysis Results

VI CONCLUSIONS

The finite element analysis (FEA) is carried out for two different types of materials, those are aluminum and carbon UD/Epoxy.

Following are the important conclusions drawn from FEA:

- The von-mises stress acting on the propeller produced from aluminum is 92.642 N/mm2, corresponding deformat ion is 0.496mm.
- The von-mises stress acting on the propeller produced from carbon UD/epoxy is 55.585 N/mm2 and is observed that the value is within the allowable stress
- limit . Deformat ion produced for carbon UD/epoxy material is 0.297mm.
- Fatigue analysis is conducted on the propeller model and the results shows that carbon UD/epoxy material is having good fatigue life with a value of 1×10^7 cycles with 0.7 safety factor.
- Finally it is concluded that carbon UD/epoxy material can give a better performance with respect to static analysis and the same material is showing a very high fatigue life.

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