Design and Analysis of an Impeller of A Centrifugal Pump

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Abstract- *The impeller of a centrifugal pump is an essential part in converting input drive into kinematic energy. It is a complex structure and additionally experimentation strategy is cost expending to try with.CFD examination is an answer for this issue. At first the impeller model is geometrically built and modified on the basis of specific execution parameters and the flow and pressure analysis is carried out. As the material utilized as a part of planning any item extraordinarily influences the different configuration parameters like weight, machinability , quality and so on. In this work four distinct materials were picked they are aluminum alloy, carbon fiber, S2-glass, R-glass. The basic emphasis has been put to analyze the structural analysis and modal analysis of the impeller for these materials and to look at the consequences of the carbon fiber reinforced polymers(Carbon fiber, S2-glass, R-glass),with Aluminum alloy. The impeller model is created utilizing CATIA and the examination is finished by importing this model into ANSYS 16.0 workbench.*

Keywords- Impeller design, Aluminum alloy, FRPs', Fatigue analysis, Modal analysis.

I. INTRODUCTION

The centrifugal pump is an extremely simple machine. It is an individual from a family of rotary machines and comprises of two fundamental parts:1)The rotational component or impeller and 2) The stationary component or casing(volute). The function of the radial pump is as basic as its configuration. It is filled with fluid and the impeller is rotated. Rotation imparts energy to the liquid causing it to exit at a greater velocity than it possessed when it entered. This outward flow reduces the pressure at the impeller eye, allowing more liquid to enter .The liquid that exits the Impeller is collected in the casing (volute) where its velocity is converted to pressure before it leaves the pump's discharge. Since the impeller is a dynamic part of the pump adding vitality to the liquid, its geometry plays a major part in the centrifugal pump execution. Modern design practices demand a detailed understanding of the internal flow for design and off-design operating conditions. Today's computer competency and in addition the advancement of numerical strategies' exactness brought turbo-apparatus Computational Fluid Dynamics (CFD) techniques from pure research work into the competitive mechanical pump market. Keeping in mind the end goal to further expand the execution of the impeller the materials which it is made of can be changed taking into account the working condition. Although the larger part of applications carbon fibers are utilized to give necessary without addition of weight.

II. LITERATURE SURVEY

Amit H. Bhuptani, Ravi K.Patel, K.M.Bhuptani generated the model of a closed impeller, using empirical equations and analysis of the existing impeller, along with four modified impeller by changing its vane angle by 2°.The maximum efficiency of the existing impeller by selecting the optimum vane angles combination is obtained and concluded an more efficient outlet vane angle then the existing.

Mohan Kumar M, Hudson E Daniel Raj, M.Varatharaj in their work constructed an impeller and numerical investigation is done based on the effect of design parameters which include blade number, inlet blade angle, trimmed impeller profile and the impeller diameters h using CFD and validated the role of key impeller parameters in improving the performance of the centrifugal pump.

Santosh Shukla, Apurva Kumar Roy, **Kaushik Kumar** proposed that, the material used in designing any object greatly effects the various design parameters. A 3D model is developed using CATIA and with four different materials (Cu alloy, Stainless Steel, Bronze, Titanium alloy) analysis was done. It was observed that titanium alloy can be considered as the constructional material for the blades as it gives minimum deformation.

Manish Dadhich, Dharmendra Haryani, Tarun Singh carried out CFD analysis of a centrifugal pump using K-Ɛ turbulent modeling and SIMPLEC algorithm. In their work the mass flow rate and the speed of the impeller are varied at a rate of increase of 10% and decrease of 10% and the flow analysis and pressure analysis is carried out in the case of water and fuel oil. Then, fatigue analysis is done. Their work concluded that there was only a slight variation at different conditions in the case of oil and water. When efficiency is found that in the case of fuel oil the efficiency is decreased. In fatigue analysis for both cases the factor safety was acceptable and the pump is safe to run on the operating conditions.

Sanjay Sharma, Sheetal Kumar Jain, Vikas Sharma, Dhirendra Agarwal, Manish Dadhich carried out fatigue and modal analysis on a high-speed rotating impeller as they are important in the design and further development to prevent pre-mature failures. The finite element analysis is done for a high tuned design and analyzed using ANSYS. In modal analysis the first ten natural frequencies were compared to the frequency. The conclusions drawn are like In the fatigue analyses fatigue safety factor were plotted and it is observed that fan will not run safely for its designed life i.e. 106 cycles on the operating conditions. In the FEA analysis it is observed that the maximum deformation takes place at the edges. In the modal analysis it is observed operating speed frequency due to number of RPM doesn’t match with the natural frequency of the fan at every mode.

III. DESIGN OF IMPELLER

Firstly, using the empirical relations the values of all the design parameters are found out. Then the values required for the design of impeller are considered

Parameters	Value
Inlet Diameter (D_i)	109.26mm
Outlet Diameter(D_o)	254.20mm
Inlet Angle (β_1)	13.98°
Outlet Angle (β_2)	28°
Blade Number (Z)	8

Now, with reference to the tangent circulaarc method proposed by **Gundale V.R, Joshi G.R** the required values are calculated and the vane profile is generated. From which the impeller model is designed using CATIA VR5.

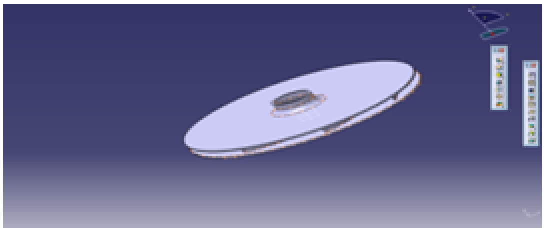


Fig.1.Impeller model in CATIA V5

IV. CHANGE OF PARAMETERS

The most effecting design parameters of the impeller are now modified and the impellers are reconstructed according to these values. The changes made to the impellers models are as follows:

- The inlet angle is changed from 8°-15°.
- The outlet angle is modified to 25°-30°.
- The number of blades are changed from 4-15.

On considering the changes and by keeping all the other parameters constant the impeller models are generated. For each impeller model generated a change in the curvature of the vane profile is observed.

V. SIMULATION OF FLOW

The CFD approach was carried out to analyze the behavior of flow field in the ANSYS-FLUENT 16.0 software. The models generated in CATIA V5 are imported into the FLUENT software. FLUENT is a powerful CFD tool that enables to quickly simulate fluid flow for the success of designs. It solves the Reynolds Average Navier-stokes equations using K-Ɛ turbulence model.

1. Governing equations

The steady, conservative forms of Navier-Stokes equations in two dimensional forms for the incompressible flow of a constant viscosity fluid are as follows:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y} = 0$$

X-momentum

$$\frac{\partial (UV)}{\partial X} + \frac{\partial (VV)}{\partial Y} = -\frac{\partial P_n}{\partial X} + \frac{1}{R_e}(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2})$$

Y-momentum

$$\frac{\partial (UV)}{\partial X} + \frac{\partial (VV)}{\partial Y} = -= -\frac{\partial P_n}{\partial X} + \frac{1}{R_e}(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2})$$

Where, $X=\frac{X}{D}, Y = \frac{y}{D}, P_n = \frac{p}{\rho U_{\infty^2}}, V = \frac{v}{u_\infty}, R_e \frac{\rho U_\infty}{\mu} D$

2. Transport Equation for the standard K-Ɛ model.

The least complex and most generally utilized two-condition turbulence model is the standard k-ε model that comprehends two separate transport conditions to permit the turbulent kinetic energy and its dissipation rate to be independently determined. The transport equations for k and ε in the standard k-ε model are:

$$\rho.\frac{DK}{Dt} = \frac{\partial}{\partial x_i}[(\mu+\frac{\mu_t}{\partial_k})\frac{\partial_k}{\partial x_i}]+G_k+G_b-\rho\varepsilon - Y_M$$

$$\rho\frac{D_\varepsilon}{D_t} = \frac{\partial}{\partial_{x_i}}\left[\left(\mu + \frac{\mu_t}{\partial_s}\right)\frac{\partial s}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Where, $\mu_t=\rho C_\mu \frac{k^2}{\varepsilon}$

In these equations,G_k represents the generation of turbulent kinetic energy due to the main velocity gradients.G_b is the generation of the turbulence kinetic energy due to buoyancy. ∑k and σ€ are the turbulent Prandtl numbers for k and Ɛ, respectively.

All the values including turbulent kinetic energy k, its dissipation rate Ɛ are shared by the fluid and the volume fraction of each fluid in each computational volume is tracked throughout the domain.

3. Boundary condition

Centrifugal pump domain is considered as rotating frame of reference with a rotational speed of 500 rpm. The working fluid through the pump is water. K-Ɛ turbulence model with turbulence intensity 5% is considered. Inlet static pressure and outlet mass flow rate of 2 kg/s are given as boundary conditions.

4. Flow along the vanes

The flow of fluid along the vane of the impellers is firstly analyzed for the pressure and velocity distributions and the co-efficients' of lift (C_l) and drag (C_d) are found out for each impeller whose parameters are varied, which results in variation in the curvature from impeller to impeller. On calculating the efficiency of the vane profile using the relation, $\frac{C_l}{C_d} = \eta$, and by finding the resultant force from the lift and drag forces from the relations

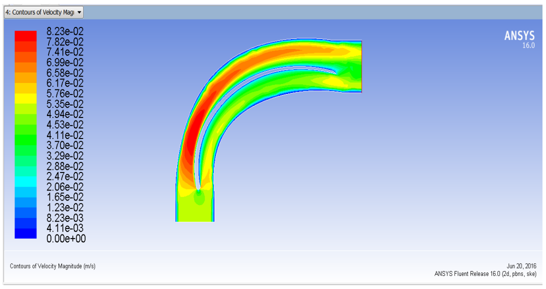
Drag Force: $F_D = \frac{1}{2}\rho_w C_d V^2 dx$

Lift Force: $F_L = \frac{1}{2}\rho_w C_l V^2 dx$

Resultant Force $R=(F_D^2+F_L^2)^{1/2}$

From resultant forces for each impeller and the efficency we find the best suited varied parameters of the impellers profiles. This results in the best suited vales of the parameters are Inlet Angle=12°, Outlet Angle=26°.

The pressure and velocity contours of the along the vane profile are as shown:



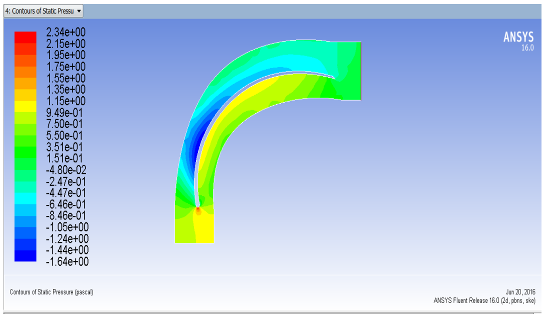


Fig.2.Static pressure along the vane

Fig.3.Velocity along the vane

Considering 12° and 26°, to be the optimum parametric values of the inlet and outlet angles of the impeller, the pressure analysis is carried out to find the optimum number of blades of the suitable for the impeller. Now, by varying the inlet, outlet angles and the number of blades three more impellers are generated. The blades numbers considered are 4, 10, 15 respectively. These impellers are analyzed for static pressure and velocity distributions but resulting in no improvement in the pressure generated by them when compared to the impeller with parameters inlet angle12°,Outlet angle:26°,Number of blades:8.

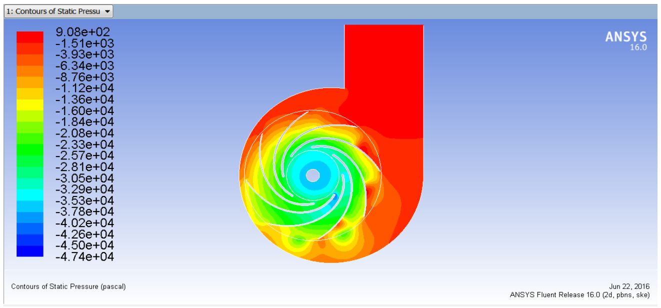
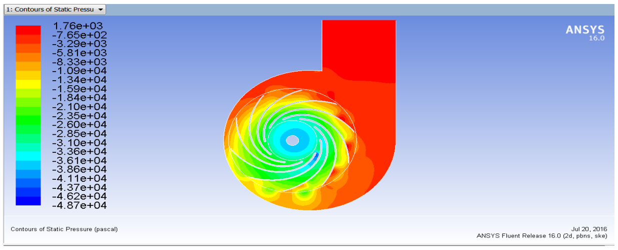
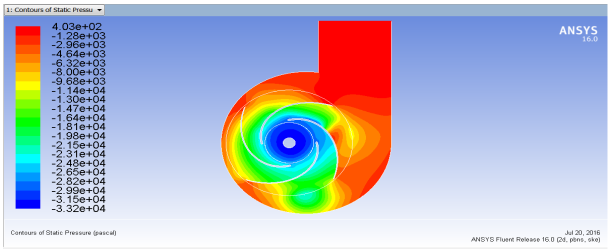


Fig.4.Pressure analysis along the impeller with 8 blades





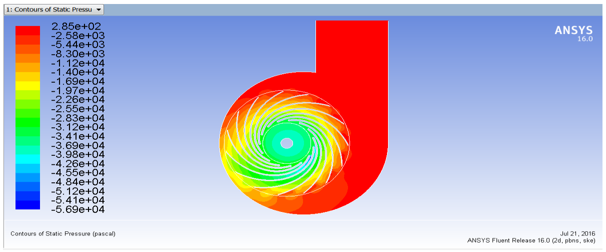


Fig.5.Impeller with 10 blades
Fig.6.Impeller with 4 blades
Fig.7.Impeller with 15 blades

This is because, increase in blade number results in overfilling of the impeller and lower number of blades results in

Therefore, only optimum number of blades should to be chosen for effective performance of the impeller.

Now, as the most effective model of the impeller is generated with the optimum parameters the various material properties are assigned to this model.

VI. TYPE OF MATERIAL OF THE IMPELLER

The choice of pump material primarily depends upon the application, and the selection is very important to achieve long pump lifetime. The material in the impeller is the most important factor because the impeller is heavily affected by wear and erosion-corrosion due to its high velocity relative to the liquid. The most promising material is the fiber reinforced polymer composite. For example, in **Fiber reinforced polymers-**Carbon fiber reinforced polymer (CFRP) are distinguished from other structural plastics by their combination of low density, high modulus of elasticity, high fatigue strength, thermal stability, low friction coefficient, and high wear resistance. When comparing FRP composites to Aluminum, one of the lightest metals used, a standard assumption is that an aluminum structure of equal strength, would likely weigh 1.5 times that of the carbon fiber structure. So, in this work further studies are done by comparing the structural, fatigue and modal analysis of impeller made of Aluminum Alloy and three types of FRP materials. They are:

- Carbon UD/Fiber: The fiber consists of sp2 hybridized carbon atoms arranged two-dimensionally in a honeycomb structure in a plane. These fibers are placed in the form of lamina Uni-Directionally.

- Fiberglass
  1. S2-Glass: Magnesium alumino silicate glasses.
     Composition:$64\text{-}66\%\ SiO_2,\ 24\text{-}25\%\ Al_2O_3,\ 0\text{-}0.2\%\ CaO, 9.5\text{-}10\%\ MgO, 0\text{-}0.2\%\ Na_2O+K_2O, 0\text{-}0.1\%\ Fe_2O_3$.
  2. R-Glass: Calcium alumino silicate glasses.
     Composition:$55\text{-}60\%\text{-}SiO_2, 23\text{-}28\%\text{-}Al_2O_3, 0\text{-}0.35\% B_2O_3, 8\text{-}15\%\text{-}CaO, 4\text{-}7\%\ MgO, 0\text{-}1\%\ Na_2O+K_2O, 0\text{-}0.1\% Fe_2O_3$.

VII. STRUCTURAL ANALYSIS

Structural analysis is the determination of the effects of loads or pressures on physical structures and their components. Here, the pressure applied on the impeller is imported from the pressure contour of the optimum model. The impeller model meshed is as shown below:

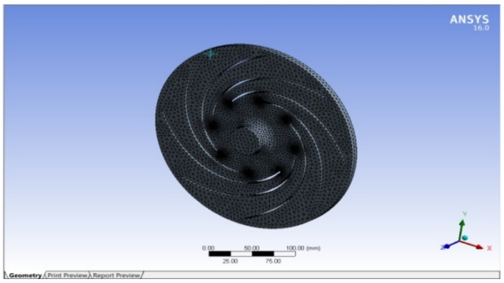


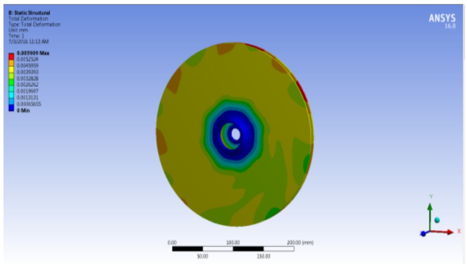
Fig.8.Meshed impeller model

Number of nodes: 36192,
Number of elements: 172918

In the structural analysis we get the contour of Total deformation, Equivalent stress, Factor of Safety. The imported load here is 0.0221269Mpa.

1. Deformation Analysis

1.a. Deformation Analysis and stress analysis plots for Al alloy are as follows:



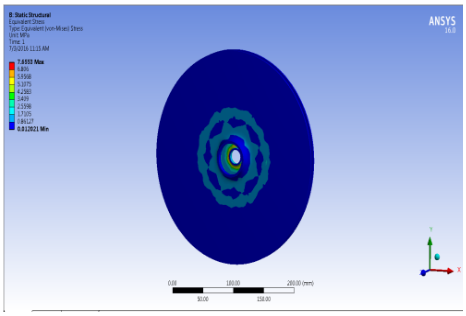


Fig.10.Total deformation of Al Alloy
Fig.11.Equivalent stress of Al Alloy

1.b. Carbon UD/ Fiber

Total deformation and stress of impellers in the case of carbon UD/fiber

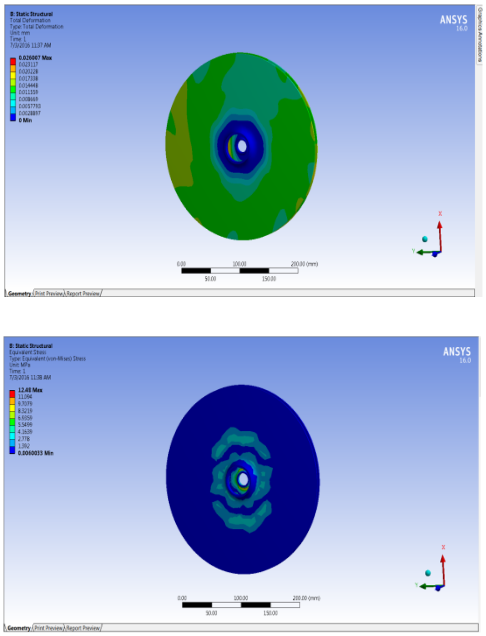
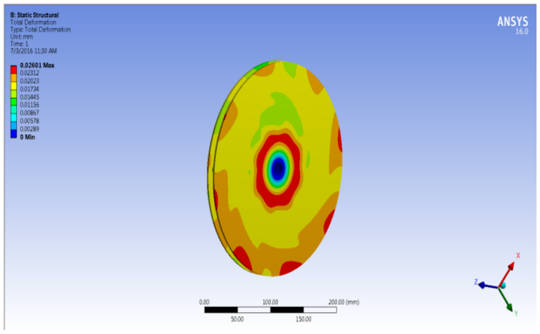


Fig.13.Deformation of Carbon UD/Fiber
Fig.14.Equivalent stress of Carbon UD/Fiber

1.c. S2 Glass

Total deformation and stress in the case of S2-Glass.



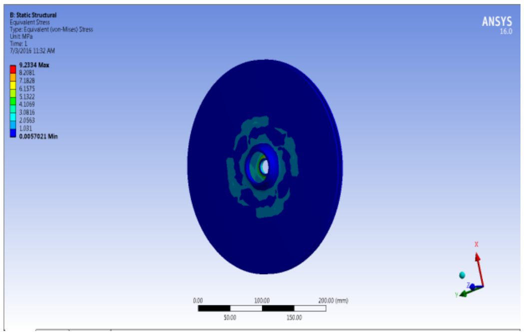


Fig.15.Deformation of S2 glass
Fig.16.Equivalent stress of S2 glass

1.d. R-Glass

Total deformation and equivalent stress plots.

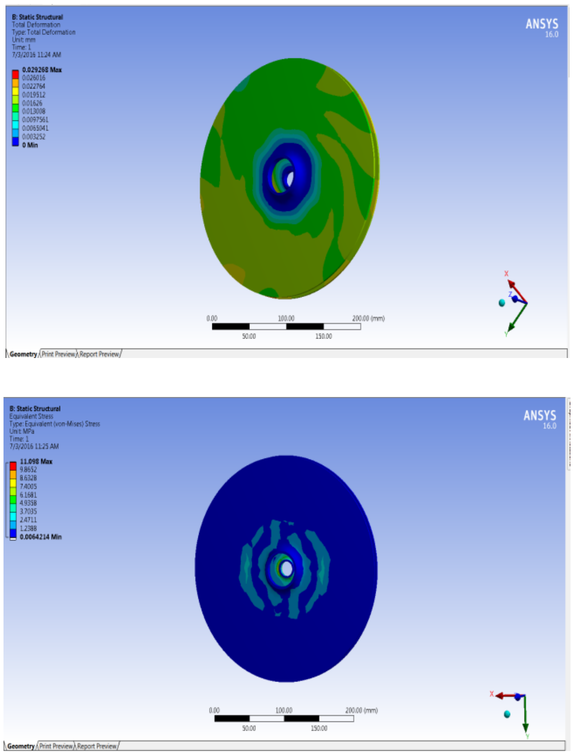


Fig.19.Deformation of R-Glass
Fig.20.Equivalent Stress of R-Glass

The above contours show the deformations of the impellers of different materials at 500 RPM. The variation of deformations is shown in the colored bar and it is seen that the deformation of the Aluminum alloy is minimum of all the materials i.e., 0.006mm,when compared to other materials whose deformations are at a range of 0.02-0.03mm.

2. Fatigue Analysis

In fatigue analysis fatigue factor of safety contours are plotted at a given design life cycle of 10^{12} cycles.

2.a. Aluminum Alloy

The factor of safety for the impeller of Al alloy:

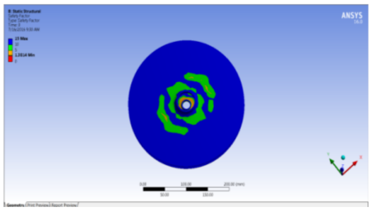


Fig.21.Safety Factor of Al Alloy

2.b. Carbon UD/Fiber

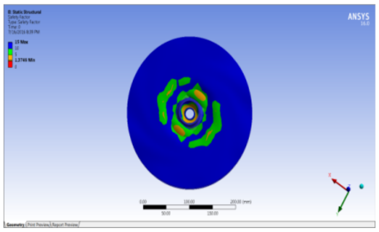


Fig.22.Safety factor of Carbon UD/Fiber

2.c. S2 Glass

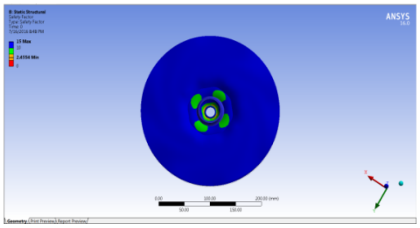


Fig.23.Safety factor of S2 glass

2.d. R- Glass

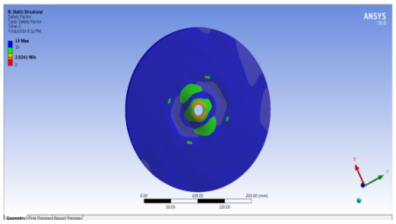


Fig.24.Safety Factor of R-Glass

The above figures' shows the fatigue factor safety contour plots of the four materials at the given design life of 10^{12} cycles. In fatigue factor of safety, values less than the minimum safety factor indicate the failure is reached before the design life.

From the plots it is observed that no material reached its limit, but minimum factor of safety is observed at the eye of the impeller, which may fail first. The factor of safety is more for S2-Glass and minimum for Carbon fiber and Aluminum alloy. The areas with minimum safety factor show the failure before the designed life.

VIII. MODAL ANALYSIS

Modal analysis is utilized to decide the vibration characteristics of a structure or a machine component while it is being designed. The machine might b ore rotating non-rotating. Utilization of modal investigation is to decide the natural frequencies and mode state of the structures and both these factors are critical configuration parameters.

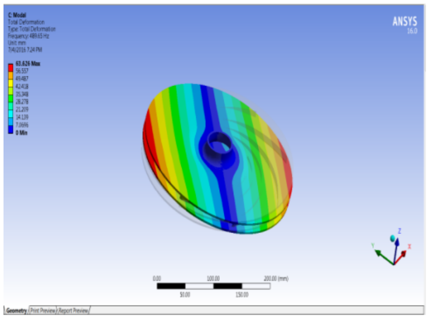
In this analysis it is being checked that impeller operating speed frequency doesn't match with fan natural frequency to avoid resonance phenomena which causes the vibration failure to the impeller and better performance of the impeller in the operating conditions.

Since, the impeller is running at 500RPM, the frequency generated due to this speed is

$$f = \frac{N}{60} = 8.33\text{Hz}$$

Now, using ANSYS- Modal analysis the natural frequencies are being detected for each material at different modes.

a. Aluminum Alloy



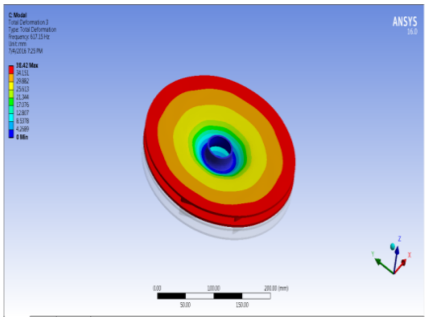
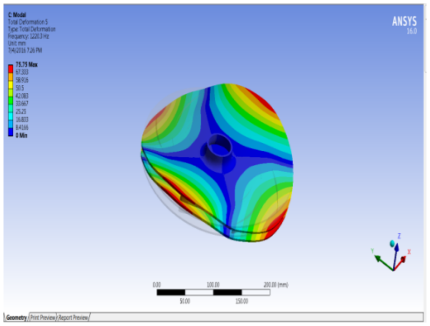


Fig.22 Shape at mode 1

Fig.23.Shape at mode 4



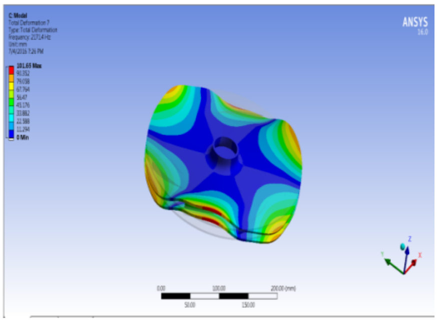
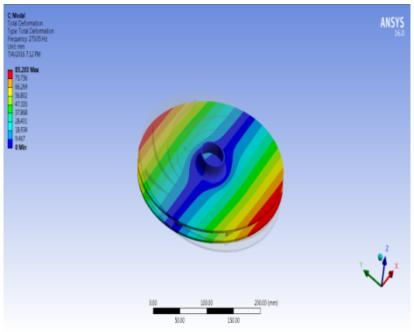


Fig.24 Shape at mode 5
Fig.25.Shape at mode 7

b. Carbon UD/fiber



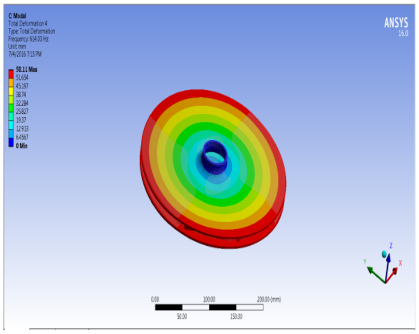
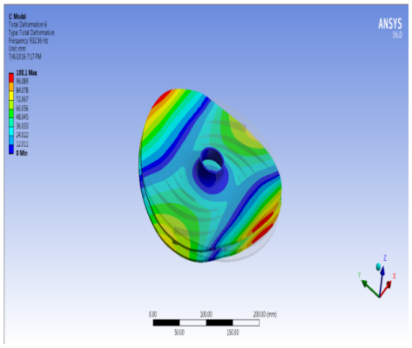


Fig.26.Shape at mode1
Fig.27.Shape at mode 4



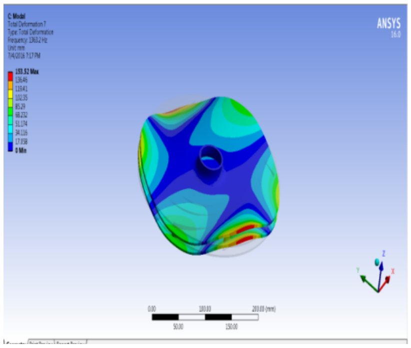
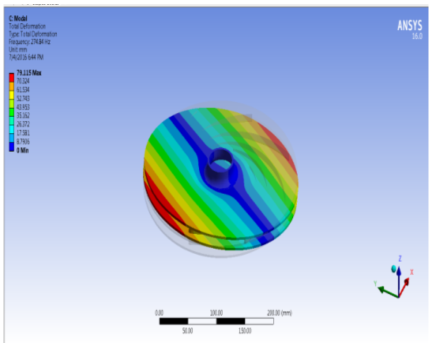


Fig.28.Shape at mode 6
Fig.29.Shape at mode 7

c. S2 Glass



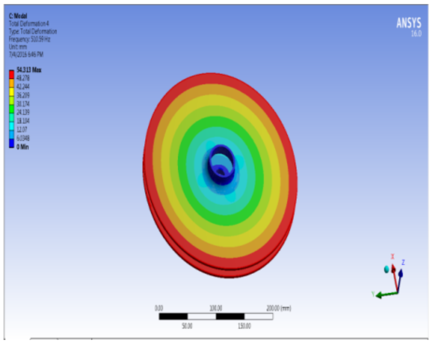
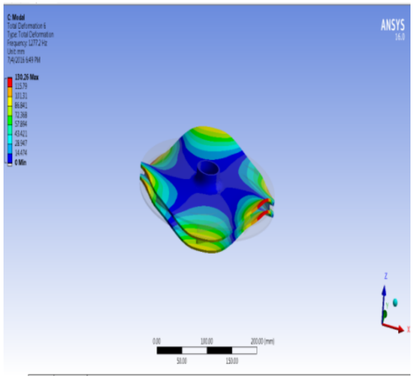


Fig.30.Shape at mode 1
Fig.31.Shape at mode 4



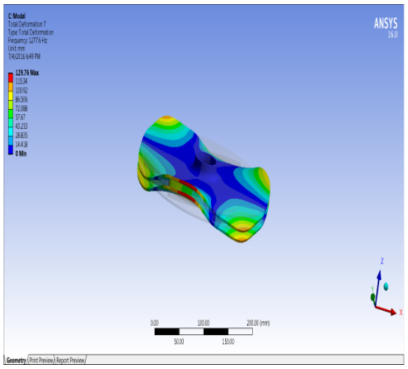
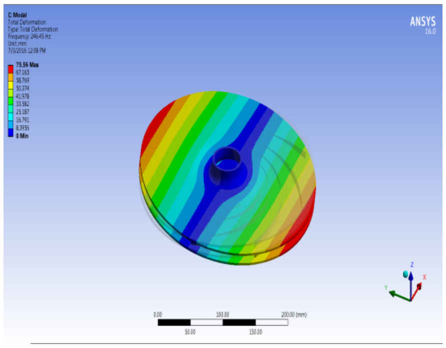


Fig.32.Shae at mode 6
Fg.33.Shape at mode 33

d. R-Glass



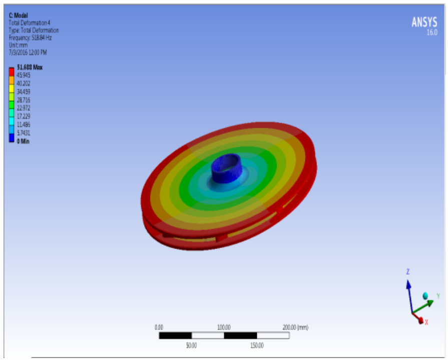
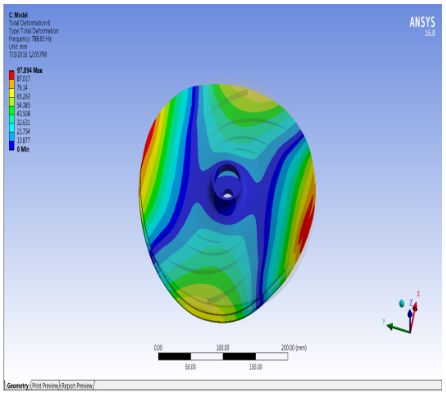


Fig.34.Shape at mode 1
Fig.35.Shape at mode 4



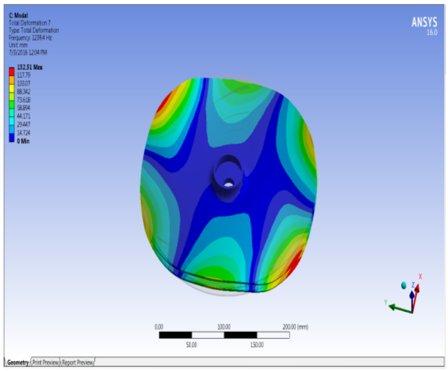
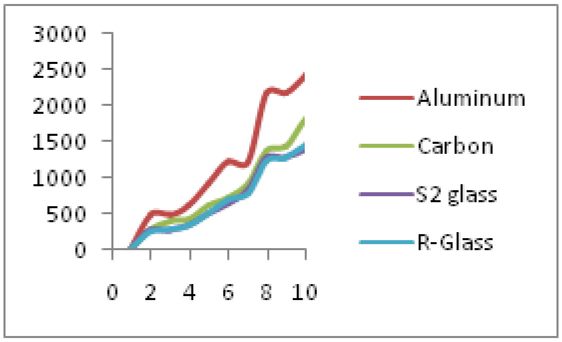


Fig.36.Shape of mode 6
Fig.37.Shape at mode 7

In the diagrammatic perspectives, the 10 common natural frequencies of the four materials are recognized. Four modes are displayed in this paper. Here, it is observed that the mode states of the considerable number of impellers are marginally comparative. As evidenced from the figures the relative displacements for modes (1–4) are low contrasted with higher mode shapes. For higher modes (5–7), the most extreme relocations take places on the outer shroud with a very little displacement at the Flow Hub zone.

Since all the three composites have different mass and stiffness properties they have different modal frequencies. On comparing, the results of the impellers of the materials, the natural frequencies of Al Alloy are maximum and that of Carbon fiber. So, the deformations are found to be minimum for Al alloy and maximum in the case of Carbon Fiber.
The change in natural frequencies at 10 modes for every material due to the operating conditions of the impeller at plotted. The graph is shown for Mode Vs Frequencies.



Change in Modal frequencies

It is clear from the plot that the, modal frequencies of S2-Glass and R-Glass are close to each other at some cases.

XI. RESULTS

In this work, the geometry of the impeller is modeled and the most effective parameters are found out for the impeller and the impeller model with the optimum parameters is generated. The material properties of impeller are changed and the structural analysis, fatigue analysis and modal analysis is carried out for these materials and compared.

- The optimum parameters for the impeller model are found.
- In the fatigue analysis, the total deformation of the Aluminum Alloy is said to be minimum than the Fiber reinforced polymers.
- The safety factor of all the impellers is said to be good and a failure is likely to occur at the impeller eye after some life cycles.
- In modal analysis it is observed that operating speed frequency of the impeller does not match with the natural frequencies of the impellers and the resonance phenomena is almost avoided and the impellers are safe.

Compared to the lightest metal the FRP's offer more effective properties with less weight

- The weight of impeller made of Aluminum alloy is:10.6kg
- The weight of impeller model of Carbon fiber:6.136kg
- The weight of impeller model of S2 glass:6.89kg
- The weight of impeller model of R-glass:7.66kg

Aluminum provides low density and therefore low weight, high strength, excellent corrosion resistance. Compared to aluminum alloy, S2 glass exhibits high strength and stability under extreme temperature and corrosive environments. R-glass also provides corrosion to acids and can be used at those environments. Carbon also exhibits high strength but it is brittle and would shatter which results in failure of the impeller.

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