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Structural Analysis on Impeller of an Axial Flow Compressor using Fem

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Abstract: **The impeller of an axial flow compressor is selected for structural analysis. A light weight novel filament wound axial impeller of a multistage counter rotating axial compressor for compressing water vapor at low cost. This is used to compress the water vapor and it can be used as a refrigerant. The structural capabilities need to be analyzed due to its light weight material.**

The novel axial composite impeller has been developed using commercial tools pro-e. We have chosen the suitable materials for this study, namely Kevlar-49, Carbon and S-Glass with a standard epoxy resin for the composite matrix. Static and dynamic behaviors of the component were analyzed using finite element analysis commercial tool ANSYS 14.5.

We analyzed the stress distributions and displacements on the composite impeller in static analysis. The stress concentration regions were identified in this analysis. For transient analysis, we have applied dynamic force at various operating speeds of the impeller and analyzed the deflections and stress concentration regions.

Keywords: Composite axial impeller, Finite element method, Stress concentrations, deflections.

1. INTRODUCTION

The axial flow compressor is used to compress the water vapor is used as refrigerant. This refrigerant doesn't cause global warming due to its non-toxicity and nonflammable. Water vapor is used as a refrigerant and it will have a higher coefficient of performance (COP) thermodynamically. In turbo chiller innovation, water can serve as a refrigerant as well as a heat transfer medium.

The volume flow of water will be very high when we compare with usually used refrigerants and it requires very higher pressure ratios. Due to the high pressure ratios, the tip speed ratios are also higher and it depends on the impeller design. Due to its complexity, the designer should take a challenge to design the impeller to suit the application.

The higher pressure ratios can be achieved by higher rotational speeds and larger diameters of impeller. The larger diameters require larger utilization areas and also the weight of the impeller becomes higher. To alleviate these difficulties, researchers developed a light weight novel axial wound composite impeller. It is necessary to have a static and dynamic analysis on this specially designed impeller and its fatigue life of this impeller. In this present study, we have concentrated on static and dynamic analyses for various mentioned materials.

1.1. *Material selection:* The material properties for novel axial wound impeller of three fibers-epoxy resin composites are tabulated in table 1; these properties are used to analyze the structural stability of the impeller in Finite Element model. The materials with higher specific strengths are used for this analysis. The composite materials used are Kevlar-49, Carbon and S-Glass along with epoxy resin. These composite materials are high corrosion resistance with water vapor. Composite impeller is much lighter and stronger than titanium alloy blade.

Table 1
Material properties of composites

Material property	**Notation**	**Units**	**Kevlar-49/Epoxy**	**Carbon/Epoxy**	**S-glass/Epoxy**
Density	ρ	Kg/mm^3	1.38	1.59	1.95
Young's modulus	E_1	Mpa	76.8×10^3	155×10^3	50×10^3
Young's modulus	E_2, E_3	Mpa	5.5×10^3	12.1×10^3	15.2×10^3
Poisson's ratio	V_{23}	---	0.37	0.458	0.428
Poisson's ratio	V_{12}, V_{13}	---	0.34	0.248	0.254
Shear modulus	G_{12}, G_{13}	Mpa	2.07×10^3	4.4×10^3	7.4×10^3
Shear modulus	G_{23}	Mpa	1.4×10^3	3.2×10^3	3.2×10^3
CTE	X_1	$/^oc$	-4×10^{-6}	-1.8×10^{-8}	6.34×10^{-6}
CTE	X_2, x_3	$/^oc$	5.7×10^{-5}	2.43×10^{-5}	2.33×10^{-5}

2. MODELING

In this study; one of the patterns (8-B), with curved blades is selected to investigate structural stability and compressing capacity of the impeller. The same thickness has been given for outer shroud, flow hub and center hub. The blade angle set at the center hub (leading edge) is set at 25^o and 90^o at outer hub (trailing edge) relative to the radial direction. The specifications of the impeller can be found at Table 2.

Table 2

Impeller specifications in mm:

Impeller radius	240
Impeller width	134
Flow hub radius	133.4
Center hub radius	34
Blade thickness	2.8

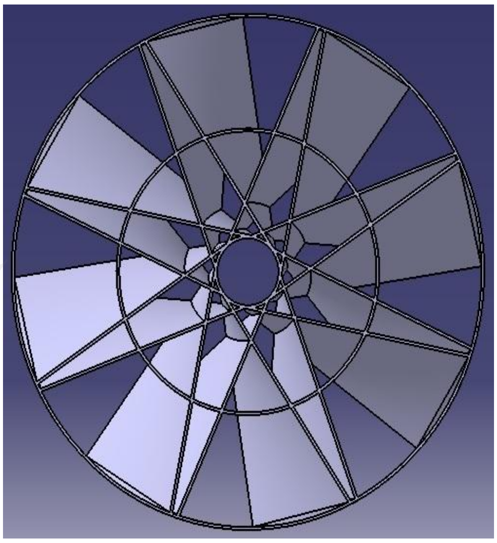


Figure1. 3D impeller

A 3-D model of the impeller is developed in pro-E 5.0 which is exported to FEM software, Ansys 14.5. Then the properties of the composite material are given different in all three perpendicular directions (orthotropic). Since the properties are different all the directions, the model was sectioned into different parts like Outer shroud, Flow Hub, inner central hub and 8×4 blade sections which will have its own co-ordinate system. The outer shroud, flow hub and inner center hub have straight (0˚) fibers. The solid model of impeller is shown in Figure 1; in the impeller the inner center hub is fixed and speed is given in the rotational direction.

2.1. Mesh: A free mesh technique is used to mesh the model which divides the model into number of elements and nodes. A free mesh has an advantage of automatic size of the element and also generates mesh very quickly. Free mesh is chosen for our preliminary analysis. The element type is solid186 is selected for the impeller model. The number of element divisions is given as 10 under size control and smart size is given as 9. The mesh has been generated with 65,283 nodes and 194,848 linear tetrahedral elements. The Numerical model of the meshed geometry is shown in Figure 2.

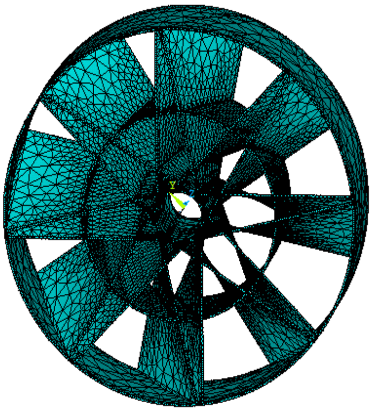


Figure2. Mesh

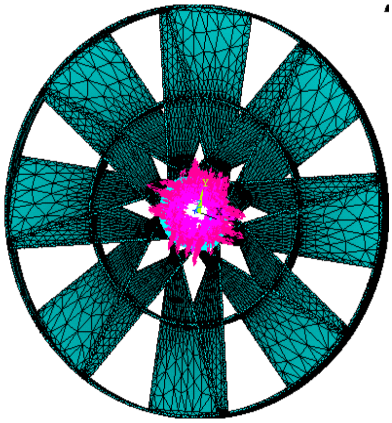


Figure3. Boundary conditions and loading

2.2. Boundary conditions and Loading: The inner center hub is constrained with all nodes and symmetric boundary conditions were selected for this analysis as shown in Figure 3. Rotational speed is given with respect to Z- direction in terms of number of revolutions per minute.

2.3. FEA Solver: The Finite Element Analysis (FEA) is a numerical method for solving problems of manufacturing and mathematical physics. A linear sparse solver is the default solver in ANSYS is used for this analysis. This solver is designed to run on the basis of available memory. It does not require a larger matrix factorization and it runs in memory. Some of the assumptions are considered for the analysis as mentioned below.

- The impeller material is assumed as orthotropic elastic material.
- The angular acceleration effect is neglected.
- The temperature field is 90^0 C as operating temperature of the model.
- No damping for transient analysis.

3. STATIC ANALYSIS

A linear static analysis of the impeller is to calculate the maximum stress and deflection. The following are the assumptions for static analysis;

- Steady state load condition (gravity and rotational velocity).
- Doesn't include an inertial effect (mass and damping).
- Doesn't consider a time varying force on the impeller structure.

The static analysis in Ansys was done in steps. The rotational speed is increased 1000 revolutions per minute (RPM) per step. The maximum rotational speed is 12,000 RPM where the von-misses stress and deflections were found maximum for Kevlar-49/Epoxy and S-Glass/Epoxy. For Carbon/Epoxy, the maximum von-misses stress and deflections occurred at 13,000 RPM. Further increment in rotational speed causes damage of impeller is found. The maximum stress concentration regions were identified in the analysis.

Results: Considering the shroud housing clearance as low as possible of the axial compressor for higher efficiency and higher pressure ratios. Figure 4 Show the both maximum and minimum displacement of nodes on the outer edge of the shroud. S-Glass has maximum deflection than the Kevlar-49 and carbon. Figure 5 Show the normalized value of the maximum and minimum stresses of the impeller of each material with various rotational speeds. Among all composite materials S-Glass/Epoxy is the weakest and Carbon/Epoxy is the strongest with a speed. The impeller with Kevlar-49/Epoxy material the elements exceed failure stress at 12,000 RPM. Carbon/Epoxy impeller starts to failure at 13,000 RPM. And around 12,000 RPM the S-Glass/Epoxy impeller is starts to fail. From these results, it was found that the failure occurred at the junction of blade edge and outer shroud. The failure region is needs to be taken care to avoid structural failures. Figure 6 show the maximum stress zones for three impellers at corresponding rotational speeds. The red zones indicate the maximum von-misses stresses of the impeller for each composite

These results from the static stress analysis can be used to estimate the fatigue life of the composite impellers.

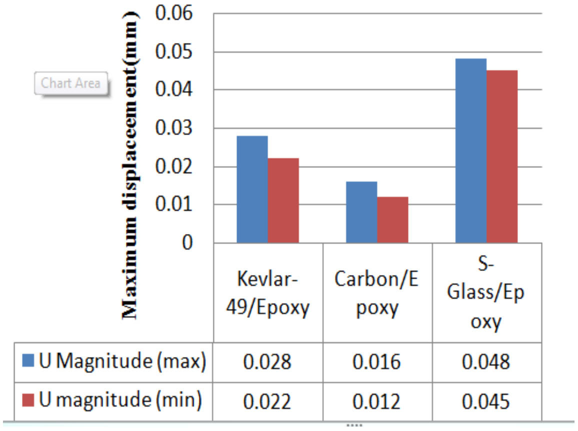


Figure4. Maximum displacements under operating conditions

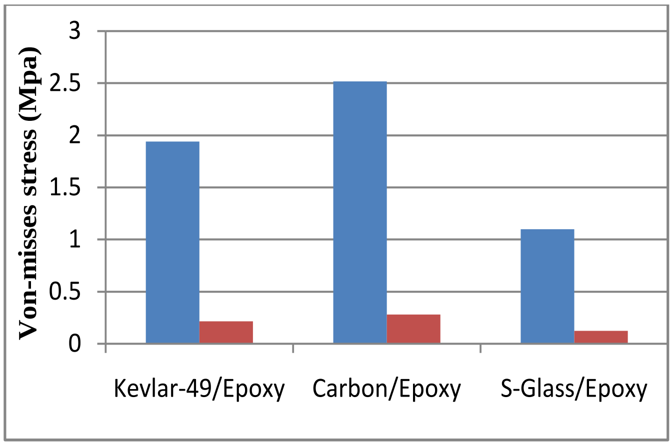
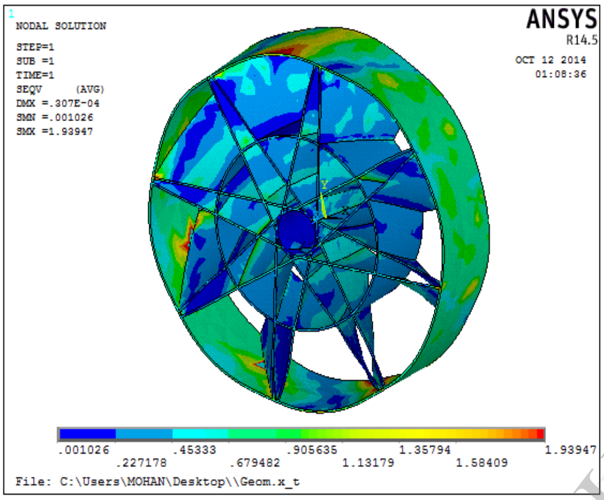
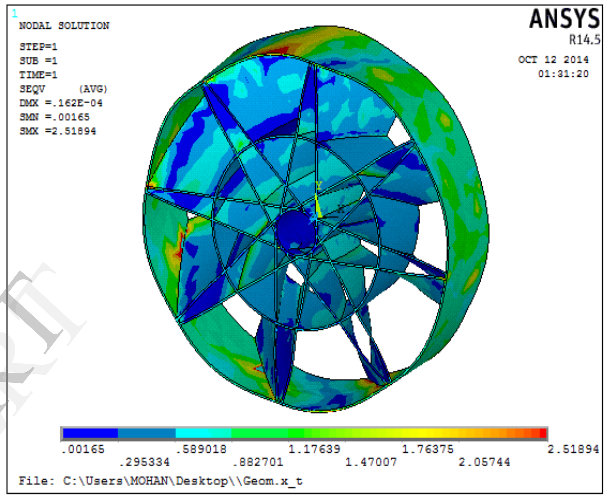


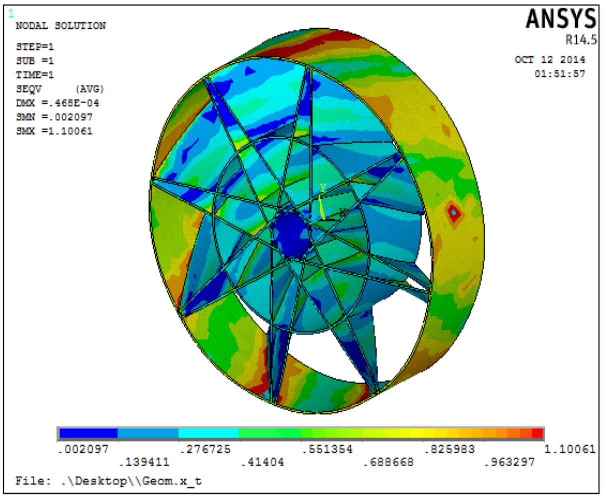
Figure5. Von-misses stress under operating condition



Kevlar-49/Epoxy at 12000 RPM



Carbon/Epoxy at 12000 RPM



S-Glass/Epoxy at 12000 RPM

Figure6. Maximum von misses stress zones of the impeller

4. TRANSIENT ANALYSIS

The transient dynamic analysis is called as the 'Time-History Analysis', this technique is used to find the dynamic response of a structure under the action of any general time dependant loads. Dynamic force is selected to know the stress concentration and deflection of the impeller at different time periods. It must consider the importance of damping effect and inertial load at time-scale loading. Then the inertia and damping effects are not important in this study, and might be able to use a static analysis instead.

There are three methods available to do a transient dynamic analysis which are full, reduced, and mode superposition. We choose the full method, uses the full system matrices to calculate the transient response (no matrix reduction). For transient analysis, we have applied dynamic force at various operating speeds of the impeller and analyzed the deflections and stress concentration regions.

Results: Figure 7 show the maximum displacement of the impeller with a various time periods and varying speeds. Carbon/Epoxy has least deflection than the Kevlar-49/Epoxy and S-Glass/Epoxy. Figure 8 show the normalized value of maximum stresses of the impeller at each material with various speeds and varying time periods. Carbon/Epoxy is the strongest and S-Glass/Epoxy is the weakest with a speed. Kevlar-49/Epoxy has higher stress than that for the Carbon/Epoxy and S-Glass/Epoxy during the time period of 5 seconds to 10 seconds. Carbon/Epoxy has higher stress than that for the Kevlar-49/Epoxy and S-Glass/Epoxy after 10 seconds. Figure 9 show the maximum stress zones for carbon/Epoxy impeller at corresponding rotational speed. It is assumed that the impeller reaches 2,500 RPM in 5 seconds. The Carbon/epoxy impeller started failure at 13,000 RPM. From these results, it was found that the failures occurred at the junction where the blade edge and outer shroud intersects. The red zones indicate the maximum von-misses stresses of the impeller for Carbon/Epoxy material.

On these results base to estimate the fatigue life of this novel wound composite impellers.

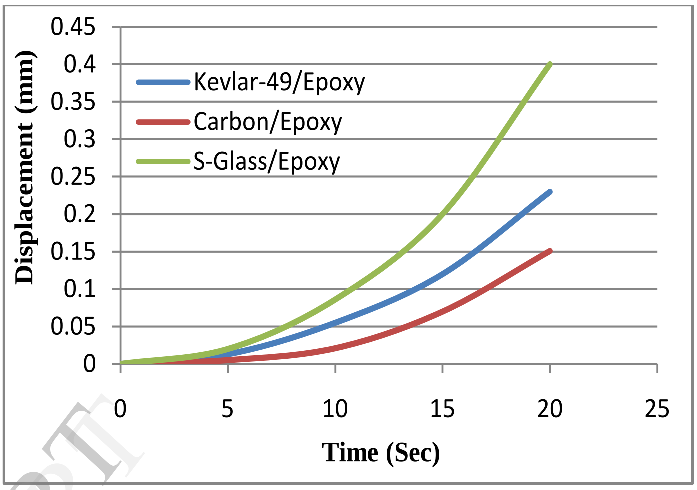


Figure7. Maximum displacements under different time period

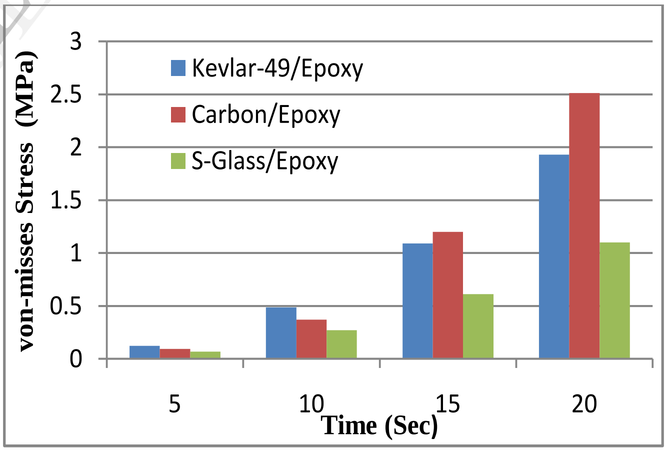
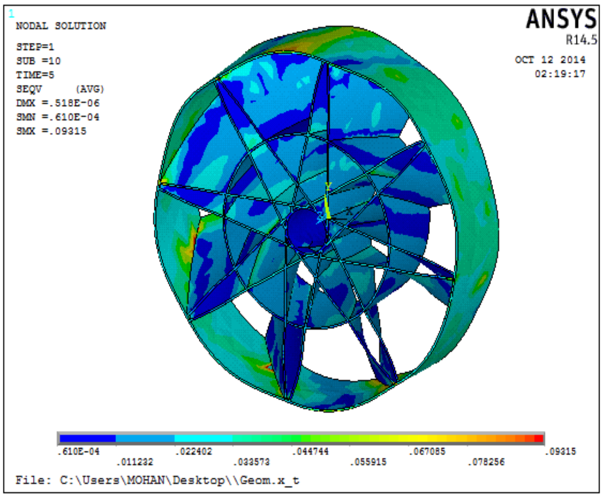
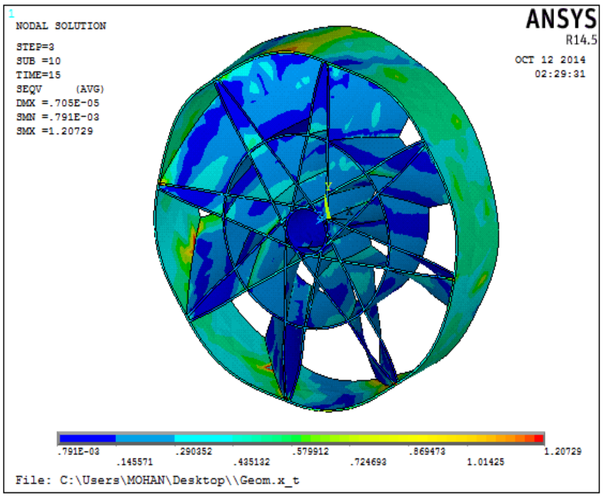


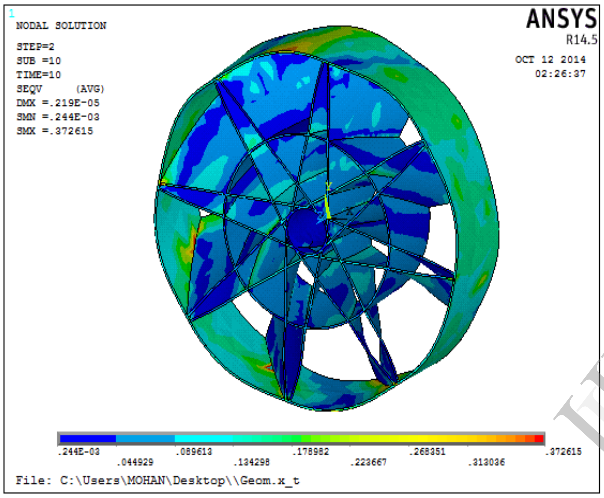
Figure8. Maximum stresses under various time periods



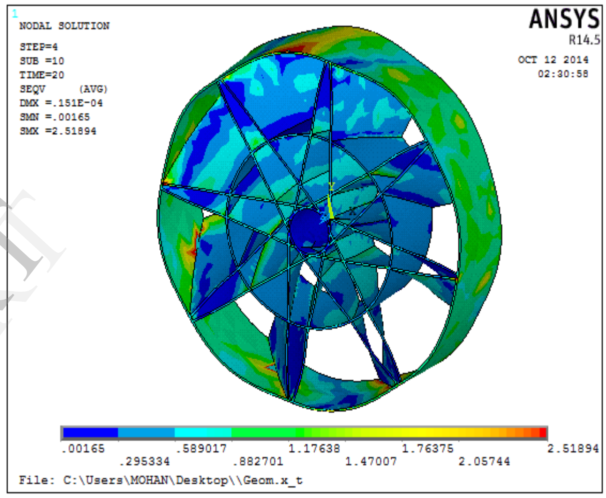
Impeller at 2,500 RPM



Impeller at 9,000 RPM



Impeller at 5,000 RPM



Impeller at 13,000 RPM

Figure9. Maximum von misses stress zones for Carbon/Epoxy

5. CONCLUSION

In this study, we analyzed the impeller for maximum von-misses stresses and deflections for various materials in static analysis and various rotational speeds with various materials in transient analysis. Thus, it is concluded from the results that the impeller structure depends on the stiffness and stresses in the area where the intersections of various parts. Also it was found that the maximum stresses are occurred at the outer edges of the impeller even for smaller rotational speeds for all the chosen materials of impeller. By observing the three composite impellers from the static and transient analysis, the Carbon/Epoxy is more efficient than Kevlar-49/Epoxy and S-Glass/Epoxy. These results may be useful for estimating the fatigue life of the impeller for various materials.

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