ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Random Vibrational Analysis of High Speed Centrifugal Compressor

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Abstract

An air compressor is a device that converts power (usually from an electric motor, a diesel engine or a gasoline engine) into potential energy by forcing air into a smaller volume and thus increasing its pressure. The energy in the compressed air can be stored while the air remains pressurized. The energy can be used for a variety of applications, usually by utilizing the kinetic energy of the air as it is depressurized. The centrifugal air compressor is a dynamic compressor which depends on transfer of energy from a rotating impeller to the air.

In this thesis, practical analysis and analytical analysis using FEA software ANSYS will be used for vibrational characteristics. A centrifugal air compressor will be modelled in 3D modelling software CATIA. The most used material for compressor blades is Aluminum alloy. In this project comparison is made for Aluminum Alloy Impeller natural frequencies through practical analysis and analytical analysis. Modal analysis and random vibrational analysis will be done on the compressor to verify the strength using the three materials.

Analysis will be done in ANSYS.

Keywords: ***Random vibrational Analysis, Vibrational Analysis, Natural Frequencies, Centrifugal Compressor, Impeller***

INTRODUCTION

For the centrifugal compressor design, it is an important point to prevent failure for long term operation. From the viewpoint of impeller failure, static and dynamic stresses should be taken into consideration for proper impeller design. Prediction of static stress is relatively easy compared to dynamic stress because of two factors:

- The unsteady external excitation force and vibration response are complicated, making it difficult to calculate these characteristics precisely, and
- It is likewise difficult to confirm the simulation results of vibration response since the actual measurement of vibrational stress on the rotating blades presents its own set of challenges.

Because it is difficult to predict dynamic stress when designing a compressor, the criteria for preventing fatigue failure of impeller tend to be very conservative. For the past decade, as chemical and liquefied natural gas (LNG) plant capacity has increased, so the size requirements for the compressor increased. As a consequence, it is necessary to achieve a lower natural frequency for impeller in order to prevent impeller resonance. The most important point is to accuratelypredict dynamic stress on impeller and then apply reasonable design criteria. This is the motivation of this study and suggestions on how to solve this question, based on analytical will be presented in this thesis.

The goal of this study is to predict the frequency and level of dynamic stress for impeller as accurately as possible. Impeller dynamic stress is caused by pressure and velocity distribution in the rotating direction. It is mainly caused by wake of the inlet guide vane, which is installed in front of the impeller. During rotation, the number of wakes times rotating speed is the frequency

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induced on the impeller. And when the frequency and the impeller's natural frequency resonate, large dynamic stress fluctuations can occur.

Impeller

Critical speed of the compressor

Y= deflection in mm

W= force on impeller = 10575.276 N

L= length of shaft from centre of bearing to the centre of the Impeller = 25 mm

E= young's modulus of shaft material = 210000 N/mm^2

I= moment of inertia of shaft

d= Diameter of the shaft

Nc= critical speed of the Impeller

Critical speed of centrifugal compressor, Nc= $\frac{946}{\sqrt{Y}}$ rpm

$$Y = \frac{WL^3}{3EI} \text{ mm}$$

$$I = \frac{\pi}{64} d^4$$

$$\Rightarrow \quad Y = \frac{64WL^3}{3Ed^4}$$

$$\Rightarrow \quad Y = \frac{64x10575.276x25^3}{3x210000x14^4} = 0.4369 \text{ mm}$$

$$Nc = \frac{946}{\sqrt{Y}} = \frac{946}{\sqrt{0.4369}} = 1432.675 \text{ mm}$$

Experimental analysis by using FFT Analyzer

CoCo FFT signal analyzer

Experimental setup for FFT analysis

The figure shows the experimental setup for FFT analysis. The Impeller is fixed to the bench vice using a metal rod which is fixed to the Impeller and the bench vice. The piezo electric sensor kept at the top of the Impeller to characterise the vibrational levels. The piezo electric sensor is connected to the CoCo hardware setup. The CoCo hardware setup consists a hammer which can be used to give energy to the testing specimen that is Impeller.

Experimental setup for vibrational analysis

The figure shows the experimental setup for vibrational analysis. The Impeller kept on a base on a machine which gives energy randomly to the Impeller. The piezo electric sensor kept on the Impeller to characterize the vibrational levels.

Natural Frequency Test

Natural frequencies of the Impeller is obtained using impact hammer method. Fig. 4-4 shows the photograph of instruments, hardware and software used for Natural Frequency Test (NFT) of the Impeller. The sensitivity of the impact hammer is used for present test is 10.6 mV/g and maximum force can be applied 500 lb impact hammer is attached to the channel 1 of FFT analyser and

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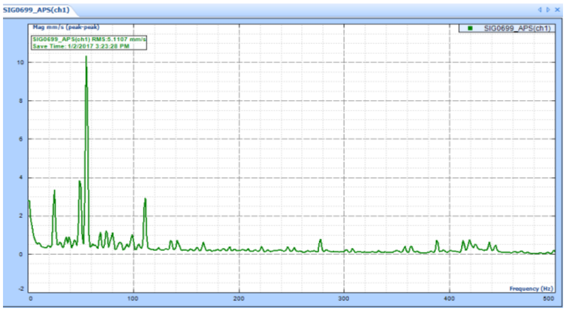
accelerometer is attached to channel 2 of FFT analyser. The sensitivity of the accelerometer is 106 mV/g. The frequency range is selected for present measurements is 0 Hz to 400 Hz. Impact force is applied on the motor generator system and vibration levels are measured using accelerometer and FFT analyser. Total four impacts are considered to average recorded data in the frequency range of 0 Hz to 400 Hz. Coherence spectrum is used identify the natural frequencies in the spectrum. Coherence spectrum shows the ratio of output energy from accelerometer to input energy from impact hammer. All peaks in the spectrum near to coherence values are near to 0.9 are considered as natural frequencies. Fig. 8 shows the frequency spectrum obtained from the NFT test.

Photograph of instruments, hardware and software used for Natural Frequency Test (NFT) on Impeller



Frequency spectrum at top of the Impeller

	Actual frequency(Hz)
Mode1	20
Mode2	27.5
Mode3	32.5
Mode4	38.75
Mode5	46.25

Forced Vibration Measurements

Forced vibrations of Impeller system is measured on it's top, using CoCo FFT four channel analyser (Model 6348)and piezo electric sensor (Model 9300) to characterize the vibrations levels. CoCo is a hardware platform that can run in either DSA (Dynamic Signal Analyser) or VDC (Vibration Data Collector) mode.

Sensitivity of accelerometer (sensor) is 106 mV/g and sensing material is ceramic. The sensor is connected to channel 1 of FFT analyser and place at the top of the Impeller. The frequency range is set to 0 to 400 Hz because operating speed is only 25Hz. All measurements are recorded in analyser after 32 averages in the frequency range of 0 to 400 Hz with the resolution of 0.5 Hz (800 lines are used in entire frequency range). Signal are recorded in the time domain then it is converted to frequency domain by using hanning window. Then this measurement data is exported to Engineering Data Management (EDM) software for post processing. The acceleration (m/sec^2) date is converted to velocity (mm/sec) data by using inbuilt tools available in the (EDM) software.

Frequency spectrum is plotted by considering the velocity (mm/sec) in Y-axis and frequency (Hz) in the X-axis. All the vibrations levels are presented as the average of four readings. Fig. 3 shows the photograph of vibration measurement at the Impeller using FFT analyser and piezo electric sensor.

Vibration measurement at the top of the Impeller using FFT analyzer and piezo electric sensor

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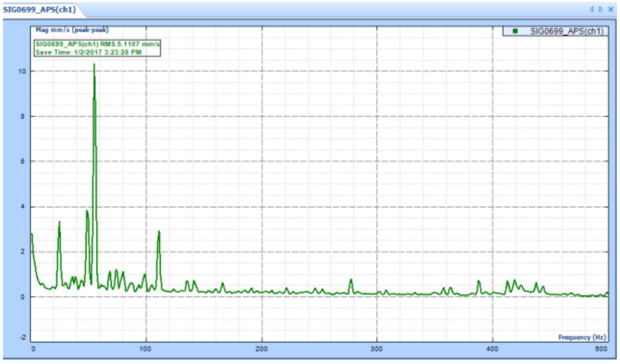
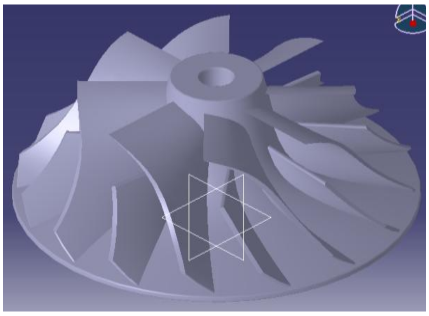


Frequency spectrum of the impeller

Peak velocity: 10.35 mm/sec RMS Value: 5.1 mm/sec

3D modelling of modified alloy wheel



Material properties of Aluminum Alloy

Presently used for impellerare Aluminum Alloy, Magnesium alloy and Monel K500

MaterialProperties

Property	Aluminum Alloy	Magnesium Alloy	Monel K500
Elastic Modulus, N/mm^2	71000	45000	169000
Poisson's Ratio	0.33	0.35	0.295
Shear Modulus, N/mm^2	236692	16667	62551
Mass Density, Kg/m^3	2770	1800	8910
Tensile Strength, N/mm^2	280	193	250
Compressive Yield Strength, N/mm^2	310	193	250

Modal Analysis

A modal analysis determines the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component. It can also serve as a starting point for another, more detailed, dynamic analysis, such as a transient dynamic analysis, a harmonic analysis, or a spectrum analysis. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. You can also perform a modal analysis on a pre-stressed structure, such as a spinning turbine blade.

If there is damping in the structure or machine component, the system becomes a damped modal analysis. For a damped modal system, the natural frequencies and mode shapes become complex.

For a rotating structure or machine component, the gyroscopic effects resulting from rotational velocities are introduced into the modal system. These effects change the system’s damping. The damping can also be changed when a Bearing is present, which is a common support used for rotating structure or machine component. The evolution of the natural frequencies with the rotational velocity can be studied with the aid of Campbell Diagram Chart Results.

Random Vibration Analysis

This analysis enables you to determine the response of structures to vibration loads that are random in nature. An example would be the response of a sensitive electronic component mounted in a car subjected to the vibration from the engine, pavement roughness, and acoustic pressure.

Loads such as the acceleration caused by the pavement roughness are not deterministic, that is, the time history of the load is unique every time the car runs over the same stretch of road. Hence it is not possible to predict precisely the value of the load at a point in its time history. Such load histories, however, can be characterized statistically (mean, root mean square, standard deviation). Also random loads are non-periodic and contain a multitude of frequencies. The frequency content of the time history (spectrum) is captured along with the statistics and used as the load in the random

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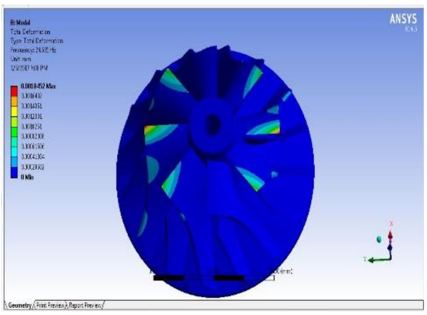
vibration analysis. This spectrum, for historical reasons, is called Power Spectral Density or PSD. In a random vibration analysis since the input excitations are statistical in nature, so are the output responses such as displacements, stresses, and so on.

Analytical results

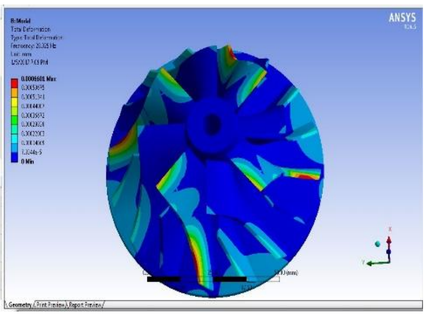
Modal analysis of impeller using Aluminum Alloy

Mode shape 1



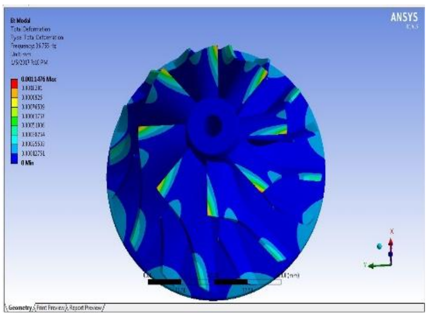
Mode shape 1 of aluminum alloy. At this mode the natural frequency of the impeller is 24.535Hz and deformation is 0.0018452 mm.

Mode shape 2



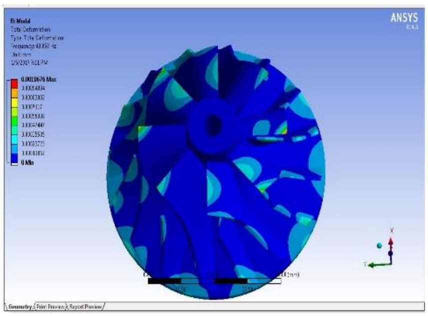
Mode shape 2 of aluminum alloy. At this mode the natural frequency of the impeller is 28.329Hz and deformation is 0.0006601 mm.

Mode shape 3



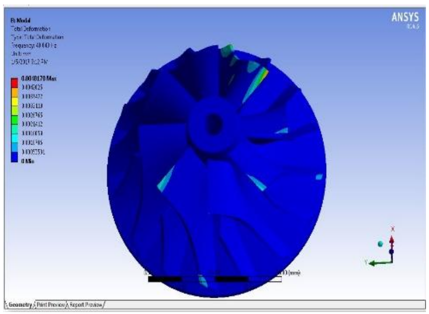
Mode shape 3 of aluminum alloy. At this mode the natural frequency of the impeller is 36.7555Hz and deformation is 0.0011476 mm.

Mode shape 4



Mode shape 4 of aluminum alloy. At this mode the natural frequency of the impeller is 43.058Hz and deformation is 0.0010676 mm.

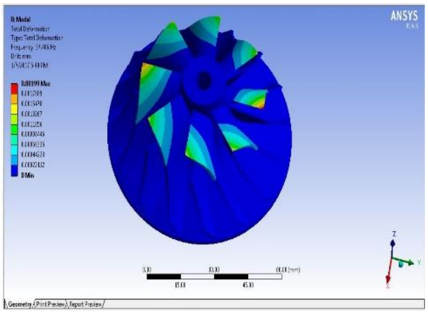
Mode shape 5



Mode shape 5 of aluminum alloy. At this mode the natural frequency of the impeller is 48.043Hz and deformation is 0.0048178 mm.

Modal analysis of impeller using Magnesium Alloy

Mode shape 1



Mode shape 1 of Magnesium Alloy. At this mode the natural frequency of the impeller is 37.486Hz and deformation is 0.00199 mm.

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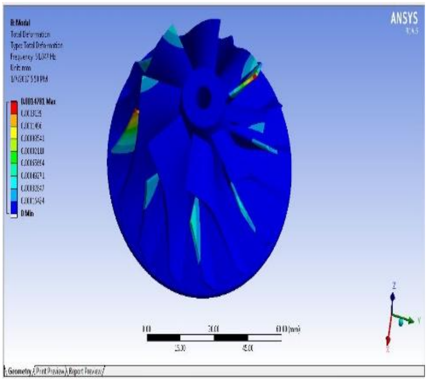
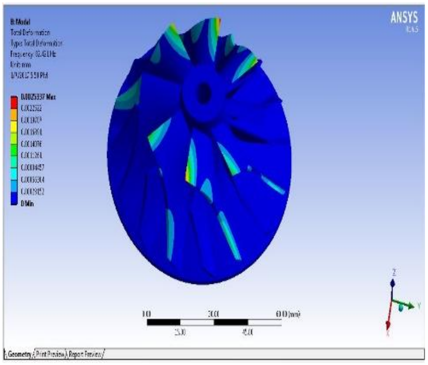
Mode shape 2



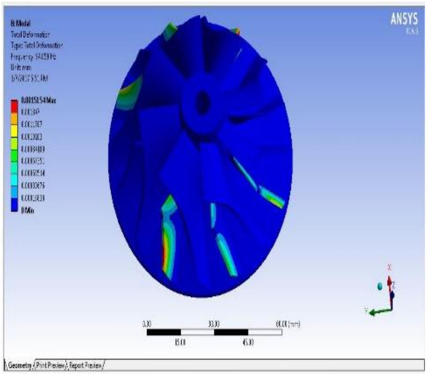
Mode shape 2 of Magnesium Alloy. At this mode the natural frequency of the impeller is 51.047Hz and deformation is 0.0014781 mm.

Mode shape 3



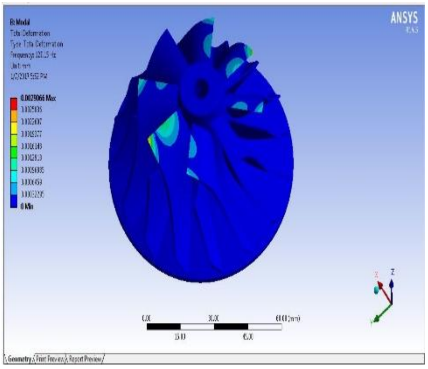
Mode shape 3 of Magnesium Alloy. At this mode the natural frequency of the impeller is 82.42Hz and deformation is 0.002533 mm.

Mode shape 4



Mode shape 4 of Magnesium Alloy. At this mode the natural frequency of the impeller is 94.059Hz and deformation is 0.0015154 mm.

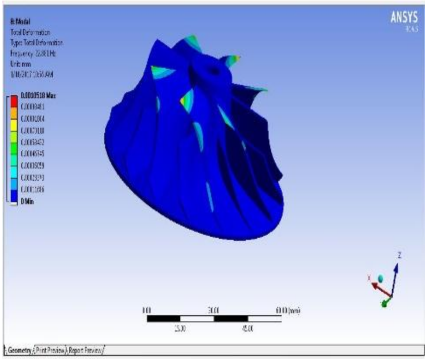
Mode shape 5



Mode shape 5 of Magnesium Alloy. At this mode the natural frequency of the impeller is 127.15Hz and deformation is 0.0029066 mm.

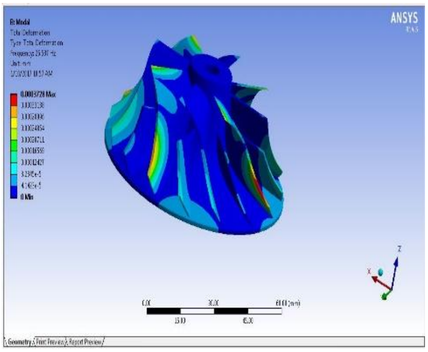
Modal analysis of impeller using Monel K500 Alloy

Mode shape 1



Mode shape 1 of Monel K500. At this mode the natural frequency of the impeller is 22.881Hz and deformation is 0.0010518 mm.

Mode shape 2



Mode shape 2 of Monel K500. At this mode the natural frequency of the impeller is 26.587Hz and deformation is 0.0003728 mm.

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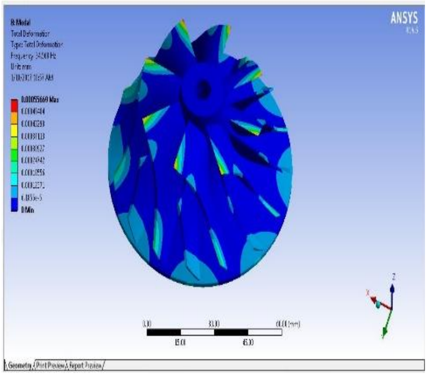
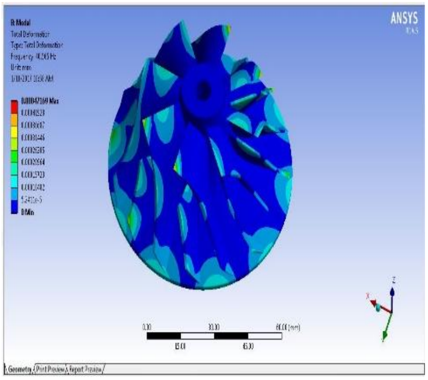
Mode shape 3



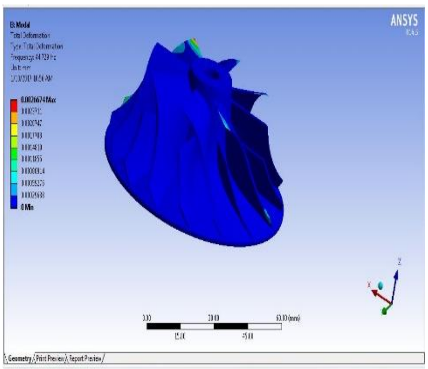
Mode shape 3 of Monel K500. At this mode the natural frequency of the impeller is 34.568Hz and deformation is 0.00055669 mm.

Mode shape 4



Mode shape 4 of Monel K500. At this mode the natural frequency of the impeller is 40.565Hz and deformation is 0.00047169 mm.

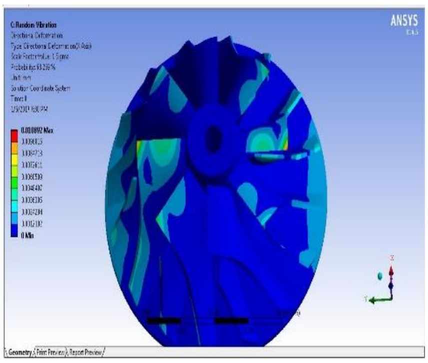
Mode shape 5



Mode shape 5 of Monel K500. At this mode the natural frequency of the impeller is 44.729Hz and deformation is 0.002667 mm.

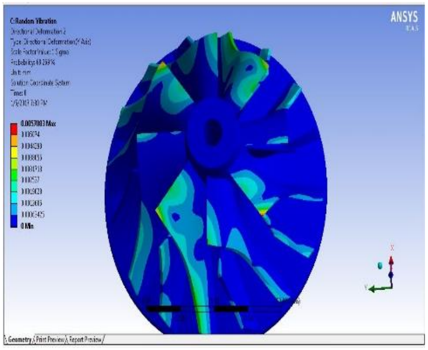
Random vibrational analysis of impeller using Aluminum Alloy

Deformation in X direction



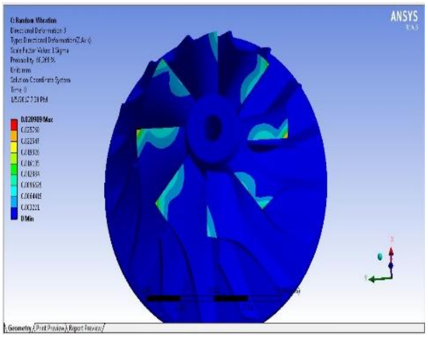
Deformation of the Aluminum Alloy Impeller in X direction in random vibrational analysis. The deformation value is 0.010892.

Deformation in Y direction



Deformation of the Aluminum Alloy Impeller in Y direction in random vibrational analysis. The deformation value is 0.0057083 mm.

Deformation in Z direction



Deformation of the Aluminum Alloy Impeller in Z direction in random vibrational analysis. The deformation value is 0.028989 mm.

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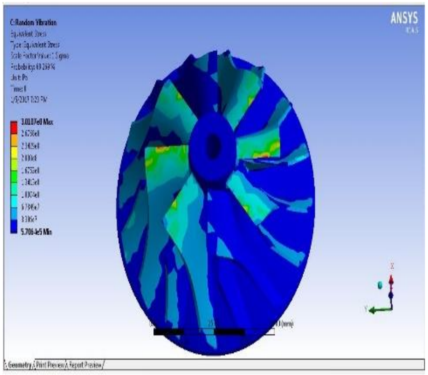
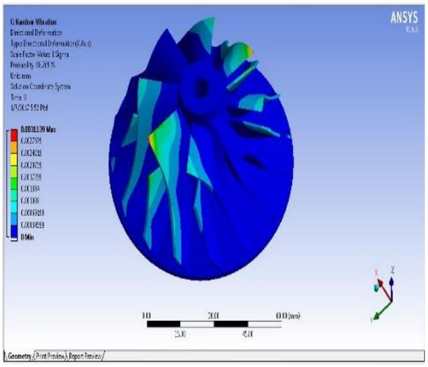
Von- misses stress



Stress induced in Aluminum Alloy Impeller in random vibrational analysis. The stress induced is 301.07 MPa

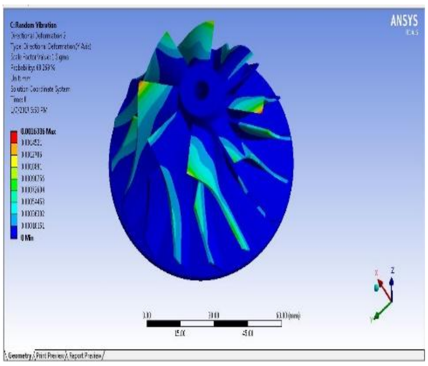
Random vibrational analysis of Impeller using Magnesium Alloy

Deformation in X direction



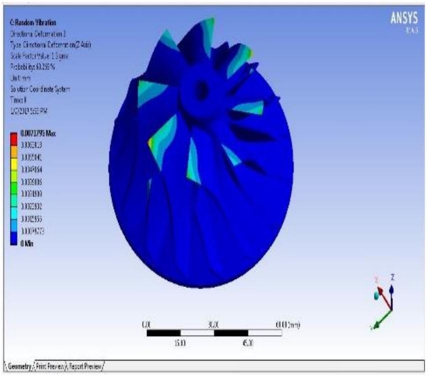
Deformation of the Magnesium Alloy Impeller in X direction in random vibrational analysis. The deformation value is 0.0031139 mm.

Deformation in Y direction



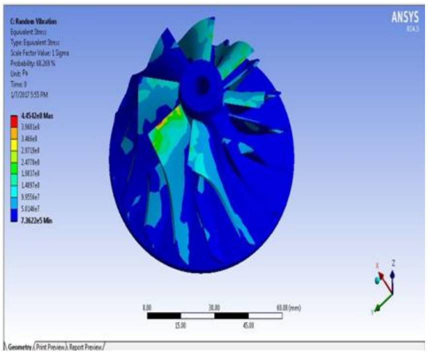
Deformation of the Magnesium Alloy Impeller in Y direction in random vibrational analysis. The deformation value is 0.006336 mm.

Deformation in Z direction



Deformation of the Magnesium Alloy Impeller in Z direction in random vibrational analysis. The deformation value is 0.0071795 mm.

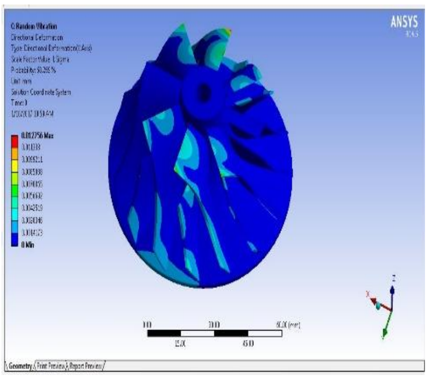
Von- misses stress



Stress induced in Magnesium Alloy Impeller in random vibrational analysis. The stress induced is 445.42 MPa

Random vibrational analysis of impeller using Monel K500 Alloy

Deformation in X direction



Deformation of the Monel K500 Impeller in X direction in random vibrational analysis. The deformation value is 0.0012756 mm.

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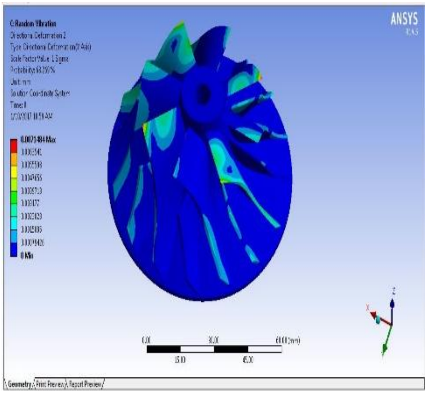
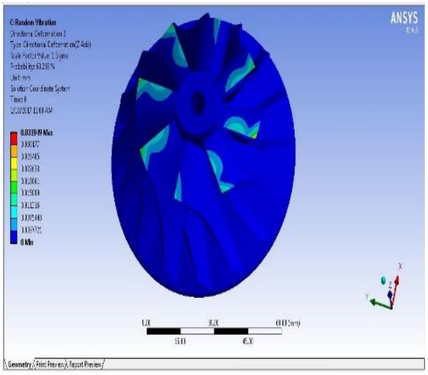
Deformation in Y direction



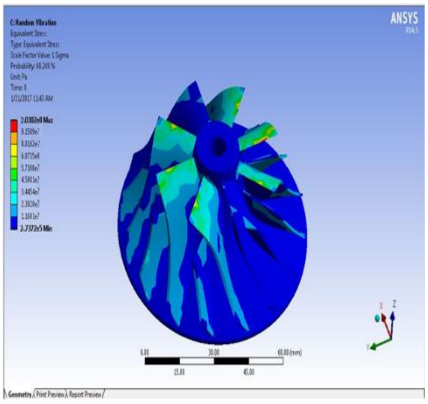
Deformation of the Monel K500 Impeller in Y direction in random vibrational analysis. The deformation value is 0.007148 mm.

Deformation in Z direction



Deformation of the Monel K500 Impeller in Z direction in random vibrational analysis. The deformation value is 0.033949 mm.

Von- misses stress



Stress induced in Monel K500 Impeller in random vibrational analysis. The stress induced is 203.02 MPa

RESULTS AND DISCUSSIONS

Modal analysis results actual versus analytical frequencies

	Aluminum Alloy	
	Actual frequency(Hz)	Analytical frequency(Hz)
Mode1	20	24.535
Mode2	27.5	28.329
Mode3	32.5	36.755
Mode4	38.75	43.058
Mode5	46.25	48.043

Modal analysis results

Mode	Aluminum Alloy		Magnesium Alloy		Monel K500	
	Frequency (Hz)	Deformation mm	Frequency (Hz)	Deformation mm	Frequency (Hz)	Deformation mm
1	24.535	0.0018452	37.486	0.00199	22.881	0.001518
2	28.329	0.0006601	51.047	0.0014781	26.587	0.0003728
3	36.755	0.001476	82.421	0.0025337	34.568	0.00055669
4	43.058	0.0010676	94.059	0.0015154	40.565	0.00047169
5	48.043	0.0048178	127.15	0.0029266	44.729	0.0026674

Random vibrational analysis results

		Aluminum Alloy	Magnesium Alloy	Monel k500
Deformation, mm	X axis	1.09e-02	3.11e-03	1.28e-02
	Y axis	5.71E-02	1.63E-03	7.15E-03
	Z axis	2.90E-02	7.18E-03	3.39E-02
Von mises stress, Mpa	Min	0.57064	0.73622	2.74E-01
	Max	301.07	445.42	2.030E+02
Allowable stress, Mpa		310	255	460

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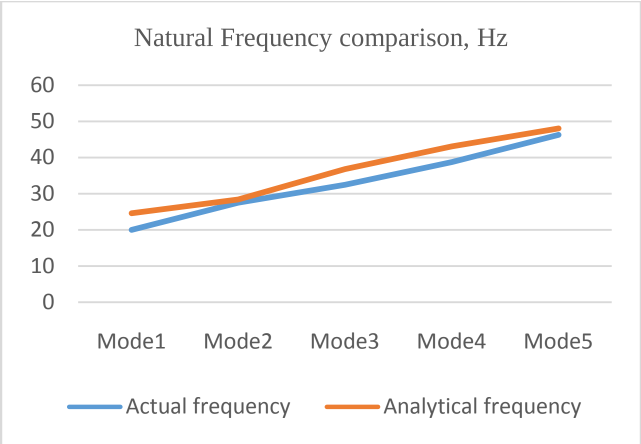
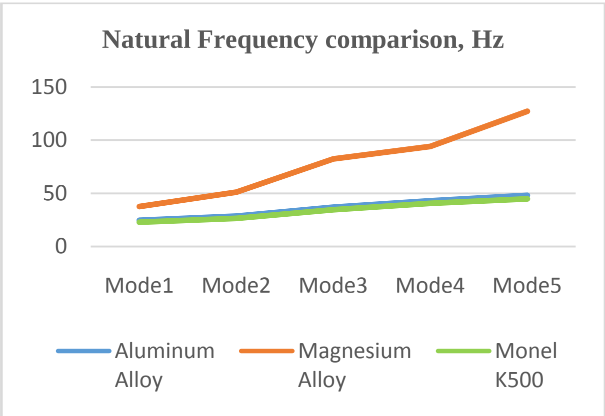
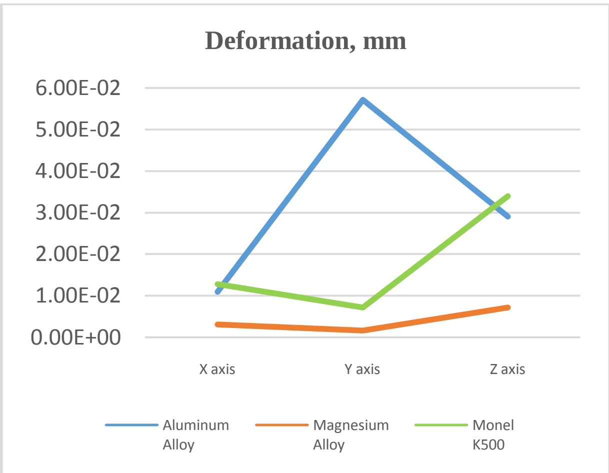
Graph between actual frequencies versus analytical frequencies



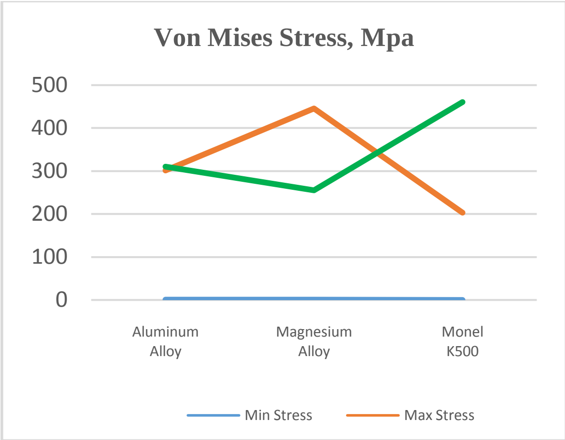
Graph among natural frequencies of the three material Impellers in Modal analysis



Graph among deformations of the three material Impellers in Random vibrational analysis



Graph among stresses of the three material Impellers in Random vibrational analysis



Conclusion

The objective of this thesis is to determine the natural frequencies of the Impeller and analyze behavior of the Impeller under the random vibrations. An Impeller of air compressor was designed and analysis was performed on that using ANSYS. Practical testing performed using Aluminum alloy. The results are compared for practical testing versus analytical values to determine the natural frequencies. By observing the results of practical and analytical for Aluminum alloy, the values are less percentage of deviation. So the analytical values can be predicted.

In analytical, analyses like modal analysis and random vibrational analysis are performed. While natural frequency values are compared for three materials Monel K500 have high values of natural frequency. By observing the analytical results the Aluminum alloy and Monel K500 are in safe range and factor safety is more for Monel K500 compared to the Aluminum Alloy

Finally concluded that using Monel K500 is better for Impeller than Aluminum for more life and reliability.

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