Modal Analysis of Compressor Impeller of Turbocharger by changing the Different Materials

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Abstract- In this paper, it is presented that the modal analysis of the compressor impeller of turbocharger in locomotive diesel engine. The centrifugal compressor is the key component of turbochargers. Air is used as working fluid and Aluminum Alloy, AISI 4340 and Inconel Alloy 718 materials are used for impeller. The modal of the impeller is drawn by using Solid Works 2016 and is analyzed by using ANSYS 14.5. The design of the impeller, 68000 rpm is considered for this research. A modal analysis has been found out to investigate the frequency and deformation of the impeller. By changing the different materials, the frequency and deformation of the impeller is increased. The frequency and deflection of the Inconel Alloy 718 are found better results than other two materials.

Indexed Terms- Analysis, Deformation, Frequency, Impeller, Modal, and Turbocharger

I. INTRODUCTION

A turbocharger consists of a compressor and turbine operating on a single common shaft. These are often designed for use on automobile internal combustion engines. When installed, the hot exhaust gases exiting the cylinders pass through the turbine side of the turbocharger, spinning the turbine blades, and thus the shaft. The shaft then transmits power to drive the compressor. The exhaust gases then continue out to the exhaust manifold and continue as usual. As the compressor spins, it raises the pressure of the incoming air from the air intake. The high pressure air is often directed through a charged air cooler (also known as an intercooler) to further raise the density of the air [1].

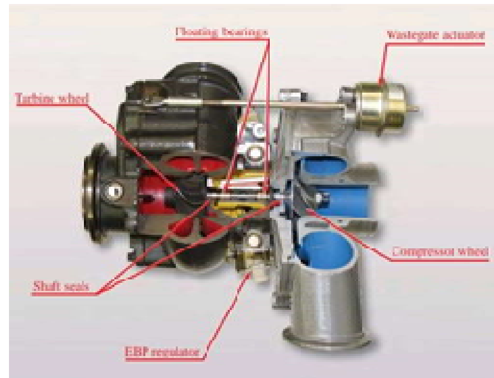


Fig 1 Operation of Turbocharger [2]

Turbochargers are a class of turbo machinery intended to increase the power of internal combustion engines. This is accomplished by increasing the pressure of intake air, allowing more fuel to be combusted [2]. Figure 1 shows the operation of turbocharger.

II. DESIGN PROCEDURE FOR COMPRESSOR IMPELLER

In this research, the design parameter of impeller is collected at 'Diesel Locomotive Workshop (YWAHTAUNG), Sagaing Division in Myanmar '. The centrifugal compressor of the station has the following parameter;

Power=810kW
Outlet Temperature, T_2=408 K
Capacity, Q=0.19 m^3/sec
Outlet Pressure, P_2 = 500 kPa
Air mass flow rate, m° = 1.6 kg/sec
Slip factor, σ=0.85

Ambient pressure and ambient temperature is 1.2 bars and 30˚ C. Design calculation can be divided into three main parts for turbocharged compressor.

These are:

i) Calculation of Impeller Inlet Dimensions
ii) Calculation of Impeller Outlet Dimensions
iii) Efficiency of Compressor

i. Calculation of Impeller Inlet Dimensions

The fluid moves through the impeller where work is done on it to increase its staticpressure fromP_1 to P_2. Impeller inlet and outlet pressure ratio,

$$r_p = \frac{P_2}{P_1} \quad (1)$$

Shaft Diameter, D_s (Aluminum Alloy (7050-T7651))

$$\eta_c = \frac{\text{Output}}{\text{Input}} = \frac{\rho g Q H}{m \times C_p \times (T_{02} - T_{01})} \quad (2)$$

Hub Diameter, D_hThe hub diameter is 12.5% increased of standard shaft diameter.

$$D_h = 1.125 \times D_s \quad (3)$$

Inlet Absolute Velocity, $V_0$the impeller inlet hub Mach number is 0.2 to 1 for compressible fluid. The value of Mach number is 0.3 (assumed) [8].

$$D_1 = 1.025 \times D_0 \quad (4)$$

Impeller Inlet Velocity and Inlet Blade Anglethe air enters the impeller eye to tip in the axial direction. The prewirl angle is zero so that $V_1 = V_{f1}$. Inlet Absolute Velocity, U_1

$$U_1 = \frac{\pi D_1 N}{60} \quad (5)$$

Inlet Blade Angle, β_1

$$\beta_1 = \tan \frac{V_1}{U_1} \quad (6)$$

Number of Blades, n

$$n = \frac{0.63\pi}{1 - \sigma} \quad (7)$$

Impeller Inlet Width, b_1

$$b_1 = \frac{Q}{\pi D_1 V_1 \varepsilon_1} \quad (8)$$

ii Calculation of Impeller Outlet Dimensions

Impeller outlet dimensions can be found out the following equations.Assume K' = 0.55

$$D_2 = \frac{60\sqrt{H_p g}}{\pi N \sqrt{K'}} \quad (9)$$

K' is the pressure coefficient which has a value between 0.5 and 0.65 depending on the type of impeller [8].

The Outlet Peripheral Velocity, U_2

$$U_2 = \frac{\pi D_2 N}{60} \quad (10)$$

Outlet blade angle, β_2The compressor industry commonly uses a backward leading blade with angle, of between about 55-75 deg[8]. Choose: β_2= 65 deg.

The impeller outlet width, b_2

$$b_2 = \frac{Q_2}{\pi D_2 V_2 \varepsilon_2} \quad (11)$$

iii Efficiency of Compressor

Input power of the compressor can be calculated the following equations.

$$\text{Input Power} = m \times C_p \times (T_{02} - T_{01}) \quad (12)$$

Compressor Efficiency, η_c

$$\eta_c = \frac{\text{Output}}{\text{Input}} = \frac{\rho g Q H}{m \times C_p \times (T_{02} - T_{01})} \quad (13)$$

Table 1.Resulting Data of Compressor

No.	Name	Value	Units
1	Pressure ratio, r_p	4.167	-
2	Shaft Diameter, D_s	0.016	m
3	Inlet Blade Angle,β_1	33	degree
4	Outlet Blade Angle, β_2	65	degree
5	Number of blades, n	14	-
6	Impeller Inlet Diameter, D_1	0.052	m
7	Impeller Outlet Diameter, D_2	0.169	m
8	Impeller Inlet Width, b_1	0.016	m
9	Impeller Outlet Width, b_2	0.007	m
10	Compressor Efficiency, η_c	92.58	%

Table 1 describes the resulting data of compressor for Aluminum Alloy.

III. MODAL ANALYSIS OF COMPRESSOR IMPELLER

Modal analysis is the most common application of the finite element analysis. A turbo-compressor impeller was designed and analyzed using the ANSYS 14.5. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions.

The designed compressor operates at 68000 rpm. The corresponding working frequency can be calculated as;

$$\omega_n = \frac{2\pi N}{60} \quad (14)$$

$$f_n = \frac{\omega_n}{2\pi} \quad (15)$$

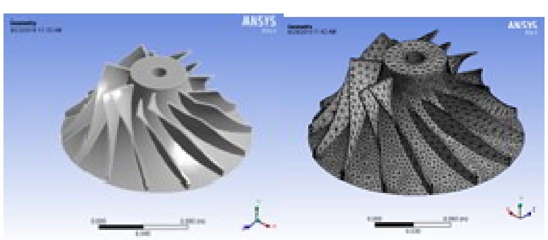
Where, f_n=Natural frequency (Hz)

ω_n=Rotational velocity of turbine (rad/s)

So, the corresponding working frequency for 68000 rpm is 1020 Hz.

Modal and Mesh of Compressor

The modal is created using SolidWorks 2016 and analyzed using ANSYS 14.5 for compressor impeller with different the materials.Figure 2(a) show the 3D modal of compressor impeller for turbocharger in locomotive. Tetrahedron mesh generation method is used for meshing as shown in Figure 2(b).



(a) (b)

Fig 2(a) Modal and (b) mesh of Compressor

Modal Analysis of Compressor

In the modal analysis, the boundary condition is regarded. The locations of fixed support are the tip of compressor wheel. Figure 3 shows the boundary condition of impeller.

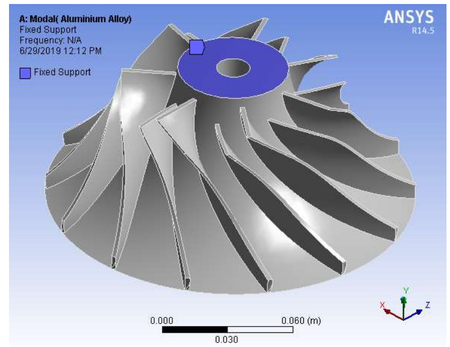


Fig 3 Boundary Condition of Compressor

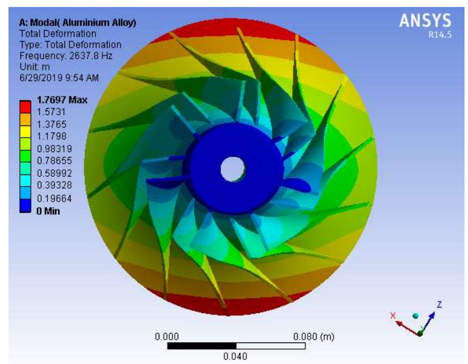


Fig 4 Natural Frequency of Mode Shape 1 at Total Deformation for Aluminum Alloy

For global mode shape 1 to 6 for Aluminum Alloy, the natural frequency is 2637, 2638, 2933, 4996, 4998 and 5006 Hz, while turbine working frequency is 1020 Hz. As both the frequencies do not match so the structure has no tendency of resonance. This mode shapes are shown in Figures 4, 5, 6, 7, 8 and 9.

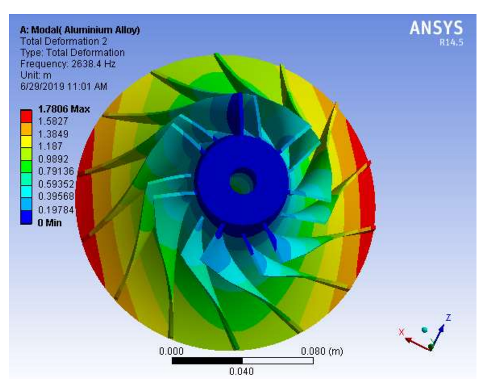


Fig 5 Natural Frequency of Mode Shape 2 at Total Deformation for Aluminum Alloy

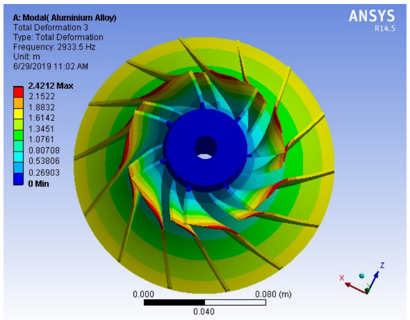


Fig 6 Natural Frequency of Mode Shape 3 at Total Deformation for Aluminum Alloy

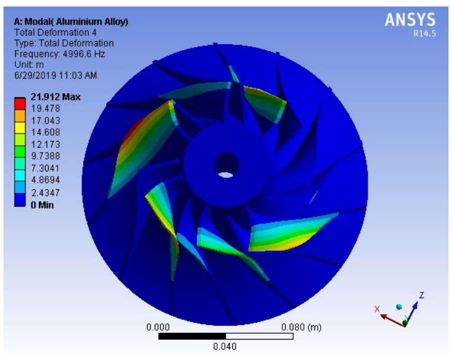


Fig 7 Natural Frequency of Mode Shape 4 at Total Deformation for Aluminum Alloy

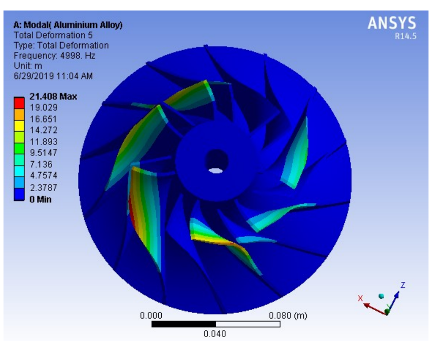


Fig 8 Natural Frequency of Mode Shape 5 at Total Deformation for Aluminum Alloy

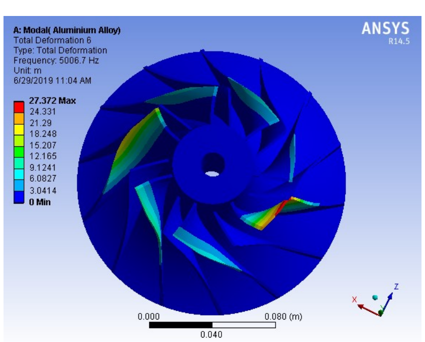


Fig 9 Natural Frequency of Mode Shape 6 at Total Deformation for Aluminum Alloy

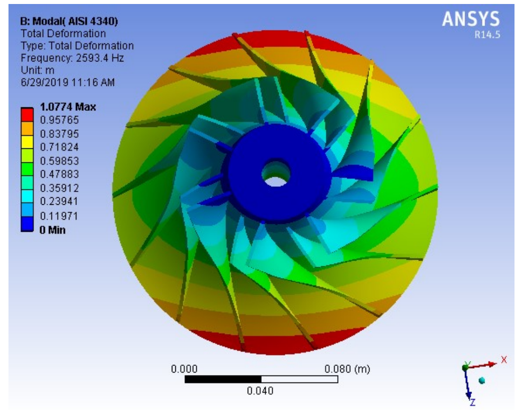


Fig 10 Natural Frequency of Mode Shape 1 at Total Deformation for AISI 4340

For global mode shape 1 to 6 for AISI 4340, the natural frequency is 2593, 2594, 2909, 5099, 5103 and 5108 Hz, while turbine working frequency is 1020 Hz. As both the frequencies do not match so the structure has no tendency of resonance. This mode shapes are shown in Figures 10, 11, 12, 13, 14 and 15.

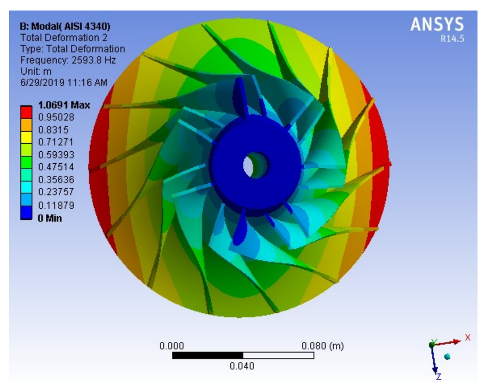


Fig 11 Natural Frequency of Mode Shape 2 at Total Deformation for AISI 4340

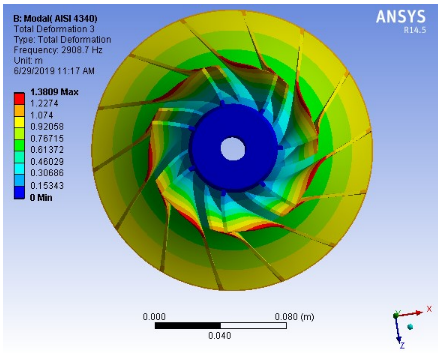


Fig 12 Natural Frequency of Mode Shape 3 at Total Deformation for AISI 4340

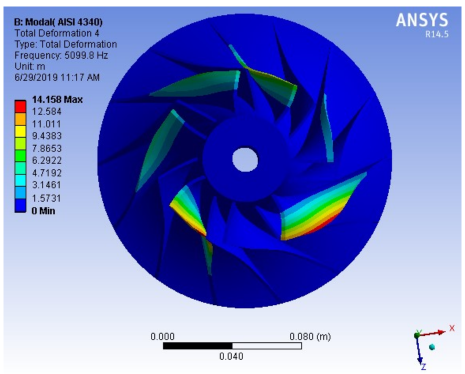


Fig 13 Natural Frequency of Mode Shape 4 at Total Deformation for AISI 4340

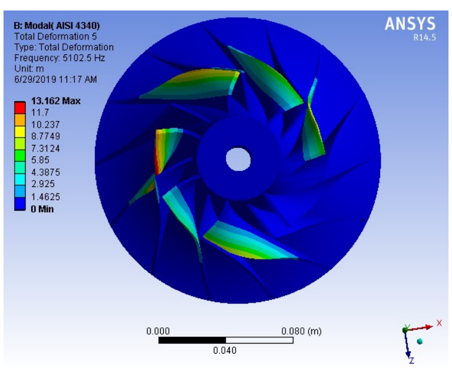


Fig 14 Natural Frequency of Mode Shape 5 at Total Deformation for AISI 4340

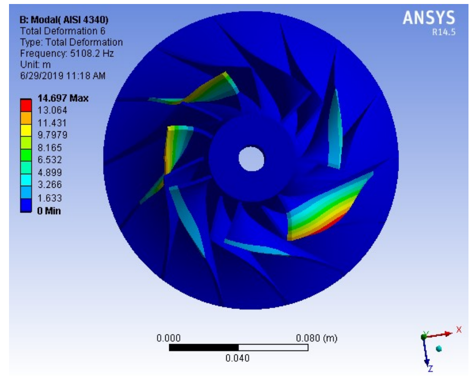


Fig 15 Natural Frequency of Mode Shape 6 at Total Deformation for AISI 4340

For global mode shape 1 to 6 for Inconel Alloy (718), the natural frequency is 2553, 2555, 2846, 4845, 4876 and 5057 Hz, while turbine working frequency is 1020 Hz. As both the frequencies do not match so the structure has no tendency of resonance. This mode shapes are shown in Figures 16, 17, 18, 19, 20 and 21.

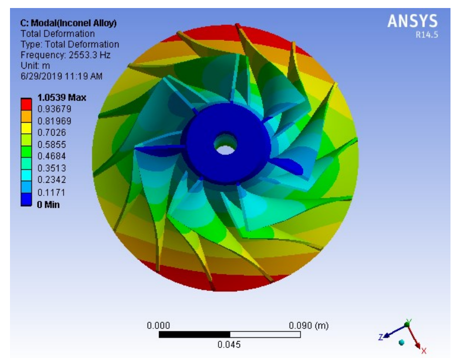


Fig 16 Natural Frequency of Mode Shape 1 at Total Deformation for Inconel Alloy 718

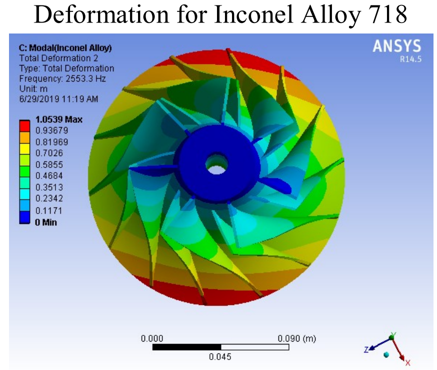


Fig 17 Natural Frequency of Mode Shape 2 at Total Deformation for Inconel Alloy 718

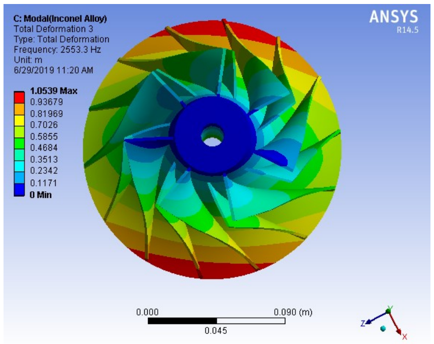


Fig 18 Natural Frequency of Mode Shape 3 at Total Deformation for Inconel Alloy 718

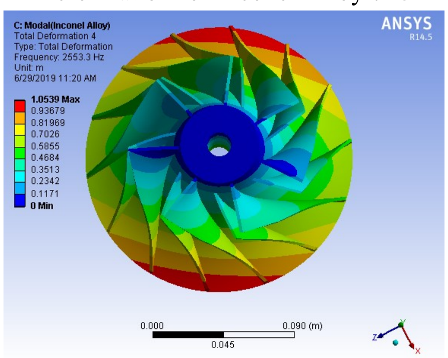


Fig 19 Natural Frequency of Mode Shape 4 at Total Deformation for Inconel Alloy 718

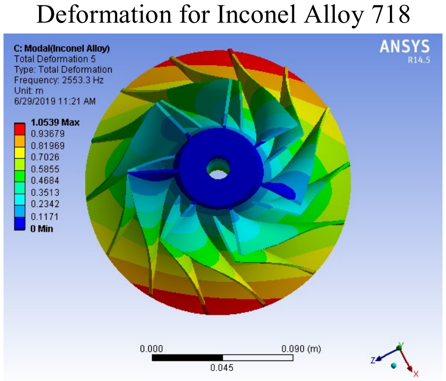


Fig 20 Natural Frequency of Mode Shape 5 at Total Deformation for Inconel Alloy 718

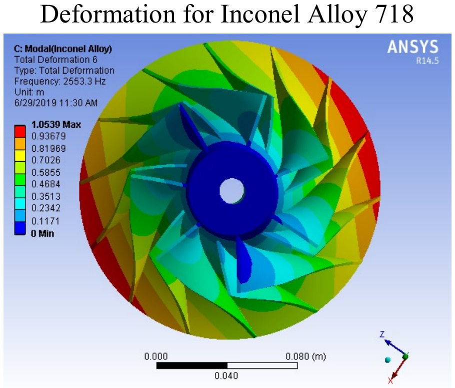


Fig 21 Natural Frequency of Mode Shape 6 at Total Deformation for Inconel Alloy 718

IV. RESULT AND DISCUSSION

The designed compressor operates at 68000 rpm so the corresponding working frequency of compressor is 1020 Hz. The variation of frequency and deformation for three different materials of compressor impeller were analysed by using modal analysis. Table 2 and 3 show natural frequency and deflection for compressor impeller

Table 2 Modal Analysis of Natural Frequency for Compressor Impeller

Types of Materials	Frequency(HZ)					
	1	2	3	4	5	6
Aluminum Alloy	2637	2638	2933	4996	4998	5006
AISI 4340	2593	2594	2909	5099	5103	5108
Inconel Alloy 718	2553	2554	2845	4845	4876	056

Table 3 Modal Analysis of Deformation for Compressor Impeller

Types of Materials	Deformation(m)					
	1	2	3	4	5	6
Aluminum Alloy	1.76	1.78	2.42	21.9	21.4	27.3
AISI 4340	1.07	1.06	1.38	14.1	13.1	14.6
Inconel Alloy 718	1.05	1.05	1.05	1.05	1.05	1.05

V. CONCLUSION

The design of the compressor impeller was carried out. Modal analysis was carried out on compressor impeller with three different materials and the results are compared. The three materials were used for the material properties and the designed compressor working frequency was 1020 Hz and natural frequencies for global mode shapes were 2637 Hz for Aluminum Alloy, 2593 Hz for AISI 4340 and 2553 Hz for Inconel Alloy 718, respectively. The working frequencies do not match with natural frequencies of the runner at global mode shape. From the above results table, it can be concluded that the minimum frequency and deflection of Inconel Alloy (718) are found better results than other two materials. In this design, the greatest total deformation can be seen in the compressor impeller outlet blades and the smallest total deformation can also be seen in the compressor impeller inlet blades.

The other components such as casing and diffuser should be designed and analyzed for the future study. The casing and impeller assembly should be analyzed to increase the efficiency by decreasing the clearance. The compressor blade design should be modified because it influences on its performance.

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