

# Mechanical Strength Capabilities & Vibrations Assessment of Thrust Gear Box used in Wind Turbines: A Case Study

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**Abstract** - Wind energy is a form of renewable source of energy which is available in nature sans pollution. The wind energy is harnessed through wind turbines, one of whose main components is the thrust gear box. The thrust gear box is a vital part of the wind turbine which not only increases the rotational speed, but also overcomes the thrust loading, exerted by the rotating parts. Thus, the mechanical strength and vibrations is an important aspect of the thrust gear box. Structural and dynamic simulation analysis of the thrust gear box was executed through Finite Element Analysis (FEA) software, performed under the operating condition. A standard thrust gear box was considered as the base line design under the loading conditions for the case study. A simulation analysis was performed to evaluate its mechanical strength capabilities and vibrations assessment. The structural integrity was assessed by examining the von Mises stress with the yield strength and the Factor of Safety (FoS). The design was modified to meet the mechanical strength capabilities & vibration's performance through change in dimensional and alternative material recommendations. To meet this criterion, the dimensions at the high stress locations were modified, to reduce the high stress concentrations, and an alternative material of higher strength were suggested. The simulation studies showed that the dimensional changes and alternative material showed an improvement in the mechanical strength, where the FoS was found to be greater than 1, which were acceptable. Furthermore, the dynamic analysis was assessed by evaluating the natural frequencies of the thrust gear box with the rotor speed and the gearbox speed. The natural frequencies and modes were found to be within the acceptable range, and hence, the modified thrust gear box was recognized to be safe under vibrations caused due to the rotating parts.

**Key Words:** Thrust Gear Box, Mechanical Strength, Vibrations assessment, design requirements, material recommendations

## 1. INTRODUCTION

Wind power is one of the fastest-growing renewable energy technologies. Usage is on the rise worldwide, in part because costs are falling. Global installed wind-generation capacity

onshore and offshore has increased by a factor of almost 75 in the past two decades. Wind is used to produce electricity using the kinetic energy created by air in motion [1]. This is transformed into electrical energy using wind turbines or wind energy conversion systems. Wind first hits a turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the kinetic energy to rotational energy, by moving a shaft which is connected to a generator, and thereby producing electrical energy through electromagnetism.

The amount of power that can be harvested from wind depends on the size of the turbine and the length of its blades. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. Theoretically, when wind speed doubles, wind power potential increases by a factor of eight [2].

A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases [3]. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it is a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity.

A wind turbine consists of five major and many auxiliary parts. The major parts are the tower, rotor, nacelle, generator, gearbox, main shaft and foundation or base [4]. Without all of these, a wind turbine cannot function. The wind turbine blade assembly and parts are shown in Figure 1.

Literatures have shown that the thrust gear box is one of the vital components of the wind turbine assembly, which undergoes tremendous amounts of loads. However, it is also one of the most commonly overlooked components of the wind turbine assembly. Open literatures do not show any research conducted to suggest possible design changes to the

thrust gear box, to enhance the Margin of Safety of the thrust gear box [5].

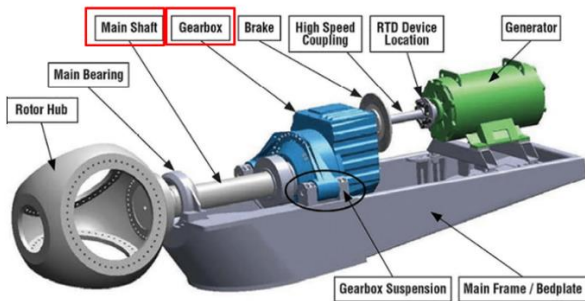


Fig 1. Wind turbine blade assembly and parts

## 2. Objectives:

Before. The objective of this research can be described in 2 phases.

**Phase1:** This includes the validation of structural integrity of the current design of thrust gear box under the given loading conditions.

**Phase2:** Includes recommendation for design enhancement for the component thrust gear box and recommendation for material changes to withstand the given loading conditions.

Validations of mechanical strength capabilities and vibrations assessments are done using the Finite Element tools. For the current research, a simulation software is used for the validations of the mechanical strength and vibrations assessment. Finite Element Analysis enables the ease in predicting the potential design flaws and thus, minimises the risk to the product failure, under working conditions. Eventually, the objective of the research paper is in the predictions of failures of the thrust gear box in the initial design stage.

The objective of the current research is attained through the Linear static structural analysis, performed to verify the stress levels in the components for loads experienced by the thrust gear box under the operating conditions. By performing the linear static structural analysis, the mechanical strength capabilities of the thrust gear box can be assessed, and the appropriate recommendations for the design and material changes can be proposed for expanding the shelf life of the thrust gear box used in wind turbines. The operating loads considered for the Finite Element Analysis are, Moment loads, Couple loads, Thrust, Torque loads, and Component mass loads.

## 3. Methodology and Process Map:

As mentioned in the objectives, the structural integrity was validated and conclusions are given based on 2 phases using FE analysis performed using Ansys workbench. In phase 1, the validation of structural integrity of the current

design of thrust gear box and main shaft under the given loading conditions were conducted. In phase 2, the recommendations for design enhancement for the thrust gear box component, while in phase 3, the recommendation for material change to withstand the given loading conditions were suggested. Figure 2 shows the phase descriptions.

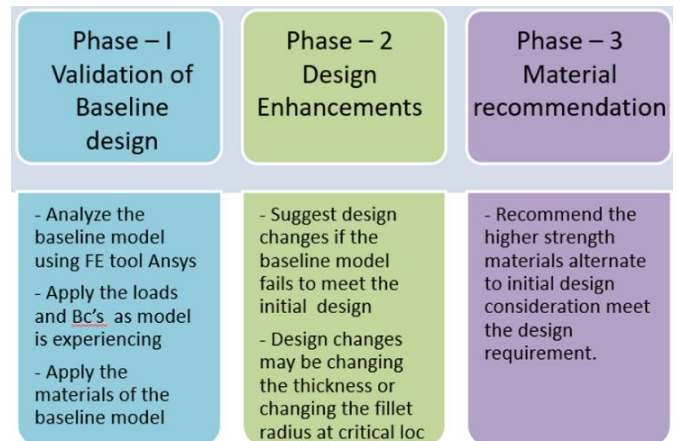


Fig 2. Phase Descriptions

## 4. Process Map:

### 4.1 Current Design:

The steps involved in the FE analysis of the current design which was performed using Ansys workbench are shown in the process map for the current design in Figure 3. The designed component was considered for redesign based on the stress tensors as well as stress distribution and deflections observed on the components under operating conditions [6].

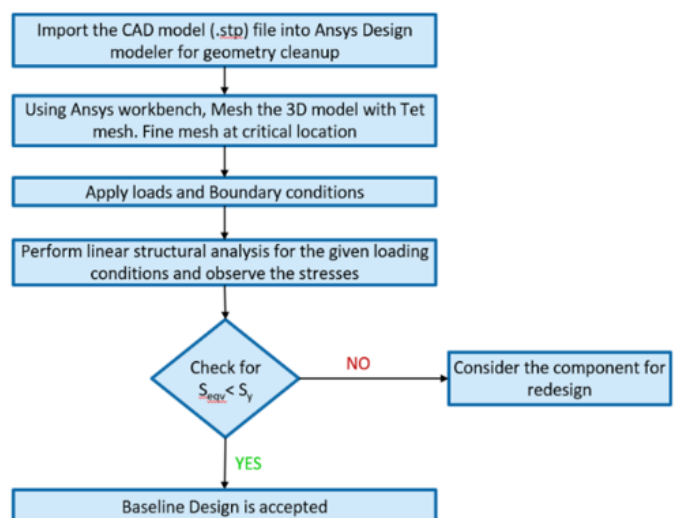


Fig 3. The process map for the current design.

## 4.2 Process Map - Design Recommendation

Paragraph. The steps involved in the FE analysis of the current design which was performed using Ansys workbench are shown below[7-9]. The simulations through the Ansys work bench showed that the initially designed component did not meet the design requirements and thus the component was considered for redesign. This was based on the stress tensors as well as stress distribution and deflections as observed in the simulations of the components under operating conditions.

Design modifications and enhancements were recommended by increasing the thickness of the rib at the base of the thrust gear box, so as to reduce the working stress level below the material yield stress limit. Material of higher strength, i.e., greater than the yield strength was also proposed. Success criteria was defined as the stresses in the components to be maintained at a value below the material yield stress[10]. In the design recommendations, the critical locations where von Mises stress exceeds the material yield limit were identified. Design changes were suggested to reduce the stress by increasing the thickness of the base ribs and increasing the fillet radius of the base line design. The implementation of the said design changes, the stresses at these critical locations were reduced to a great extent. The process map involved in the FE analysis for the design changes is shown in Figure 4.

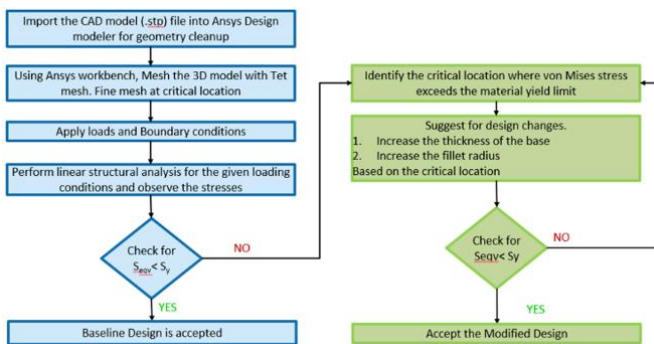


Fig 4. Process map for Design Changes

## 4.3 Process Map - Material Recommendation:

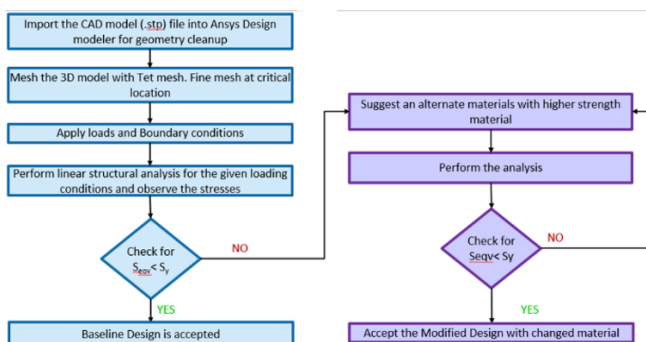


Fig 5. Process map for material changes

The process map involved in the FE analysis for the material changes is shown in Figure 5. In the current design, cast Iron is consider for the stress evaluation. However, the simulated von Mises stress was higher the yield stress material which is unaccepted. Thus, the component was considered for a change in material recommendation. The component was considered for the recommendation of an alternate material which has a higher strength than the material used in current design. Thus, grey cast iron material was suggested as its strength is higher than that of the normal cast iron. The simulated stresses of the thrust gear box with material properties as that of grey cast iron showed that the generated von Mises stress was lower than the yield stress, thus generating a FoS greater than 1.

## 5. Capability Assessment of the Thrust gear box- Current Design

### 5.1 CAD and FE model:

The model of thrust gear box was opened in a CAD software, solid edge, where the geometry cleanup is performed. In cleanup process, small holes, small features, small fillets which were considered to be insignificant or non-critical for analysis were removed[11]. Only those features which were considered critical to the design were retained for analysis. The model was considered for the analysis with cast iron material properties. The geometry was checked for any free edges and any discontinuities in the 3D model. The 3D CAD model was then exported to .stp which was subsequently imported into Ansys design modeler.

The CAD model was imported into the design space. Higher order element, Solid 186 was used for meshing the geometry. Contact 170 and target 169 were used for establishing bonded contact between upper and lower parts of the geometry. Part I meshed with the fine mesh and the critical regions to capture the geometry. The FE model of the component is shown in Figure 6. After meshing, the CAD model showed the total number of elements to be 171,864 and total number of nodes to be 294,139.

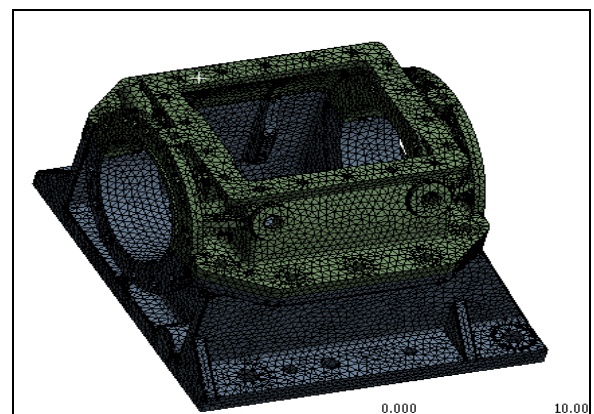


Fig 6. FE model of the component

### 5.2 Material Properties

The material considered for analysis was cast iron. The properties are tabulated as shown in Table 1.

Table 1. Material Properties of Cast Iron.

Property	Value	Unit
Young's Modulus	1.6 E7	psi
Poissons Ratio	0.28	
Yield Strength	40,000	psi

### 5.3 Loads and Boundary Conditions:

The main holding down bolt holes which are connecting to the base frame of the wind turbine assembly were constrained in all directions. In the design, a total of 4 holding down bolts are present [12-13]. The loads and Boundary conditions are shown in Figure 7. Figure 7(a) shows the Loads and boundary conditions-fixed support, and Figure 7(b) shows the loads and boundary conditions-Propeller mass.

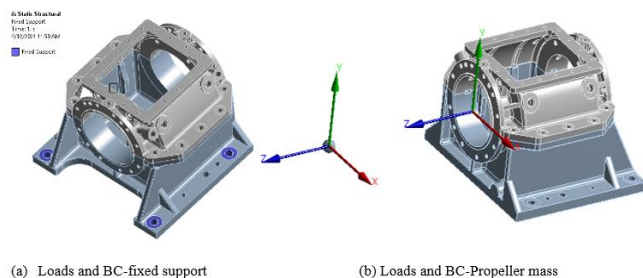


Fig 7. Loads and Boundary Conditions.

A Propeller which is 24" from the thrust gear box and having a mass of 1500 lbs was considered for analysis. This is an overhung load which creates a large moment load. Mass element was created at the CG point of the propeller and assigned a 3D mass of 1500 lbs and connected to the thrust gear box using remote connection. The load and boundary condition- gravity load is shown in Figure 8.

Couple loads are generated when the propeller rotates and transfers the rotation to the main shaft. This couple load was applied in X and Z direction. The loads and BC-couple loads is shown in Figure 9.

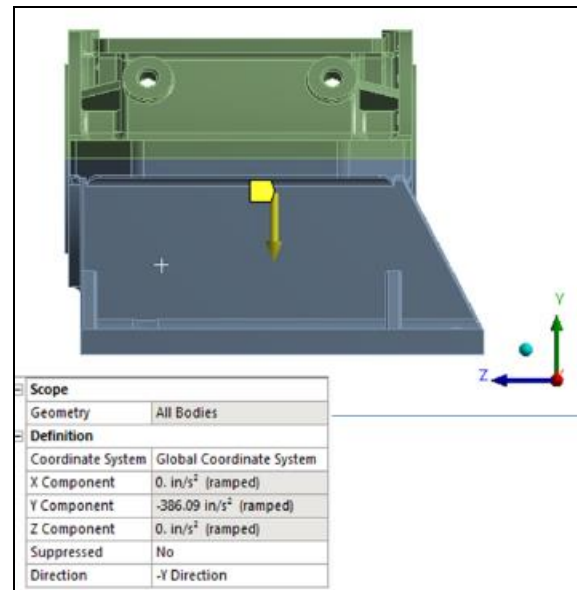


Fig 8. Loads and BC-Gravity load

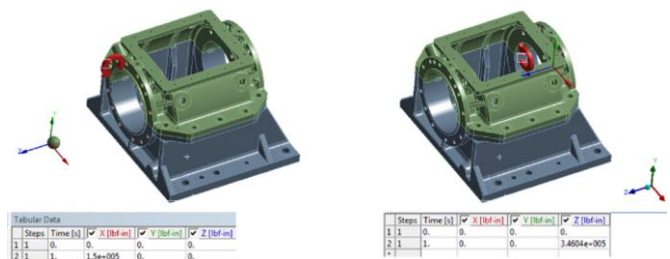


Fig 9. Loads and BC-Couple load.

### 5.4 Results: Current Design:

After the completion of the simulation, the components were checked for deformation and stresses as experienced under working conditions. Maximum deflection was observed on the flange of the component. This is mainly due to the extremely high overhanging mass which is lumped at the propeller. This causes the top case of the flange region to experience high deformation equivalent of 0.05". The total deformation plot is shown in Figure 10(a) and the Von-Mises Stress plot is shown in Figure 10(b).

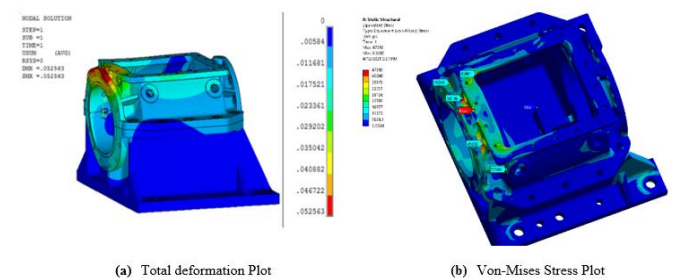


Fig 10. Resultant Plots

The stress plot shown in Figure 10(b), shows a few locations on the top case where the stress exceeds the material yield limit. The locations are mainly at the ribs and at the fillet location of ribs. It is also observed that the stress had exceeded at the fillets of the inspection cut-out region.

The Factor of Safety (FoS) was calculated based on the working stress and the material allowable limit using the formula shown in Equation 1.

$$FoS = \left[ \left\{ \frac{\sigma_Y}{\sigma_W} \right\} - 1 \right] \times 100 \quad \text{Eq (1)}$$

where, *FoS* is the factor of safety,  $\sigma_Y$  is the yield stress, and  $\sigma_W$  is the working stress. Upon substituting the values of  $\sigma_Y$  and  $\sigma_W$ , we get,

$$FoS = \left[ \left\{ \frac{45000}{50196} \right\} - 1 \right] \times 100$$

$$FoS = -10.35$$

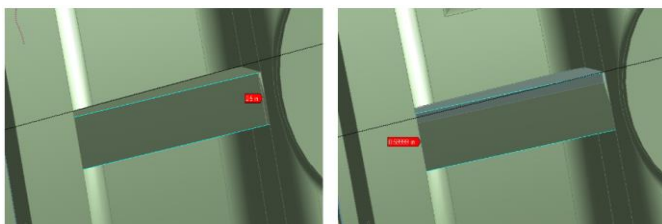
The *FoS* obtained was negative i.e., not greater than 1 and thus the baseline design was not accepted.

### 6. Design and Material Change recommended design model

After observing a negative margin on the components, changes were done to improve the design. The changes to the design were the increase in the thickness of the rib and increase in the fillet radius where high stresses were observed. A change in the material was also recommended.

#### 6.1 Design Change Recommendation:

The thickness of 0.5" on the ribs for the current design is shown in Figure 11 (a). Multiple iterations were performed at an incremental value to the thickness at the rate of, 0.52", 0.54", 0.56", 0.57", 0.58", 0.59" and 0.6". With each iterations the stresses levels on component were checked. It was recommended to increase the thickness of the rib to 0.6", which showed that the working stress was lower than the yield stress and the *FoS* was greater than 1. From this the final conclusion on this thickness number is arrived to 0.59999 which is shown in Figure 11 (b).



(a) Thickness of the ribs 0.5"-Current design (b) Thickness of the ribs 0.59999"-Suggested change

Fig 11. Rib Thickness

### 6.2 Results: Design Recommendation:

Simulations were performed for the multiple design iterations and the von Mises stress, and the deformations were evaluated. The total deformation plot for thrust box with rib thickness of 0.6" is shown in Figure 12.

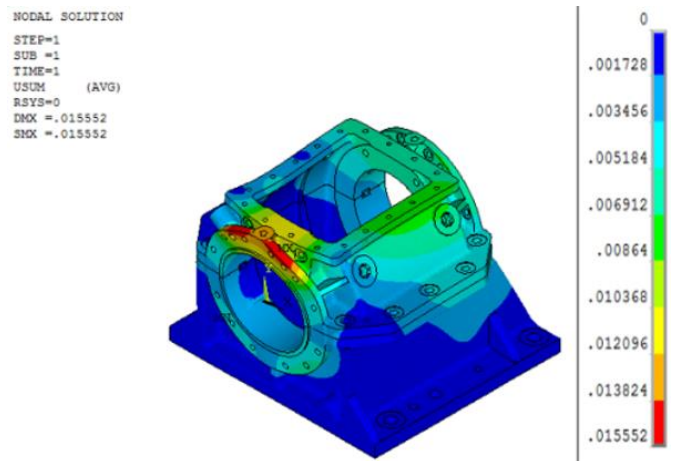


Fig 12. Deformation plot after Design change

The stress plot showed that the stresses had not exceeded the material yield limit. The stresses at the rib location were found to be reduced and within the acceptable limit.

The Factor of Safety (*FoS*) was calculated based on the working stress and the material allowable limit using the formula shown in Equation 2.

$$FoS = \left[ \left\{ \frac{\sigma_Y}{\sigma_W} \right\} - 1 \right] \times 100 \quad \text{Eq (2)}$$

where, *FoS* is the factor of safety,  $\sigma_Y$  is the yield stress, and  $\sigma_W$  is the working stress. Upon substituting the values of  $\sigma_Y$  and  $\sigma_W$ , we get,

$$FoS = \left[ \left\{ \frac{45000}{41571} \right\} - 1 \right] \times 100$$

$$FoS = 8.24$$

The *FoS* obtained was positive and greater than 1 and thus the modified design was accepted.

### 6.3 Material change Recommendations:

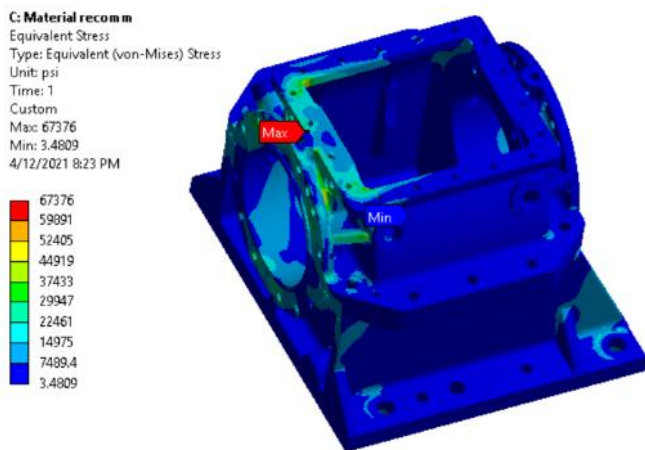
Higher strength material properties were proposed. For the current case study, grey cast iron was recommended for the material change. The grey cast iron material properties are listed in Table 2.

**Table 2.** Grey Cast Iron material properties

Property	Value	Unit
Young's Modulus	2.451e+7	psi
Poissons Ratio	0.275	
Density	0.2565038	lb/inch <sup>3</sup>
Tensile Strength	72518.9	psi

**6.4 Results-Material Recommendations:**

The von Mises stress plot is shown in Figure 13.



**Fig 13.** Von Mises Stress plot

From the von Mises stress plot, it was observed that the stresses developed throughout the thrust gear box gear box was low, which had not exceeded the material yield limit. The maximum stress observed was 67 psi.

The Factor of Safety (FoS) was calculated based on the working stress and the material allowable limit using the formula shown in Equation 3.

$$FoS = \left[ \left\{ \frac{\sigma_Y}{\sigma_W} \right\} - 1 \right] \times 100 \quad \text{Eq (3)}$$

where, *FoS* is the factor of safety,  $\sigma_Y$  is the yield stress, and  $\sigma_W$  is the working stress. Upon substituting the values of  $\sigma_Y$  and  $\sigma_W$ , we get,

$$FoS = \left[ \left\{ \frac{73000}{67376} \right\} - 1 \right] \times 100$$

$$FoS = 8.34$$

The FoS obtained was positive and greater than 1 and thus the material change was accepted.

**7. Vibrational Analysis:**

Vibration analysis was performed to evaluate the natural frequencies of the thrust gear block. The vibration analysis is often performed at the preliminary stage of the design. The main focus of the vibration analysis is to study the resonance of the part, which in turn gives an understanding on the part interactions with the adjacent parts. Through this analysis, it is ensured that the resonance does not lie in the operating speeds else the design is modified changed to move the frequencies away from the operating speeds. Generally, a change in the stiffness or mass of the component is implemented to change the natural frequencies. The operating speed of the gear box is 4000 rpm and the 1E excitation is 66 Hz. The mode shapes are obtained near the 1E excitation frequency. The natural frequencies of the component are listed in the Table 3.

**Table 3.** Mode no. and Natural frequencies

Mode no	Frequency (Hz)
1	60.2
2	60.2
3	60.8
4	61.1
5	61.8
6	62.0
7	62.5
8	62.7
9	62.9
10	63.9
11	64.6
12	64.6
13	65.1
14	65.5
15	65.7
16	65.9
17	66.8
18	66.9
19	67.1
20	67.5
21	68.2
22	68.6
23	68.7
24	69.1
25	69.5
26	69.6

**7.1 Mode Shapes:**

The Mode Shapes are shown in Figure 14. Mode shape for the frequency 65.9Hz is shown in Figure 14 (a). Mode shape

for the frequency 66.7 Hz is shown in Figure 14(b). Mode shape for the frequency 66.8 Hz is shown in Figure 14(c). Mode shape for the frequency 67.1 Hz is shown in Figure 14(d).

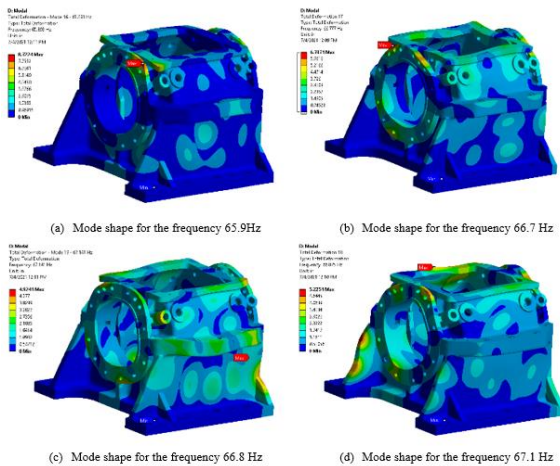


Fig 14. Mode Shapes

Thus, it is observed that the operating frequency was largely different from the natural frequencies obtained from the simulations, and thus, it can be stated that the thrust gear box is safe from resonance caused due to operating speeds.

### 8. Summary of findings:

The following observations were summarised from this case study

- A high deformation and a FoS of less than 1 was obtained for the for the base line design, which indicated low mechanical strength. This concluded that the design was unstable and prone to destruction.
- An increase in the rib thickness to 0.6" from 0.5", and increasing the fillet radius, showed an improvement through lower deformations and FoS greater than 1, which indicated a higher mechanical strength. This concluded that the modified design was stable and can overcome any destruction.
- Simulations using the material properties of grey cast iron also showed FoS greater than 1, again showing an enhanced mechanical strength indicating a stable thrust gear box. This concluded that grey cast iron was more suited as the thrust gear box material than cast iron.
- The vibrations simulation analysis, showed that the operating frequency was different from the natural frequencies obtained. This indicated that the thrust gear box is safe from resonance caused due to operating speeds.

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