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# Modal Frequencies of Box Truss Model Gear Box Using Machine Learning

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**Abstract**—A Gearbox is a speed variable device which changes the speed of power transmission according to the requirements of the torque. Gearbox casing plays an important role in power transmission in the machines. It encloses the entire gear train assembly which transmits power continuously resulting in loss of energy causing friction and vibrations. The conventional type of gearbox casing of closed type gearbox which is generally made of cast iron material is replaced with the mild steel material in a gearbox truss type. The important property required for a gearbox casing is damping. Gray cast iron has good damping properties. In spite of that using mild steel reduces the weight of structure and sustains vibrations. *In high speed driven machines, generally gray cast iron is used as the gearbox casing material. However, an effort is made to change the material.* In this way it is possible to replace high dense casing into a lighter one and thus can sustain vibrations. The advantage of this novel structure is to save the materials and cost of the gearbox. In this study, by considering the specifications, kinematic analysis is done and according to it box truss type gearbox is designed. Experimentation was done on the casing using vibrations tester (Accelerometer). More deformations were drawn from Machine Learning to extract n number of frequencies and deformations. Compared all the results obtained from Modal Analysis, Machine Learning and Experimentation.

**Keywords**—Gearbox casing, Closed type gearbox, Truss type gearbox, Damping, Gray cast iron, Mild steel, Machine learning

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# 1. Introduction

A Gear Box is a speed variable device which changes the speed of power transmission according to the requirements of torque. In lathe machine, gearboxes are used to deliver varied speed and torque to the headstock spindle depending on the work being done. Usually, the gearbox is placed inside the headstock. Gearboxes provide a wide range of cutting speeds and torque from a constant speed power input enabling proper cutting speeds or torque to be obtained at the spindles as required in the case of cutting drives and desired feed rates in the case of feed drives. Gearbox is used in many real-life applications such as automotive transmission, industrial transmission etc. Gearbox encloses the gear train assembly which transmits power continuously and due to which loss of energy takes place causing friction and the machines undergoes vibrations. Basically, gearbox consists of clutch shaft, counter shaft, Main shaft, gears, bearings. A clutch shaft is a shaft that uses engine power to transmit energy to other shafts. Counter shaft is the shaft that connects directly with the clutch shaft. Main shaft is the shaft that runs at the vehicle's speed. It carries power from the counter shaft by use of gears and according to the gear ratio. The material used in manufacturing gearbox are alloy steels, carbon steels and mild steels. The manufacturing processes used are shell molding or mold casting.

An experimentation was conducted on truss type gearbox to extract data points such as velocities, acceleration and deformation at different speeds using vibration measuring device. The data points that are extracted are made into a dataset then trained to machine learning algorithm and also used some python packages like PyTorch and TensorFlow. The obtained results show that mild steel truss gear box is also suitable for building gearbox by using machine learning algorithms.

# 2. Related Work

Several research works have taken place in the recent past on choosing the right gearbox material which has good damping properties, freedom from noise & most importantly which can maintain correct NVH (Noise, Vibration and Harshness) level of the vehicle. In most of the research, different types of analysis like Vibration Analysis, Modal & Stress Analysis, Finite Element Analysis, Dynamic Analysis, Thermal Analysis, etc., was thoroughly carried out to determine vibration modes, time-frequency response, noise level, resonance etc. on different types of vehicles (i.e., a car or a truck). [1] Shivaraju et al. in their work on "Vibration Analysis for Gearbox casing using Finite Element Analysis" (ANSYS software) determined the natural vibration modes and forced harmonic frequency response for gearbox casing. [2] Fujin et al. in their work studied dynamic vibrations of the transmission gearbox using FEM numerical simulation method to lessen the vibration and noise (They have performed analytical and experimental analysis of a car transmission system).[3] & [4] Ashwani Kumar et al. has studied the free vibration analysis of truck transmission housing and concluded that the natural frequency varies from 1002-2954Hz.[5] Snežana Ćirić Kostić et al. has worked upon natural vibrations of the housing walls and concluded that it can be prevented or intensified depending on the design parameters.[6] Mohamed Slim Abbes et al. have studied on the numerical simulation of the overall dynamic behavior of a parallel helical gear transmission. [7] Shrenik M. Patil and S.M. Pise et al. carried out Modal and Stress Analysis of differential gearbox casing with optimization and concluded by saying advanced finite element analysis such as structural modification and optimization are often used to reduce component complexity, weight and subsequently cost.

# 3. Objectives

This paper is aimed to replace the gearbox casing of closed type gearbox which is generally made of cast iron material with the mild-steel material in a box truss type design. In addition to it, Modal Analysis is performed using numerical techniques to study the static and dynamic conditions of a Closed type Gearbox Casing (CTGBC) and the Box Truss Gearbox Casing (BTGBC) to interpolate the frequencies and deformations to find the resonance points.

# 4. Methodology

The present disclosure relates, in general, to the gearbox and more specifically relates to the "Box Truss Model Gearbox" in which deformations are calculated at different modal frequencies using Machine Learning.

Figure 22.1 depicts the step-by-step approach adopted to achieve the objectives.

According to the flowchart (as shown in Fig. 22.1), the ray diagram is a graphical representation of the drive arrangement. It gives information about the number of shafts and number of gears on each shaft, followed by design of gears, shafts and design of gearbox casing. The structural analysis is performed on the Box Truss type Gearbox Casing (BTGBC) to calculate deformation, stresses, mode shapes and natural frequencies. By conducting experimentation on the Box Truss type Gearbox Casing using vibration measuring instrument (i.e., Accelerometer) acceleration, velocities and deformations are extracted at different speeds. Lastly, Machine Learning algorithm is implemented to extract deformations of different frequencies in a frequency range by giving required interval using suitable Python code.

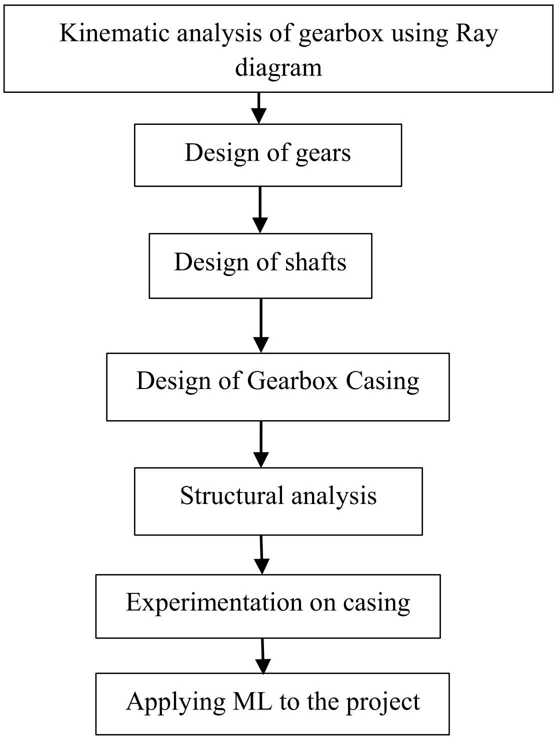


**Fig. 22.1** Chronological order of box truss type gearbox Casing development

The literature was reviewed first to identify the existing problems in the current automotive transmission industry. After observing the shortcomings of the existing gearbox casing material in the transmission sector, the team worked on identifying the problem and it was found that many metal ores are getting depleted day by day and slowly getting obsolete. As a result, an effort was made to replace the current Closed type Gearbox Casing (CTGBC) material which is generally made of gray cast iron with the mild steel in a Box Truss type design. Thereafter, a 3D model of gearbox casing was made using SolidWorks 2022 version. The gearbox is designed according to the kinematic analysis and the gear dimensions and shaft dimensions are calculated. The 3D model of Closed type Gearbox Casing (CTGBC) and Box Truss type Gearbox Casing (BTGBC) are shown in Fig. 22.2 and Fig. 22.3 respectively, followed a series of analysis which mainly includes Structural analysis, Static analysis, Meshing, Modal analysis and Harmonic analysis was performed to check whether the design is safe or not.

A study of the average dimensions of high speed driven gearbox which is generally made of cast iron material has revealed the length of the gearbox as 40mm, width of the gearbox as 24.5mm (approx. 25mm), height of the gearbox as 25.8mm (approx. 26mm) and the thickness as 22mm. However, the Box Truss design gearbox retained the same values of length, width and height but the thickness of the

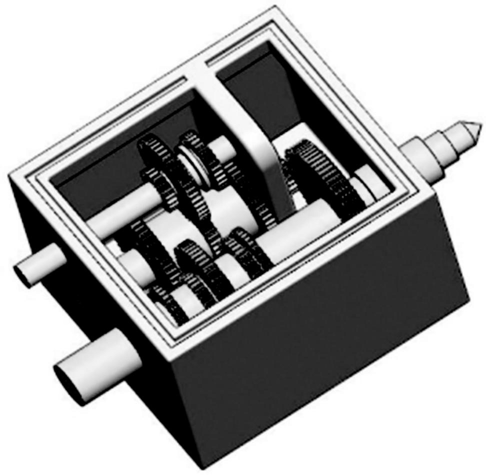

**Fig. 22.2** Closed type gearbox casing (CTGBC)

**Fig. 22.3** Box truss type gearbox casing (BTGBC)

mild steel gearbox was noted as 4.80mm (approx. 5.0mm) instead of 22mm so as to reduce the material which in return reduces the overall weight/payload of the entire gearbox casing.

The below table (Table 22.1 and Table 22.2) shows the material properties of the designed Box Truss Gearbox Casing and the existing Closed type Gearbox Casing respectively.

**Table 22.1** Material properties of box truss gearbox casing

| Name of the material | Mild Steel (St 32) |
|---|---|
| Tensile Strength | 400(MPa) |
| Young's modulus | 200(GPa) |
| Density | 7750(Kg/$m^3$) |
| Poisson's ratio | 0.31 |
| Heat Conductivity | 50(W/mK) |
| Hardness | 120(HB) |

**Table 22.2** Material properties of closed type gearbox casing

| Name of the material | Gray Cast Iron |
|---|---|
| Tensile Strength | 250(MPa) |
| Young's modulus | 150(GPa) |
| Density | 7150(Kg/m$^3$) |
| Poisson's ratio | 0.27 |

In the design of gearbox casing of the Box Truss type design only one truss (the diagonal element of the Open type Gearbox Casing) was given because we had found through the analysis part that the design was safe, not in its critical zone and was able to withstand the vibrations. So only one truss was given on each side of the Box Truss type Gearbox Casing (BTGBC).

The spur gears are designed which consists of 17 tooth pinion ($T_p$) and 78 toothed gears ($T_g$) running at 240rpm and ranging up to 840rpm, to calculate the Factor of Safety ($f_s$) and to prove the gear design is satisfactory. By calculating Torque transmitted by the gears, pitch line velocity, velocity factor, effective load, permissible bending stress and Lewis factor we resulted at a Factor of Safety ($f_s$) of 1.58 and 1.76 for Static and Dynamic conditions respectively.

Torque transmitted by the gears:

$$M_t = \frac{60 * 10^6 * Kw}{2\pi n} \tag{1}$$

Static load:

$$P_t = \frac{2M_t}{d_p} \tag{2}$$

Dynamic load:

$$= \frac{21v(Ceb + P_t)}{21v + (\sqrt{Ceb + P_t})} \tag{3}$$

Factor of safety:

$$f_s = S_p/P_{eff} \tag{4}$$

Transmission shafts are subjected to axial tensile force, bending moment or torsional moment or their combinations. Most of the transmission shafts are subjected to combined bending and torsional moments. The design of transmission shafts consists of determining the correct shaft diameter from strength and rigidity considerations. The calculation of shaft diameter was done by considering the following:

When the shaft is subjected to axial tensile force, the tensile stress is given by:

$$= 4P/\pi d^2 \tag{5}$$

When the shaft is subjected to pure bending moment, the bending stress is given by:

$$= 32M_b/\pi d^3 \tag{6}$$

When the shaft is subjected to pure torsional moment, the torsional shear stress is given by:

$$= [M_b*(d/2)]/(\pi d^4/64) \tag{7}$$

According to Maximum Shear Stress Theory, the principal shear stress is:

$$d^3 = \frac{\left[16 * \sqrt{M_b^2 + M_t^2}\right]}{\pi * \tau_{\max}} \tag{8}$$

There are two shafts in the gearbox, shaft diameter is calculated according to the maximum shear stress theory. The diameter of the first shaft and second shaft are 80mm and 60mm respectively. Lastly machine learning algorithm was implemented to derive mode shapes.

In general, machine learning algorithms are used to make a prediction or classification. Based on some input data, which can be labelled or unlabeled, your algorithm will produce an estimate about a pattern in the data. If the model can fit better to the data points in the training set, then weights are adjusted to reduce the discrepancy between the known example and the model estimate. The algorithm will repeat this "evaluate and optimize" process, updating weights autonomously until a threshold of accuracy has been met.

ML helps in finding the maximum number of frequencies and the deformations and shows the resonance frequency points by which we can avoid deformations in the casing and by increasing the density of the metal at that point or by using external dampers.

## 5. Results

In this study, efforts are made to introduce mild steel Box Truss type Gearbox Casing (BTGBC) and study the structural behavior of box truss gearbox casing for the speed ranging from 240 rpm to 840 rpm under both static and dynamic conditions.

In the above experimentation, for the Box Truss Gearbox Casing (BTGBC) a series of analysis was done in comparison with Closed Type Gearbox Casing (CTGBC) to check the deformation at different locations of the gearbox housing. (Figure 4 and Figure 5 shows Simplified model of CTGBC and BTGBC respectively for analysis)

Structural analysis was done to calculate the nodal displacements, later from which stresses, strains and reaction forces could be derived. Later, it is then followed by Finite Element Method (FEM) which helps in numerically solving the differential equations arising in engineering and mathematical modelling which is implemented to identify behavior of complex structures. Meshing is done in Finite

Element Analysis (FEA) to get accurate solution and improve the quality of the solution. (Fig. 22.6 and Fig. 22.7 shows the meshed model of CTGBC and BTGBC respectively.)

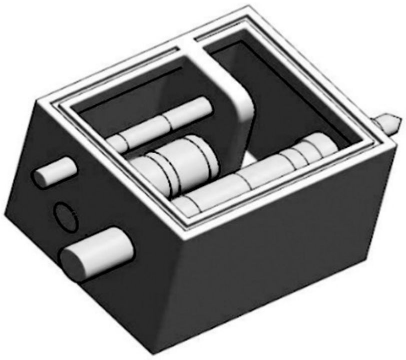

**Fig. 22.4** Simplified model of closed gearbox

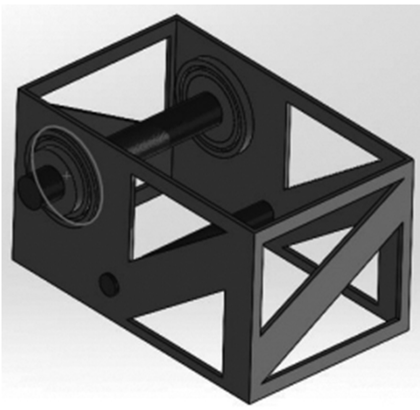

**Fig. 22.5** Simplified model of box truss gearbox

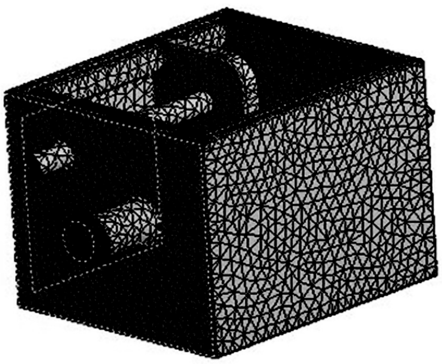

**Fig. 22.6** Meshed model of closed gearbox

From the experimental results of Static Analysis which is on the BTGBC to calculate the deformation (in mm.) and equivalent von mises stresses (in MPa) at each speed we can say that as speed increases deformation and stress concentration increases. The below table (Table 22.3) shows the Static Analysis results on Box Truss type Gearbox Casing (BTGBC).

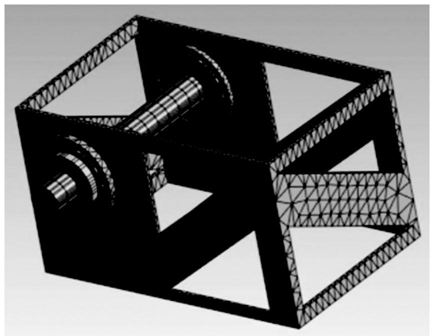

**Fig. 22.7** Meshed model of box truss type gearbox

**Table 22.3** Static analysis on box truss type gearbox (deformation and maximum stresses in BTGBC)

| S No | Output speed (rpm) | Maximum deformation (mm) | Maximum stresses (MPa) |
|---|---|---|---|
| 1 | 240 | 0.046 | 6.38 |
| 2 | 250 | 0.050 | 6.92 |
| 3 | 280 | 0.062 | 8.69 |
| 4 | 315 | 0.079 | 10.99 |
| 5 | 355 | 0.101 | 13.96 |
| 6 | 450 | 0.162 | 22.44 |
| 7 | 560 | 0.251 | 34.76 |
| 8 | 710 | 0.404 | 55.87 |
| 9 | 840 | 0.565 | 78.20 |

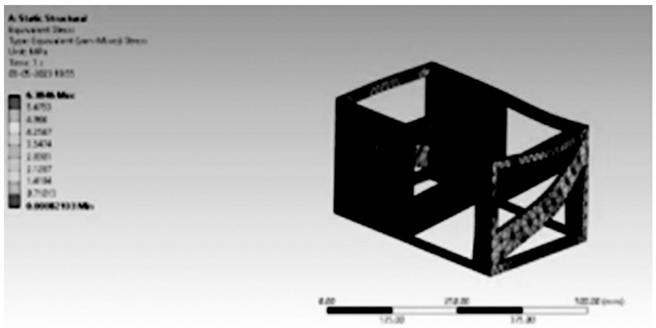

**Fig. 22.8** Maximum deformation in static response at 240 rpm

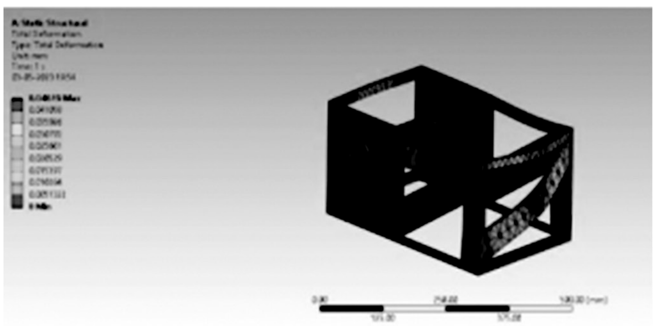

**Fig. 22.9** Equivalent stress in static response at 240 rpm

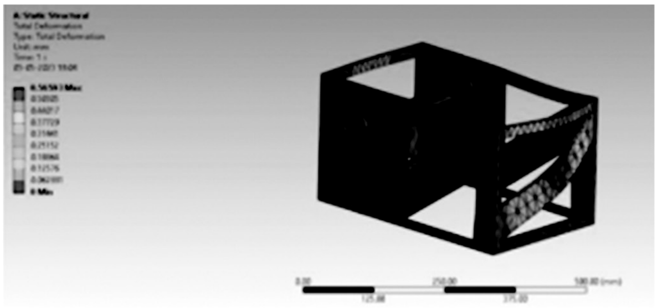

**Fig. 22.10** Maximum deformation in Static Response at 840 rpm

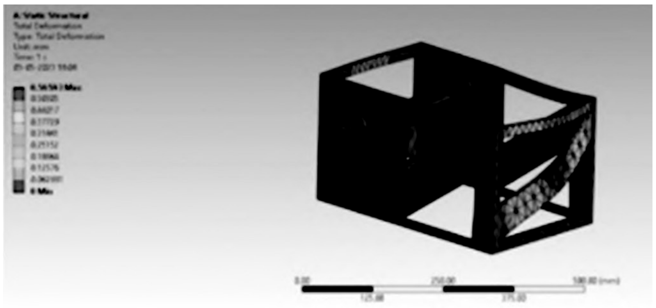

**Fig. 22.11** Equivalent stress in static response at 840rpm

From Modal Analysis test results, we can find deformation, deformation location and mode of bending at corresponding natural frequency levels. Table 22.4 shows the occurrence of mode shapes at different frequency levels.

**Table 22.4** Mode shapes of box truss type gearbox

| Mode Shape | Frequency (Hz) | Deformation Location | Types of Mode |
|---|---|---|---|
| 1 | 277.31 | Right & left Top edges | Bending along y axis |
| 2 | 326.35 | Front Top edge | Bending along x axis |
| 3 | 399.27 | Left Top edge | Twisting along yz plane |
| 4 | 587.36 | Right top edge | Bending along y axis |
| 5 | 666.53 | Bottom shaft | Bending along xy & yz plane |

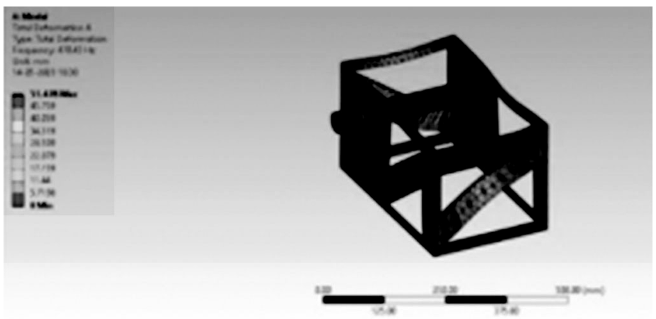

**Fig. 22.12** 1st mode shape of box truss type gearbox

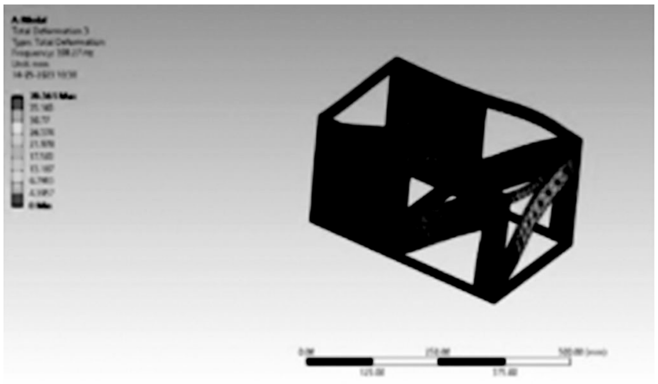

**Fig. 22.13** 2st mode shape of box truss type gearbox

Harmonic Analysis is used to develop the Frequency Response Function of the natural frequencies using the ANSYS tool. It is carried out with the given boundary conditions for different speeds in Box Truss Gearbox model. At each speed, torque transmitted is calculated which is shown in the table (Table 22.5) below.

**Table 22.5** Calculation of torque for 5 speeds

| S. no | Input speed (rpm) | Output speed (rpm) | Torque (N-mm) |
|---|---|---|---|
| 1 | 1410 | 240 | 29856 |
| 2 | 1410 | 250 | 28645 |
| 3 | 1410 | 280 | 25579 |
| 4 | 1410 | 710 | 10086 |
| 5 | 1410 | 840 | 8528 |

After thorough calculation of the analysis results and later integrating it with the Machine Learning algorithm we could generate a tabular column showing deformation (in mm) and different modal & resonance frequencies level (in Hz).

**Table 22.6** Machine learning results

| S. no | Frequencies (Hz) | Deformation (mm) |
|---|---|---|
| 1 | 277 | 14.377 |
| 2 | 278 | 14.895 |
| 3 | 279 | 15.899 |
| 4 | 280 | 16.343 |
| 5 | 281 | 17.568 |
| 6 | 282 | 18.922 |
| 7 | 283 | 19.211 |
| 8 | 284 | 20.564 |
| 9 | 285 | 21.245 |
| 10 | 286 | 22.584 |
| 11 | 306 | 29.102 |

| S. no | Frequencies (Hz) | Deformation (mm) |
|---|---|---|
| 12 | 316 | 33.879 |
| 13 | 326 | 35.624 |
| 14 | 336 | 37.445 |
| 15 | 346 | 38.696 |
| 16 | 356 | 39.398 |
| 17 | 366 | 40.866 |
| 18 | 374 | 42.478 |
| 19 | 376 | 42.865 |
| 20 | 386 | 45.96 |

## 6. Discussion

As metal ores are getting depleted day by day and foundry technology is getting extinct and produces high amount of radiation, so slowly technology is becoming obsolete. Therefore, to minimize the usage of material an effort was made to introduce mild steel as gearbox casing material instead of using denser grey cast iron as the casing material. To reduce material further in mild steel we had chosen Box Truss type/Open Box type design over the Closed Box. Oil spill/Lubricant spill is managed by a Transparent Sheet made of polycarbonate. Theoretical analysis was performed (i.e., Structural Analysis and Dynamic Analysis) on ANSYS to study deformation of the casing and found that gray cast iron casing has less deformation than mild steel casing. However, mild steel casing is not in a critical zone. Lastly, Artificial Intelligence (AI) was implemented to study different mode shapes (in software package ANSYS has a limitation in understanding/reading out those values). In AI we could extract/ derive "n" number of mode shapes.

Vibrational experimentation on gearbox casing is done using a vibration tester/Accelerometer in which we obtain vibration testing parameters like vibration acceleration, vibration velocity and vibration displacement that means amplitude.

A sensor connected to the accelerometer should be placed on the machine at different points or locations of maximum deformation obtained from modal analysis. (Vibrational accelerations, velocities and displacements are observed.)

Figure 22.14 shows the Maximum Deformation Locations on the gearbox casing when it is made to run at a speed ranging from 240rpm to 840rpm.

At different speeds of the gearbox we obtained different vibration velocities, accelerations, and displacements at the above-mentioned locations.

Figure 22.15 shows the working model of Box Truss type Gearbox Casing (BTGBC).

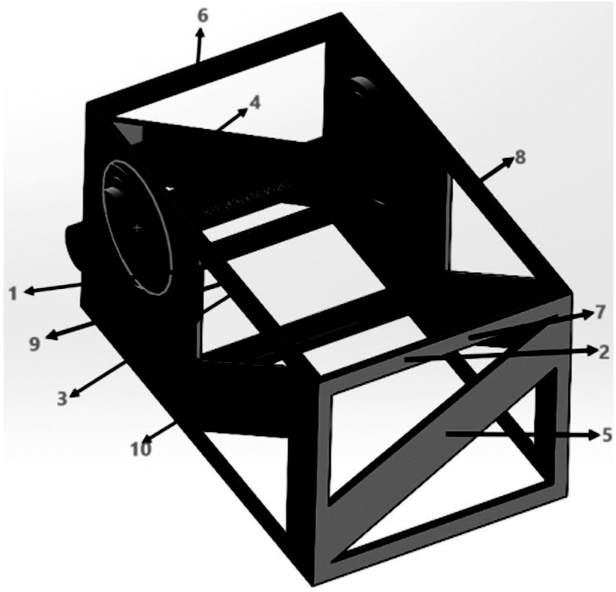


**Fig. 22.14** Maximum deformation location

**Fig. 22.15** Fabricated model of the box truss type gearbox casing (BTGBC)

## 7. Conclusion

The gear train is designed based on kinematic ray diagram and mechanics of design of machine elements for 12 RPMs and 1HP motor. CTGBC (Closed Type Gearbox Casing) and BTGBC (Box Truss type Gearbox Casing) were designed using gray cast-iron and mild steel materials respectively. Modal analysis is performed to study the behavior of both casings under different speed conditions. For all speeds and frequencies, the CTGBC has 15-25% less deformation and stresses in static analysis compared to BTGBC. However, the deformation and maximum stresses thus developed is BTGBC are within the limits and design is safe.

The important property for good functioning of gearbox is high damping property. As per the literature, the damping coefficient of gray cast iron is $30x10^{-3}$ whereas, for mild steel is $1.4x10^{-3}$. However, in the current project, an effort is made to study the behavior of mild steel box truss gearbox under dynamic and static conditions. The theoretical study reveals that mild steel in spite of having inferior damping property can withstand deformation and maximum stresses in peak conditions. In addition to it, to withstand higher frequencies greater than 350 Hz, dampers have to be introduced at the inner lines of BTGBC.

It is observed that 6 to 11 % variations in maximum deformation between CTGBC and BTGBC been noticed in modal analysis, whereas in harmonic analysis there is 10-15% variations in amplitude at lower frequencies and 40-50% variations in amplitudes at higher frequencies. Velocity of CTGBC is observed to be 10-15% less than BTGBC at lower frequencies, whereas the acceleration of CTGBC is 10-15% less than BTGBC at lower frequencies. Hence, BTGBC is observed to be safe at lower frequencies up to 350Hz.

According to the experimental results, it is observed that there is around 10-15% variation between the experimentation and Ansys results. Resonance frequencies were derived using Machine learning by which we can reduce even more stress and deformations by using additional supports or by increasing the density of the material at those particular locations.

The advantages of BTGBC over CTGBC are, the weight of the structure of BTGBC is reduced thus reducing the overall payload, fabrication process is easier and fast compared to foundry manufactured method, cost of the gray cast-iron is 45% higher than mild steel hence the overall cost of BTGBC is reduced.

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