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HARMONIC RESPONSE ANALYSIS OF GEARBOX

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ABSTRACT

Gearbox is a structural member that provides support to the gear train that it houses. All loads from the gears are transferred on to the gearbox through bearings which support the shaft and connect them to gearbox, which in turn is passed to the chassis. The loads acting on the gearbox are of two types, one that acts due to meshing of the gear, and the other that acts due to unbalance in any parts of the gearbox. The load acting due to unbalance is sinusoidal in nature and hence it is necessary that harmonic response analysis is conducted on the gearbox so that it does not fail under this condition. In this paper, a gearbox for hybrid transmission system has been designed on which modal and harmonic response analysis has been done to find the stress and the safe operating frequencies for different materials to avoid resonance.

Keywords: harmonic, sinusoidal, resonance.

INTRODUCTION

Vibration is a mechanical phenomenon that occurs in machines with components that are in movement. Each machine has a specific vibration signature related to the construction and state of the machine. If this machine is made to operate in ranges it is unfamiliar with (due to defects, peaks in input parameters, external factors etc.) then resonance occurs due to which the machine can break down. Hence, it is necessary to carry out harmonic analysis to identify operating ranges and maximum frequency of operation. In an automobile, gearbox which houses the gear train undergoes this effect. It is a structural component that undergoes loading of varying magnitude. In this paper, modal and harmonic analysis performed for different materials of gearbox to find stress, deformation and safe operating ranges to avoid resonance is covered.

The gearbox is a load bearing structure that should have enough stiffness to prevent resonance. Research work has verified ANSYS modal analysis result with experimental result proving the accuracy of the software [1]. Four commonly encountered local faults, tooth wear, tooth crack, broken tooth and insufficient lubrication of the gear tooth breakage are the main reasons for vibration in the gearbox, out of which broken tooth leads to maximum vibration [2]. The unbalance caused due to broken teeth is similar to having a weight at a given eccentricity, which is calculated using balancing equations [3].

In this paper, a gearbox that has been designed for a uniquely developed power-split transmission system has been chosen. This gearbox was designed in SOLIDWORKS as shown in Figure-1. It has been divided into two parts with them forming an assembly. The length, width and height are 491.95mm, 205mm and 262.43mm respectively. The mounting points were decided after conducting static structural analysis on the gearbox which were increased each time the gearbox failed. This was done to ensure that there are minimum mounting points needed in the gearbox, hence reducing the cost of it.

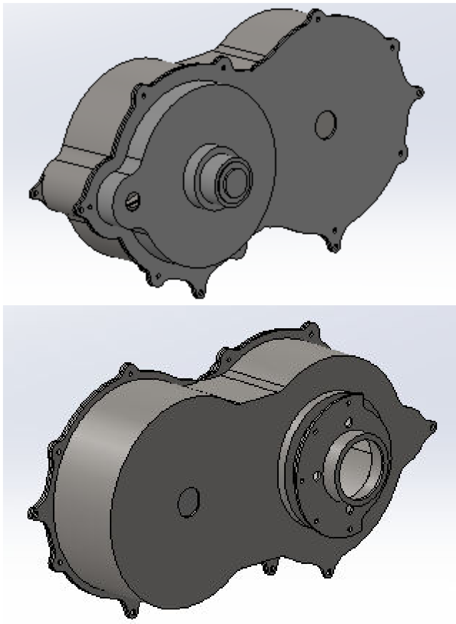

Figure-1. Gearbox 1 & 2.

Gearbox undergoes fatigue loading due to the nature of the operation. There are two kinds of loads that act on the gearbox at any given point of time:

a) Load due to torque transmitted by the gear

b) Load due to any defects in the gear sets or the shaft.

These loads that are acting, change with time which makes analysing the gearbox complex. There are four major defects that are possible in gears:

- Tooth meshing faults
- Misalignment
- Cracked and/or worn teeth

- Broken teeth

Out of these defects, broken teeth cause the maximum forces to act on the gear box due to creating an unbalance at eccentric position. The gears that this gearbox set houses are shown in Table-1. The highlighted gear is chosen as it has the highest pitch circle diameter and mass compared to the rest.

Table-1. Gears and their pitch diameter values.

S. No.	**Gear**	**Pitch dia** (mm)	**Material**	**Mass** (kg)
1	Sun and engine gear	42	EN-24	0.159
2	Planet	63	EN-19	0.596
3	Ring (with external and internal teeth)	168	EN-19	1.478
4	Mating with engine gear	168	EN-24	2.280
5	Reduction gear	105	AISI 4140R	0.652

CALCULATIONS

Calculation for the force caused due to a broken tooth of the selected gear is done and is compared with another gear of smaller diameter to establish that the gear with larger pitch diameter causes more force. The following formulas have been used to calculate the force caused due to eccentricity.

Natural frequency $\omega = \sqrt{(k/m)}$

Frequency ratio $r = \Omega/\omega$

Displacement $X_o = \frac{(m_u r^2 e/m)}{\sqrt{(1-r^2)^2+(2\zeta r)^2}}$

Force $P_o = m_u e \Omega^2[(1+(2\zeta r)^2)/((1-r^2)^2+(2\zeta r)^2)]^{1/2}$

Table-2. Calculation of force caused due to eccentricity.

Parameter (symbol , unit)	**Reduction gear**	**Mating with engine gear**
Mass of gear (m , kg)	0.652	2.28
Stiffness (k , N/m)	1420000	1420000
Unbalance mass (m_u , kg)	0.0015	0.0015
Eccentricity (e, m)	0.0525	0.084
Damping ratio (ζ)	0.02	0.02
Speed of motor(N, rpm)	1750	1750
Natural frequency(ω, rad/s)	183.17	183.17
Omega (Ω ,rad/s)	1475.78	789.18
Frequency ratio (r)	0.12	0.23
Displacement (X_o , m)	$1.05*10^{-5}$	$3.01*10^{-5}$
Force (P_o , N)	2.68	4.47

As observed in Table-2, the force caused by the gear mating with engine gear is higher than the other reduction gear. This force will change its direction sinusoidally as the gear turns. Along with this force, torque due to gears' meshing will be transmitted to gearbox through the shaft which is calculated by appropriate positioning of bearings and gears on the shaft. Weight of the gears are also measured and added to the forces acting due to torque transmission, hence the magnitude and direction of forces on the shaft are defined. Calculations are done as per American Society of Mechanical Engineers (ASME) standards. An example of solid shaft is as shown in Figure-2, where the mass of gears, radial and tangential forces transferred by them are indicated.

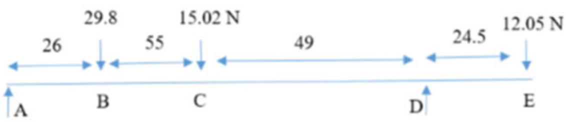

Figure-2. Line diagram of solid shaft.

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The forces acting due to meshing of the gear which is mating with engine gear is calculated in the following method:

$$\text{Torque}=\frac{9.55*10^3*P}{N}=\frac{9.55*10^3*14}{1750}=76.4\text{ Nm}$$

$$D=m_o*z=1.75*96=168\text{mm}$$

$$M=F_t*R$$

$$76.4*10^3=F_t*(168/2)$$

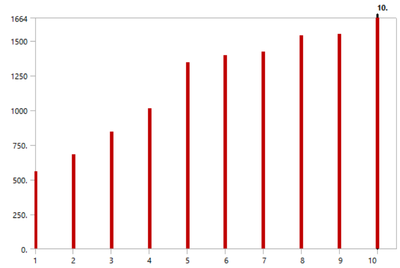
$$F_t=909.52\text{N}$$

$$F_r=F_t\tan(\varphi)=909.52*\tan 20=331.03\text{ N}$$

Similarly forces due to each individual gear is calculated and applied to those sections of the gearbox that hold the bearings which support the shaft. For analysis, the mounting points on the gearbox are considered to be fixed geometry. Modal analysis is done for seven different materials to find the 10th node. Harmonic analysis is then conducted to calculate the structure's response at several frequencies to obtain a graph of displacements versus frequency. From this analysis, for different materials, the operating range has been established and material with minimum deflection at operating frequency has been identified.

METHODOLOGY

The gearbox assembly that was modelled on SOLIDWORKS is imported to ANSYS 15.0. Required material values are stored in engineering data. Modal analysis is chosen as the analysis system first to find out 10 modal frequency values. The mounting tabs are fixed after which solution is found. Figure-3 is an example of modal analysis done for AISI 4130 material. Harmonic response analysis system is selected next. Material is appropriately chosen and in analysis setting, two times the 10th modal frequency value obtained is applied in range maximum. So the analysis will be conducted from 0-3327.6 Hz for AISI 4130 material. Mounting tabs are fixed and the forces are applied at the bearing positions after including the unbalanced force calculated previously as well. Equivalent von-mises stress, deformation, frequency response for normal stress and directional deformation are selected in solution and system is solved.



Mode	Frequency [Hz]
1.	556.34
2.	678.86
3.	839.73
4.	1008.9
5.	1340.9
6.	1390.9
7.	1416.9
8.	1535.2
9.	1546.4
10.	1663.8

Figure-3. Modal analysis for AISI 4130.

RESULTS

Operating frequency calculated for the system is 235 Hz. Equivalent von-mises stress and deformation are found at this frequency to see the behavior of the system. From Table-3 it can be observed that Nylon and polycarbonate which are also materials with which gearboxes are manufactured in addition to general cast iron, aluminium usage, fail. The stress and deformation values are higher than their tensile limit strengths. Their maximum operating frequency is also lower compared to the rest of the materials which is also less than the operating frequency of the system. This will lead to resonance and breakdown of the system. Stainless steel provides the best results compared to all the materials tabulated. It has the least deformation and is among the materials that have least stress and high operating frequency. Maximum operating frequency is the value at which if system operates, resonance takes place leading to a greater amount of damage. Hence, further or higher the value better are the chances for the system not to reach that point.

Table-3. Stress, deformation and maximum operating frequency of different materials.

S. No.	Material	**Stress** (MPa)	**Deformation** (mm)	**Maximum operating frequency** (Hz)
1.	Stainless steel	47.755	0.0302	559.37
2.	Cast iron	63.219	0.049	469.31
3.	AISI 4130	59.944	0.032	556.34
4.	Aluminium	59.455	0.097	542.93
5.	Brass	67.212	0.075	364.74
6.	Nylon	1283.1	197.57	189.61
7.	Polycarbonate	1406.8	180.03	155.81

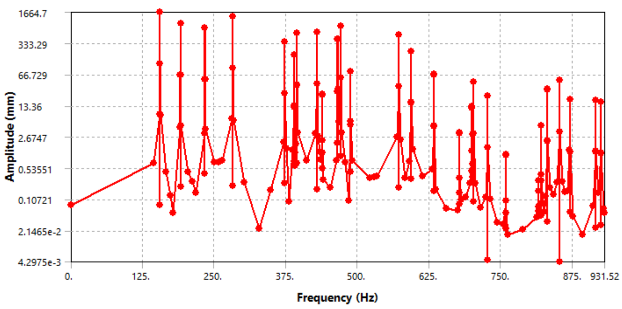


Figure-4. Directional deformation v/s frequency graph for polycarbonate material.

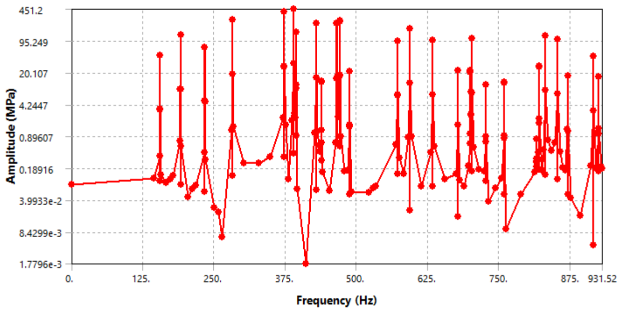


Figure-5. Normal stress v/s frequency graph for polycarbonate material.

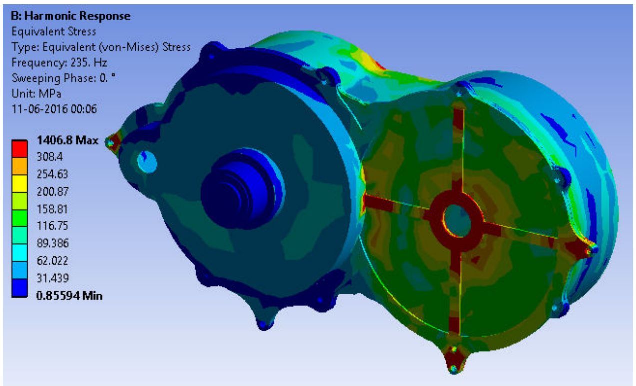


Figure-6. Equivalent von-mises stress of polycarbonate material.

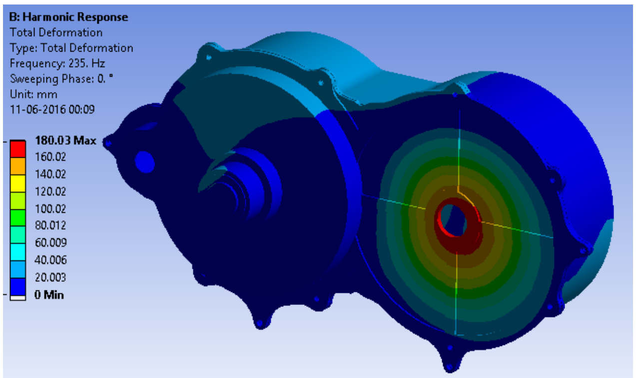


Figure-7. Deformation of polycarbonate material.

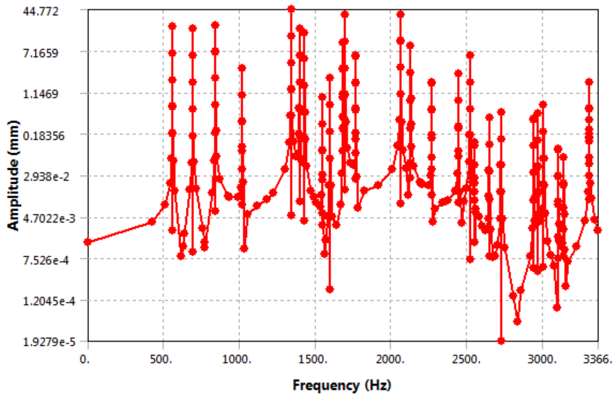


Figure-8. Directional deformation v/s frequency graph for stainless steel material.

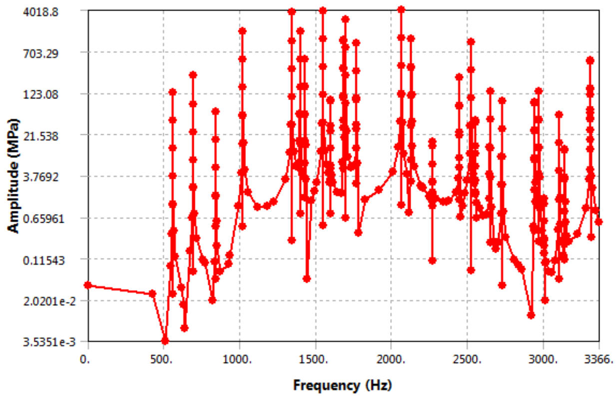


Figure-9. Normal stress v/s frequency graph for stainless steel material.

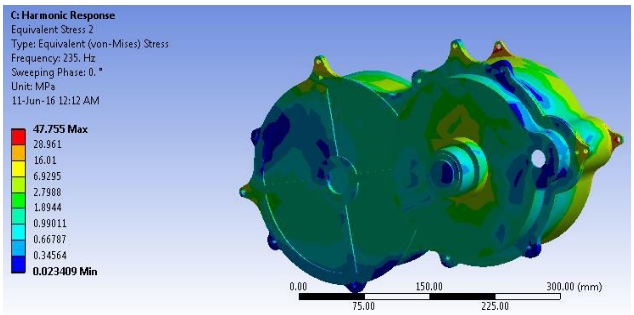


Figure-10. Equivalent von-mises stress of stainless steel material.

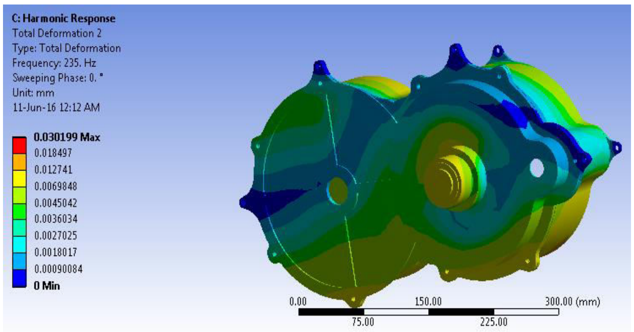


Figure-11. Deformation of stainless steel material.

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