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Investigation of Modal Parameters on Planetary Gearbox using Finite Element Analysis to Minimize Vibration

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Abstract— **The advantage of a planetary transmission is determined by load distribution over multiple planet gears. It is thereby possible to transfer high torques utilizing a compact design. The designed transmission system comprising two degrees-of-freedom compound planetary gear train with two conjoined planetary gear trains and four torque-transfer devices. The different combinations of states of various torque-transfer devices yield multiple modes of operation. Planetary gears have problem of vibration. Since a planetary gear has internal and external meshes in several gear pairs, power distribution is unequal in gears, and loads can be concentrated in a specific planet gear. These vibrations are transferred to the gearbox casing through shafts and bearings. As the gearbox is coupled to engine, there are more probabilities of coincidence of natural frequency of engine and gearbox which causes resonance and leads to damage in gearbox. The natural frequencies and mode shapes are important parameter in the design of a structure for dynamic loading conditions. Subsequently, it is necessary to investigate modal parameters of gearbox and study the dynamic characteristics of gearbox. In this work, modal analysis is done using Finite Element Analysis and results shows range of frequencies obtained is suitable for gearbox which can avoid maximum amplitude of vibration and hence resonance. Dynamic analysis in ANSYS is used to solve the vibration problem, by using the modal analysis method of dynamic analysis; natural frequencies and mode shapes of systems are found out. The fundamental frequency obtained by the analysis is 87.015 Hz which is far away from the forcing frequency which is engine frequency in the range of 30-50 Hz and avoids resonance. Results of modal analysis after structural modification are also presented which shows enhancement in rigidity of the gearbox.**

Index Terms— Planetary gear transmission system, Modal Analysis, Natural Frequency, Mode shape, Finite Element Analysis

I. INTRODUCTION

Noise and vibration in the environment or in industry are caused by particular processes where dynamic forces excite the structures. The noise and vibration effects leads to annoyance, fatigue and reduced comfort, safety issues and even health hazards. Most vibration problems are allied to resonance phenomena. Resonance occurs when the dynamic forces in a process excite the natural frequencies in the surrounding structures. This is the object to study and investigate the modal parameters and they also form the basis for a complete dynamic description of a structure.

As the significance of dynamic behavior of engineering structures is better appreciated, it becomes important to design them with proper consideration of dynamics. Finite element analysis as a computer modeling approach has provided engineers with a versatile design tool, especially when dynamic properties need to be examined. This numerical analysis requires rigorous theoretical direction to discover meaningful outcomes in relation to structural dynamics. An important part of dynamic finite element analysis is modal analysis.

Modal analysis process determines the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a mathematical model for its dynamic behavior. The formulated mathematical model is referred to as the modal model of the system and the information for the characteristics is known as its modal data. The dynamics of a structure are physically decomposed by frequency and position.

Parag V. Bute et al had done vibration analysis by using finite element method as a computational technique and validating it by physical experimentation using FFT analyzer. This can be an important tool while designing the gear housing free from fatigue failures caused by the resonance. The design of the gear housing should incorporate a methodology for dealing with factors causing vibrations and to promote scientific means to minimize the effects of resonance. Also FEA method was used to study the dynamic properties such as mass, stiffness of gear housing under consideration[1]. Nilofar Hajikhan Pathan et al reviews the test procedure and system identification of modal analysis but discuss the main practical problems with which engineers, performing modal analysis on industrial structures are confronted on a daily basis. They used a numerical approach to develop theoretical models of the behavior of spur gears in mesh, to help to predict the effect of gear tooth stresses and transmission error. The method utilizes software in the FEA domain for analyzing the effects of the variation in the values of the design parameters influencing the modal behavior. Also the computational approach will give the results more close to practical values through simulation[2]. Ashwani Kumar et al studied the loose fixture mounting effect of heavy vehicle transmission gearbox housing. This study was completed in three phases. In first phase the aim was to find the actual suitable boundary condition. After finding the boundary condition in second phase the fixture bolts were loosened to monitor the effect of looseness and in third phase the positional looseness based study was completed. The looseness of transmission housing causes heavy vibration and noise. In order to prevent this noise and vibration the transmission housing is tightly mounted on the chassis frame using bolts. Truck transmission system determines the level of noise together with the chassis, engine and bodywork. Vehicle transmissions under torsional vibration condition caused rattling and clattering noises. Reciprocity principle was used to determine the failure frequencies for transmission housing. In reciprocity principle gear and shafts are suppressed and all the forces transmitted through the bearings are applied on the empty housing. FEA based ANSYS 14.5 has been used as analysis tool. [3]. R.V. Nigade et al reports finite element analysis and modal testing of gearbox top cover of an integrally geared centrifugal compressor. Modal analysis involved extraction of mode shapes and natural frequencies. Impact testing using hammer excitation was used to experimentally determine the vibration properties of the gearbox top cover. Authors also conducted a parametric study using FEA, to study the effect of wall thickness and rib thickness of gearbox top cover on its natural frequencies and associated mode shapes [4]. Mr.Vijaykumar, et al has discussed about the vibration analysis of gear-box using FEA. An ANSYS Software is used to find out the natural frequency and harmonic frequency of gear-box casing resulting into the determination of range of frequencies to avoid resonance. The modal analysis is done to find Natural Frequency and Harmonic Frequency. The results of both are compared and vibration analysis is done on the gear-box. The fault detection and diagnosis is done from the given vibration analysis[5]. Shrenik M. Patil et al did the analysis of entire gearbox casing. They were calculated the natural frequencies of model in free-free conditions using Ansys10, and by applying the boundary conditions also to compare with experimental and operating frequencies[6]. Shuting Li had done fundamental study on resonance frequency behavior of three-dimensional, thin-walled spur gears from experimental tests and finite element analyses. Effects of gear wall thickness, teeth mesh stiffness and assembly errors on resonance frequency behavior of the thin-walled gears are also investigated experimentally and peak speeds of the thin-walled gears are measured. Natural frequencies and mode shapes of the lump-mass model system are analyzed. Effects of tooth module, web thickness, web position, rim thickness, face width and gear hub on natural frequencies of the thin-walled gears are investigated by FEM calculations[7]. D.S. Chavan, et al perform the modal analysis of power take off gear box to measure the natural frequency and obtain mode shape pattern. The analysis is done both by analytical and experimental methods. After analyzing the data from both methods, the resonance found for one of the component of gearbox. This creates the vibrations in the gearbox. FEA is done for this component with modifications to avoid the resonance. Mode shapes and frequencies obtained from EMA & FEA methods are used to understand the generation of vibration in PTO gearbox & to provide recommendations to reduce it[8]. Tianmu ZHANG et al constructed an analysis model of planetary gearbox housing based on finite element method/boundary element method (FEM/BEM). Its vibration and acoustic radiation characteristics were investigated. The finite element model is established using ABAQUS. The main factors affecting its dynamic characteristics were observed through modal analysis. Then impact of main structural parameters on transmission characteristics was investigated. The acoustic radiation analysis model was established using VA-One on the basis of vibration characteristics analysis. [9]. Bagul A. D et al studied the application of ANSYS software and also FFT analyzer to determine the natural vibration modes and find the free frequency of the Gearbox casing. The result of analysis can show the range of natural frequencies of gearbox casing component with maximum amplitude of it. The mass and stiffness matrices are then determined by exact analytical integration[10]. The research carried out by Abhinav Saxena et al has focused on gear teeth faults and available methods could not detect a crack in the planetary gear plate under all operating conditions. A wavelet domain methodology was suggested for the analysis and feature extraction of the vibration data from the planetary gear system of military helicopters. Complex Morlet wavelets were employed and the time domain knowledge, preserved by the wavelet decomposition, is used to extract useful features that distinguish between faulted and healthy gear plates from experimental data made available from both on-aircraft and test cell experiments. A statistical method based on the z-test was also suggested to evaluate the relative performance of these features. [11].

. II. Finite Element Analysis

Finite Element Method has becomes a powerful tool for the numerical solution of a wide range of engineering problems due to large memory digital computers. Finite Element Analysis has become an integral part of Computer Aided Engineering (CAE) and is being extensively used in analysis and design of many real-life complex systems. While it started off as an extension method of matrix methods of structural analysis. In this section we discuss the modeling of gearbox casing, and finite element analysis of gearbox casing using FEA. Finite Element method (FEM) simulates a physical parts behavior by dividing the geometry into a number of elements of standard shapes, applying constraints. Uses of proper boundary conditions are very important since they strongly affect the results of the finite element analysis in modal analysis. The finite element method is a numerical method can be used for the accurate solution of complex mechanical and structural vibration problems. In this method, the actual structure is replaced by several pieces or elements, each of which is assumed to behave as a continuous structural member called a finite element. The elements are assumed to be interconnected at certain point known as joints or nodes. Since it is very difficult to find the exact solution of the original structure under the specified loads, a convenient approximate solution is assumed in each finite element. During the solution process, the equilibrium of forces at the joints and the compatibility of displacement between the elements satisfied, so that the entire is made to behave as a single entity.

Only linear behavior is valid in a modal analysis. If non-linear elements are specified, they are treated as linear. In the modal analysis, if contact elements are included in geometry, the contact should be bonded, their stiffness are calculated based on their initial status and never changed. Material properties can be linear, isotropic or orthographic and constant or temperature dependent. We must define both Young’s modulus (and stiffness in some form) and density (or mass in some form) for a modal analysis. Non-linear properties are ignored in the modal analysis. The procedure of Modal analysis using ANSYS Workbench is:

A. *Definition of Material Properties*

The material properties of the Steel material which are used for the analysis are given in Table I.

TABLE I
MATERIAL PROPERTIES OF MILD STEEL

Material Properties	Values
Elastic modulus, *E*	210 GPa
Poisson's ratio, μ	0.3
Density, ρ	7800 Kg/m^3

B. *Creation of Model*

The gearbox casing is made up of mild steel material. The model of gearbox casing is developed by using CATIA V5 R20 software. The model generated of the gearbox casing is shown in Figure 1. The file is saved with file extension as *.igs.

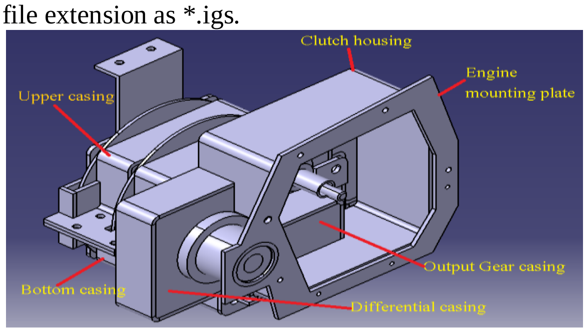


Figure 1. Geometry of Gearbox Casing

C. *Import of the Solid Model in ANSYS Workbench*

The saved file of solid model of the gearbox is imported in ANSYS Workbench.

D. *Mesh Generation of Solid Model*

Any continuous object has finite degree of freedom and it is not possible to solve in this format. Finite Element Method reduces degree of freedom of the system to be analyzed from infinite to finite with the help of discretization. All the calculations are made at limited number of points called as nodes. Entity joining nodes and forming a specific shape such as quadrilateral, triangular, hexahedral or tetrahedral etc. is known as Element. The geometry is meshed in mechanical model window of an ANSYS 14.5. The automatic mesh method is applied for the geometry. This method creates the hexahedron and tetrahedron elements according to geometry. For left side plates of casing, sweep method is applied with 3 numbers of divisions, which divides thickness of plate with 3 elements. The meshed Gearbox model is shown in Figure 2.

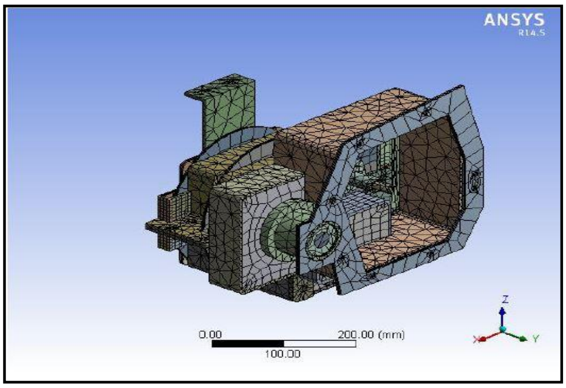


Figure 2. Meshed Geometry of Gearbox

E. *Application of Boundary Conditions and Loading Conditions*

The geometry is constrained with different boundary conditions as it is mounted on vehicle frame. These constraints are shown in Figure. 3 and described as:

1. Fixed support is used as it is fixed to frame, named B-mount of gearbox.
2. Frictionless support is used as engine is fixed on mounting plate. This support constrains motion of mounting plate in normal direction of plate surface.
3. The displacement of C-mount is constrains along the axis of gearbox and it is allowed to rotate about engine axis.

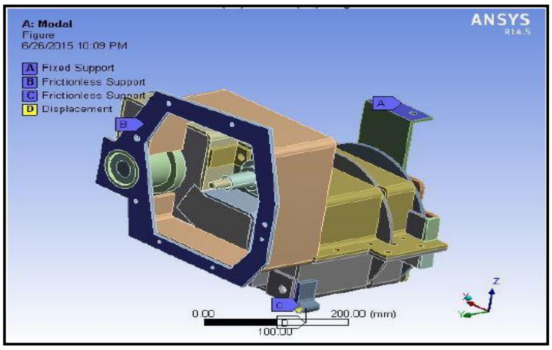


Figure 2. Meshed Geometry of Gearbox

F. *Setting setups as per type of analysis*

Settings are made in the software for modal analysis such as number of modes of vibration to be extracted as 6 and directional vectors to be selected. Total deformation option is selected for the solution of modal analysis.

G. Generation of the desired results:

After settings, the ANSYS model is pushed for solution. After solution, results are generated for the modes of vibration. The total deformations for first six modes are shown in Figures 5a, 5b, 5c, 5d, 5e, 5f.

III. Results of Modal Analysis

First, through modal analysis, the natural frequencies and vibration modes of all structure parts are determined, and then the parts where the vibration amplitude is comparatively larger are found out. Secondly, a comparison between the excitation frequency and the natural frequency is made, and tries to make external excitation frequency so as to avoid the natural frequency of gearbox. It imposes actual boundary conditions on the gearbox casing, carries on modal analysis, and then extracts the first six orders of principal modes from the results.

TABLE II
FIRST SIX NATURAL FREQUENCIES OF GEARBOX CASING

Mode Number	Natural Frequency, Hz
1	87.452
2	94.176
3	137.9
4	358.39
5	386.97
6	422.63

The result of natural frequencies obtained with ANSYS Workbench is also presented graphically as given in Figure 4:

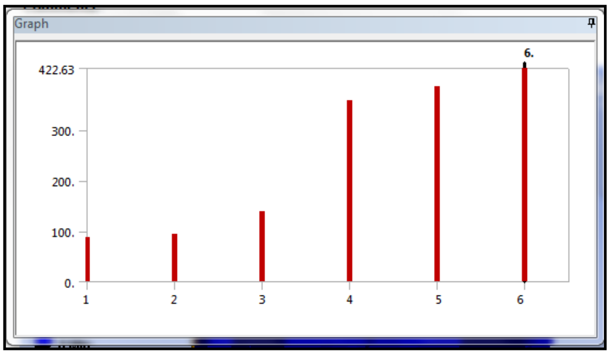
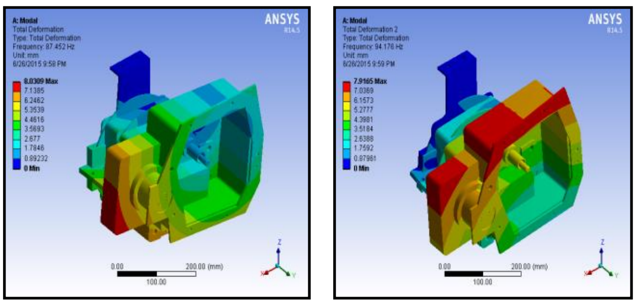
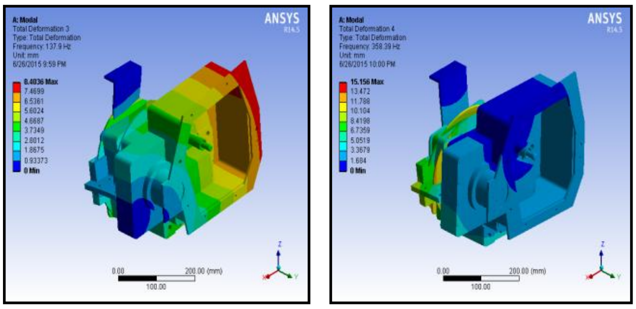


Figure 1. Graphical representation of natural frequencies with ANSYS

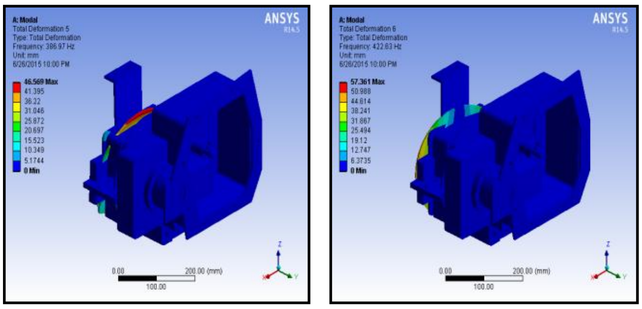
The total deformations in six modes of vibration are shown in figures below:



(a) (b)



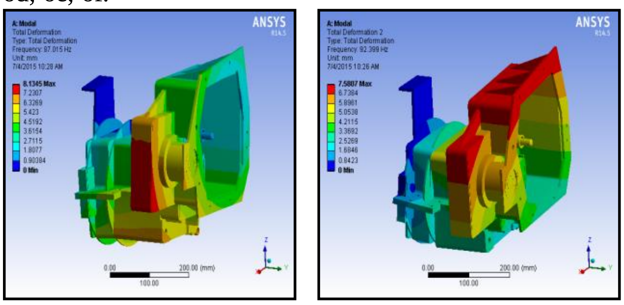
(c) (d)



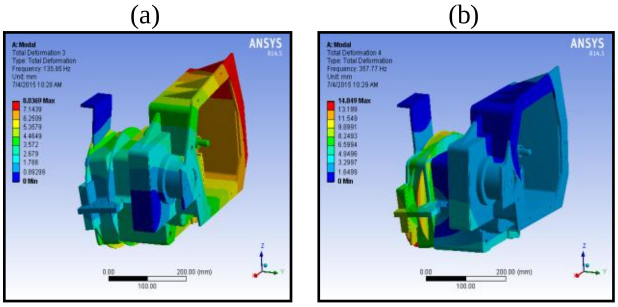
(e) (f)

Figure 5. Different modes of vibration at first 6 natural frequencies

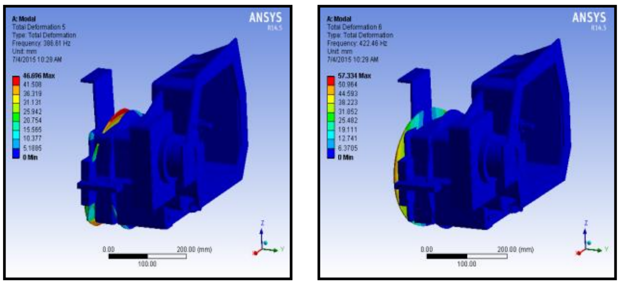
From the modal analysis results, it can be grasped that the first few low order modes of the gearbox mainly represent the vibration of gearbox. The vibration of the clutch housing and differential casing in gearbox casing assembly is not obvious. Thus it can be perceived that the rigidity of these parts is weaker than that of the upper casing, bottom casing and the supporting parts. On this basis that the structural material and structural style will not be altered, the stiffeners will be added on the clutch housing casing to enhance the structural rigidity of the weak parts. The results of mode shapes after adding stiffeners on clutch housing are shown in Figure 6a, 6b, 6c, 6d, 6e, 6f.



(a) (b)



(c) (d)



(e) (f)

Figure 6. Different mode shapes at different 6 natural frequencies after structural modification

The above results show enhancement in rigidity of gearbox casing and the total deformation in second, third and fourth natural frequency are reduced which is shown in Figures 6b, 6c and 6d. Deformation is reduced after structural modification by some amount. The reduction in total deformation of gearbox is presented in graph shown in Figure 7.

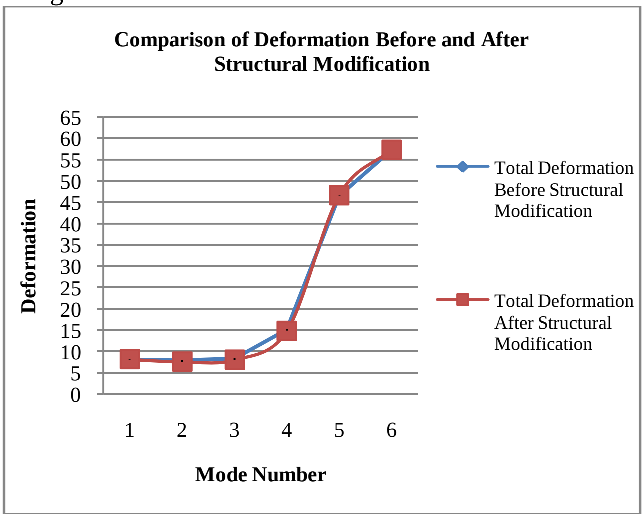


Figure 7. Comparison of deformation values before and after structural modifications

The FEM results of natural frequencies for gearbox before and after structural modification are tabulated in Table III.

TABLE III
NATURAL FREQUENCIES OF GEARBOX BY FEM

Mode	Frequency in Hz (Before Structural Modifications)	Frequency in Hz (After Structural Modifications)
1	87.452	87.015
2	94.176	92.399
3	137.9	135.85
4	358.39	357.77
5	386.97	386.61
6	422.63	422.46

Gearbox can be vibrated at various orientations. The first mode of vibration is the important mode. If forcing frequency of any harmonic component (engine) is close to the natural frequency of first mode of vibration, resonance occurred. At this condition the component is said to be running at critical speed. The fundamental frequency obtained after structural modification by the analysis is 87.015 Hz.

IV. Conclusions

The analysis result gives the range of frequency that is suitable for gearbox casing which can avoid maximum amplitude of vibrations. The fundamental frequency obtained after structural modification by the analysis is 87.015 Hz which is far away from the forcing frequency i.e. engine frequency which is in the range of 30-50 Hz. From the analysis it is possible to avoid critical speeds and hence to avoid resonance. Hence the results obtained in this analysis gives strong recommendation that there is no resonance occurs in gearbox.

Lastly all the result obtained from modal analysis after structural modification indicates reduction in deformation and enhancement in rigidity of gearbox structure which can be verified from Figure.7. It can be seen from the analysis results, modal parameters of the gearbox structure are investigated to minimize vibration using Finite Element Analysis.

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