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Performance Evaluation of Planetary Gear Train for Hybrid Transmission System

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ABSTRACT

Planetary gear box is designed for Hybrid vehicles for better fuel economy, control and efficiency comprising 2DoFcompound planetary gear train with two conjoined planetary gear trains and four torque-transfer devices. For better controlled operations of vehicles, different combinations of states of various torque-transfer devices used which yield multiple modes of operation. The planetary gear train allows the addition of power of two prime-movers to drive the load, which can split the power from one prime-mover into requirements of the energy storage system while catering to the output needs and provides a high over drive ratio, which permits regeneration even at moderate speeds. But, planetary gearboxes suffer from many practical problems like noise and 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. For this reason, the dynamic analysis of planetary gear train casing is more important. Modal analysis can provide natural frequencies and vibration modes which are essential information to learn about most of the dynamic characteristics of gearing systems. In this paper, study of vibration analysis is done using Finite Element Analysis.Performance evaluation of the planetary gearbox is done based on vibration response using Experimental Modal Analysis of gearbox casing. From the result, this analysis can show the range of the frequency that is suitable for gearbox casing which can prevent maximum amplitude. Experimental modal analysis has been carried out on the gearbox casing to verify the numerical method predictions of natural frequencies.

Keywords— **Experimental Modal Analysis, Finite Element Analysis, Natural Frequencies, Mode shapes**.

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I INTRODUCTION

A modal testing has become to identifying the understanding and simulating dynamic behavior and response of structure. Experimental modal analysis (EMA) or model testing is a non-destructive testing based on vibration response of the structures [1]. Impact hammer excitation is one of the most widely used techniques in modal analysis. The vibration response of the structure to the impact excitation is measured by signal analysis and transformed into Frequency Response Function by FFT technique. The measurement of the frequency response function is the heart of modal analysis. FRFs are used to extract such modal parameters as natural frequency and mode shape. In wide range of practical applications the modal parameters are required to avoid resonance in structures affected by external periodic dynamic loads. Planetary gears are used in a wide range of commercial and military applications. Their multiple load path design increases reliability and compactness. Noise generated by the planetary gear and vibration transmitted to the surrounding structure, however, are concerns among gear designers. Experimental modal analysis techniques are applied to characterize the planar dynamic behavior of two spur planetary gears. Rotational and translational vibrations of the sun gear, carrier, and planet gears are measured. Experimentally obtained natural frequencies, mode shapes, and dynamic response are compared to the results from lumped-parameter and finite element models [2]. ***Modal analysis can provide natural frequencies, modal damping and vibration modes which essential information is to learn about most of the dynamic characteristics of gearing systems [3].*** ZhipengFeng, Ming J.Zuo[4] gives information about Fault diagnosis of planetary gearboxes via torsional vibration signal analysis. Torsional vibration signals are theoretically free from the amplitude modulation effect caused by time variant vibration transfer paths due to the rotation of planet carrier and sun gear, and therefore their spectral structure are simpler than transverse vibration signals. Thus, it is potentially easy and effective to diagnose planetary gearbox faults via torsional vibration signal analysis. In a power transmission gear system, the vibrations generated at gear mesh are transmitted to the gearbox housing through the shafts and bearings. More degrees of freedom are required to get information about other modes of vibration and stress distribution. The complicated geometry of casing and the complex torque applied by cylinders make their analysis difficult. However, optimized meshing and accurate simulation of boundary conditions along with ability to apply complex torque provided by various FEM packages have helped the designer to carry torsional vibration analysis with the investigation of critical stresses. The natural frequencies of model in free-free conditions are calculated using Ansys10, and by applying the boundary conditions also to compare with experimental and operating frequencies [5]. One of the papers contains the study about vibration analysis for gearbox casing using Finite Element Analysis (FEA). In this paper authors apply ANSYS software to determine the natural vibration modes and forced harmonic frequency response for gearbox casing. In a lightly damped system when the forcing frequency nears the natural frequency the amplitude of the vibration can get extremely high. This phenomenon is called resonance (subsequently the natural frequency of a system is often referred to as the resonant frequency). In rotor bearing systems any rotational speed that excites a resonant frequency is referred to as a critical speed. If resonance occurs in a mechanical system it can be very harmful – leading to eventual failure of the system. Consequently, one of the major reasons for vibration analysis is to predict when this type of resonance may occur and then to determine what steps to take to prevent it from occurring. In this paper, the analysis is to find the natural frequency and harmonic frequency response of gear box casing in order to prevent resonance for gearbox casing [6]. Gearbox vibration signals are usually periodic and noisy. Time-frequency domain average technique successfully removes the noise from the signal and captures the dynamics of one period of the signals. Time domain techniques for vibration signal analysis as waveform generation, Indices (RMS value, Peak Level value, and crest factor) and overall vibration level do not provide any diagnostic information but may have limited application in fault detection in simple safety critical accessory components. The statistical moment as kurtosis is capable to identify the fault condition but skewness trend has not shown any effective fault categorization ability in this present gear fault condition. In frequency domain analysis, it is concluded that FFT is not a suitable technique for fault diagnosis if multiple defects are present on gearbox. The envelope analysis and Power Spectrum Density techniques have shown a better representation for fault identification. The Hilbert Transform and PSD techniques are suitable for multiple point defect diagnostics for condition monitoring. The study about vibration analysis for gearbox casing using Finite Element Analysis (FEA) is given in one of the papers. This analysis is to find the natural frequency and harmonic frequency response of gearbox casing in order to prevent resonance for gearbox casing. [7]. Most noise and vibration problems are related to resonance phenomena. Resonance occurs when the dynamic forces in a process excite the natural frequencies, or modes of vibration, in the surrounding structures. This is one reason to study the modes and second reason is that they form the basis for a complete dynamic description of a structure [8].

A. Experimental Modal Analysis

The Experimental modal analysis is a non-destructive testing based on vibration response of the structures. The technique widely used in modal analysis is based on impact hammer excitation. It is well known that (mechanical) structures can resonate, i.e. that small forces can result in important deformation, and possibly, damage can be induced in the structure. The majority of structures can be made to resonate, i.e. to vibrate with excessive oscillatory motion. Resonant vibration is mainly caused by an interaction between the inertial and elastic properties of the materials within a structure. Resonance is often the cause of, or at least a contributing factor to many of the vibration and noise related problems that occur in structures and operating machinery. To better understand any structural vibration problem, the resonant frequencies of a structure need to be identified and quantified. Today, modal analysis has become a widespread means of finding the modes of vibration of a machine or structure. In every development of a new or improved mechanical product, structural dynamics testing on product prototypes is used to assess its real dynamic behavior. So, basically modal analysis is the study of the natural characteristics of structures. Understanding both natural frequency and mode shape helps to design structural system for noise and vibration application. The theoretical modal analysis of solid model leads to a description of the behavior of the structure as modes of vibration so-called the modal model. Experimental modal analysis is the field of measuring and analyzing the dynamic response of a structure when excited by a stimulus. It is useful in verifying FEA results as well as determining the modal parameters of a structure. Experimental modal analysis is a four-step process to extract the modal parameters as shown in Fig. 1 below:

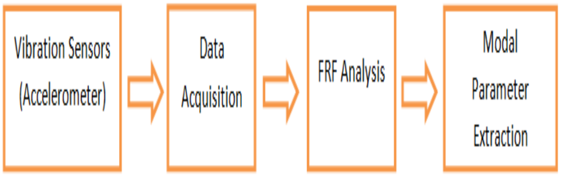

Fig.1 Experimental Modal Analysis Process

B.Natural Frequency

A natural frequency is the frequency at which the structure would oscillate if it were disturbed from its rest position and then allowed to vibrate freely. All structures have at least one natural frequency. Nearly every structure has multiple natural frequencies.

C. Mode Shapes

Modes (or resonances) are inherent properties of a structure. Resonances are determined by the material properties (mass, stiffness, and damping properties), and boundary conditions of the structure. Each mode is defined by a natural (modular resonant) frequency, modal damping, and a mode shape. If either the material properties or the boundary conditions of a structure change, its modes will change. Deformation patterns at the natural frequencies take on a variety of different shapes depending on the excitation force frequency. These deformation patterns are referred to as the structure's mode shapes.

I. FINITE ELEMENT ANALYSIS

A. 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 gearbox casing is modeled in CATIA V5. The .iges file of model is imported in ANSYS workbench. The main objective of this work is to perform the Finite Element Analysis of gearbox casing using CAE Tools, so as to determine the natural frequencies of gearbox. The material properties are required in CAE to perform analysis.

Steps in Modal Analysis

The procedure for a modal analysis consists of four main steps:

1. Build the model

2. Apply boundary conditions, point masses if any and obtain the solution

3. Expand the modes

4. Review the results

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.

Pre-processing

- Import planetary gearbox geometry model from CAD.
- Setting the type of analysis to be performed which is modal analysis.
- Set required number of modes to extract as 6 modes.
- Applying the mesh in which the process of providing the analysis on continuum into a number of element.
- Applying the element properties i.e. material properties. The material properties for the commonly used material for gearbox are as given in Table I.
- Applying the point masses to the model. However in modal analysis, loads are not required to run the analysis. Applying the boundary condition for the housing at three locations. Fig.4. shows FEA model of the gearbox with boundary conditions.

TABLE I.
MATERIAL PROPERTIES OF MILD STEEL

• ***Properties***	• ***Values***
• Young's Modulus, E	• 210000 MPa
• Poisson's Ratio, μ	• 0.3
• Density, ρ	• 7850×10^{-6}Kg/mm^3

B. Finite Element Modeling

Any continuous object has finite degree of freedom & it's just 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. To get value of variable at where between the calculation points, interpolation function is used also called as shape function. There are three methods to solve any engineering problem namely, analytical experimental and numerical. Finite Element Analysis belongs to numerical method category. Finite element modeling of any solid component consists of generating geometry, applying material properties, meshing the component, defining the boundary constraints or conditions, and applying the proper load type on load application point.

C. Geometry of Gearbox Casing

Gearbox casing is conceptually designed, taking into account all the requirements of space, mounting of auxiliary parts. The gearbox has welded construction. So, Gearbox dimensions are fixed based on values given in Table II.

TABLE II.
WALL THICKNESSES OF GEARBOXES IN MM

Material	Non-case Hardened gears	Case Hardened gears
CI Casting	0.007L+6mm	0.010L+6mm
Steel Casting	0.005L+4mm	0.07L+4mm

Where, L is the largest dimension of the housing in mm.
By using accurate dimensions the solid model of gearbox casing is generated by using CATIA V5 software. The solid model generated of the gearbox casing is shown in Fig. 2.

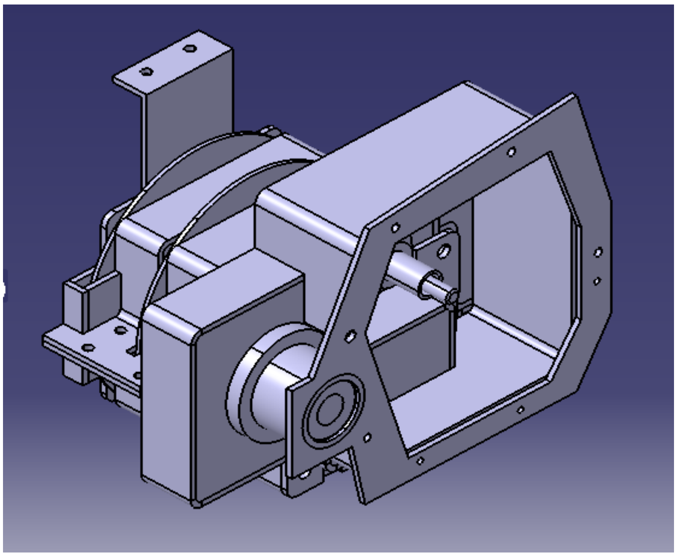

Fig. 2Gearbox Model with casing

D. Mesh Generation

The geometry is meshed in mechanical model window of anANSYS 14 Workbench. The automatic mesh method is applied for thegeometry. 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 Fig. 3.

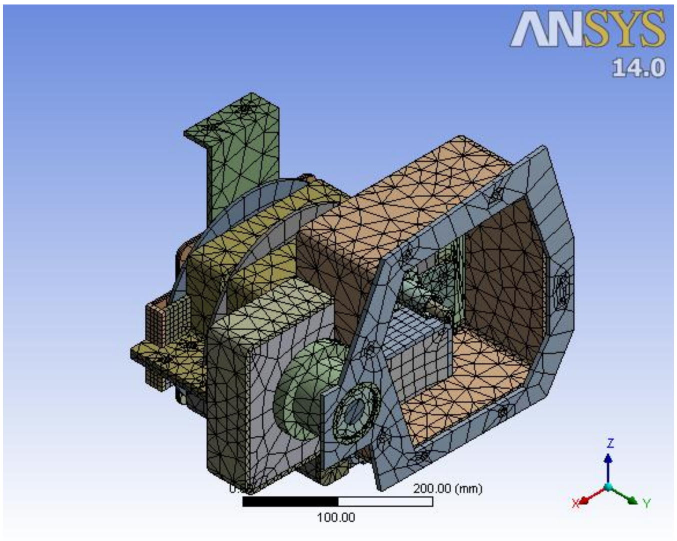

Fig. 3 Meshed Model of Gearbox casing

E. Boundary Conditions

The geometry is constrained with different boundary conditions as it is mounted on vehicle frame. These constraints are described as:
A. Fixed support is used as it is fixed to frame, called B-mount of gearbox.
B. Frictionless support is used as engine is fixed on mounting plate. This support constrains motion of mounting plate in normal direction of plate surface.
C. The displacement of C-mount is constrains along the axis of gearbox and it is allowed to rotate about engine axis.

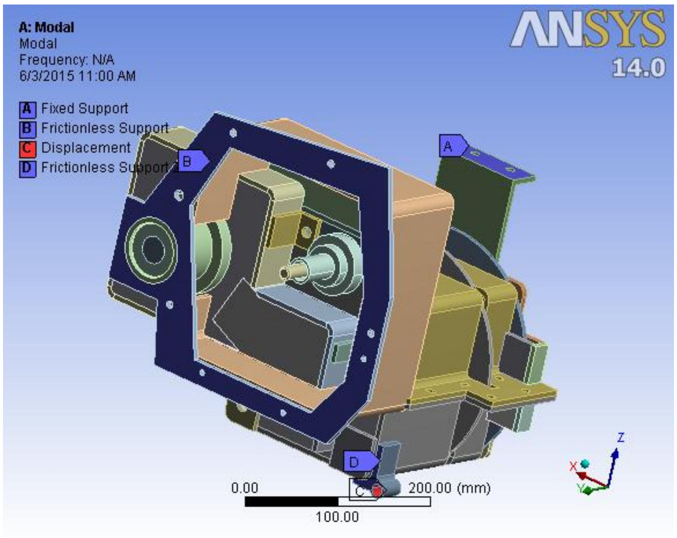

Fig. 4 Constrained Model of casing

II. FEA SOLUTION AND RESULTS

A modal analysis is performed with number of modes is 6.The details of the support is in Fig. 4.

A. Result of Natural Frequencies

Following table in the Fig.5 and graph in Fig.6shows natural frequencies at each calculated modes.

Mode	Frequency [Hz]
1.	86.913
2.	93.419
3.	134.71
4.	357.05
5.	387.95
6.	424.47

Fig. 5Results of natural frequencies

Fig. 6Results of natural frequencies

B.Mode Shapes

The following figures show the modes of vibration of gearbox at each corresponding natural frequencies.

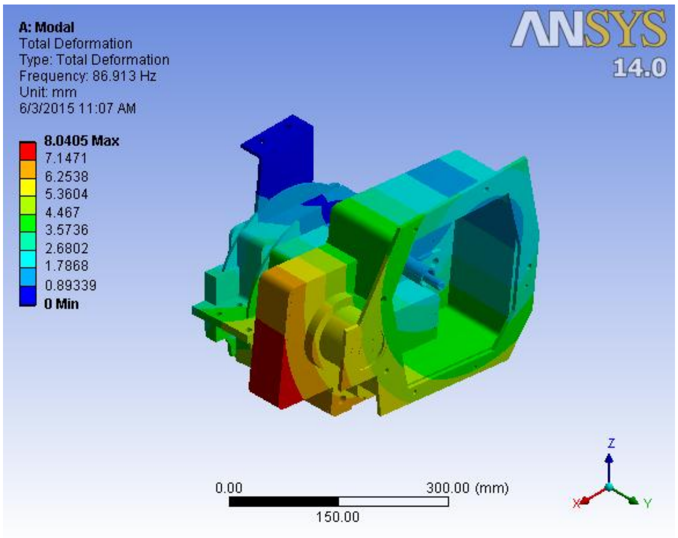

Fig. 7 First Mode of vibration at frequency 86.913 Hz

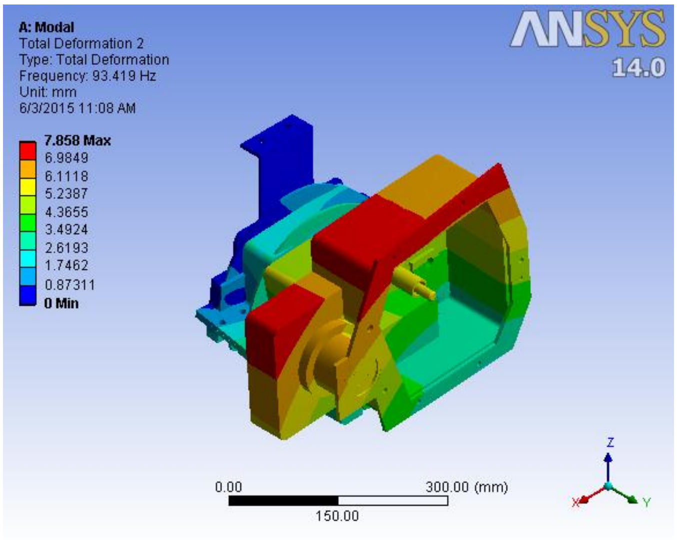

Fig. 8 Second Mode of vibration at frequency 93.419 Hz

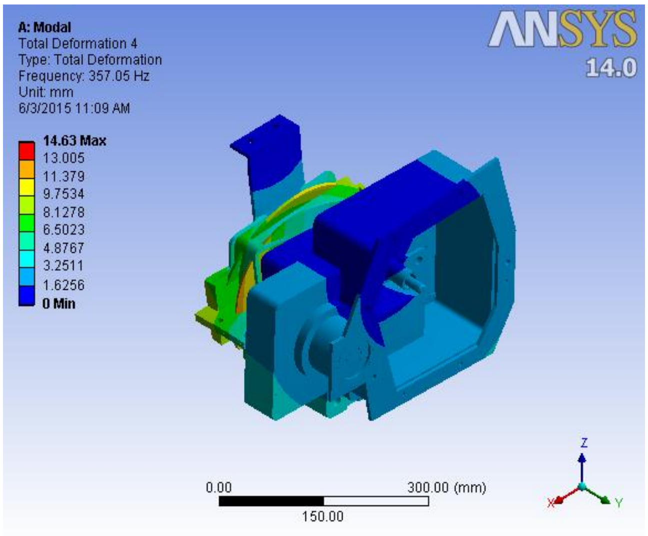

Fig. 9 Third Mode of vibration at frequency 134.71 Hz

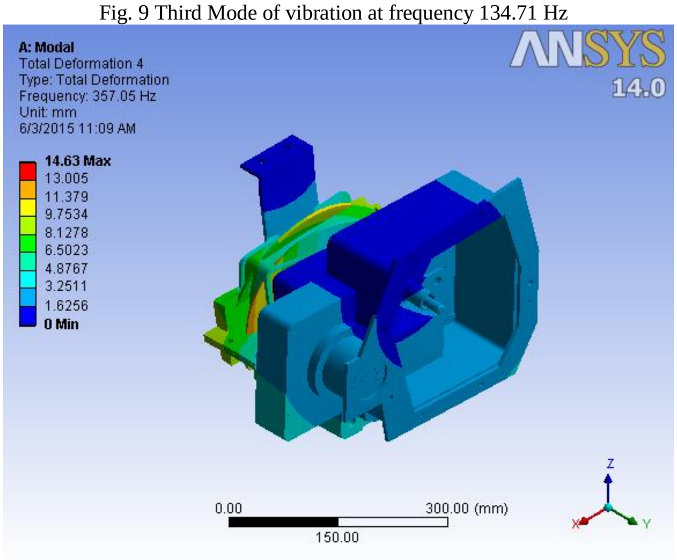

Fig. 10 Fourth Mode of vibration at frequency 357.05 Hz

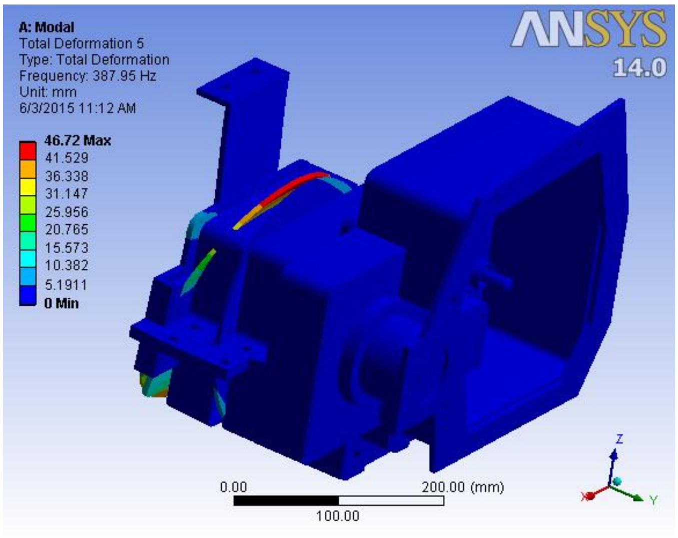

Fig. 11 Fifth Mode of vibration at frequency 387.95 Hz

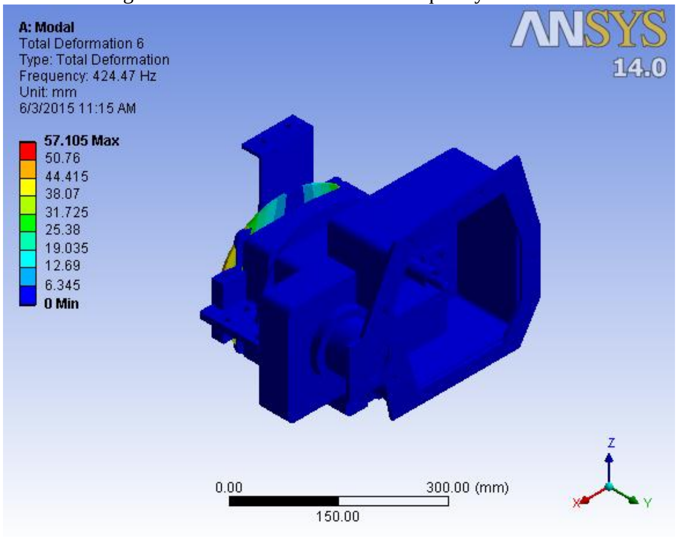

Fig. 12 Sixth Mode of vibration at frequency 424.47 Hz

III. Conclusions

The analysis results can show the range of frequency that is suitable for gearbox casing.This frequency range avoidsmaximum amplitude of vibrations of gearbox. The fundamental frequency obtained by the analysis is 86.913 Hz which is far away from the forcing frequency i.e. engine frequency which is in the range of 30-50 Hz. So, the results obtained in this paper gives strong recommendation that there is no resonance occurs and the performance of gearbox based on vibration response of gearbox casing is better. The theoretical study of Experimental Modal Analysis has been done in this paper.

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