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Finite element analysis of Spiral bevel gears pair used in an Automobile Differential gear box

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ABSTRACT

This paper covers the static, fatigue, modal and harmonic analysis of Spiral bevel gears pair used as drive pinion and crown wheel in the differential gearbox of Tata Ace vehicle, using a popular commercial finite element analysis software ANSYS. The main goals are to estimate the life and early detection of failure of the spiral bevel gears pair, during operation. The solid models of gears are created by using the widely used solid modeling software CATIA V5. The goals are achieved by comparing the results of FEA of new gears pair with the results of gears pair having a crown pinion with one tooth broken. A review of work done so far on Finite element analysis of bevel gears is also presented.

Keywords: *Spiral bevel gears, Finite Element Analysis, Static, Fatigue, Modal, Harmonic analysis, Life, Differential gearbox*

1. INTRODUCTION

Gears are the main components of mechanical power transmission systems. Spiral Bevel gears are critical machine components used in almost all automotive differential gear boxes and main rotor drive systems for rotorcrafts. Due to the demand for maximum power capacity, reliability and minimum weight the fatigue strength of individual gear is significant. Failure of a gear during operation results not only in higher cost of replacement or repair but also the down time of the system. Hence early detection of the failure of gear may play a significant role in saving these costs. Due to advancements in the technology lots of procedures have been developed to study the behavior of geared systems before failure. Finite element analysis is one of them used widely to carryout structural, fatigue, modal and harmonic analysis of geared transmission systems. In this paper, various literatures on the work done so far on finite element analysis of bevel gears have also been reviewed.

Wilcox [1] developed a finite element method software to calculate stresses in bevel and hypoid gear teeth. It was showed that fatigue stress in gear teeth can be quantitatively related to cutter radius and tooth contact pattern parameters.

Vijayakar and Houser [2] developed an algorithm by using a combination of finite element and surface integral method to predict contact stress distribution and deformation in gear teeth. The results obtained were compared with other methods available.

Bibel and Handschuh [3] has detailed a method of meshing of three-dimensional model of spiral bevel gear set and carryout finite element analysis. By using the contact algorithm present in commercial FE software, they modeled deformable gear tooth contact with the automatic generation of non-penetration constraints.

Ural et. al [4] used linear elastic fracture mechanics theory combined with finite element method to predict and simulate fatigue crack growth in spiral bevel gear. They employed a parallel PC-cluster approach to reduce the computation time.

Saravanan et.al [5] has carried out static and dynamic finite element analysis of asymmetric profile bevel gears, to improve the load carrying capacity. As in practical power transmission using bevel gears both forward and backward rotations are not always needed, hence they showed that asymmetric profile gears can be used to improve load capacity. Asymmetric profile was generated by adopting different values of pressure angle at drive side and coast side of the bevel gear.

Hua et.al [6] proposed an enhanced lumped parameter modeling approach to perform dynamic analysis of spiral bevel gear rotor system and compared with finite element modeling. The dynamic mesh force function predicted from the proposed method was compared with that predicted from finite element method.

Deng et.al [7] analyzed the contact fatigue on the surface of teeth and the bending fatigue in the root of teeth by proposing a three-dimensional finite element model of straight bevel gear pair based on the cumulative fatigue criterion and stress-life equation. They found that maximum contact fatigue stress occurs near the pitch line and the maximum bending stress occurs at the highest point of single tooth contact for gears. Both the above stresses are directly proportional to operating torque.

Bhavi et.al [8,9,10] has reviewed work done so far in the field of analysis and testing of differential gear box of an automobile. They have carried out static and multi body dynamic analysis of differential gear box assembly of Mahindra Bolero and determined the limiting torque at which the gearbox fails. In one paper, they have proposed an experimental setup to determine the fatigue life of spiral bevel gears by using noise and vibration approach. They have tested a pair of spiral bevel gears for its suitability for the required application by running it for several required number of cycles before failure. They have measured the change in characteristics of noise and vibrations produced by the spiral bevel gears pair after specified number of life cycles, which can be used as a basis for early detection of gears failure.

From the previous work, it is observed that limited work is recorded in finite element analysis of straight tooth bevel gears and a very scarce work is recorded in the finite element analysis of spiral bevel gears which may be due to very complex shape and geometry of the spiral bevel gears which makes it very difficult to carry out the finite element modeling and analysis.

2. OBJECTIVE AND METHODOLOGY

The main objective of this work is to compare the results of finite element analysis of a new spiral bevel gear pair with that of a spiral bevel gear pair with one broken teeth of the bevel pinion and hence to estimate the life and early detection of failure of the spiral bevel gears pair, during operation. In the current study static, fatigue, modal and harmonic analysis of the crown wheel and pinion pair used in differential gear box of Tata Ace vehicle is carried out by using a popular commercial finite element analysis software ANSYS.

The crown pinion and wheel are dismantled and taken out from the differential gear box. The solid models of the crown wheel and pinion under study are created with the help of a coordinate measuring machine (CMM) from which *.stp* files of the gear components are generated. Then the .stp files were refined and assembled in the widely used solid modeling software CATIA V5. The crown pinion and wheel assembly is imported in ANSYS workbench for further carrying out finite element analysis. The contact surfaces between the meshing teeth of wheel and pinion are identified and defined as *No separation* (Tangential sliding allowed, but contact elements in normal direction glue with target element to restrict normal motion). The shaft surface of the crown pinion and center of wheel are provided with frictionless support and the input torque is applied to the pinion. The rated torque for the given differential gearbox is 37.2Nm, hence by adopting a factor of safety of 2, the torque applied on the crown pinion is 75Nm. For fatigue analysis zero based loading cycle is selected with Goodman theory.

Test Gears. Spiral bevel crown wheel and pinion from differential gearbox of Tata Ace vehicle

Number of Teeth on pinion is 8 and on crown wheel is 39

Material. AISI/SAE 4140 steel is the widely-used material for spiral bevel gears used in automobile differential gearboxes. It is a high tensile steel having composition as follows [11]:

C-0.4%, Mn-0.8%, Cr-0.95% and Mo-0.25%

Mechanical properties [11]. Ultimate tensile strength - 1000MPa

Yield strength – 800MPa

Density – 7.9e3 kg/m^3

The S-N curve for fatigue life estimation is referred from "Atlas of Fatigue Curves" [12].

3. RESULTS AND DISCUSSION

Static analysis. From the static analysis, Figure1.1 we find that Maximum Equivalent Von-mises stress 361.57MPa occurs in pinion and maximum deformation of 0.030939 mm occurs at the edge of the teeth of pinion as shown in Figure 1.2. From this it is evident that the part which is more prone to failure in a spiral bevel gear pair is pinion.

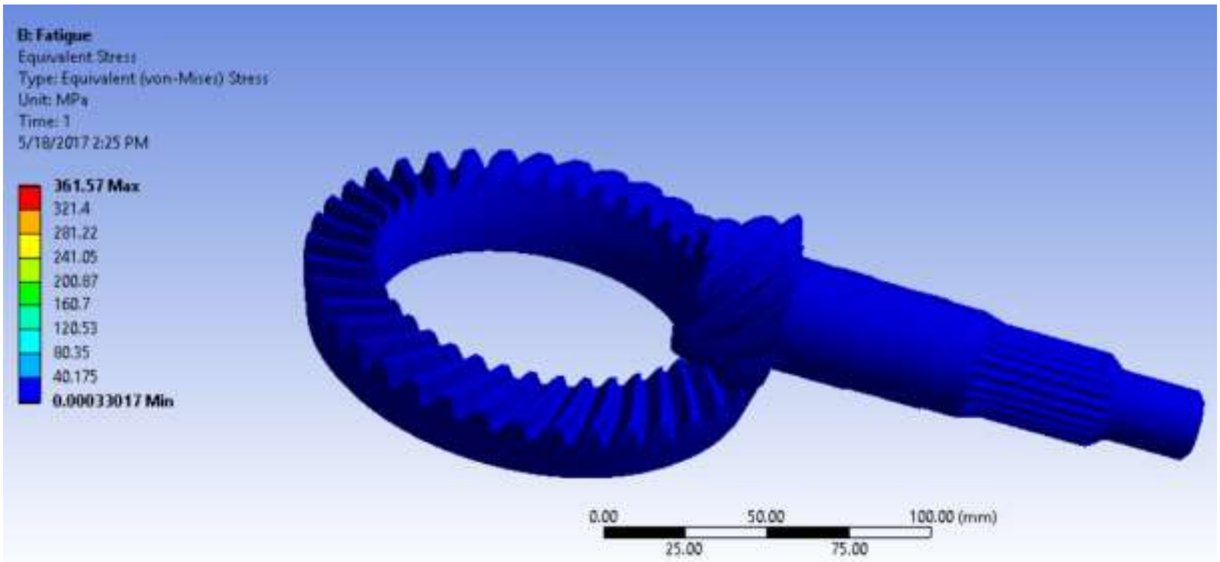

Figure1.1 Equivalent Von-mises stress (Static)

Modal analysis. The fundamental natural frequency for a new unused gear pair was found to be 417.11Hz whereas that for a pair with one broken tooth of the pinion was 779.9Hz. By comparing the fundamental natural frequency it can be seen that as the fundamental natural frequency of damaged gear pair is 362.2 Hz more than that of new gear pair, which shows that the vibration characteristic of the new gear pair and damaged gear pair will be different when measured experimentally. Hence by comparing and continuously measuring (On board) the noise and vibration the early detection of gear failure can be made. And also, the condition of the crown pinion and wheel pair i.e., new or used or damaged, can also be known by comparing the noise and vibration characteristics.

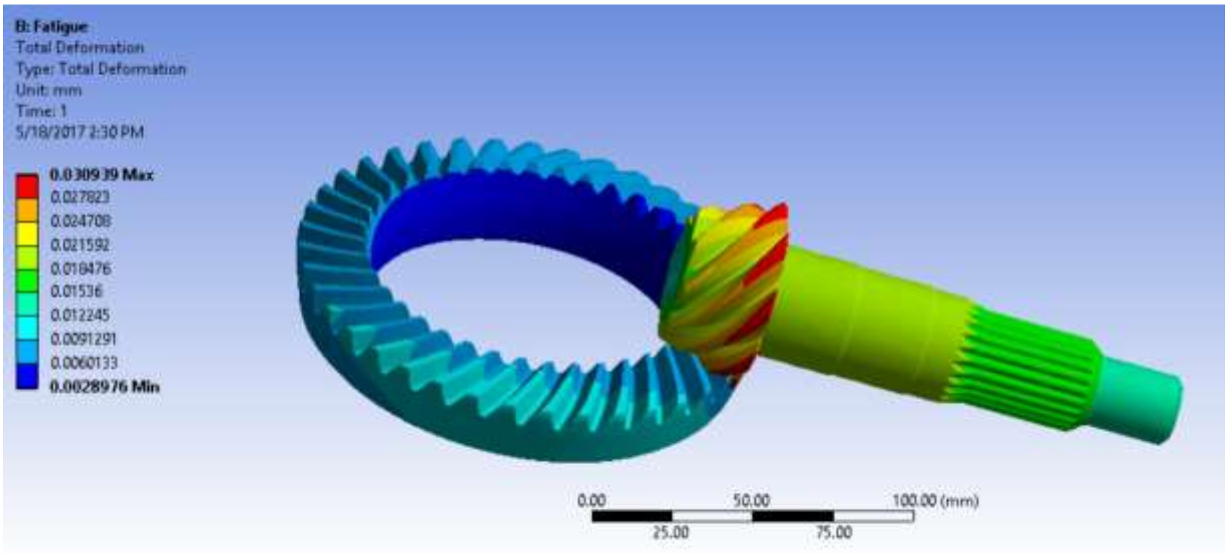

Figure1.2 Total Deformation (Static)

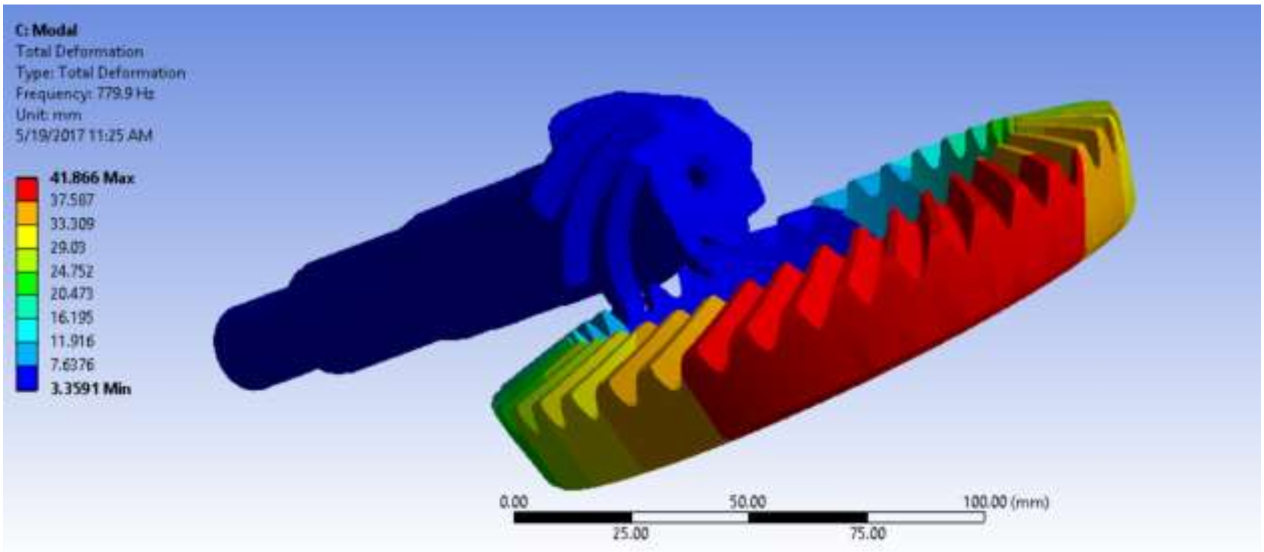

Figure1.3 Fundamental natural frequency of gear pair with a broken pinion teeth 779.9 Hz

Fatigue. For fatigue analysis, fatigue tool is selected with zero based loading cycle, because when the teeth engage, each tooth experiences a bending load and when they disengage the load is relieved (becomes zero). From fatigue analysis, it was found that the minimum number of cycles the pinion can sustain before failure was 10^7cycles which is an infinite life and the minimum factor of safety was found to be 1.6707. Maximum equivalent alternating stress was found to be 218.39 MPa as shown in Figure1.4.

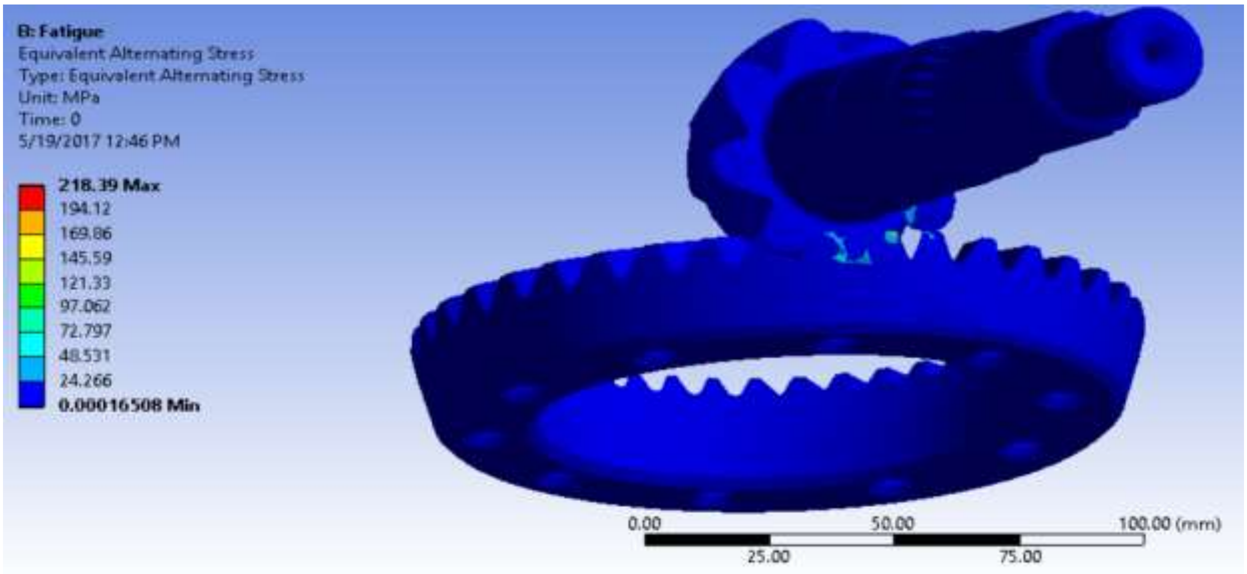

Fig.4 Equivalent Alternating Stress

Harmonic Response. Comparison of Harmonic Response of New gear pair and Gear pair with one broken tooth of pinion are shown in Fig.5 and Fig.6. From plots, we can observe that both stresses and Vibrations are high for damaged gear pair than that for new gear pair. From which it can be concluded that by comparing the noise and vibration characteristics of new and damaged spiral bevel gear pairs signature of failure of spiral bevel gears can be obtained.

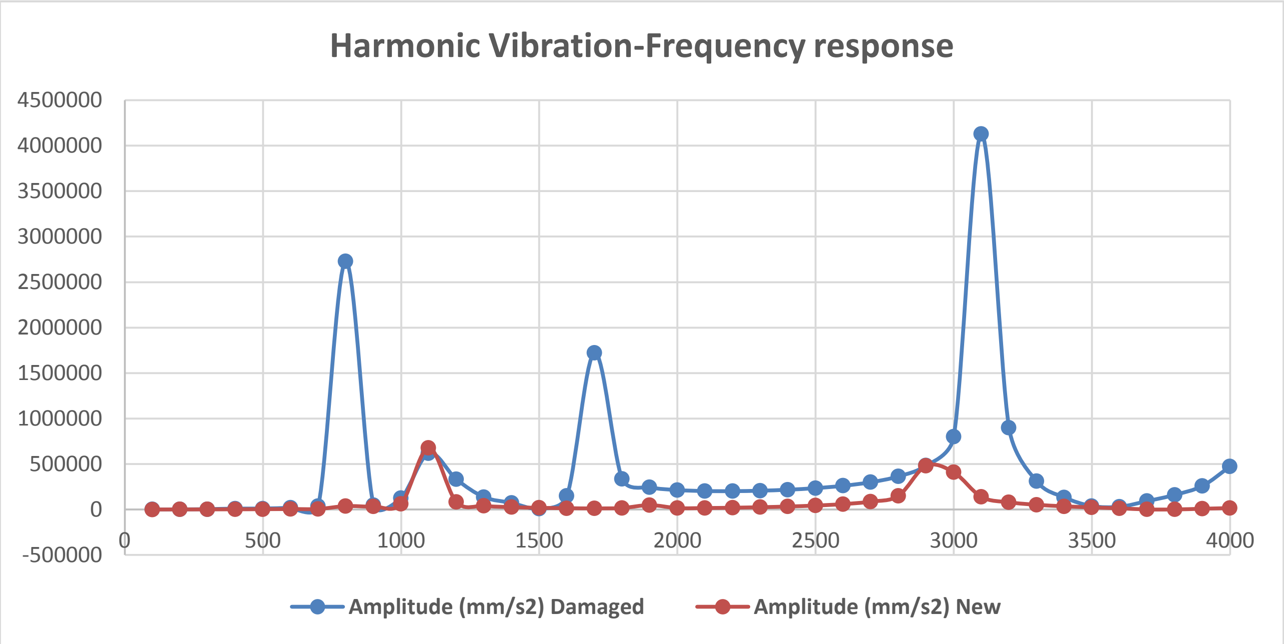

Figure 1. 5 Vibration-Frequency response

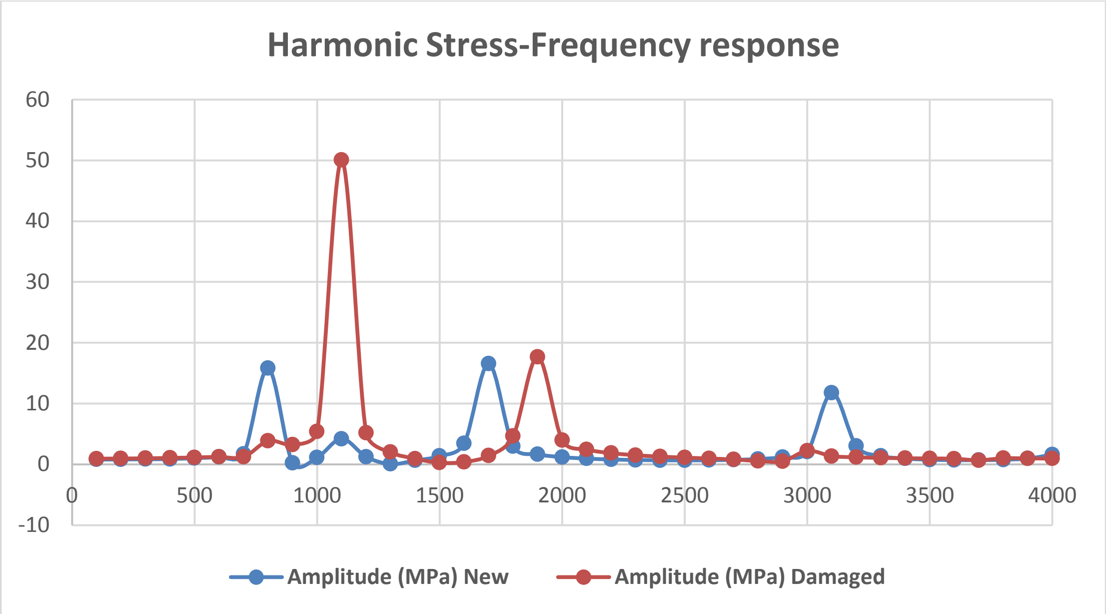

Figure 1.6 Stress-Frequency response

4. CONCLUSION

Maximum Equivalent Vonmises stress was found to be 361.57Mpa and Maximum deformation was 0.030939mm which are will within the allowable limits, as the yield strength of the AISI 4140 steel is 800MPa [11]. From fatigue analysis, the gear pair showed infinite life, factor of safety of 1.6707 and a maximum equivalent alternating stress of 218.39MPa.

From modal analysis, the fundamental natural frequency of new gear pair and the gear pair with one broken tooth of pinion differed by 362.2Hz which shows that by comparing the noise and vibration characteristics of new and damaged gear pair it is possible for early detection of failure.

Stress-frequency response and Vibration-frequency response plots obtained from Harmonic response analysis showed that peak values of stress and vibrations for damaged gear are far more than that of new gears. Hence from harmonic response also the new gear pair and damaged gear pair can be differentiated which can be an important finding for early detection of failure of spiral bevel gear pairs used in automobile differential gearbox.

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