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A comparative analysis on two gear tooth materials for low speed and high torque transmission

Sushovan Chatterjee[1*], Krishanu Gupta[2]

[1] Department of Mechanical Engineering, Cooch Behar Government Engineering College, West Bengal 736170, India
[2] Department of Mechanical Engineering, National Institute of Technology Agartala, Tripura 799046, India

Corresponding Author Email: sushovan.chatterjee@gmail.com

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ABSTRACT

The present investigation is devoted to explore the static stresses developed on gear tooth material at low speed and high torque for two different materials; C45 steel and high density polyethylene (HDPC). Subsequently a 3D spur gear pair is modeled in CATIA work bench and the stresses developed were analyzed using finite element analysis using ANSYS workbench 14.5. The results of bending stress distribution, modal displacement and modal frequencies for the first four modes were finally compared for both cases of the metallic and the HDPE made gear pairs.

1. INTRODUCTION

Gears are important mechanical components that are used in the power transmission unit of different mechanical and automobile systems. Therefore, it becomes a necessary and an important area of research in order to improve the efficiency of different mechanical power transmission systems by improving the workability of gear systems. Thus, study of gear tooth damage has become a very important area of research. The gears are one of the most imperative and crucial component in a mechanical power transmission unit, and its robustness led to the choice as mechanical component in many engineering applications. Based on the application in which the gear pair to be employed, selection of material for the gear pair becomes a very significant parameter, with subsequent static and modal analyses. Also, bending stress being an essential phenomenon in study of gears, as stress beyond the permissible range, leads to failure of gear tooth in contact. Spur gear are those category gears which are generally used in low speed and high torque applications, and for very large speed reduction. The key intent of this paper is to design a spur gear pair and compare the bending stresses induced due to the applied load on the teeth, and study the modal behaviour of the same, considering two different materials, which may be applied for any low speed and high torque transmission. The core motive of choosing a pair of spur gear is due to the advantage of these gears having high power transmission efficiency.

There are enormously available literature on analysis and optimization on gear tooth material. Vijayarangan et al. [1] compared the performance of two orthotropic gear materials (glass/epoxy and graphite/epoxy) with mild steel gear. The variation of stresses and displacements both along the involute tooth profile and across the tooth thickness were found to be very similar. Comparing the results under different conditions they proposed graphite/epoxy as a material for power transmission gears. Using Finite Element Method (FEM) and cyclic symmetry, Ramamurti et al. [2] proposed a new approach to analyze stress on spur gear teeth, where the boundary conditions in between the two adjacent teeth are avoided. It computes the stress distribution in the adjacent teeth from the analysis of one tooth with fixed boundaries. It was observed that the tips of unloaded teeth experienced no stress when the load moves down the tooth profile. Loutridis [3] presented a method for checking the gear faults based on the newly developed empirical mode decomposition (EMD) scheme. He developed a theoretical model for a gear pair with a tooth root crack. An experimental rig was set up consisting of two electrical machines, a pair of spur gears, a power supply unit with the necessary speed control electronics and the data acquisition system. The experimental vibratory signals generated were decomposed into oscillatory functions called intrinsic mode functions. An empirical law was established which relates the energy content of the intrinsic modes to the crack magnitude. The author also concluded that the instantaneous frequency can be used as a sensitive indicator of the existence of damage in the gear pair. Gligorijevic et al. [4] deals with a set of major gear design criteria which are used for gear material selection such as surface fatigue limit index, bending fatigue limit index, surface fatigue lifetime index, bending fatigue lifetime index, wear resistance of toots flank index and machinability index. They studied a suitable model ELECTRA for ranking different alternative gear materials using multiple criteria. The method is capable of ranking materials from the best to the worst while estimating their incomparability's and indifferences. Podzharov et al. [5] proposed the use of high (nearly 2) contact ratio spur gears to reduce the tooth stiffness variation by increasing the number of teeth on mating gears using computer programs for the calculation of static and dynamic transmission error. According to their findings, gears with high contact ratio have less static and dynamic transmission error than standard gears. Pedersen [6] showed that bending stress can be reduced by using asymmetric gear teeth and by shape optimizing the gear through changes in tool geometry. He suggested that the bending stress reduction can be obtained with the help of two new different types of asymmetric rack cutter: one where the drive side pressure angle was fixed at 20° and other where the coast side pressure angle was fixed at 20°. Prasad et al. [7] proposed a model substituting the metallic gear of sugarcane juice machine with plastic gear to reduce the weight and noise considering two types of plastic materials namely Nylon and Polycarbonate. Static analysis of the 3D model was performed using ANSYS 10.0. Based on deflections and stresses from the analysis the best one between Nylon and Polycarbonate spur gears was chosen. The maximum torque, allowable stress and tangential load of the spur gear were calculated. Based on results and analysis they found that Nylon gears are suitable as compared to cast iron spur gears. Hence nylon gears are best suitable for the application of sugarcane juice machine under limited load conditions. Spur gear is the most common and cost effective type of gears used. Gopichand et al. [8] used commercial software MATLAB to design a spur gear and which gives the involute tooth profile with accurate dimensions. A suitable material should be selected for the design based on transmitting power and gear ratio. The material selected for the pinion should be stronger than the gear material. The inputs in their work were speed, power, gear ratio, life, whereas the outputs obtained were number of teeth, pitch circle diameter, face width, module, tip circle diameter etc.

Comparative survey conducted by Mahendran et al. [9] on composite spur gear for the purpose of weight reduction revealed that, induced stress, deformation and weight of composite spur gears found very much less as compared to cast steel spur gear. Based on their study analysis of torque loading and stress induced was done in the application of gear box used in automobile vehicles using ANSYS.

Composites are nowadays a better alternative for replacing metallic gears as they provide adequate strength. Using computer aided manufacturing; Pawar et al. [10] tried to replace metallic gears by composite material in order to improve the mechanical properties and efficiency of mechanical machines. They prepared both metallic gears of steel alloy and aluminum silicon carbide. They considered Lewis formula for bending strength and Hertz Equation for contact stress during their deign analysis to account for various factors which have influence on gear rating. Al-SiC composite was prepared by stir casting and various mechanical tests were conducted for evaluating properties of composite. From the analysis it was found that gears manufactured from composite provides less weight compared to steel gear. The finite element analysis also showed less chances of failure in Al-SiC gear. Nowadays composite materials are widely used in various engineering structures including space crafts, bridges and buildings. This is because composite materials provide much improved mechanical properties such as adequate strength with weight reduction, less chances of failure for which it is considered to be a better alternative for replacing metallic gears.

Desai et al. [11] modeled spur gear using Solidworks CAD software and carried out bending stress analysis using ANSYS 14. They adopted a replacement of metallic gear of Alloy Steel by the composite gear of 30% Glass filled Poly-ether-ether-Ketone (PEEK), (GF 30 PEEK). Analytical and finite element method was applied for determining the bending stress of gear tooth. By stress analysis it was found that the strength of the GF 30 PEEK spur gear is more when compared with alloy steel spur gear. It was also found that the density of the GF 30 PEEK was less as compared to alloy steel. In accordance with their report, alloy steel spur gear can be replaced by GF 30 PEEK spur gear due to its high strength and low weight characteristics.

From literature review, Dhaduti et al. [12] suggested that due to lower weight to stiffness ratio, composite gears may be replaced by conventional material gears in power transmission systems. The asymmetric gears reported to be advantageous in various practical applications. Repeated stress on fillets causes fatigue failure of the gear tooth. Rajaprabakaran et al. [13] considered a finite element model of spur gear with a segment of three teeth and reducing the stress concentration by adding different shaped holes at various locations. The maximum stress found to appear at fillet on gear without any hole. They also tried an aerodynamic structured hole in the path of stress flow with different modifications to the aero fin hole by varying the parameters. The stresses and displacements were calculated and analyzed such that maximum stress at the fillet is reduced. From the results it was found that as the size of the hole decreased, stress induced in the gear decreased significantly due to the modulation of hole in the stress flow direction. As the size of the hole decrease material will be more due to which gear will be stiffer and displacement will be lower.

Our recent analysis on involute spur gear pair (having 25° pressure angles) reveled that, both metallic and non-metallic gear pair can sustain bending as well as contact stresses under similar operating environment of low speed high torque application [14].

In a study carried out by Yanfang Cui et al. [16], authors aimed at finding out a way to overcome the difficulties that prevails in the present fatigue analysis of spur gear. In accomplishing the task, a pair of spur gear teeth was brought to mesh together, which by using the plane engagement theory and blade profile equations, equations were derived. The meshing for the teeth in mate were done in ANSYS simulation for attaining the maximum stress points and consequently the fatigue results were obtained, found that the analysed results were in close proximity with those obtained directly by calculations.

The prime objective of the present investigation is to analyze the development of static bending stress in a pair of gear transmitting 4.1 kW power, with a speed of 30 rpm and 1306 Nm torque. The main objective of the present gear mechanism is to convert input pulse provided by the pinion connected to the prime mover into corresponding output response comprising of lower speed ranges and higher torque.

2. GEOMETRY, MODELING AND MESHING

Models for numerical analysis were designed using a modelling software and these were imported to an analysis tool as IGES files for further analysis. Gupta and Chatterjee [15] studied about gear pairs and found out the stresses in the gear teeth for different pressure angles. In this paper, the reason of the geometry of the gear pair is solely depending on the application. The geometrical parameters of the proposed gear pair is appended in Table 1. And the solid model is shown in Fig. 1.

Table 1. Geometrical modeling parameters for the gear system

Parameters	Pinion	Gear
Number of teeth	17	75
Module(mm)	4	4
Pressure angle(degree)	20	20
Face width(mm)	40	40

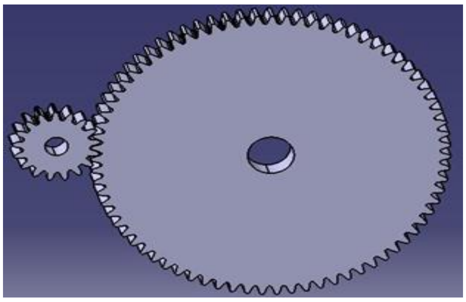


Figure 1. Geometric model of spur gear pair

For bending stress analysis, tetrahedron type element is employed for meshing in the analysis tool. After that the boundary conditions are applied for the pair of gear as shown in Fig. 2.

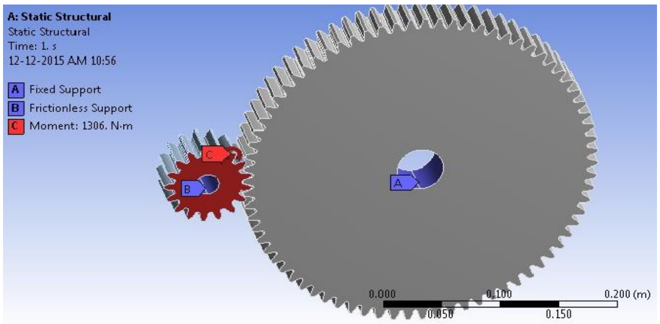


Figure 2. Boundary conditions for present analysis on spur gear pair

3. RESULTS

3.1. Bending stress

At the starting condition a turning moment of 1306 Nm is applied on the gear teeth and this amount of torque was transferred from pinion to gear. The distribution of bending stress for the C45 steel made spur gear is shown in Fig. 3.

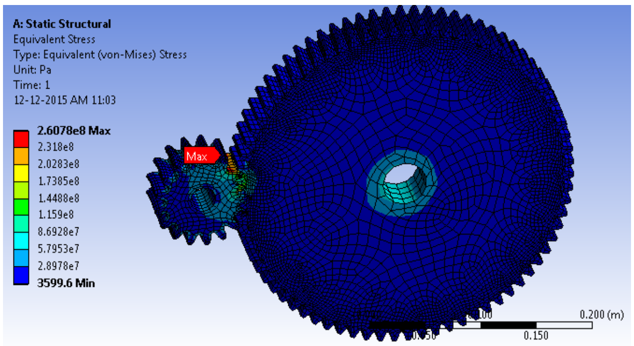


Figure 3. Bending stress distribution for steel C45 made gear pair

The similar profile of bending stress distribution for HDPE made gear pair is also shown in Fig. 4. From both Fig. 3 as well as Fig. 4, it is seen that maximum bending stress occurs at the base of the root and at the point of contact.

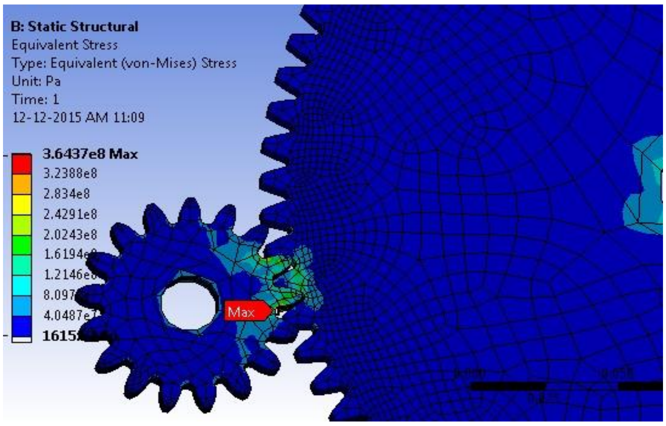


Figure 4. Bending stress distribution for HDPE made gear pair

3.2. Modal analysis

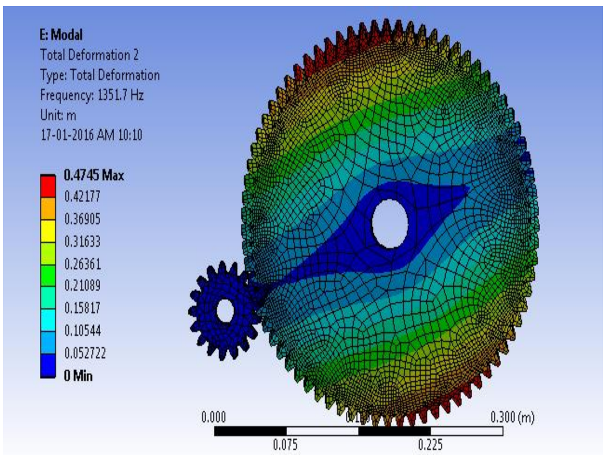
Modal analysis is performed in this work for analyses the natural frequencies of the gear pairs. The different mode shapes of the gear pairs are found. No external force is applied for these analyses. The frequency results corresponding to mode shapes are shown in Table 2.

Table 2. Natural frequencies at first four different modes

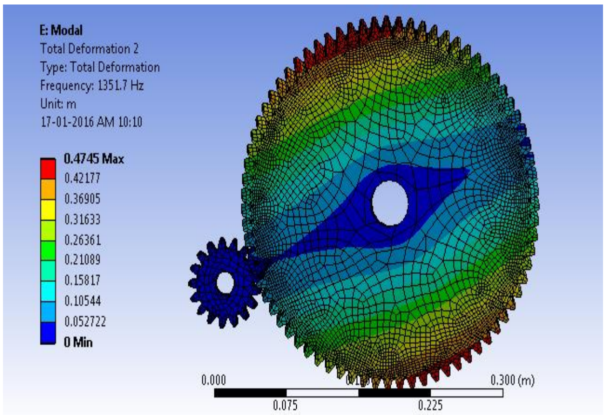
Mode	Frequency (Hz)	
	For C45 steel made gear pair	For HDPE made gear pair
1	0.00637	0.001335
2	1345.9	268.3
3	1351.7	284.72
4	1365.3	287.37

It is observed that the natural frequency of the gear pair almost converges in between mode 3 and mode 4 for both cases of two different materials.

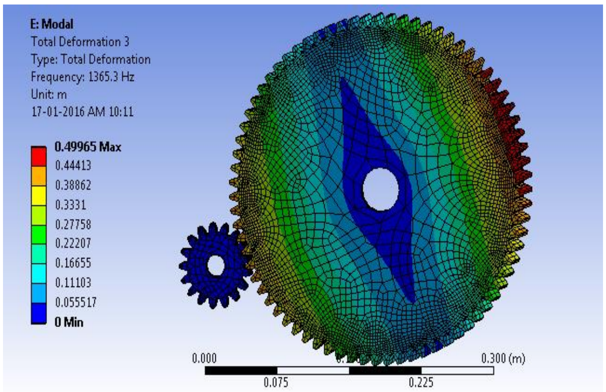
For more clarity the aforementioned modal analysis, modal displacement contour for the C45 steel made gear pair and HDPE made gear pairs are appended in table 3 and table 4 respectively.



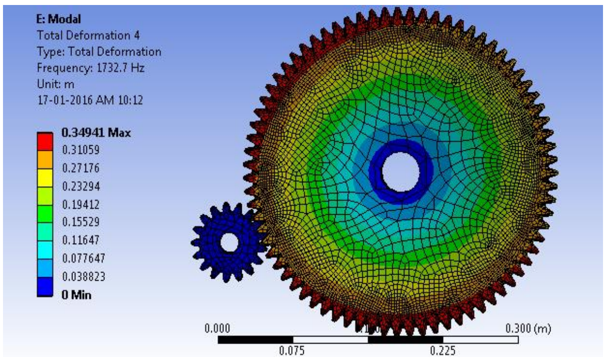
(1) 1st mode shape



(2) 2nd mode shape

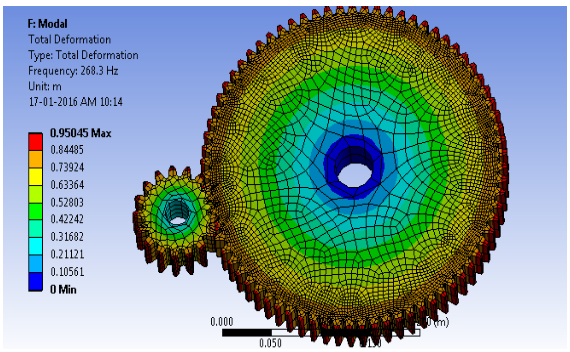


(c) 3rd mode shape

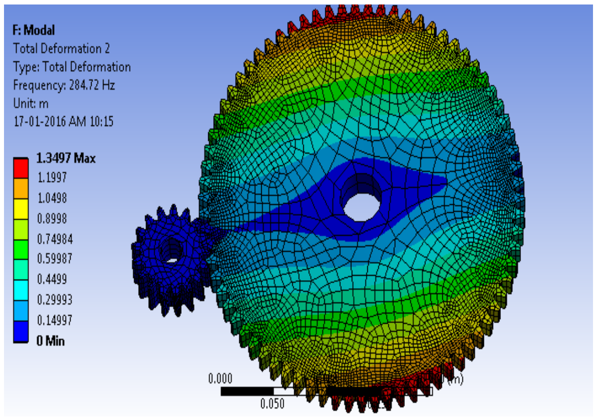


(4) 4th mode shape

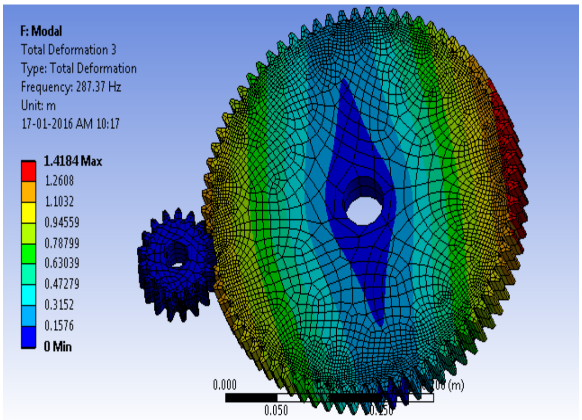
Figure 5. Modal displacement for C45 steel made gear pair



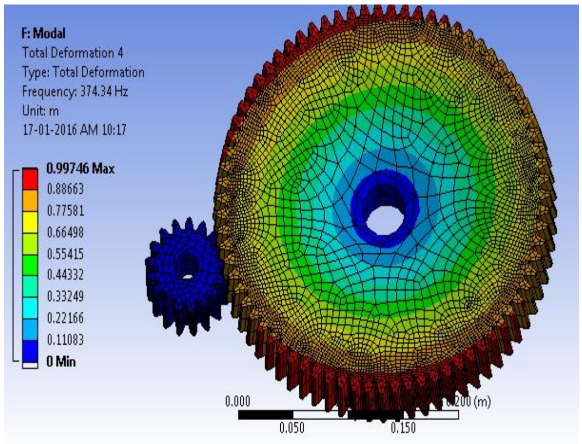
(1) 1st mode shape



(2) 2nd mode shape



(3) 3rd mode shape



(4) 4th mode shape

Figure 6. Modal displacement for HDPE made gear pair

4. CONCLUSION

In the present study the equivalent stresses of the two different spur gears were investigated by harnessing the assists of the platforms of finite element meshing and simulation. Subsequently modal analysis of the investigated gear pairs were carried out to unearth the vectors of natural frequency and maximum deformation rate corresponding to diverse mode shapes.

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NOMENCLATURE

The following are the generally used gear nomenclatures to carry out the different formulations in the calculation [15].

$\mathbf{N_P}$, $\mathbf{N_G}$	Number of teeth on Pinion and Gear
m	Module
p	Circular pitch
P	Diametral pitch
d′	Pitch circle diameter
$\mathbf{d_a}$	Tip circle diameter
$\mathbf{d_b}$	Base circle diameter
$\mathbf{d_t}$	Root circle diameter
$\boldsymbol{\phi}$	Pressure Angle
$\mathbf{h_a}$	Addendum
$\mathbf{h_f}$	Dedendum
c	Clearance
$\mathbf{h_t}$	Whole depth
s	Tooth thickness on pitch circle
$\mathbf{r_A}$	Addendum circle radius
$\boldsymbol{\omega_1}$	Angular velocity of pinion
v	Pitch line velocity
$\boldsymbol{\alpha}$	Half angle of tooth
$\boldsymbol{\sigma}$	Bending Stress on tooth fillet
T	Torque transmitted
B	Face width
y	Lewis form factor