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Design and analysis of composite spur gears using finite element method

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Abstract. In this study, the parametric design and contact analysis of composite spur gears are investigated numerically. Composite gear provides an adequate strength to weight ratio, more hardness, durability and low maintenance cost. It is emerging better alternatives for replacing metallic gears. The finite element model of spur gear is developed with the assistance of the Ansys software. In this study each design factor such has stress distributions, strain and deformation are considered to compare composite gear with steel and polymer gears. An APDL gear model has been developed for the design evaluation and comparison study.

1. Introduction

Gears are the most important components in modern mechanical engineering world. The use of gears has more common in all the industries. The advantages of spur gear are simplicity in design and can be manufactured easily, economically and less maintenance.

At present scenario composite gears plays an important role in wide space of research especially in gear motors, gear pumps, electromechanical actuators and drive shafts for car etc., Composite gears have better mechanical characteristics like wear resistance, corrosion resistance, lubricant free, noiseless, high strength to weight ratio. Senthilvelan and gnanamoorthy [1] investigated the effect of tooth fillet radius on nylon 6/6 spur gears under different loading conditions. It was concluded that the high fillet radius gears exhibited more life and less fillet radius gears shows more deflection on gears. Also it was concluded that in low loading conditions less fillet radius gears fail in crack initiation on root region and high fillet radius gears fail in micro crack on pitch region also the temperature raise depends on fillet radius. Senthilvelan and gnanamoorthy [2] investigated the performance of unreinforced nylon 6 and 20% short glass fiber reinforced nylon 6 under different rotational speed conditions. The rotational speed influences the performances on both types of gears at high speed conditions and high stress levels. It was concluded that in all speed conditions glass fiber reinforced nylon spur gears shows higher performance over nylon gears. Shanmugasundaram et al. [3] proposed the optimized design of spur gears by using circular root filet instead of standard trochoidal root filet. Simulations were performed under various speed conditions to determine the deflection, bending stress and contact stress. It was concluded that circular root filet gears were increases the strength and to minimize the tooth failure of the gear. Yong-jun et al. [4] performed the dynamic contact simulations on helical gears with and without tooth profile modification. The simulations and experimental results were compared in different load conditions. The study concluded that the profile modification of helical gears were effective on vibration reduction around the working condition. Bharat et al. [5] investigated the contact stress analysis of spur gears using finite element method. Analytical methods of calculating gear contact stresses use Hertz's equations, which were originally derived for contact between two cylinders. The

Spur gears were modelled in Pro-e software and analysed in ansys. It was concluded that the contact stress decreases with increasing module of the gear. Sushil kumar et al. [6] performed the analysis on contact and bending stress of involute spur gears using numerical method. The spur gears were modeled and assembled in catia software and then imported to Ansys. The numerical results were validated with analytical results interms of contact stresses. Vivek et al. [7] performed the stress analysis of mating teeth of spur gear to find maximum contact stress in gear teeth. Steel and grey cast iron materials were used in this gear analysis. The maximum contact stresses were obtained through hertz equation and it was validated with the finite element analysis. They concluded that the gray cast iron gear has less deformation compared to steel gear. Mahebub et al. [8] investigated the comparative finite element analysis on metallic and non-metallic materials. The 3D model of spur gear was generated in Pro-engineer modeling software and simulated in Ansys workbench and it was concluded that non-metallic gears provides extra benefits only for limiting strength applications compared to metallic gears. Pawar et al. [9] proposed the Al- SiC composite spur gear with different weight fractions and hardness test, microstructure test were conducted. The study concluded that the major variation in material hardness and toughness of the gear has increased by adding 10% SiC content. Sajad et al. [10] investigated the dynamic response of spur gear using finite element analysis. The gear teeth were analyzed for different operating speeds and obtained the corresponding displacements, stress distributions and strains. It was concluded that maximum stress occurs on root of the teeth and bending stress increases with increasing speed of the gear. AL-Qrimli et al. [11] investigated the static analysis on three dimensional model of the steel spur gears in numerical method using Abaqus software. The numerical results were validated with analytical results interms of contact stresses. The finite element results were validated with analytical results interms of contact stresses. They observed that the maximum contact stress appears on the pitch circle of the spur gear tooth. From the above literature studies it can be concluded that there has been no report focused on Ansys parametric design language (APDL) for contact stress analysis on composite spur gear. This APDL coding provides the detailed gear design.

In the present study the spur gears has been modeled and analysed using Ansys parametric design language (APDL) in finite element analysis software. This APDL program used to analyse different gear materials. In this work composite, polymer and steel gears are taken to perform the analysis on different speed conditions. The Stress distributions, deformations and strains were obtained using finite element analysis software.

2. Modelling of gear in Ansys

The spur gears are designed for the applications of lathe machine and oil pump etc. The PSG design procedure used to evaluate the parameters of spur gear. The spur gear is sketched and modelled in finite element software using the basic dimensions as shown in table 1.

2.1. Material property

Three different materials are selected for this analysis which are, composite material, Peek material and steel. The material properties of composite, peek and steel are obtained from reference [14] and [16]. The material properties of the glass fiber/epoxy composite is E_1=37.86 GPa, E_2=8.11 GPa, v=0.26, G_{12} = 3.57 GPa, G_{23} = 3.13 GPa, ρ = 1810 kg/m^3 and peek material is E =3.76 GPa, v =0.37, ρ= 1300kg/m^3 and steel material is E =193 GPa, v =0.3, ρ= 7750kg/m^3.

2.2. Specifications of gear

The specification of gears are: power 2.25kw, speed 750 rpm, center distance 150mm, number of teeth 60 and face width 25mm for lathe applications. Using these specifications the dimensions of spur gear are calculated as follows.

Table 1. Dimensions of the spur gears

S. No.	Description	Symbol	Value	Units

1	No. of Teeth on Pinion	zp	60	
2	No. of Teeth on Gear	zg	60	
3	Pressure Angle	ϕ	20	°
4	Module	m	2.5	mm
5	Addendum	ha	2.5	mm
6	Dedendum	hd	2.89	mm
7	Pitch Circle Diameter	dp	150	mm
8	Pitch Circle Radius	rp	75	mm
9	Base Circle Radius	rb	70.47	mm
10	Addendum Circle Radius	ra	77.5	mm
11	Dedendum Circle Radius	rd	71.8	mm
12	Face Width	b	25	mm
13	Fillet Radius	rp	0.98	mm
14	Center distance	a	150	mm
15	Shaft Radius	rs	16	mm
16	Total angle	Ta	360	°
17	Bottom clearance	c	0.25	

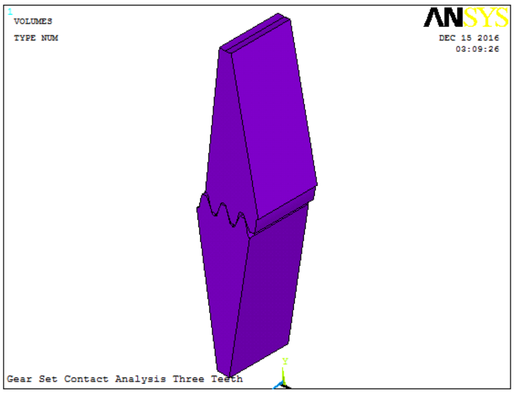

Figure 1. Illustrate the 3D models of spur gear pair engaged position.

The involute spur gear 3D model is sketched and modelled in Ansys through APDL coding. The dimensions of the spur gear set are given in Table 1. The values are same for both gears used in assembly. The Figure.1 shows the 3D models of pair spur gear.

3. Calculation of contact stress using hertz equation

The importance of contact analysis is to prevent gear pitting failure. Contact stresses in gears are calculated by using Hertz equations which was originally derived for contact between two cylinders.

Power (P) = 2.25 kW = 2250 watts

Speed (N) = 750 RPM

Power (P) $= 2*\pi*N*T / 60$

2250 $= (2*\pi*750*T) / 60$

T $= (2250*60)/ (2*\pi*750)$

Torque = 28.64788 N-m

Torque T = F * (d/2)

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Force F = T/ (d/2)

= 28.64788/0.075

Force F = 381.97185 N

Evaluate the contact stress using hertz equations:

Contact stress equation given in [2]

$$\sigma_c = \frac{2P}{\pi BL}$$

$$B = \sqrt{\frac{2P\left(\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\right)}{\pi L\left(\frac{1}{d_1} + \frac{1}{d_2}\right)}}$$

$$\sigma_c{}^2 = \frac{1}{\pi(1-\mu)}\left(\frac{PE}{Lr}\right)$$

Where,

σ_c = maximum value of contact stress (N/mm^2)

B = half width of deformation

P = force pressing the gears together (N)

B = half width of deformation (mm)

L = axial length of gear (mm)

d_1, d_2 = diameters of two gears (mm)

E_1, E_2 = moduli of elasticity of two gear materials (N/mm^2)

μ_1, μ_2 = Poisson's ratio of two gear materials

$$r_1 = r_2 = r$$

$$r = \frac{d_p \sin\phi}{2} = r_p \sin\phi$$

$$r_p = 75mm$$

$$L = b = 25mm$$

$$P = \frac{p_t}{\cos\phi}$$

P_t is the tangential component of resultant force P between two meshing teeth.

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$$p_t = \frac{2T}{d_p} = \frac{2*28.64}{0.150} = 381.972N$$

$$\sigma_c = \sqrt{\frac{1}{\pi(1-\mu)}\left(\frac{p_t E}{br_p \sin\phi \cos\phi}\right)}$$

$$\sigma_c = \sqrt{\frac{1}{\pi(1-0.22)}\left(\frac{381.972*68.2}{25*75*\sin 20*\cos 20}\right)}$$

$$\sigma_c = \sqrt{17.637.51}$$

$$\sigma_c = 4.19Mpa$$

The maximum contact stress of spur gear is obtained using hertz equations as 4.19 Mpa.

4. Finite element analysis of spur gear

An APDL program is developed to plot a one pair of teeth in contact. Finite element contact models and contact analysis are carried out using APDL coding for various gears under rotational force. In gear meshing, surface-surface contact is considered and target element (TARGE170) also used to represent the contact pairs.

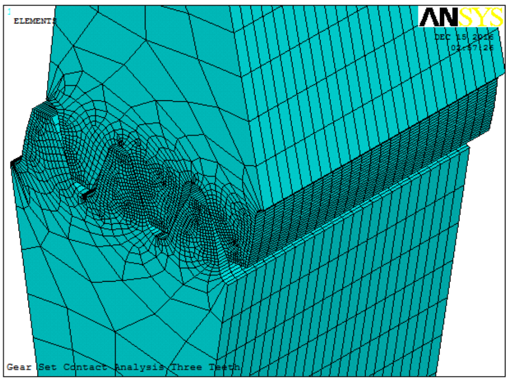

Figure 2. Meshing of Spur gear

This target surface is discretized by a set of target segment elements. Contact element (CONTA174) is used to represent contact and sliding between 3-D "target" surfaces. CNCHECK command is used to check the contact status between the contact and target elements in the mating surface of the gears as shown in Fig.3.

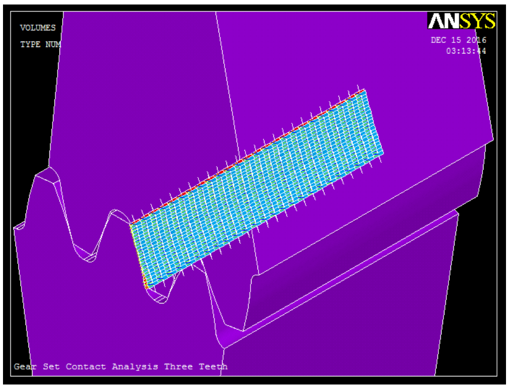

Figure 3. Contact pair of spur gear

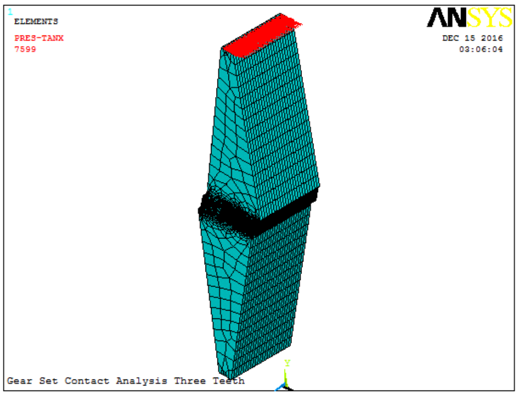

Figure 4. Boundary conditions of spur gear

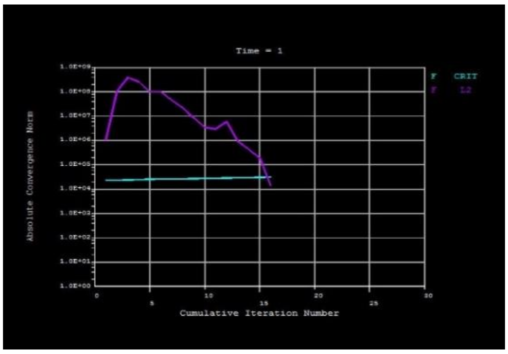

Figure 5. Non-linear convergence graph

In order to get the perfect contact, both contact and target elements refer to the same set of characteristic parameters such as contact stiffness, allowed penetration tolerance, friction coefficient, and so on. Fine meshing is generated in order to get accurate results which are shown in figure 2. Load applied at the upper (driving) gear of the inside gear rim and DOF applied at bottom (driven) pinion of the inside rim. The rotational pressure of 7599 N/m^2 is applied in clockwise direction on the inner rim of the upper gear as shown in Fig. 4. After applying boundary conditions next step to solve the problem. In contact analysis if the problem is solved the nonlinear convergence graph generated automatically. In this graph X-axis denoted that iteration numbers and Y-axis denoted that force convergence values. From fig. 5 it can be seen that the position of convergence with respect to number of iterations.

5. Results and discussions

The design and analysis spur gears are carried out for three different materials with various speeds. Figure 6 shows the stress distribution and maximum von mises stress occurs at the root of the tooth based on the loading conditions. Stress value in composite gear is less compared to peak gear which improves the efficiency of the gear.

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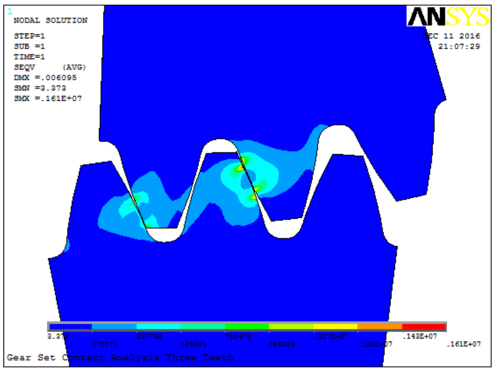

Figure 6. Position of maximum Contact Stress

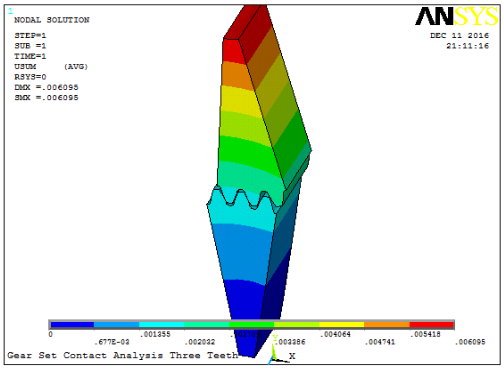

Figure 7. Maximum Displacement Vector sum

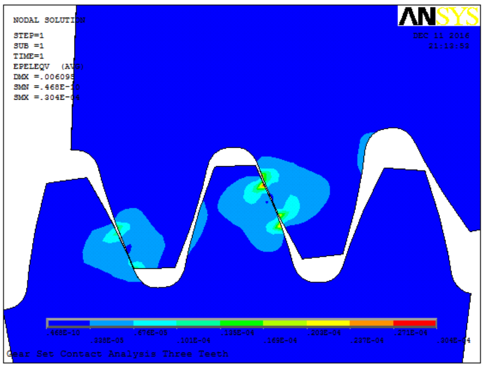

Figure 8. Von mises Elastic Strain in pair of gears

Fig.7. shows the displacement pattern in the pair of gears. From the result, it can be seen that the maximum deformation of composite material gear is very less compared other two gear materials which is shown in Table.2. In strain distributions plot (Fig.8) the von mises strain for composite gears is less compared to peek gears. Fig. 9 shows the stress distribution pattern of the individual gear after loading. From the graph it could be concluded that the maximum stress occurs in the tip of the gear teeth.

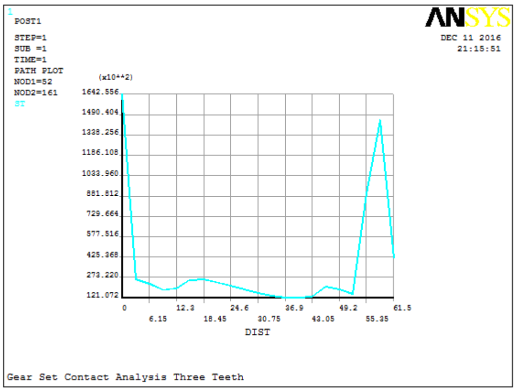

Figure 9. Path Distance Vs Stress

Table 2. Comparison between composite, peek and steel materials at 500 rpm speed

S. No	Results	Composite material	Peek material	Steel material
1	Contact stress (Mpa)	2.41	1.81	1.42
2	Stress in X direction (Mpa)	2.65	2.53	2.05
3	Stress in Y direction (Mpa)	2.21	2.38	1.12
4	Displacement (mm)	0.9143E-2	0.160023	0.3998E-2
5	Strain	0.457E-4	0.608E-3	0.731E-6
6	Strain in X direction	0.269E-4	0.321E-3	0.526E-5
7	Strain in Y direction	0.197E-4	0.287E-3	0.459E-5

Table 3. Comparison between composite, peek and steel materials at 750 rpm speed

S. No	Results	Composite material	Peek material	Steel material
1	Contact stress (Mpa)	1.61	1.25	0.969
2	Stress in X direction (Mpa)	1.77	1.66	1.15
3	Stress in Y direction (Mpa)	1.47	1.59	1.12
4	Displacement (mm)	0.6095E-2	0.103084	0.1998E-2
5	Strain	0.304E-4	0.387E-3	0.632E-6
6	Strain in X direction	0.179E-4	0.207E-3	0.370E-5
7	Strain in Y direction	0.131E-4	0.173E-3	0.395E-5

The Stress distributions, deformations and strain rate are obtained for three different gear materials in two different speed conditions are shown in table 2 and table 3. From the analysis results it can be concluded that the deformation of composite material is very less compared to steel and plastic material. So we conclude that composite material has better alternative for steel and plastic material.

6. Conclusion

In this paper, the gear tooth contact analyses in spur gears through finite element analysis are carried out. A general finite element model was developed for evaluating the contact stress in spur gears of equal geometry in both gears. FEA was used to simulate the gear tooth contact behavior through the mesh, contact elements and adaptive method with the aid of an augmented Lagrange contact algorithm. The detailed procedures to create a 3D model in finite element software were described. The displacements, stress distributions and strain for three different materials with two different speeds were obtained. From the result it could be concluded that the deformation of composite material gear is very less compared to steel and plastic materials. Also the rotational speeds of the spur gear influences the behavior of the materials like stress, strain and deformation etc. Therefore the composite material has better alternative for steel and plastic material.

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