Design and analysis of composite drive shaft for automobile application

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Abstract: The objective of this paper is to design and analyze a composite drive shaft for power transmission applications. Composite structures substitutes conventional metallic structures and having many advantages. Its main advantages consist of higher specific stiffness and higher specific strength of composite materials. This paper deals with the design of conventional two-piece steel drive shafts with one-piece automotive composite drive shaft. A one-piece drive shaft for rear wheel drive automobile was designed using Carbon/Epoxy composites. .A composite shaft made of Carbon/Epoxy composites can be tested with the help of torque tester. The composite materials arehaving lower density which results in to reduction in the weight of shaft significantly. The design parameters are selected with the objective of minimizing the weight of composite drive shaft &increase in torque capability compared with a conventional two-piece steel drive shaft. By analysing performance conventional two piece steel drive shaft can be replaced by one piece composite drive shaft.

Keywords – carbon/epoxy, drive shaft,

1. INTRODUCTION

Fossil fuels used for automobile like petrol, diesel etc. are non-renewable source of energy. So, main intention in automobile sector is to improve mileage of vehicle. One of the ways to increase the mileage of vehicle is to reduce its weight. There are a variety of alternatives being explored by the automobile companies, there is more than one possible answer. At this point the only certainty is that no single material or type of material will dominant. The biggest questions the automotive industry faces today is which materials are to be used, to reduce the weight of the vehicle and save fuel.
Almost all automobiles, which correspond to design with rear wheel drive and front engine installation, have transmission shafts [1]. An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The weight reduction of the drive shaft can have a certain role in the general weight reduction of the vehicle and is a highly desirable goal, if it can be achieved without increase in cost and decrease in quality [2, 3]. The material which is being used today is high strength steel. Metallic drive shafts have limitations of weight and low critical speed. The fundamental bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus [4].
The torque capability of the drive shaft for passenger cars should be larger than 3500 Nm and the fundamental bending natural frequency should be higher than 6500 rpm to avoid whirling vibration [1, 2]. Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminum is normally lower than 5700 rpm. When the length of the drive shaft is around 1.5 m, the steel drive shaft is usually manufactured in two pieces to increase the fundamental bending natural frequency [5].
Polymer matrix composites are most common composite material being used in drive shaft. The most common are carbon epoxy, glass epoxy and carbon/glass epoxy hybrids. The advanced composite materials such as Graphite, Carbon and Glass with suitable resins are widely used because of their high specific strength (strength/density) and high specific modulus (modulus/ density) [6, 7].Substituting composite structures for conventional metallic structures has many advantages because ofhigher specific stiffness and strength of composite materials [8]. Since, carbon fiber epoxy composite materials have more than four times specific stiffness of steel or aluminum materials, it is possible to manufacture composite drive shafts in one-piece without reducing whirling vibration over 6500 rpm[9].
The two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle. In addition, the use of single torque tubes reduces assembly time, inventory cost, maintenance, and part complexity. Analytically it was proved that composite drive shaft has many benefits such as reduced weight and less noise and

vibration.But experimental investigations regarding performance of composite drive shaft have not doneto compare with conventional steel drive shaft.To decrease the bending stresses various stacking sequences can be used. By doing the same, we can maximize the torque transmission, static torque capability, buckling torque capability and bending natural frequency.

The objective of this work is, to analyse the comparative performance of carbon epoxy composite drive shaft with respect to conventional steel drive shaft for torque transmission capability. By analysing performance conventional two piece steel drive shaft can be replaced by one piece composite drive shaft.

2. Theoretical background

All the automobiles, which correspond to design with front engine installation andrear wheel drive, have transmission shafts. An automotive propeller shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle[3]

2.1 Function of drive shaft:

1. It should transmit torque from the engine transmission to the differential gear box.
2. It is necessary to transmit maximum low-gear torque developed by the engine during the operation.
3. The drive shafts must also be capable of rotating at the very fast speeds required by the vehicle [2].

2.2 Demerits of a Conventional Drive Shaft

1. They have less specific modulus and strength.
2. They have increased weight.
3. Steel drive shafts have less damping capacity.
4. Its corrosion resistance is less as compared with composite materials.[1]

2.3 Merits of Composite Drive Shaft

1. They have high specific modulus and strength.
2. They possess property like reduced weight.
3. As the weight reduces, fuel consumption will be reduced.
4. They have good corrosion resistance.
5. Greater torque capacity than steel shaft [5, 7].

3.Design Variables

The design variables of the problem are:

1. Number of plies
2. Stacking Sequence
3. Thickness of the ply

Thedesign variables are having limiting values as given as follows:

1. Number of plies: The number of plies required depends on the design constraints, allowable material properties, and thickness of plies and stacking sequence. The value for sufficient number of plies based on the investigations was found up to 32 numbers of plies [8,11].
   $n \geq 0$
   $n = 1,2,3\ldots32$
2. Stacking Sequence: The stacking sequence in composite material gives orientation of fiber with respect to axis of job[8,11].
   $-90 \leq \theta k \leq 90$
   k = number of ply
   k =1, 2…… n
3. Thickness of the ply: This parameter shows thickness of each ply in direction the normal to axis of job[8,11].
   $0.1 \leq tk \leq 0.5$

4. Design Constraints

1. Torque transmission capacityof the shaft [8,11]:
   $T \geq Tmax$
2. TorsioanalBucking capacityof the shaft:
   $Tcr \geq Tmax$
3. Lateral fundamental natural frequency of the shaft:
   $Ncrt \geq Nmax$

5. Design of steel drive shaft

The following specifications were selected for automobile drive shaft:

1. The torque transmission capacity of the driveshaft (T) = 180 N-m.
2. The shaft needs to withstand torsional buckling (Tb) such that Tb > T.
3. The minimum bending natural frequency of the shaft (f_{nb}(min)) = 25 Hz.
4. Outside diameter of the driveshaft (d_0)= 50mm.
5. Length of the driveshaft = 1.8 m.

The material most widely being used for conventional drive shaft is steel. The steel selected was SM45C, since it is The properties of SM45C steel are:

Young's modulus (E) = 207GPa,
Poisson's ratio (ν) = 0.3,
Density of steel (ρ) = 7600 kg/m3
Ultimate shear strength τult = 80 MPa

1. Torsional strength: The primary load in the drive shaft is torsion. The maximumshear stress, τmax, in the drive shaft is at the outer radius (ro), and isgiven as,

$$\frac{\tau_{max}}{F.O.S.} = \frac{Tr_o}{J}$$

T = maximum torque applied in drive shaft (N-mm)
ro = outer radius of shaft (mm)
J = polar moment of inertia (mm4)
F.O.S.= Factor of safety = 3

$$J = \frac{\pi}{32}(d_o^4 - d_i^4)$$

$$\frac{\tau_{max}}{F.O.S.} = \frac{T r_o}{\frac{\pi}{32}(d_o^4 - d_i^4)}$$

$$\frac{80}{3} = \frac{180 \times 10^3 \times 25}{\frac{\pi}{32}(d_o^4 - d_i^4)}$$

di = 46 mm

Hence, the inner radius is,

$$ri = 23\ mm.$$

Thus the wall thickness of the hollow steel shaft:

$t = r_0 - ri$

$= 25 - 23 = 2$ mm

2. Torsional buckling: This requirement asks that the applied torsion be lessthan the critical torsional buckling moment. For a thin, hollow cylinder madeofisotropic materials, the critical buckling torsion, Tb is given as follows,
   A shaft is considered as a long shaft, if:

$$\left[\frac{1}{\sqrt{1-\nu^2}}\right]\frac{L^2 \times t}{(2r)^3} > 5.5$$

$$\left[\frac{1}{\sqrt{1-0.3^2}}\right]\frac{1.8^2 \times 2}{(2 \times 24)^3} > 5.5$$

$$6.142 > 5.5$$

For long shaft, the torsional buckling capacity:

$$T_b = \tau_{cr}(2\pi r^2 t)$$

Where critical stress is given by,

$$\tau_{cr} = \left[\frac{E}{3\sqrt{2}(1-\nu^2)^{3/4}}\right]\left(\frac{t}{r}\right)^{3/2}$$

$$\tau_{cr} = 1259\ N/mm^2$$

$$T_b = 1259(2\pi \times 24^2 \times 2)$$

$$T_b = 9118.29\ Nm \quad (T_b > T)$$

3. Natural frequency: The lowest natural frequency for a rotating shaft is given by,

$$f_n = \frac{\pi}{2}\sqrt{\frac{EI}{mL^4}}$$

E = Young's modulus of elasticity (Pa)
m = mass per unit length (kg/m)
L = length of drive shaft (m)
I = areamoment of inertia (m4)

$$I = \frac{\pi}{64}(d_o^4 - d_i^4)$$

$$I = \frac{\pi}{64}(0.05^4 - 0.046^4)$$

$$I = 8.7 \times 10^{-8} m^4$$

Mass per unit length of shaft is given by,

$$m' = \rho\left(\frac{\pi}{4}\right)[d_o^2 - d_i^2]$$

$$m' = 7600\left(\frac{\pi}{4}\right)[0.05^2 - 0.046^2]$$

$$m' = 2.292\ kg/m$$

Natural frequency

$$f_{nb} = \frac{\pi}{2}\sqrt{\frac{207 \times 10^9 \times 8.7 \times 10^{-8}}{2.292 \times 1.8^4}}$$

$$f_{nb} = 42.97\ Hz\ or\ f_{nb} = 2578\ rpm$$

6.Design of composite drive shaft

The design of composite drive shaft consists of selection of design variables such as number of plies, stacking Sequence, thickness of the ply. To restrict design variables only 0°,±45° and 90° were considered for the composite ply orientations, because of their specific advantages. The 60% fiber volume fraction Carbon/Epoxy shaft was selected. The standard ply thickness of 0.13 mm was selected. [11]

1. Torsional strength: Assuming that the drive shaft is a thin, hollow cylinder,an element in the cylinder can be assumed to be a flat laminate.

$$\frac{\tau_{max}}{F.O.S.} = \frac{T}{2\pi r^2 t}$$

Where, r is the mean radius of the shaft.
Since the nature of loading is pure torsional shear, 70% of the plies can be set at ±45° and the remaining 30% at 0º and 90º orientations.
From fig 4.1,

$$\tau_{max} = 293\ Mpa$$

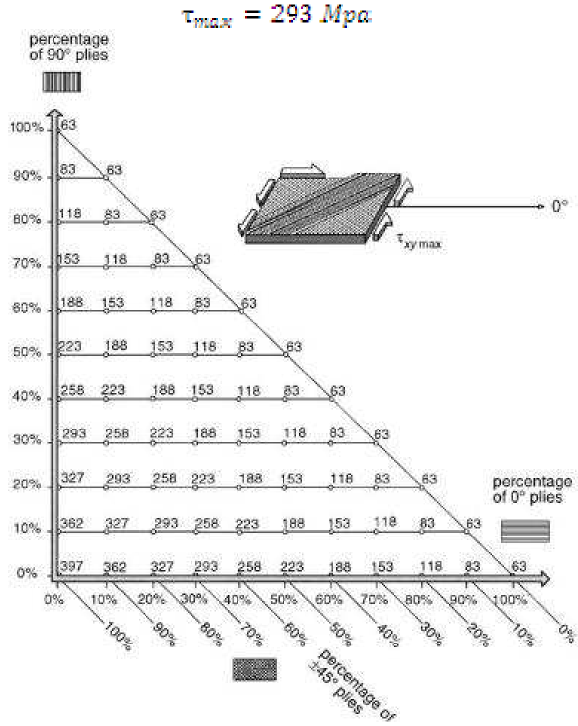

Fig.1: Maximum shear stress (τmax) as a function of ply percentages for Carbon/Epoxy Laminate (Vf = 60%; Ply thickness = 0.13 mm)[12]

Consider factor of safety as 6.

$$\frac{293 \times 10^6}{6} = \frac{180}{2\pi r^2 t}$$

$$r^2 t = 0.586 \times 10^{-6} mm$$

$$0.024^2 t = 0.586 \times 10^{-6} mm$$

$$t \geq 1.01736mm$$

Thickness of each ply is t_k,

$$t = 0.13mm$$

Number of ply (n),

$$n = \frac{t}{t_k}$$

$$n = \frac{1.01736}{0.13}$$

$$n = 7.82 \quad or \quad n \cong 8$$

Hence, corrected values of thickness and radius are given as below:

Thickness, $t = n \times t_k$

$$t = 8 \times 0.13$$

$$t = 1.04\ mm$$

Diameter,

$$d_0 = 49.04\ mm$$

$$d_i = 46.96\ mm$$

2. Torsional buckling: An orthotropic thin hollow cylinder will buckle torsionally, if the applied torque is greater than the critical torsional buckling load. Which is given by,

$$T_c = (2\pi r^2 t)(0.272)(ExE_y^3)^{\frac{1}{4}}\left[\frac{t}{r_m}\right]^{3/2}$$

$$T_c = 357.47\ \mathrm{Nm} \qquad (T_c > T)$$

Ex = longitudinal Young's moduli
= 38709.5 MPa
Ey = Transverse Young's moduli

3. Natural frequency: To find the minimum naturalfrequencyof the drive shaft, which is given by,

$$f_{nb} = \frac{\pi}{2}\sqrt{\frac{E_x I}{mL^4}}$$

Ex = longitudinal Young's moduli
L = length of drive shaft (m)
I = second moment of area (m4)

$$I = \frac{\pi}{64}(d_0^4 - d_i^4)$$

$$I = \frac{\pi}{64}(0.04904^4 - 0.04696^4)$$

$$I = 4.5187 \times 10^{-8} m^4$$

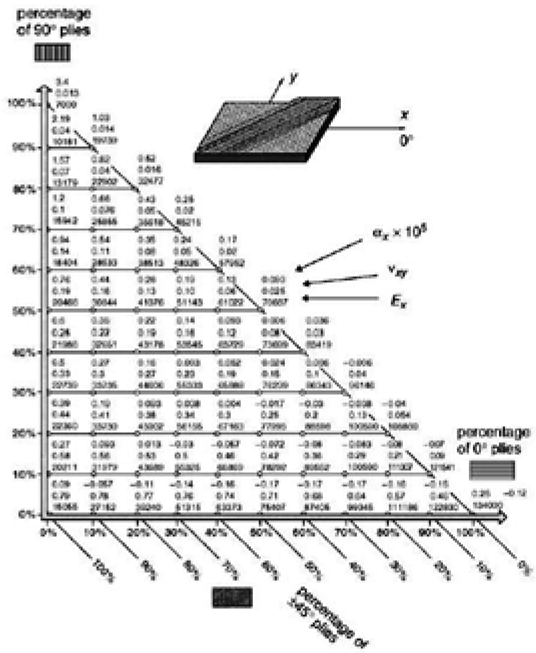

Fig. 2: Young's Modulus(Ex in MPa), Poisson's ratio (υxy) and Co-efficient of thermal expansion (α) as functions of ply percentages for Carbon / Epoxy Laminate (Vf = 60%; Ply thickness = 0.13 mm) [12]

m = mass per unit length (kg/m)

$$m' = \rho\left(\frac{\pi}{4}\right)[d_0^2 - d_i^2]$$

$$m' = 1530\left(\frac{\pi}{4}\right)[0.04904^2 - 0.04696^2]$$

$$m' = 0.2399\ kg/m$$

The minimum naturalfrequencyof the drive shaft,

$$f_{nb} = \frac{\pi}{2}\sqrt{\frac{38709 \times 10^6 \times 4.5187 \times 10^{-8}}{0.2399 \times 1.8^4}}$$

$$f_{nb} = 41.39Hz \qquad or \qquad f_{nb} = 2484\ rpm$$

7. Result

Dimensions of steel drive shaft

- Outer diameter = 50 mm.
- Inner diameter = 46 mm
- Length = 1.8 m
- Thickness = 2 mm
- Total mass = 4.1256 kg

Dimensions of carbon epoxy composite drive shaft

- Outer diameter = 49.04 mm.
- Inner diameter = 46.96 mm
- Length = 1.8 m
- Thickness = 1.04 mm
- Total mass = 0.43182 kg

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