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Experimental Investigations on Static and Dynamic Parameters of Steel and Composite Propeller Shafts for a Light Passenger Vehicle

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Abstract: *This paper describes static and dynamic analysis of steel propeller shaft and composite propeller shaft made of glass fibre reinforced polymer. Primary objective is to compare the torque bearing capacity, stiffness and weight savings of composite propeller shaft with that of steel propeller shaft. The design constraints are angle of twist and natural frequency. Finite element analysis with full torsional load on 3-D model of composite propeller shaft was done using finite element technique and analytical results were compared with experimental results. Composite propeller shaft had greater angle of twist, higher stiffness and higher natural frequency than that of existing steel propeller shaft. A weight reduction is achieved by using composite propeller shaft.*

Keywords: *Composite propeller shaft, Glass fibre reinforced polymer, Angle of twist, Natural frequency, Static analysis, Dynamic analysis*

Nomenclature:
SPC ………..Steel Propeller Shaft
CPS………..Composite Propeller Shaft
E …………..Elastic Modulus
v……………Poisson's ratio
G………….. Shear Modulus
T……………Torque ability

I. Introduction

Weight reduction has been the main focus of automobile manufactures. Transmission propeller shaft, a potential item for weight reduction in automobiles, accounts for 7-15 percent of sprung weight, which is the entire weight of the vehicle supported above the suspension springs. Application of composite structures reduces the weight of propeller shaft without any reduction on the torque bearing capacity and stiffness in automobile transmission system.

Propeller shaft should be capable of absorbing dynamic vibrations and impacts due to road irregularities and transfer maximum transmission energy from the engine to differential with minimum energy loses to rotate the wheels. So, increasing energy transmission capability of a propeller shaft ensures a more compliant transmission system. A material with maximum strength and minimum shear modulus is the most suitable material for a propeller shaft; Important characteristics of composites[7] that make them excellent for propeller shaft instead of steel are higher strength-to-weight ratio, superior fatigue strength, excellent corrosion resistance, higher natural frequency, etc.

In the present work, a steel propeller shaft used in passenger cars is replaced with a composite propeller shaft made of glass/epoxy composites. Dimensions of steel propeller shaft (SPS) and composite propeller shaft (CPS) are considered to be same. Primary objective is to compare their load carrying capacity, stiffness and weight savings of CPS.

II. Design Specifications

2.1 Steel propeller shaft (SPS)

Design parameters of existing steel propeller shaft used in this work includes: total length (composite shaft),500 mm; outer diameter, 77 mm; inner diameter,47mm;thickness, 15mm; shaft weight, 3.41 kg; material being mild steel with elastic modulus (E) , 207 GPa; poisons ratio(v),0.3; Shear modulus of steel (G) , 80 GPa; and the torque ability (T),1500 N-m.

2.2Composite Propeller Shaft (CPS)

Composite propeller shaft is developed using filament winding technology and is designed for a thickness of 9.5mm with $15^o/54.7^o/75^o/90^o$ layers. The thickness of each layer with respect to $15^o/54.7^o/75^o/90^o$ layers is 1.2mm/1.2mm/1.2mm/0.5mm respectively and the types of loops being helical for $15^o/54.7^o/75^o$ layers and hoop for 90^o layer. The length and outer diameter are similar to that of steel propeller shaft. Propeller shaft is made using Epoxy/Eglass composite material having Young's Modulus 4e+005 MPa, Poisson's Ratio 0.36, Density 6e-006 Kg/mm3, Tensile Yield Strength 2500 Mpa, Compressive Yield Strength 3150 Mpa. This material is assumed to be linearly elastic and orthotropic.

Degrees	Type of loop	Thickness(mm)
+90	Hoop	0.5
Mat		0.3
+- 15	Helical	1.2
+- 54.7	Helical	1.2
+-75	Helical	1.2
90	Hoop	0.5
+-75	Helical	1.2
+-54.7	Helical	1.2
+-15	Helical	1.2
90	Hoop	0.5
90	Hoop	0.5
Total thickness		9.5

Table 1 Winding loops with angles and thickness

III. Design Of Composite Propeller Shaft

The composite propeller shaft should satisfy two main design specifications such as static torque capability and bending natural frequency. The composite material helps in sustaining the torque and increase the bending natural frequency.

The composite propeller shaft is designed to bear a torque capability of 1500N-m which is similar to that of steel propeller shaft. The length and outer diameter of the composite shaft is maintained same as steel shaft. The inner diameter of the CPS is determined using (1) where fs is Maximum allowable stress, D is outer diameter, d is inner diameter, T is torque and fos is the factor of safety. The CPS is then manufactured using these dimensions. The angle of twist of the propeller shaft is determined using (2), where J is the polar moment of inertia, G is shear modulus, L is length of shaft and **θ** is angle of twist. The natural frequency is determined using (3) where fn is natural frequency, E is elastic modulus of epoxy glass, I is moment of inertia, m is mass of shaft, l is length of shaft.. The basic formulae used in the design and analyses of the composite propeller shaft are given below:

$$T = \frac{\pi}{16}\frac{(D^4 - d^4)}{D} * \frac{fs}{2*fos} \quad (1)$$

$$\frac{T}{J} = \frac{G\Theta}{L} \quad (2)$$

$$fn = \alpha^2 * \sqrt{\frac{E\,I}{ml^4}} \quad (3)$$

PARAMETER	STEEL SHAFT	COMPOSITE SHAFT
Outer diameter	77 mm	77 mm
Inner diameter	47 mm	58mm
Length of shaft	500 mm	500 mm
Thickness	15 mm	9.5 mm
Torque	1500 N-mm	1500 N-mm

Table 2 Dimensions of composite propeller shaft

IV. Fabrication Of Composite Propeller Shaft

Fabrication of composite propeller shaft is done by a sequence of steps. The steps that are involved during the fabrication are:

4.1 Mandrel setup

A steel pipe of 540mm length and 65mm outer diameter is taken so that the process of machining gives us the desired dimensions such as 538mm length and 58mm diameter as shown in fig.1

4.2 Releasing Agents

Releasing agent is then applied on the mandrel as it helps the component to get released out of the mandrel easily without damaging the mandrel or the component fabricated.

4.3 Material

In the fabrication process of composite propeller shaft Epoxy resin (LY-556) and Hardener (U-972) is used. This mixture is firstly applied on the wax polish and then a layer is placed on the mandrel and the resin is applied again. This process is continued till the last layer.

Fig.1 mandrel setup

Fig.2 filament winding

4.4 Filament winding on the machine

The mandrel is fitted onto the cnc machine for filament winding where the mandrel rotates while a carriage moves horizontally, laying down fibers in the desired pattern. The filament used is glass fiber and are coated with synthetic resin LY556 as they are wound. The mandrel is completely covered to the desired thickness of 9.5mm as shown in fig.2

4.5 Oven curing process

The next stage implemented is oven curing in which the shaft along with mandrel is placed in the oven as shown in fig.3 which is set to room temperature. The next two hours is maintained at 120 degrees. The temperature is varied between 120 and 150 for 30 minutes and maintained at 150 for next 4 hours. Thus the shaft is placed in oven for a span of 7 hours and then the machine is shut down. Allow shaft to cool in the oven until it attains room temperature. The process of curing increases the strength and hardness of shaft as shown in Fig.3

Fig.3 oven curing

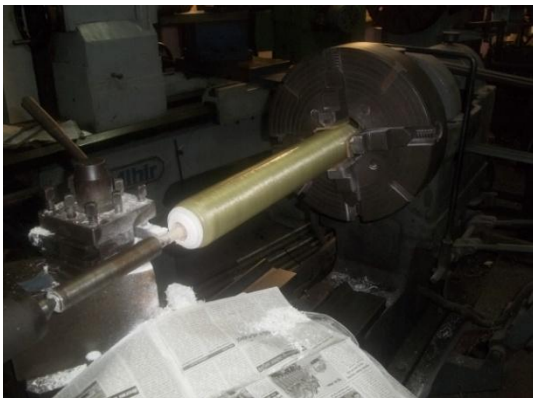

Fig.4 machining the composite propeller shaft

4.6 Machining

After oven curing the end pins of the shaft are cut, the shaft is cut with a cutter to the required length shown in fig 4

The mandrel is extracted by the process of hydraulic extraction and the glass fiber composite shaft remains.

4.7 Welding
After machining C clamp is fitted at both the ends and the spline shaft and the universal coupling are welded to that C clamp. Excess material is removed and the fabrication of composite propeller shaft is finished.

Fig.5 composite propeller shaft

V. METAL – Composite Joint
Joining a metal and a composite material is of major concern in any manufacturing of composite products. In composite propeller shaft we have joined the metal spline with the composite shaft using the following procedure:

1. Material of some thickness was removed at the ends of the composite hollow shaft to a certain depth
2. Adhesives were applied at both the ends
3. A C clamp of the thickness same as material removed is chosen with certain height which fits correctly at both the ends is fitted and placed in oven for curing.
4. After curing the metal C clamp and the composite hollow shaft are joined very tightly due to the strong adhesives.
5. The spline shaft and the universal coupling are welded to the metal C clamp at both the ends using arc welding technique and excess material is removed for smooth finish.

Thus the joint is successfully fabricated and tested experimentally.

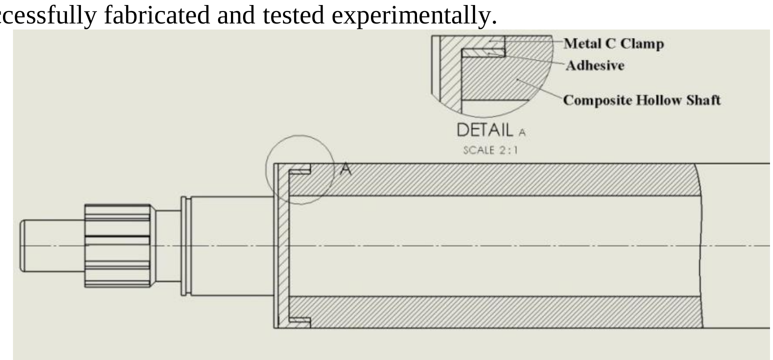

Fig.6 Sectional view of Metal to Composite joint

VI. Experimental Testing Details
The steel propeller shaft and composite propeller shaft are tested experimentally under static and dynamic conditions.

6.1 Experimental Static test
Under static test both the propeller shafts undergo torsion test where the shaft is twisted and the angle of twist, the shear stress, modulus of rigidity, strain energy, ultimate torsional stress, etc are determined. This test is conducted using torsion testing machine which consists of two jaws, one jaw capable of rotating whereas the other jaw remains stationary. The propeller shaft is mounted between the two jaws and torque is applied to determine the angle of twist the pointer is fixed to the propeller shaft and torque is applied. As the propeller shaft twists, the pointer rotates and using a radial scale the angle of twist is determined as shown in Fig.7

6.2 Numerical Static test

A static analysis is done to find the find torsional behavior of the shaft using the software anys14.5 with boundary conditions: One end of the shaft is fixed in all direction; Moment is applied on the other end. Pipe element (3node 289) is used. The shaft is modeled using Solidworks and static analysis is done on it, to obtain its maximum stress, angle of twist for the torque applied. The material properties of mild steel propeller shaft being elastic modulus (E), 207 Gpa; poisons ratio (v), 0.3; density, 7500kg/mm3. Torque applied (T), 1541.28N-m. The material properties of composite propeller shaft being elastic modulus (E) , 50Gpa; poisons ratio,0.34; density,2100kg/mm3, torque applied(T),1778.4N-m.

6.3 Experimental Dynamic test

Under dynamic test the propeller shaft is simply supported on a work bench. A Piezo electric sensor which is connected to the CRO is put in contact with the propeller shaft. The propeller shaft is then hit with hammer. The sensor senses these vibrations and converts them into electrical signals. This conversion is done using accelerometer and we get a time vs. voltage graph. This data obtained from the accelerometer are put into MATLAB to get frequency using fast Fourier transforms. FFT analyzer converts the time vs. voltage inputs to amplitude v/s frequency. The process with repeated on both composite and metal propeller shafts and the frequency obtained for both the shafts are compared as shown in Fig.8

6.4 Numerical Dynamic test

The modal analysis is done using the software ANSYS 14.5 with no boundary conditions applied. The pipe element (3node289) is chosen with the total no. of modes being 70. The shaft is modeled using Solidworks and modal analysis is done on it at different modes to obtain its first highest natural frequency. The material properties of mild steel propeller shaft being elastic modulus (E), 207 Gpa; poisons ratio (v), 0.3; density, 7500kg/mm3. The material properties of composite propeller shaft being elastic modulus (E) , 50Gpa; poisons ratio,0.34; density,2100kg/mm3, torque applied(T),1778.4N-m.

Fig.7 Hydraulic operated Torsion Testing Machine for Static Parameters **Fig.8** Vibration testing setup

VII. Results And Discussions

7.1 Static testing

The propeller shaft is tested with a hydraulic torsion test rig. Shear modulus, angle of twist and torque are compared for both metal and composite propeller shaft. The reason for the stiffness and stress variations may be due to its lower volume fraction obtained in the fabrication process or due to lack of complete curing. A weight reduction of 37.9% is achieved by using a composite propeller shaft in place of steel propeller shaft. For a light passenger vehicle, the toque is theoretically estimated to be 1500n-m.Therefore a torque of 1500 n-m is applied to find the angle of twist and shear modulus. Angle of twist of 1.4deg is obtained at a torque of 1541.17 N-m with a shear modulus of 12.57gpa for a steel propeller shaft. Angle of twist of 1.4deg is obtained at a torque of 1707.26 N-m with a shear modulus of 15.8gpa for a composite propeller shaft as shown in Fig.9. The reason for increased stiffness is lower density of E-glass/epoxy composite combination. Through finite element analysis the angle of twist obtained for steel propeller shaft is 1.32deg with a maximum shear stress of 18.953 N/mm2 and for composite propeller shaft it is 1.37deg with a maximum shear stress of 27.774 N/mm2 at a torque of 1500n-m.

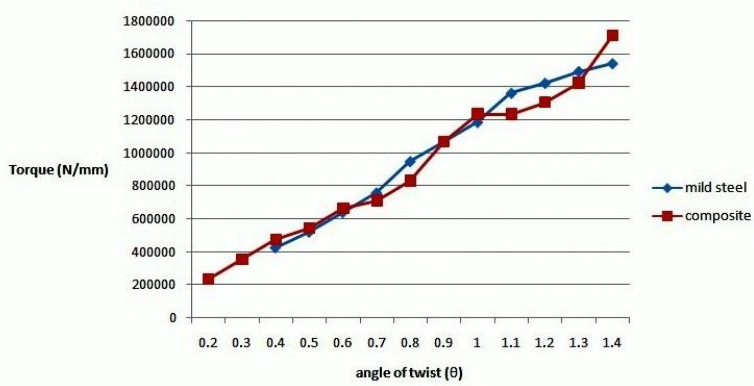

Fig. 9 Torque-angle of twist curves for Steel and Composite propeller shaft

7.2 Dynamic testing

Propeller shaft is simply supported on a work bench and is hit with a hammer.Vibrations sensed by a piezo electric sensor are coverted to time vs voltage using hameg instrument.this time vs voltage values are coverted to amplitude vs frequency using fft analyser in mat lab as shown in Fig.10 and Fig.11.The first highest natural frequency is obtained at 28hz for a steel propeller shaft and 35hz for a composite propeller shaft.By using finite element analysis a natural frequency of 30.92hz is obtained for a steel propeller shaft and 35.48hz for a composite propeller shaft.

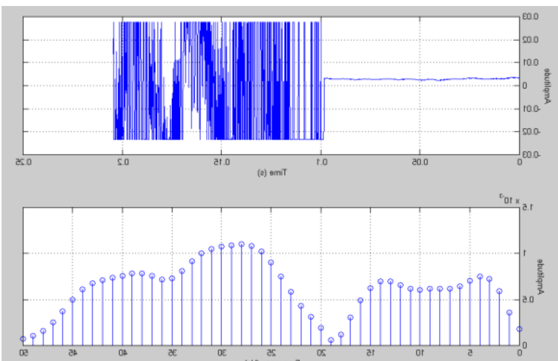

Fig.10 Amplitude-Frequency graph for steel propeller shaft

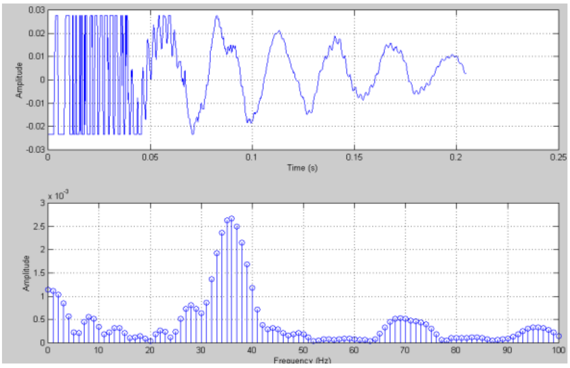

Fig.11 Amplitude-Frequency graph for composite propeller shaft

7.3 Comparison

Parameter	Mild Steel Propeller Shaft		Composite Propeller Shaft	
	Numerical	Experimental	Numerical	Experimental
Angle of twist (degrees) Torque=1500N-m	1.32	1.2	1.37	1.4
Natural frequency(Hz)	30.92	28	35.48	35
Shear stress(N/mm2)	18.953N/mm2	22.49 N/mm2	27.774 N/mm2	37.955N/mm2

VIII. Conclusion

Design and experimental analysis of composite propeller shaft using glass fibre reinforced polymer has been carried out. Composite propeller shaft is found to have higher torque (10.5%), higher stiffness (25.69%) and higher natural frequency (25%) than that of mild steel propeller shaft. Conventional mild steel propeller shaft weighs about 3.41 kg whereas the E-glass/Epoxy propeller shaft weighs only 2.1 kg, thereby weight reduction (37.9%) is achieved. Finally it is considered that composite propeller shaft has following advantages:

- Less density
- More stiffer
- Corrosion free
- High frequency

Thus composite material is the best alternate material for the automobile component Propeller shaft.

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