Design Analysis of an Automotive Composite Drive Shaft

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Abstract—Automotive drive Shaft is a very important components of vehicle. The present paper focuses on the design of such an automotive drive shat by composite materials. Now a days two pieces steel shaft are used as drive shaft. However, the main advantages of the present design is; only one piece of composite drive shat is possible that fulfil all the requirements of drive shaft. Two different designs are proposed, one is purely from Graphite/Epoxy lamina and other is using Aluminum with Graphite/Epoxy. The basic requirements considered here are torsional strength, torsional buckling and bending natural frequency. An optimum design of the draft shaft is done, which is cheapest and lightest but meets all of the above load requirements. Progressive failure analysis of the selected design is also done.

Keywords: Drive shaft, Torsional buckling, Bending natural frequency

I. INTRODUCTION

A driveshaft is a rotating shaft that transmits power from the engine to the differential gear of a rear wheel drive vehicles [1]. Driveshaft must operate through constantly changing angles between the transmission and axle. High quality steel is a common material for construction. Steel drive shafts are usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. The two piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increase the total weight of a vehicle. Power transmission can be improved through the reduction of inertial mass and light weight. Substituting composite structures for conventional metallic structures has many advantages because of higher specific stiffness and higher specific strength of composite materials. Composite materials can be tailored to efficiently meet the design requirements of strength, stiffness and composite drive shafts weight less than steel or aluminum of similar strength. It is possible to manufacture one piece of composite drive shaft to eliminate all of the assembly connecting two piece steel drive shaft. Also, composite materials typically have a lower modulus of elasticity. As a result, when torque peaks occur in the driveline, the driveshaft can act as a shock absorber and decrease stress on part of the drive train extending life. Many researchers ([2]-[4]) have been investigated about hybrid drive shafts and joining methods of the hybrid shafts to the yokes of universal joints. But this study provides the analysis of the design in many aspects.

II. DESIGN CONSTRAINTS

A. Design Specifications

The primary load carried by the drive shaft is torsion. The shaft must be designed to have enough torsional strength to carry the torque without failure. In addition, the possibility of torsional buckling must be considered for a thin-walled tube. The third major design requirement is that the drive shaft has a bending natural frequency which is sufficiently high. An optimum design of the draft shaft is desirable, which is cheapest and lightest but meets all of the above load requirements. Based on some reliable collected data the above three load-carrying requirements are summarized in Table 1.

TABLE I

LOAD REQUIREMENTS FOR DRIVE SHAFT DESIGN

Regular	**Values**	**Safety Factor**
Peak torque for 1,000,000-cycle reversed fatigue	680 N-m	3 for composites, 2.0 for metals
Minimum buckling torque	2000 N-m	1.05
Minimum bending natural frequency	90 Hz	.05

Physical dimensions of the shaft to be designed are assumed as given in Table 2.

TABLE II

DIMENSIONS FOR THE DRIVE SHAFT

Length of the drive shaft	1850 mm
Mean radius of the drive shaft	50 mm

Two different types of material are selected for the design: 1. Graphite/epoxy and 2. Aluminum. For this design, the thickness of each lamina is considered as 0.125 mm. The properties used for this lamina were taken from PROMAL [5].

Aluminum of different thickness and shapes were available there. Since drive shafts are round shape, aluminum was selected from aluminum (6061-T6) tube with 101.6 mm outer diameter and 1.65 mm thickness. Properties were also available in PROMAL.

III. Mathematical Formulae

The shearing load (N_{xy}) is defined by Equation (1)

$$N_{xy} = \frac{T}{2 \times \pi \times r_m^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots(1)$$

Where T is the torque and r_m is the mean radius of the drive shaft.

The critical torsional buckling torque, T_b is given by Equation (2)

$$T_b = (2\pi r_m^2 t) \times (0.272) \times (E_x \times E_h^3)^{\frac{1}{4}} \times (\frac{t}{r_m})^{\frac{3}{2}} \ \ldots \ (2)$$

Where t is the overall wall thickness, r_m is the mean radius, and E_x and E_h are the average in-plane elastic moduli in the axial and hoop directions respectively.

The drive shaft is idealized as a pinned-pinned beam. Lowest natural frequency is calculated using the Equation (3).

$$f_n = \frac{\pi}{2}\sqrt{\frac{gE_x I}{WL^4}} = \frac{\pi}{2}\sqrt{\frac{E_x I}{mL^4}} \ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ ...\ (3)$$

Where, f_n is the lowest frequency in hertz. $W/g = m$ is the mass per unit length, I, ($I \approx \pi r_m^3 t$) is the moment of inertia and L is the length of the drive shaft.

To find out the mass of the hybrid aluminum/composite shaft used in equation (3) the following equation was used.

$$\rho_c v_c = \rho_{al} v_{al} + \rho_{GE} v_{GE} \ \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ ...\ (4)$$

Where, Density of Aluminum, ρ_{al} , Volume of Aluminum, v_{al} , Volume and density of Graphite/Epoxy composite laminate are, v_{GE} and ρ_{GE} respectively.

IV. Description of the Analysis Method

From Equation (1) the shearing load is found as 43290.15 N/m and with a factor of safety of 3, the applied peak load is (43290.145×3) = 129870.43 N/m. In this study this peak load is considered as first ply failure load. The torsinal strength of the proposed design should be more than this load. In order to calculate the torsional strength, at first laminate sequence is given as input to PROMAL. Then N_{xy} = 1 N/m is applied. Using Tsai-Wu failure criterion the strength ratio for each lamina was calculated. From those result the minimum strength ratio was taken and multiplying the minimum strength ratio with 1N/m, first ply failure load of the laminate was obtained. Using Equation (2), with the factor of safety, the ultimate bending torque for the drive shaft is found 2000×1.05 = 2100 N-m. The bending natural frequency of the drive shaft is found 90×1.05 = 94.5 Hz.

A. Design 1 (Using Graphite/ Epoxy Lamina only)

At first, since the load is shearing one, a drive shaft made of 4 plies of graphite/epoxy composite is proposed. But, this shaft fulfilled the requirement of torsional strength only but not the torsional buckling and natural frequency requirement. To calculate the torsional strength Tsai-Wu failure criterion is used. Since the hoop modulus has an important effect on T_b and is likely to require that fibers be placed in the hoop direction to achieve an adequate buckling strength. From Equation (2) it is likely to require that some fibers be placed in the axial direction to achieve sufficient in-plane axial stiffness. That’s why new designed is tried combing 45^0, 0^0 and 90^0 graphite epoxy lamina. Finally it is found that $\left[0/90/0/45/90/-\overline{45}\right]_s$ laminate fulfilled all the requirements for the drive shaft. Now, since there is an angle limit for wet filament winding method, the 0^0 and 90^0 laminae are tried to replace by 17^0 and 78^0 laminae. But in that case 13 laminae are not enough to fulfill those requirements. At least 10 combinations of plies sequences are tried. Among them only few results are given in this paper.

TABLE III

PHYSICAL PARAMETERS FOR DIFFERENT STAKING SEQUENCE FOR DESIGN- 1

Staking Sequence	**r_m (m)**	**t (mm)**	**L (m)**	**P (kg/ m^3)**	***m* (kg)**
$[\pm 45]_s$	.05	0. 5	1.85	1600	0.46494
$\left[90/0/90/0/90/\overline{45}\right]_s$		1.375			1.27859
$\left[0/90/0/90/0/\overline{45}\right]_s$		1.375			1.27859
$\left[0/90/0/45/90/-\overline{45}\right]_s$		1.375			1.27859

t- Thickness, *L*-Length, ρ -Density, *m*- Mass

TABLE IV

ELASTIC CONSTANTS, MOMENT OF INERTIA FOR DESIGN -1

Staking Sequence	**No of Plies**	E_x^{in} **(GPa)**	E_y^{in} **(GPa)**	**I (m^4)**
$[\pm 45]_s$	4	25.1	25.1	1.96E-07
$\left[90/0/90/0/90/\overline{45}\right]_s$	11	75.3	106	5.4E-07
$\left[0/90/0/90/0/\overline{45}\right]$	11	10.6	75.3	5.4E-07
$\left[0/90/0/45/90/-\overline{45}\right]_s$	11	82.54	82.5	5.4E-07

I- Moment of inertia

TABLE V

FAILURE LOADS, TORQUES AND FREQUENCY FOR DESIGN -1

Staking Sequence	**No of Plies**	N_{xy}**, (N/m)**	T_b **(N-m)**	f_n **(Hz)**
$[\pm 45]_s$	4	175974.4	53.51	64.20
$\left[90/0/90/0/90/\overline{45}\right]_s$	11	142597.7	2612.73	111.28
$\left[0/90/0/90/0/\overline{45}\right]_s$	11	142597.7	2198.08	132.28
$\left[0/90/0/45/90/-\overline{45}\right]_s$	11	193377	2211.27	116.54

A..1 Proposed Design 1

From the above analysis the last three designs of drive shaft fulfilled the requirements. Among these three best designs of drive shaft using only graphite /epoxy is the best one because for the first two cases the laminate fails catastrophically. So the proposed best design is $\left[0/90/0/45/90/-\overline{45}\right]_s$. The proposed designed shaft contains 11 plies of Graphite/epoxy.

B. Design-2 (Using Graphite/ Epoxy and Aluminum)

The Aluminum used in this study was itself sufficient for the peak applied torque. Lamina with fiber direction 0° is added to increase its longitudinal in-plane elastic modulus. Combination of aluminum and 0° ply is sufficient for peak torque, buckling torque and bending natural frequency. If 90° lamina was added with aluminum and 0° lamina it will increase buckling torque but decreases bending frequency. Taking several combinations, the optimal one is selected.

TABLE VI

PHYSICAL PARAMETERS FOR DIFFERENT STAKING SEQUENCE FOR DESIGN-2

Staking Sequence	r_m **(m)**	*t* **(mm)**	*L* **(m)**	**Plies**	*m* **(kg)**
Pure Al	.05	1.65	1.85	1	2.49
[Al/0]		1.78		2	2.61
[0/Al/0]		1.90		3	2.73
[0/Al/90/0]		2.03		4	2.84

TABLE VII

ELASTIC CONSTANTS, MOMENT OF INERTIA FOR DESIGN -2

Staking Sequence	**Plies**	E_x^{in} **(GPa)**	E_y^{in} **(GPa)**	**I (m^4)**
Pure Al	1	69	69	6.48E-07
[Al/0]	2	76.9	60	6.97E-07
[0/Al/0]	3	83.7	62.7	7.46E-07
[0/Al/90/0]	4	80	70.0	7.95E-07

TABLE VIII

FAILURE LOADS, TORQUES AND FREQUENCY FOR DESIGN -1

Staking Sequence	**No of Plies**	N_{xy}**, (N/m)**	T_b **(N-m)**	f_n **(Hz)**
Pure Al	1	379481	2915.9	83.59
[Al/0]	2	336234	3238.6	89.46
[0/Al/0]	3	395065	4052.6	94.50
[0/Al/90/0]	4	356104	5103.1	93.38

B..1 Proposed Design 1

From the above analysis the best design of drive shaft of hybrid laminate is [0/Al//0]. It contains one aluminum and 2 graphite/ epoxy laminae.

C. Evaluation of the two alternatives Design

In order to determine the preferred design among these two considerations of mass and cost become necessary. The evaluation method is described below.

The mass of the drive shaft based on design 1 and 2 are 1.278591 kg and 2.7257 kg respectively. The Cost per unit weight of graphite/epoxy to aluminum was taken as 5:1. Let per unit cost of aluminum: \$ x. So, cost of drive shaft proposed by design 1, is \$ 6.393x g and that of design 2 is \$ 6.1507x g .So, design 1 is better if weight is the main consideration and design 2 is better when cost is the main consideration. In order to determine the preferred design when both the cost and weight were taken into consideration, a minimizing function, F was defined as

$$F = \frac{A}{B} + \frac{C}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where, A = Mass of composite laminate
B = Mass of composite laminate if design was based only on minimum mass
C = Cost of composite laminate
D = Cost of composite laminate if design was based only on minimum cost

For design 1, $F = \frac{1.278591}{1.278591} + \frac{6.393x}{6.1507\text{x}}$
= 2.03

For design 2, $F = \frac{2.7257}{1.278591} + \frac{6.1507\text{x}}{6.1507\text{x}}$
= 3.31

The values of F are higher for design 2, so design 1 is cheaper and lighter than design 2. That's why our preferred design is design 1(drive shaft made from graphite/epoxy laminae with stacking sequence $\left[0/90/0/45/90/-\overline{45}\right]_s$).

V. Progressive failure analyses for the proposed method

Software "PROMAL" is used for the progressive failure analysis of the proposed design using "The Maximum Stress Failure Theory". Partially discounted stiffness method from [6] is used to degrade the stiffness of each failed lamina. The final failure load of the design was found, N = 282248.24 N/m.

VI. Conclusion

In this study two different designs of drive shafts are proposed. One design used graphite/epoxy and other one is a hybrid shaft made from aluminum and glass/epoxy lamina. If cost is the main consideration, then hybrid one can also give better performances. Among the different designs, drive shaft manufactured by glass/epoxy laminae with $\left[0/90/0/45/90/-\overline{45}\right]_s$ stacking sequence is selected. Because it fulfils all the requirements of a drive shaft and also will not fail catastrophically. At the end it may be concluded, the proposed drive shaft can serve all the requirements and from the progressive failure analysis its failure load is also calculated. Again, since it will not fail catastrophically, after the first ply failure, the drive shaft can be replaced or repaired. The successful application of the present design can make a huge improvement in automotive industry.

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