MATERIAL OPTIMIZATION AND WEIGHT REDUCTION OF DRIVE SHAFT USING COMPOSITE MATERIAL

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ABSTRACT

This Paper deals with the study of replacement of conventional two-piece steel drive shafts with one-piece automotive hybrid aluminum/composite drive shaft & was developed with a new manufacturing method, in which a carbon fiber epoxy composite layer was co-cured on the inner surface of an aluminum tube rather than wrapping on the outer surface to prevent the composite layer from being damaged by external impact and absorption of moisture. Replacing composite structures with conventional metallic structures has many advantages because of higher specific stiffness and higher specific strength of composite materials. By considering the thermal residual stresses of the interface between the aluminum tube and the composite layer, the optimum stacking sequence is calculated with the help of Finite element analysis. Press fitting method for the joining of the aluminum/composite tube and steel yokes was devised to improve reliability and to reduce manufacturing cost, compared to other joining methods such as adhesively bonded, bolted or riveted and welded joints. The joining of the aluminum - composite tube and steel yoke with improved reliability and optimum manufacturing cost is done by press fitting. In order to increase the torque transmission capacity protrusion shape is provided on the inner surface of steel yoke which will fit on Universal joints.

Keyword: *-Drive shaft, propeller shaft, optimization,composite material, composite drive shaft design etc.*

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1. INTRODUCTION

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. 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 9200 rpm to avoid whirling vibration. 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 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 increases the total weight of an automotive vehicle and decreases fuel efficiency. Since carbon fiber epoxy composite materials have more than four times specific stiffness ($E= \rho$) of steel or aluminum materials, it is possible to manufacture composite drive shafts in one-piece without whirling vibration over 9200 rpm. The composite drive shaft has many benefits such as reduced weight and less noise and vibration. However, because of the high material cost of carbon fiber epoxy composite materials, rather cheap aluminum materials may be used partly with composite materials such as in a hybrid type of aluminum/composite drive shaft, in which the aluminum has a role to transmit the required torque, while the carbon fiber epoxy composite increases the bending natural frequency above 9200 rpm.

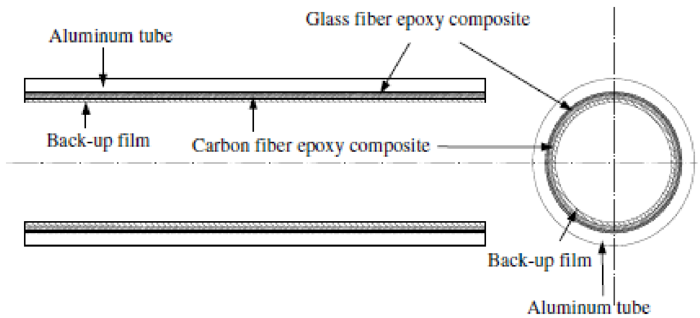

Fig-1: Schematic Diagram of the Co-Cured Aluminum/Composite Drive Shaft

2. LITERATURE REVIEW

In order to get the idea about the area of research it is essential to discuss the some of the previous study undertaken in this field. Review of the literature shows that different researchers and experts in the fields of condition monitoring of machines have discussed various aspects of the monitoring of machines. This study is an attempt to address the issues related to machines health condition and the problems associated with respective causes. The available literature is reviewed as under:

2.1 Review of Papers:-

2.1.1Manjunath K, S. Mohan Kumar, Channakeshava K. R., 2011 ,"Optimization of Ply Stacking Sequence of Composite Drive Shaft Using Particle Swarm Algorithm":-

In this paper an attempt has been made to optimize ply stacking sequence of single piece E-Glass/Epoxy and Boron /Epoxy composite drive shafts using Particle swarm algorithm (PSA). PSA programme is developed to optimize the ply stacking sequence with an objective of weight minimization by considering design constraints as torque transmission capacity, fundamental natural frequency, lateral vibration and torsional buckling strength having number of laminates, ply thickness and stacking sequence as design variables. The optimum results of PSA obtained are compared with results of genetic algorithm (GA) results and found that PSA yields better results than GA.

2.1.2 Mohammad Reza Khoshravan , Amin Paykani ,AidinAkbarzadeh ,2011 , "Design and Modal Analysis ofComposite Drive Shaft forAutomotive Application":-

This paper presents design method and vibrational analysis of composite propeller shafts.Designing of a composite drive shaft is divided in two main sections: design of the composite shaft and design of couplings. In composite shaft design some parameters such as critical speed, static torque and adhesive joints are studied; the behavior of materials is considered nonlinear isotropic for adhesive, linear isotropic for metal and orthotropic for composite shaft. Along with the design all the analyses are performed using finite element software (ANSYS). The results show significant points about optimum design of composite drive shafts.

2.1.3 M.A.K. Chowdhuri , R.A. Hossain, 2010, "Design Analysis of an Automotive Composite DriveShaft":-

The present paper focuses on the design of an automotive drive shaft by composite materials. 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 [0 / 90 / 0 / 45 / 90 / 45]s stacking sequence is selected.

2.1.4 Hak Sung Kim , Dai Gil Lee , 2005, "Optimal Design of the Press Fit Joint for a Hybrid Aluminum/Composite Drive Shaft":-

In this paper, a one-piece hybrid aluminum/composite drive shaft for a rear wheel drive automobile was designed and manufactured. A press fit joining method between the hybrid tube and the aluminum yoke using the toothed steel ring was employed to increase the reliability of joining and to reduce manufacturing cost. The failure mode map of the press fit joint between the aluminum tube and the toothed steel ring was constructed using simple equations and it has been found that the developed failure mode map can predict well the failure torque and failure mode. The developed hybrid drive shaft satisfied all the design requirements such as static torque capability and fundamental natural frequency.

2.1.5 Dai Gil Lee, Hak Sung Kim, Jong Woon Kim, Jin Kook Kim, 2004, "Design and Manufacture of an Automotive Hybrid Aluminum/Composite Drive Shaft":-

In this work, one-piece automotive hybrid aluminum/composite drive shaft was developed with a new manufacturing method, in which a carbon fiber epoxy composite layer was co-cured on the inner surface of an aluminum tube rather than wrapping on the outer surface. The optimal stacking sequence of the composite layer was determined considering the thermal residual stresses of interface between the aluminum tube and the composite layer calculated by finite element analysis. Press fitting method for the joining of the aluminum/composite tube and steel yokes was devised to improve reliability and to reduce manufacturing cost. Protrusion shapes on the inner surface of steel yoke were created to increase the torque capability of the press fitted joint. From experimental results, it was found that the developed one-piece automotive hybrid aluminum/composite drive shaft had 75% mass reduction, 160% increase in torque capability compared with a conventional two-piece steel drive shaft. It also had 9390 rpm of natural frequency which was higher than the design specification of 9200 rpm.

2.1.6 T.Rangaswamy, S.Vijayarangan, R.A. Chandrashekar, T.K. Venkatesh and K. Anantharaman, 2004, "Optimal Design and Analysis of Automotive Composite Drive Shaft":-

The overall objective of this paper is to design and analyze a composite drive shaft for power transmission applications. A one-piece drive shaft for rear wheel drive automobile was designed optimally using E-Glass/Epoxy and High modulus (HM) Carbon/Epoxy composites. In this paper a Genetic Algorithm (GA) has been successfully applied to minimize the weight of shaft which is subjected to the constraints such as torque transmission, torsional buckling capacities and fundamental natural frequency. The results of GA are used to perform static and buckling analysis using ANSYS software. The results show the stacking sequence of shaft strongly affects buckling torque.

2.2 Objectives and Scope of the present Investigations/Study:-

After studying the above literature, it is important to study the details of composites, composite fiber orientation, their advantages and limitations as compared to steels etc. Also, it is necessary to study the automobile driveshaft, its design with steel and with one piece hybrid aluminum/composite materials. It is essential to design and carry out analysis for the stresses and strains induced in one piece hybrid aluminum/composite drive shafts. The objective for optimization may be minimization of weight, cost, increase of torque transmission capacity etc.

3. THEORY

3.1 Composite:-

A material composed of two or more constituents is called composite material.The advantages of composites over the conventional materials are:

- High strength to weight ratio
- High stiffness to weight ratio
- High impact resistance
- Better fatigue resistance
- Improved corrosion resistance
- Good thermal conductivity
- Low Coefficient of thermal expansion. As a result, composite structures may exhibit a better dimensional stability over a wide temperature range.
- High damping capacity.

3.2 Drive Shaft Arrangement in A Car Model:-

Conventional two-piece drive shaft arrangement for rear wheel vehicle driving system is shown in fig-2 below

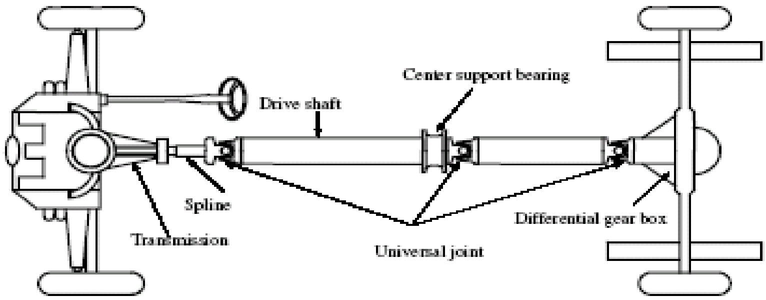

Fig-2: Conventional Two-Piece Drive Shaft for Rear Wheel Driving System

3.3 Parts of Drive Shaft and Universal Joint:-

Parts of drive shaft and universal joint are shown in fig-3 Parts of drive shaft and universal joints are

1. U-bolt nut
2. U-bolt washer
3. U-bolt
4. Universal joint journal
5. Lubrication fitting
6. Snap ring.
7. Universal joint sleeve yoke
8. Spline seal
9. Dust cap
10. Drive shaft tube

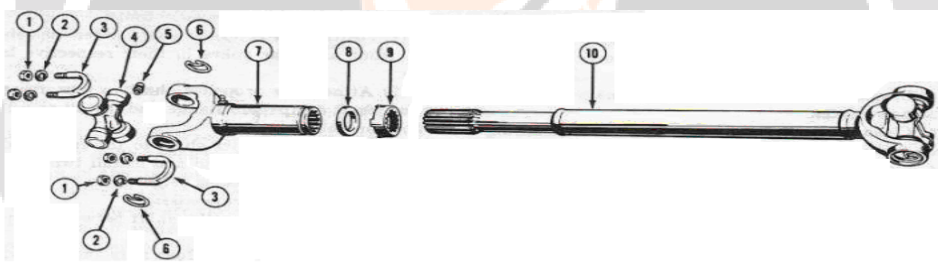

Fig-3: Parts of Drive Shaft and Universal Joint

3.4 Functions of the Drive Shaft:-

- First, it must transmit torque from the transmission to the differential gear box.
- During the operation, it is necessary to transmit maximum low-gear torque developed by the engine.
- The drive shafts must also be capable of rotating at the very fast speeds required by the vehicle.

4. RESEARCH METHODOLOGY/ REQUIREMENTS OF THE RESEARCH WORK

4.1 Description of the Problem/Problem statement:-

Fig-4:A Two-Section Drive Shaft of a Truck

Almost all automobiles (at least those which correspond to design with rear wheel drive and front engine installation) have transmission shafts. 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 and reliability. It is possible to achieve design of one-piece automotive hybrid aluminum/composite drive shaft with less weight to increase the first natural frequency of the shaft and to decrease the bending stresses using various stacking sequences. By doing the same, we maximize the torque transmission, static torque capability, buckling torque capability and bending natural frequency.This work deals with the replacement of conventional two-piece steel drive shafts with one-piece automotive hybrid aluminum/composite drive shaft for an automobile application.

5. DESIGN CONSIDERATIONS:

5.1 Selection of Material

5.1.1 Selection of Reinforcement Fiber

Fibers are available with widely differing properties. Review of the design and performance requirements usually dictate the fiber/fibers to be used. Carbon/Graphite fibers: Its advantages include high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength. Graphite, when used alone has low impact resistance. Its drawbacks include high cost, low impact resistance, and high electrical conductivity. Glass fibers: Its advantages include its low cost, high strength, high chemical resistance, and good insulating properties. The disadvantages are low elastic modulus, poor adhesion to polymers, low fatigue strength, and high density, which increase shaft size and weight. Also crack detection becomes difficult.

5.1.2 Selection of Resin System

The important considerations in selecting resin are cost, temperature capability, elongation to failure and resistance to impact (a function of modulus of elongation). The resins selected for most of the drive shafts are either epoxies or vinyl esters. Here, epoxy resin was selected due to its high strength, good wetting of fibers, lower curing shrinkage, and better dimensional stability.

Table-1: Material Properties of Steel

SN	Mechanical Properties	Symbol	Unit	Value
1	Young's Modulus	E	GPa	207.0
2	Shear Modulus	G	GPa	80.0
3	Poisson's Ratio	υ	-----	0.3
4	Density	P	Kg/m^3	7600
5	Yield Strength	S_y	MPa	370
6	Shear Strength	S_x	MPa	275

Table-2: Material Properties of Carbon/epoxy composite and glass epoxy composite

SN	Properties	Symbols	Units	Carbon/Epoxy	Glass/ Epoxy
1	Longitudinal Modulus	E_{11}	GPa	190	50
2	Transverse Modulus	E_{22}	GPa	7.7	12
3	Shear Modulus	G_{12}	GPa	4.2	5.6
4	Poisson's Ratio	υ	----	0.3	0.3
5	Density	P	Kg/m^3	1600	2000
6	Longitudinal tensile strength	St1	MPa	870	800
7	Transverse tensile strength	St_2	MPa	540	40
8	Shear strength	Ss	MPa	30	72

5.2 Design of Drive Shaft

5.2.1 Assumptions

1) The shaft rotates at a constant speed about its longitudinal axis.
2) The shaft has a uniform, circular cross section.
3) The shaft is perfectly balanced, i.e., at every cross section, the mass center coincides with the geometric center.
4) All damping and nonlinear effects are excluded.
5) The stress-strain relationship for composite material is linear & elastic; hence, Hooke's law is applicable for composite materials.
6) Acoustical fluid interactions are neglected, i.e., the shaft is assumed to be acting in a vacuum.
7) Since lamina is thin and no out-of-plane loads are applied, it is considered as under the plane stress.

5.2.2 Selection of Cross-Section The drive shaft can be solid circular or hollow circular. Here hollow circular cross-section was chosen because:

- The hollow circular shafts are stronger in per kg weight than solid circular.
- The stress distribution in case of solid shaft is zero at the center and maximum at the outer surface while in hollow shaft stress variation is smaller. In solid shafts the material close to the center are not fully utilized.

Table-3: Specification of Drive shaft

SN	Name	Notation	Unit	Value
1	Ultimate Torque	T	Nm	3500
2	Max. Speed of shaft	N	Rpm	6500
3	Length of shaft	L	mm	1250
4	Max. Diameter of shaft	d_o	mm	100
5	Thickness of shaft	t	mm	3.32

5.2.3 Mass of Drive Shaft

$$m = \rho AL = \rho(do^2 - di^2) * \frac{L}{4}$$

Where do = outer diameter (m)
di = inner diameter (m)
m = 8.58 Kg

5.2.4Torque Transmition Capacity of Drive Shaft

$$T = Ss \frac{\pi(do^4 - di^4)}{16tdo}$$

Torsional Buckling Capacity of Drive Shaft If,

$$\frac{1}{\sqrt{1-\gamma^2}} \frac{L^2 t}{(2r)^3} > 5.5$$

It is called as long shaft otherwise short and medium shaft For long shaft critical stress is given by,

$$\tau cr = \frac{E}{3\sqrt{2}(1-\gamma^2)^{3/4}} (t/r)^{3/2}$$

For short and medium shaft critical stress is given by,

$$\tau cr = \frac{4.39E}{(1-\gamma^2)} (t/r)^2 \sqrt{1 + 0.0257(1-\gamma^2)^{3/4} \frac{L^3}{(rt)^{1.5}}}$$

The relation between tortional buckling capacity and critical stress is given by,

$$Tcr = \tau cr 2\pi r^2 t$$

$$Tcr = (2\pi r^2 t) * (0.272) * [E11 * E22^3]^{\frac{1}{4}} * \left(\frac{t}{r}\right)^{\frac{3}{2}}$$

Table-4: Design Solution

	Torque transmition capacity (Nm)	**Torsional buckling capacity (Nm)**	**Frequency (rpm)**
Steel	43101.25	13361.84	9660
Carbon/Epoxy	4701.93	3951.44	20160
Glass/Epoxy	11284.632	3947.55	9300
Specification	3500(O.K)	3500(O.K)	6500(O.K)

6. CONCLUSION

- The usage of composite materials has resulted in considerable amount of weight saving in the range of 81% to 72% when compared to conventional steel drive shaft.
- Taking into account the weight saving, deformation, shear stress induced and resultant frequency it is evident that composite has the most encouraging properties to act as replacement to steel
- The present work was aimed at reducing the fuel consumption of the automobiles in particular or any machine, which employs drive shaft, in general. This was achieved by reducing the weight of the drive shaft with the use of composite materials. This also allows the use of a single drive shaft (instead of a two piece drive shaft) for transmission of power to the differential parts of the assembly.
- Apart from being lightweight, the use of composites also ensures less noise and vibration.
- If we consider cost of glass/epoxy composite, it is slightly higher than steel but lesser than carbon/epoxy.
- The composite drive are safer and reliable than steel as design parameter are higher in case of composite.
- The composite are recyclable so they can be reuse.
- Apart from being lightweight, the use of composites also ensures less noise and vibration.
- So in comparison of mass, cost, safety and recycling steel shaft can be replaced by composite drive shaft.
- Natural frequency using Bernoulli-euler beam theory and Timoshenko's beam theory are compared. The frequency calculated by using Bernoulli-euler beam theory is high as it neglects rotary inertia and transverse shear.
- The successful application of the present design can make a huge improvement in automotive industry.

7. FUTURE SCOPE

- This study leaves wide scope for future investigations. It can be extended to newer composites using other reinforcing phases and the resulting experimental findings can be similarly analyzed.
- Tribological evaluation of glass/carbon fiber reinforced epoxy resin composite has been a much less studied area. There is a very wide scope for future scholars to explore this area of research. Many other aspects of this problem like effect of fiber orientation, loading pattern, weight fraction of ceramic fillers on wear response of such composites require further investigation.

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