"Design and Analysis of Composite Drive Shaft using ANSYS and Genetic Algorithm" A Critical Review

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Abstract: This study deals with the review of optimization of drive shaft using the Genetic Algorithm and ANSYS. Substitution of composite material over the conventional steel material for drive shaft has increasing the advantages of design due to its high specific stiffness and strength. Drive shaft is the main component of drive system of an automobile. Use of conventional steel for manufacturing of drive shaft has many disadvantages such as low specific stiffness and strength. Conventional drive shaft is made up into two parts to increase its fundamental natural bending frequency. Two piece drive shaft increases the weight of drive shaft which is not desirable in today's market. Many methods are available at present for the design optimization of structural systems and these methods based on mathematical programming techniques involving gradient search and direct search. These methods assume that the design variables are continuous. But in practical structural engineering optimization, almost all the design variables are discrete. This is due to the availability of components in standard sizes and constraints due to construction and manufacturing practices. This paper discusses the past work done on composite drive shafts using ANSYS and Genetic Algorithm.

Keywords: ANSYS, Composite Material, Drive Shaft, Genetic Algorithm, Optimization.

I. INTRODUCTION

Rapid technological advances in engineering design field result in finding the alternate solution for the conventional materials. The design engineers brought to a point to finding the materials which are more reliable than conventional materials. Researchers and designers are constantly looking for the solutions to provide stronger and durable materials which will answer the needs of fellow engineers. Drive shafts are used as power transmission tubing in many applications, including cooling towers, pumping sets, aerospace, trucks and automobiles. In the design of metallic shaft, knowing the torque and the allowable shear stress for the material, the size of the shaft's cross section can be determined. In the today's days there is a heavy requirement for light weight materials vehicle.

The conventional steel material is replaceable by advanced composite materials. Composite materials are favored by most of the scientist in the design of automobiles due to its higher specific strength and stiffness. Weeton et al. [1] stated the possibilities of replacing the conventional steel material by composites in the field of automobile. Weeton et al describe the possibilities of composites used to replace the steel leaf spring as well as steel drive shaft. The advanced composite materials such as graphite, carbon, Kevlar and glass with suitable resins are widely used because of their high specific strength (strength / density) and high specific modulus (modulus / density). The first application of composite drive shaft to automotive was the one developed by Spicer U-joint divisions of Dana Corporation for the Ford econoline van models in 1985. Drive shafts for power transmission are used in many applications, including cooling towers, pumping sets, aerospace, structures, and automobiles.

In metallic shaft design, knowing the torque and the allowable service shear stress for the material allows the size of the shaft's cross-section to be determined. Beard more et al. [2] is also states the potentials of composites in structural applications. Conventional steel drive shafts are manufacture in two pieces to increase its fundamental natural bending frequency. The conventional assembly of drive shaft is made up in two pieces and joined together by u-joints due to which the overall weight of the assembly is increased.

The composite drive shaft [3] has advantages like considerable weight reduction, symmetric composite assured the dynamic balance of increasing operating speed, electrically non conductive, custom end fitting considerations, vibrations and harshness (NVH), long fatigue life and also it reduce the bearing & journal wear. The materials usually have a lower modulus of elasticity which results in when torque peaks are occurred the drive shaft may works as a shock absorber. A drive shaft must operate through constantly changing angles between the transmission and rare axle. A GA proposed by the Goldberg [6] based on natural genetics will be studied in the second phase of study. Rajiv and Krishnamurthy [4] proposed a method for converting a constrained optimization problem into an unconstrained optimization problem. Kim et al. [9] minimizes the weight of composite laminates with play drop under a strength constraint using GA.

JH Park et al. [10] explains the various loading and boundary conditions for the optimal design of laminated composites. Vijayrangan et al. [7] had proposed the GA for the optimization of Composite Leaf spring. T Rangaswamy et

al. [8] defines the procedure to design and optimized the composite drive shaft using HM – Carbon / Epoxy by Genetic algorithm.

Now days all automobiles (which are having front engine rear wheel drive) have the transmission shaft as shown in fig.1 [3]. The reduction in weight of the drive system has the advantageous in overall weight reduction of automobiles which is a highly desirable goal of design engineer.
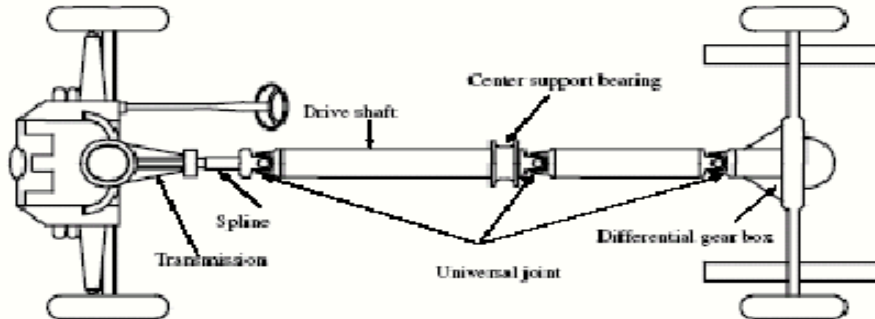

Fig. 1: Two Piece Drive Shaft Arrangement for Rear Wheel Vehicle Driving System

In the present work the focus is given on the replacement of the conventional steel drive shaft by the High Strength - Carbon / Epoxy material. A single piece composite drive shaft was designed and analyzed using the ANSYS 12.0.

II.   COMPOSITE MATERIAL

Composite consist of two or more material phase that are combine to produce a material that has superior properties to these of its individual constituent. Technologically the most important composite are those in which the dispersed phase is in the form of fibre. The composite materials can be classified on the basis of micro structures, multi phases, reinforcements, manner of packing of fibers layered compositions, method of compositions, matrix system, processing methods, etc. [5] Composite materials can be classified as:
1)   Polymer Matrix Composites.
2)   Metal Matrix Composites.
3)   Ceramic Composites.

The fibers are either long or short. Long and continuous fibers are easy to orient and process, where as short fibers cannot be controlled fully for proper orientation. The principal fibres in commercial use are various types of glass, carbon, graphite and Kevlar. All these fibers are incorporated in matrix form either in continuous length or in discontinuous length.

Table1: properties of HS – Carbon / Epoxy material.

Mechanical Properties	Symbol	Units	Steel	HS Carbon / Glass Epoxy
Young's Modulus	E	Gpa	207	210
Shear Modulus	G	Gpa	80	70
Poisson's ratio	N	-	0.3	0.3
Density	P	Kg/ M^3	7600	1600
Shear Strength	Ss	MPa	370	420

2.1 Advantages of composite materials over conventional materials
1. High strength to weight ratio.
2. High stiffness to weight ratio.
3. High impact resistance.
4. Better fatigue resistance.
5. Improved corrosion resistance.
6. Good thermal conductivity.
7. High damping capacity.
8. Low coefficient of thermal expansion.

III. SPECIFICATION OF THE PROBLEM

The passenger cars, small trucks and vans should have the torque transmission capacity more than 3500 Nm and fundamental natural bending frequency must be higher than 6500 rpm to avoid whirling vibrations. From the theory of whirling, it has been found that the critical speed of shaft is inversely proportional to the square of its length. So the vibration problem could be solve by increasing the length of shaft but it cannot be permitted due to space limitations. So that there is only an option to manufacturers to manufacture the shaft in two pieces.

IV. DESIGN REQUIREMENTS FOR STEEL DRIVE SHAFT

Table2: Design Parameters [8]

Parameter of Shaft	Symbol	Value	Unit
Outer Diameter	d_o	90	mm
Inner Diameter	d_i	83.36	mm
Length of the Shaft	L	1250	mm
Thickness of shaft	T	3.32	mm

4.1 Design of Steel Drive Shaft

Mass of the steel drive shaft,

"$m = \rho AL = \rho \times \Pi/4 \times (d_o^2 - d_i^2) \times L$"… (1)

$\quad\quad = 7600 \times 3.14/4 \times (90^2 - 83.36^2) \times 1250$

[m = 8.58 Kg]

Torque transmission capacity of steel drive shaft,

"$T = Ss \times \Pi /16 \times [(do^4 - di^4) \times do]$" … (2)

[T = 55.93 $\times 10^3$ N-m]

Fundamental Natural frequency,

The natural frequency can be found by using the two theories:

1) Timoshenko Beam theory
2) Bernoulli Euler Theory

Timoshenko Beam Theory-Ncrt

"$f_{nt} = K_s (30 \Pi p^2) / L^2 \; X \; \sqrt{(Er^2 / 2\rho)}$"…..(3)

"$N_{crt} = 60 f_{nt}$"….. (4)

f_{nt} = natural frequency base on Timoshenko beam theory, HZ

K_s = Shear coefficient of lateral natural frequency

p = 1, first natural frequency

r = mean radius of shaft

F_s = Shape factor, 2 for hollow circular cross section

n = no of ply thickness, 1 for steel shafts

"$1 / K_s^2 = 1 + (n^2\Pi^2 r^2) / 2L^2 \; X \; [1 + f_s E / G]$"…. (5)

$1 / K_s^2 = 1 + (1^2\Pi^2 86.82^2) / 2 \times 1250^2 \; X \; [1 + 2 \times 207 \times 10^3 / 80 \times 10^3]$

[K_s = 0.982]

$f_{nt} = 0.982 (30 \times \Pi \times 1^2) / 1250 \times \sqrt{(207 \times 10^3 \times 86.68^2 / 2 \times 7600)}$

[f_{nt} = 299.54 Hz]

[N_{crt} = 17972.4 rpm]

4.2 Design of Composite Drive Shaft
The specifications for the composite drive shaft are same as that of steel drive.

Mass of the Composite drive shaft

$m = \rho AL = \rho \times \Pi / 4 \times (d_o^2 - d_i^2) \times L \ldots (1)$

$= 1600 \times 3.14/4 \times (90^2 - 83.36^2) \times 1250$

[m = 1.80 Kg]

4.3 Assumptions [9]
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.

4.4 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.

Table3 - Material properties of composite material i.e. HS Carbon / Epoxy

Mechanical Properties	Units	HS – Carbon / Epoxy
E_{11}	GPa	134
E_{22}	GPa	70
G_{12}	GPa	58
N	-	0.3
ρ	Kg / m^3	1600
$St_1 = Sc_1$	MPa	880
$St_2 = Sc_2$	MPa	60
S_{12}	MPa	97

4.5 Torsional buckling capacity
The long thin hollow shafts are vulnerable to torsional buckling; so the possibility of the torsional buckling of the composite shaft was calculated by the expression for the torsional buckling load T_{cr} of a thin walled orthotropic tube : -

"$T_{cr} = (2\pi r^2 t) (0.272) (E_x E_y^3)^{0.25} (t/r)^{1.5}$" …… (6)

Where E_x and E_y are the Young's modulus of the shaft in axial and hoop direction, r and t are the mean radius and thicknesses of composite shaft.

4.6 Lateral Vibrations
Natural frequency of composite shaft is based on Timoshenko's beam theory,

"$f_{nt} = K_s \frac{30 \, \Pi \, p^2}{L^2} \sqrt{\frac{E_x r^2}{2\rho}}$ …….(7)

$\frac{1}{K_s^2} = 1 + \frac{p^2 \Pi^2 r^2}{2L^2} \left[1 + \frac{f_s E_x}{G_{xy}}\right]$ …… (8)

Where f_{nt} and p are the natural and first natural frequency. K_s is the shear coefficient of the natural frequency (< 1), f_s is a shape factor (equals to 2) for hollow circular cross-sections.

Critical speed:

$N_{crt} = 60 f_{nt}$.

V.   DESIGN ANALYSIS
Finite element analysis is a computer based analysis technique for calculating the strength and behavior of structures. In the FEM the structure is represented as finite elements. These elements are joined at particular points which are called as nodes. The FEA is used to calculate the deflection, stresses, strains temperature, buckling behavior of the member.

In our project FEA is carried out by using the ANSYS 12.0. Initially we don't know the displacement and other quantities like strains, stresses which are then calculated from nodal displacement.

5.1 Static analysis

A static analysis is used to determine the displacements, stresses, strains and forces in structures or components caused by loads that do not induce significant inertia and damping effects. A static analysis can however include steady inertia loads such as gravity, spinning and time varying loads. In static analysis loading and response conditions are assumed, that is the loads and the structure responses are assumed to vary slowly with respect to time. The kinds of loading that can be applied in static analysis includes, Externally applied forces, moments and pressures Steady state inertial forces such as gravity and spinning Imposed non-zero displacements. If the stress values obtained in this analysis crosses the allowable values it will result in the failure of the structure in the static condition itself. To avoid such a failure, this analysis is necessary.

5.2 Boundary conditions

The finite element model of HS Carbon / Epoxy shaft is shown in Figure .One end is fixed and torque is applied at other end.
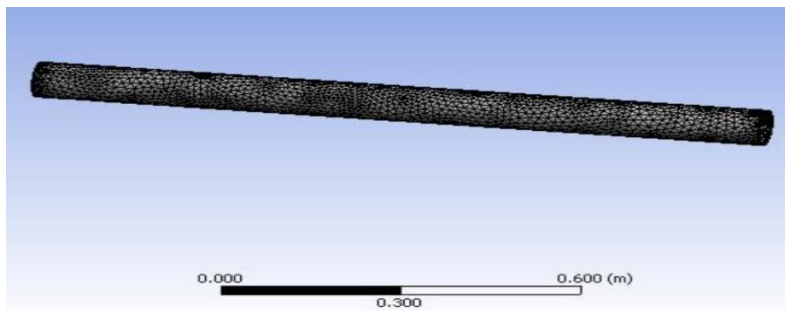
Fig: 2 - Finite element model of HS Carbon/Epoxy shaft.

5.3 Modal analysis

When an elastic system free from external forces can disturbed from its equilibrium position and vibrates under the influence of inherent forces and is said to be in the state of free vibration. It will vibrate at its natural frequency and its amplitude will gradually become smaller with time due to energy being dissipated by motion. The main parameters of interest in free vibration are natural frequency and the amplitude. The natural frequencies and the mode shapes are important parameters in the design of a structure for dynamic loading conditions.

Modal analysis is used to determine the vibration characteristics such as natural frequencies and mode shapes of a structure or a machine component while it is being designed. Modal analysis is used to determine the natural frequencies and mode shapes of a structure or a machine component. The rotational speed is limited by lateral stability considerations. Most designs are sub critical, i.e. rotational speed must be lower than the first natural bending frequency of the shaft. The natural frequency depends on the diameter of the shaft, thickness of the hollow shaft, specific stiffness and the length.

5.4 Buckling analysis

Buckling analysis is a technique used to determine buckling loads (critical loads) at which a structure becomes unstable, and buckled mode shapes. For thin walled shafts, the failure mode under an applied torque is torsional buckling rather than material failure. For a realistic driveshaft system, improved lateral stability characteristics must be achieved together with improved torque carrying capabilities.

VI. FINDINGS OF FINITE ELEMENT ANALYSIS
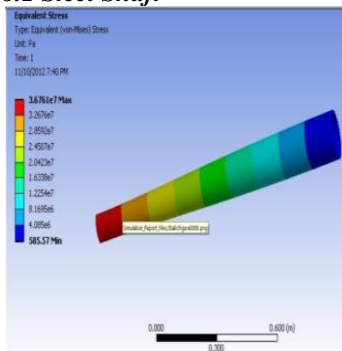
6.1 Steel Shaft

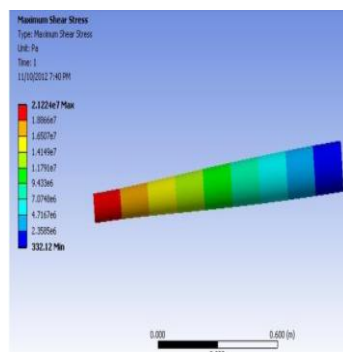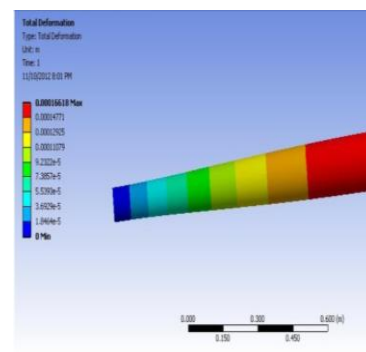Fig. 3 Equivalent Stresses   Fig. 4 Maximum Shear stresses   Fig. 5 Total Deformation
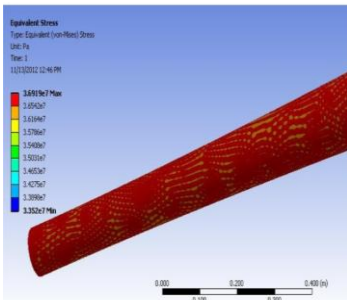
6.2 HS – Carbon / Epoxy
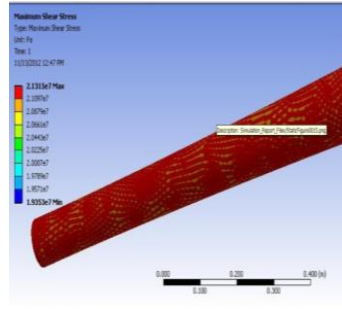

Fig. 6 Equivalent Stresses
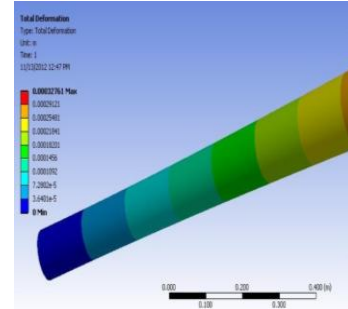

Fig. 7 Maximum Shear Stresses

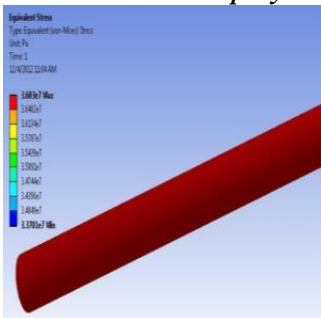Fig. 8 Total Deformation

6.3 HM – Carbon / Epoxy
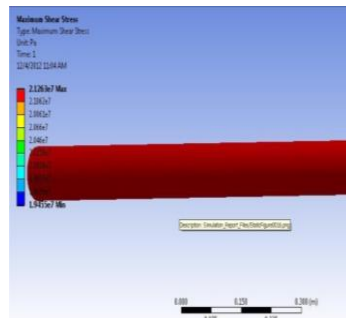

Fig. 9 Equivalent Stresses
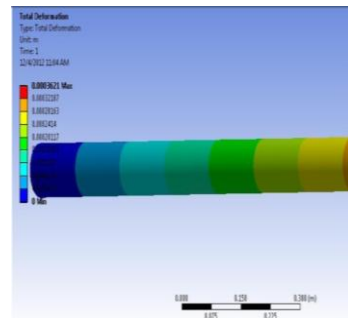

Fig. 10 Maximum Shear Stresses

Fig. 11 Total Deformation

VII. DESIGN OPTIMIZATION – GENETIC ALGORITHM (GA)

Many methods are used for the design optimization that assumes all the design variables are continuous. But in actual structural optimization almost all the variables are discrete. The GA is a stochastic global search method that mimics the metaphor of natural biological evolution. GA operates on a population of potential solutions applying the principle of survival of the fittest to produce (hopefully) better and better approximations to a solution. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from, just as in natural adaptation

7.1 Advantages of GA over other Optimization methods.

- GA does not require a problem specific knowledge to carry out a search. GA uses only the values of the objective function. For instance, calculus based search algorithms use derivative information to carry out a search.
- GA uses a population of points parallel at a time in contrast to the single point approach by the traditional optimization methods. That means at the same time GAs process a number of designs. In GA, the design variables are represented as strings of binary variables that correspond to the chromosomes in natural genetics. Thus the search method is naturally applicable for solving discrete and integer programming problems.
- GAs uses randomized operators in place of the usual deterministic ones. In every generation, a new set of strings is produced by using randomized parents selection and crossover from the old generation (old set of strings).
- GA does not require derivative information or other auxiliary knowledge only the objective function and corresponding fitness levels influence the directions of search.
- GAs use probabilistic transition rules, not deterministic ones.
- GAs work on an encoding of the parameter set rather than the parameter set itself (except in where real-valued individuals are used).

VIII. CONCLUSION

- The replacement of conventional drive shaft results in reduction in weight of automobile.
- The finite element analysis is used in this work to predict the deformation of shaft.
- The deflection of steel, HS Carbon / Epoxy and HM Carbon / Epoxy shafts was 0.00016618, 0.00032761 and 0.0003261 mm respectively.
- Natural frequency using Bernoulli – Euler and Timoshenko beam theories was compared. The frequency calculated by Bernoulli – Euler theory is high because it neglects the effect of rotary inertia & transverse shear.
- Hence the single piece High Strength Carbon / Epoxy composite drive shaft has been proposed to design to replace the two piece conventional steel drive shaft of an automobile.

The FEA analysis is done to validate the analytical calculations of the work.

The results of the work are encouraging and suggesting to replacement of conventional drive by composite has an added advantage.

The next phase of work consists of Optimization of shaft for the objective function as weight and fundamental natural frequency.

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