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Material Optimization and Weight Reduction of Drive Shaft Using Composite Material

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Abstract : *The objective of the drive shaft is to connect with the transmission shaft with the help of universal joint whose axis intersects and the rotation of one shaft about its own axis results in rotation of other shaft about its axis. Shafts must be exceptionally tough and light to improve the overall performance of the vehicle. Automobile industries are exploring composite materials in order to obtain reduction of weight without significant decrease in vehicle quality and reliability. This is due to the fact that the reduction of weight of a vehicle directly impacts its fuel consumption. Particularly in city driving, the reduction of weight is almost directly proportional to fuel consumption of the vehicle. Also at the start of vehicle the most of the power get consumed in driving transmission system, if we able to reduce the weight of the propeller shaft that surplus available power can be used to propel the vehicle. Thus, in this paper, the aim is to replace a two-piece metallic drive shaft by a composite drive shaft. The following materials can be chosen Steel, Boron/Epoxy Composite, Kevlar/Epoxy Composite, Aluminum – Glass/Epoxy Hybrid, Carbon – Glass/Epoxy Hybrid. The analysis was carried out for three different ply orientations of the composites in order to suggest the most suitable ply orientation of the material that would give the maximum weight reduction while conforming to the stringent design parameters of passenger cars and light commercial vehicle.*
Keywords : *Composite, propeller shaft, propel, ply orientation, transmission, universal joint.*

I. INTRODUCTION

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). Advanced composite materials seem ideally suited for long, power driver shaft (propeller shaft) applications. Their elastic properties can be tailored to increase the torque they can carry as well as the rotational speed at which they operate. The drive shafts are used in automotive, aircraft and aerospace applications. The automotive industry is exploiting composite material technology for structural components construction in order to obtain the reduction of the weight without decrease in vehicle quality and reliability. It is known that energy conservation is one of the most important objectives in vehicle design and reduction of weight is one of the most effective measures to obtain this result. Actually, there is almost a direct proportionality between the weight of a vehicle and its fuel consumption, particularly in city driving.

II. Literature Survey

Composites have high specific modulus, strength and less weight. The fundamental natural frequency of carbon fiber drive shaft can be twice as that of the steel or aluminium, because the carbon fiber composite material has more than 4 times the specific stiffness, which makes it possible to manufacture the drive shaft of passenger cars in one piece. A one piece composite shaft can be manufactured so as to satisfy the vibration requirements. This eliminates all the assembly, connecting the two piece steel shaft and thus minimizes the overall weight, vibrations and cost. Due to weight reduction fuel consumption will be reduced. They have high damping capacity and hence they produce less vibrations and noise. They have good corrosion resistance, greater torque capacity, longer fatigue life than steel and aluminium [1].

III. Specification Of The Problem

The fundamental natural bending frequency for passenger cars, small trucks, and vans of the propeller shaft should be higher than 6,500 rpm to avoid whirling vibration and the torque transmission capability of the drive shaft should be larger than 3,500 Nm. The drive shaft outer diameter should not exceed 100 mm due to space limitations. Because in case of front engine rear wheel drive vehicles size of drive shaft increases chasis height and reduces floor space in passenger compartment. So here outer diameter of the shaft is taken as 90 mm with little compromise between strength of drive shaft and decrease chasis height. Presently many SUVs and light commercial vehicle using front engine rear wheel drive system. The constraints for selecting propeller shaft dimensions are wheel base of vehicle, maximum torque transmission capacity and angular velocity of propeller shaft. The drive shaft of transmission system is to be designed optimally for following specified design requirements as shown in Table 3.1[2].

Table 3.1 Design requirements and specifications

SR. NO.	NAME	NOTATION	UNIT	VALUE
1	ULTIMATE TORQUE	Tmax	Nm	3500
2	MAX. SPEED OF SHAFT	Nmax	rpm	6500
3	LENGTH OF SHAFT	L	mm	1250

In actual operating condition shaft is subjected to three types of loads, which are following torsional, vibrations and buckling. We are going to analyze the drive shaft for the torsional, modal and buckling analysis using steel and four different composite materials by varying the ply angle, no. of plies and ply thickness.

IV. Design Of Steel Drive Shaft

Steel (SM45C) used for automotive drive shaft applications. The material properties of the steel (SM45C) are given in Table 3.2 [2]. The steel drive shaft should satisfy three design specifications such as torque transmission capability, buckling torque capability and bending natural frequency.

Table 3.2 Mechanical properties of Steel (SM45C)

Mechanical properties	Symbol	Units	Steel
Young's modulus	E	GPa	207
Shear modulus	G	GPa	80
Poisson's ratio	v	-------	0.3
Density	ϱ	Kg/m^3	7600
Yield strength	Sy	MPa	370
Shear strength	Ss	MPa	--

4.1 Mass of steel drive shaft

$$m = ϱAL = ϱ\,\pi(do2 - d_i^{\,2}) \times L/4$$

Where d_o = outer diameter (m)
d_i = inner diameter (m)

$$m = 8.58 \text{ Kg}$$

4.2 Torque transmission capacity of drive shaft: [2]

$$T = Ss \times \pi \times [(do\text{^}4 - di\text{^}4) \times do]/16 \quad \dots (2)$$

$$T = 55.93\ Nm$$

V. Design Of Composite Drive Shaft

Table no: 5.1 The materials and their properties that were used in this analysis [1]

Properties	E Glass	HM carbon	E Glass polyester resin	HS carbon
Young's modulus X direction	5.e+010 Pa	1.9e+011	3.4e+010 Pa	1.34e+011 pa
Young's modulus Y direction	1.2e+010 pa	7.7e+009	6.53e+009 pa	7e+009 Pa
Young's modulus Z direction	1.2e+010 Pa	7.7e+009	6.53e+009 Pa	7e+009 Pa
Major poisson's Ratio XY	0.3	0.3	0.217	0.3
Major poisson's Ratio YZ	0.3	0.3	0.366	0.3
Major poisson's Ratio XZ	0.3	0.3	0.217	0.3
Shear modulus XY	5.6e+009 Pa	4.2e+009	2.433e+009 Pa	5.8e+009 Pa
Shear modulus YZ	5.6e+009 Pa	4.2e+009	1.698e+009 Pa	5.8e+009 Pa
Shear modulus XZ	5.6e009 Pa	4.2e+009	2.433e+009 pa	5.8e+009 Pa
Density	2000 Kg/m^3	1600 kg/m^3	2100 kg/m^3	1600 kg/m^3
Allowable stress	400e+006 Pa	440e+006	420e+006 pa	600e+006

VI. Modeling and ANSYS simulation:

6.1 Selection of element type:

SHELL181 may be used for layered applications of a structural shell model as shown in Figure SHELL181 allows up to 250 layers. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Shell 181 element type provides us to give the different material properties in X, Y and Z directions.

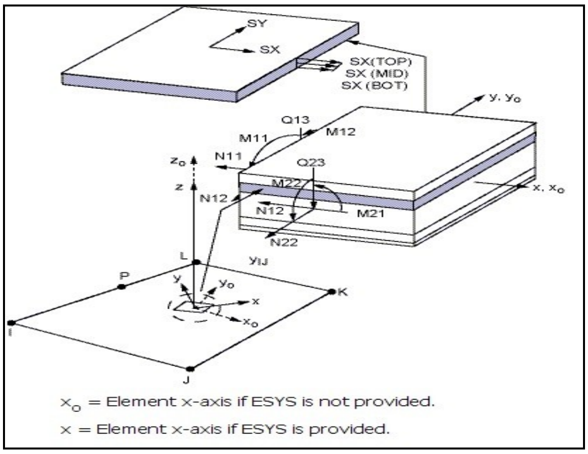

fig. 6.1.1

6.2 Selection of plies:

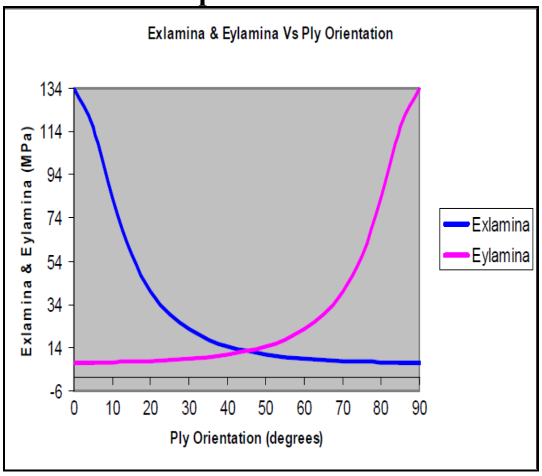

fig 6.2.1

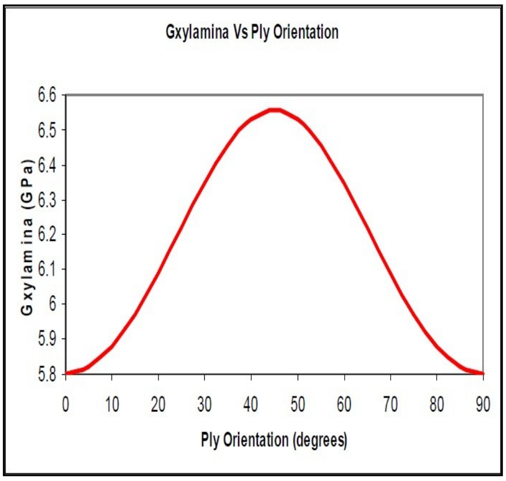

fig 6.2.2

Stress in each ply is calculated and then by using first ply failure criterion, failure of laminate is determined i.e. when first ply fails laminate is assumed to fail. Here maximum stress theory is used to find the torque transmitting capacity. This is the GA algorithm showing the variation of the Young's modulus of laminas. From the above fig it is found that the Young's modulus in the X direction is higher for smaller ply angle and suddenly falls down above the 25 degrees. But in the case of Y direction constant at lower ply angle and suddenly increase above 70degrees.The shear modulus in fig. shoes that it is having maximum value for the ply in between the 30 to 70 degrees. The shaft is subjected under both the types of load normal and shear. To optimize the above two conditions it need to select the equal no of ply angles for Young's and shear modulus.

6.3 Meshing:

We have selected area mesh for the meshing with the element size of 10, which will provide us fine meshing. We have selected quadrilateral mesh element for accurate and uniform meshing of component. The meshing is the method in which the geometry is divided in small number of elements. This meshing of propeller shaft is as shown in below fig.

6.4 Static analysis:

A static analysis can be either linear or non-linear. All types of non-linearity's are allowed such as large deformations, plasticity, creep, stress stiffening, contact elements etc. this chapter focuses on static analysis. A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those carried by time varying loads. 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. If these values exceeds above the allowable values then component is going to fail. Hence static analysis is necessary.

6.5 Torsional analysis:

The boundary condition for the torsional analysis of drive shaft are given as the one end is constrained with zero displacement in the both linear and rotational. At the other end of shaft torque is applied. We selected above Table properties for torsional analysis of drive shaft.

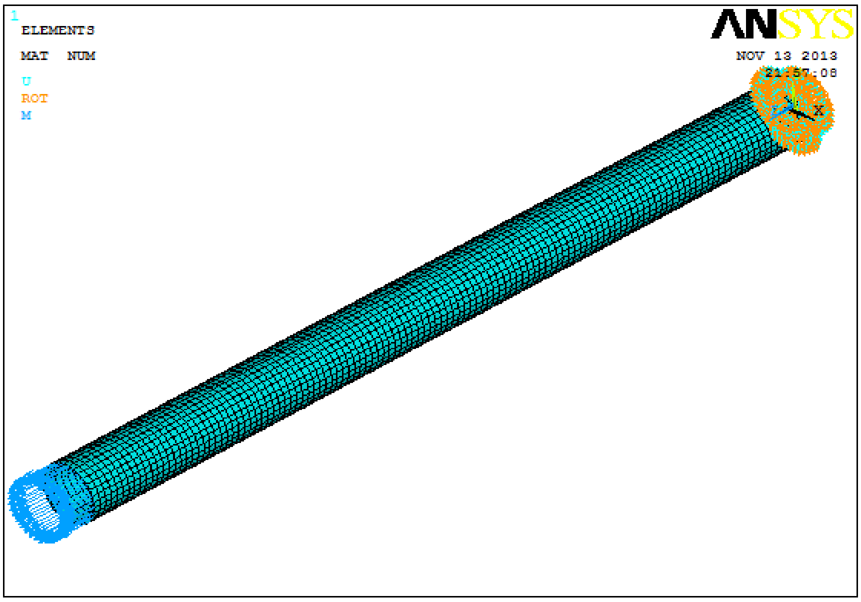

fig 6.5.1

6.6 Dynamic analysis:

Modal Analysis:

The modal analysis is one of the important analysis for drive shaft as we are eliminating two piece drive shaft and using single piece. Single piece not allowing any axial adjustment movement of drive shaft. The modal analysis is required as the 1st mode frequency of vibration must be less than shaft operating frequency to avoid failure of drive shaft.

The boundary condition applied is as shown is fig. given below.

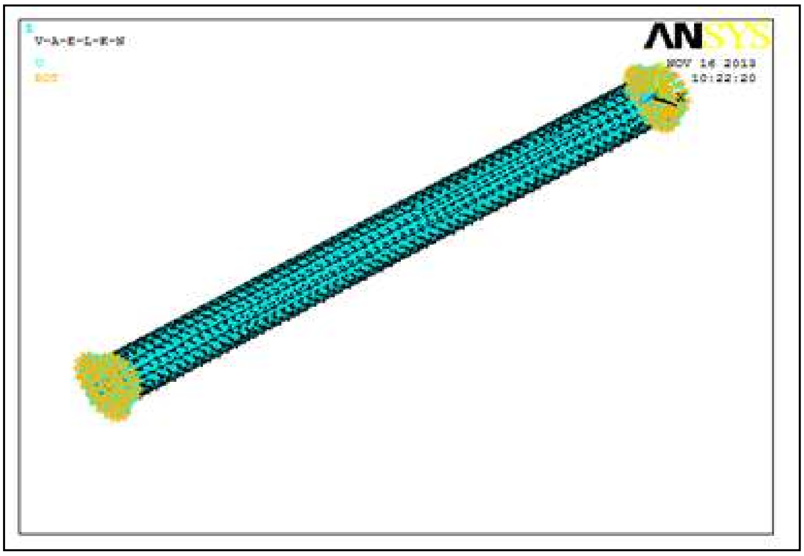

fig 6.6.1

VII. Results:

Table7.1: Results of weight optimization.

Parameters	Steel	E-Glass/Epoxy	HS Carbon/Epoxy	HM Carbon/Epoxy	Polystyrene
d_o (mm)	90	90	90	90	90
L (mm)	1250	1250	1250	1250	1250
t_k	3.318	0.4	0.12	0.12	0.12
Optimum no. of Layers	1	17	17	17	17
t (mm)	3.318	6.8	2.04	2.04	2.04
Optimum Stacking sequence	-	46/-64/-15/-13/39/-84/-28/20/27	-56/-51/74/-82/67/70/13/44/-75	-65/25/68/-63/36/-40/-39/74/-39	46/-64/-15/-13/39/-84/-28/20/27
Weight (Kg)	8.58	4.4434	1.1273	1.1274	1.4868
Weight saving (%)	-	48.22	86.86	86.86	82.67

Table no7.2: Effect of transverse shear and rotary inertia on the fundamental natural frequency

Material	Steel	E-Glass/Epoxy	HS Carbon /Epoxy	HM Carbon/Epoxy	Polystyrene
Optimum Stacking Sequence	-	46/-64/-15/-13/39/-84/-28/20/27	-56/-51/74/-82/67/70/13/44/-75	-65/25/68/-63/36/-40/-39/74/-39	46/-64/-15/-13/39/-84/-28/20/27
$N_{1st\ mode}$ (rpm)	49787	11402	101520	19987	25690

Table no7.3: Defection of drive shaft for various materials.

Material	Steel	E-Glass/Epoxy	HS Carbon/Epoxy	HM Carbon/ Epoxy	Polystyrene
Deflection (m)	0.00911	0.04113	0.002946	.04080	0.1974

Optimized plies selections are as following:

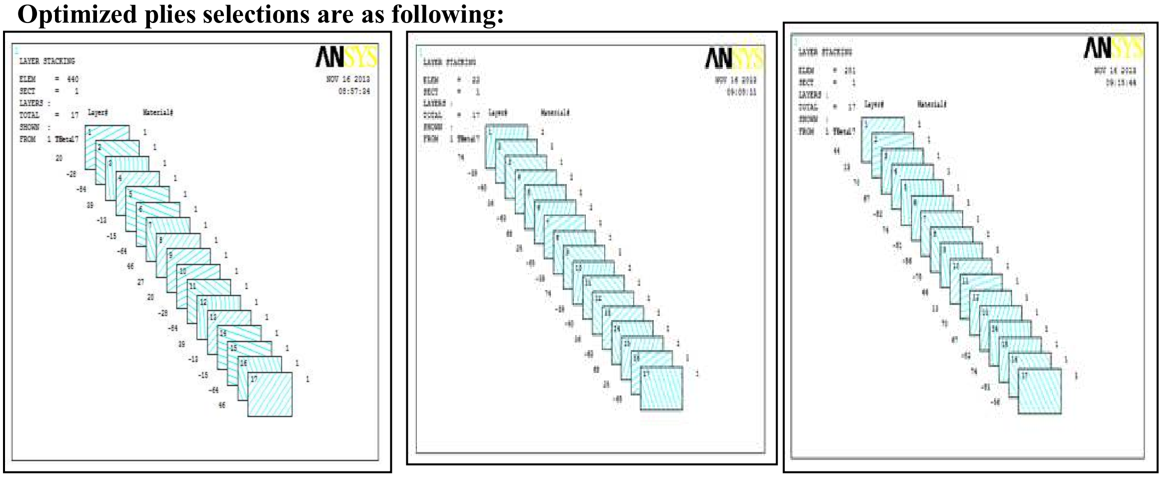

fig 7.1

Above fig shows optimum stacking sequence for E Glass and polystyrene, HS Carbon/Epoxy, HM Carbon/ Epoxy respectively.

Displacement results of analysis:

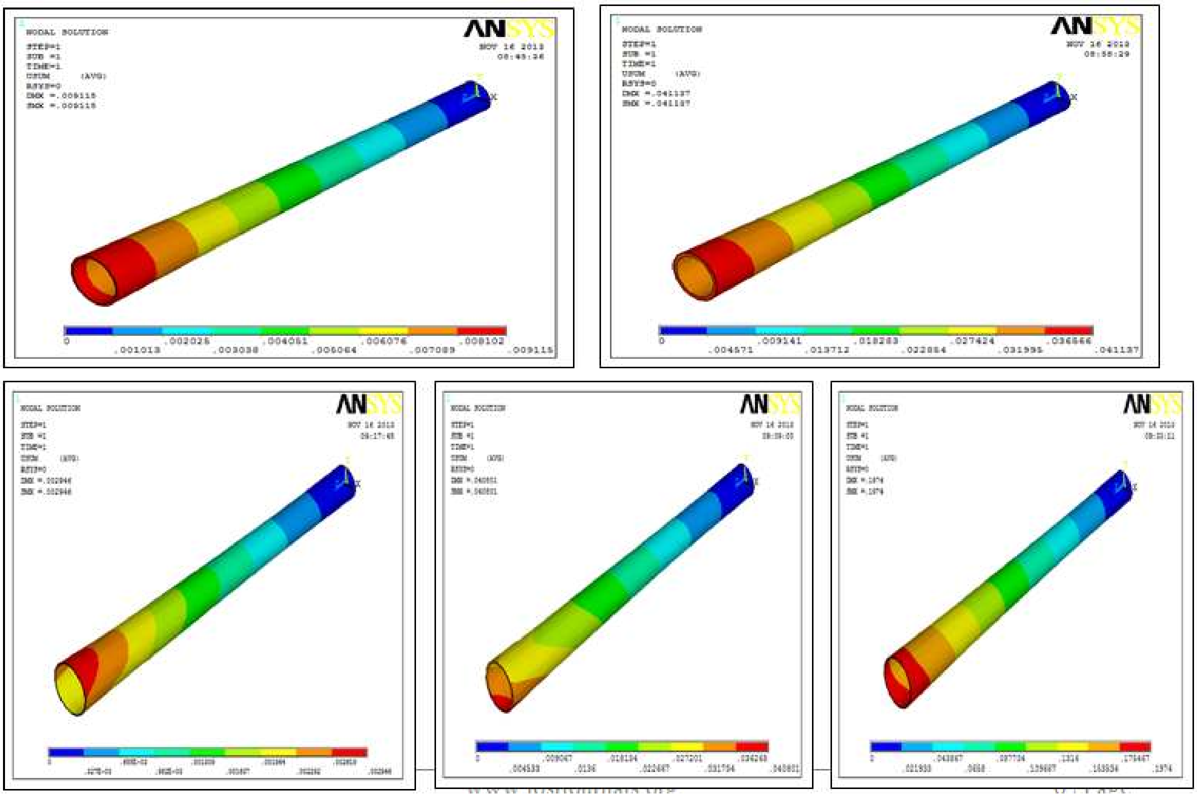

fig 7.2

Above fig showing the deformation of drive shaft for the E Glass, HS Carbon/Epoxy, HM Carbon/ Epoxy, polystyrene respectively.

Von Mises stress distribution:

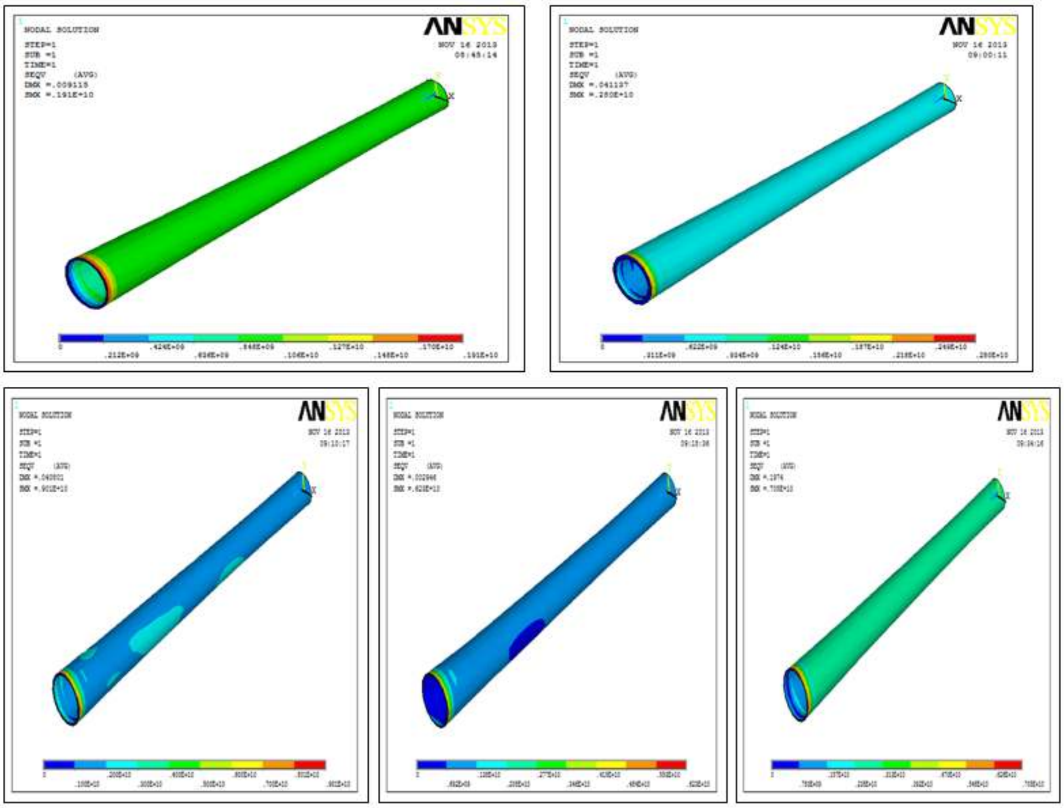

fig 7.3

Above fig showing the Von Mises stress distribution of drive shaft for the E Glass, HS Carbon/Epoxy, HM Carbon/ Epoxy, polystyrene respectively.

1st mode of drive shaft:

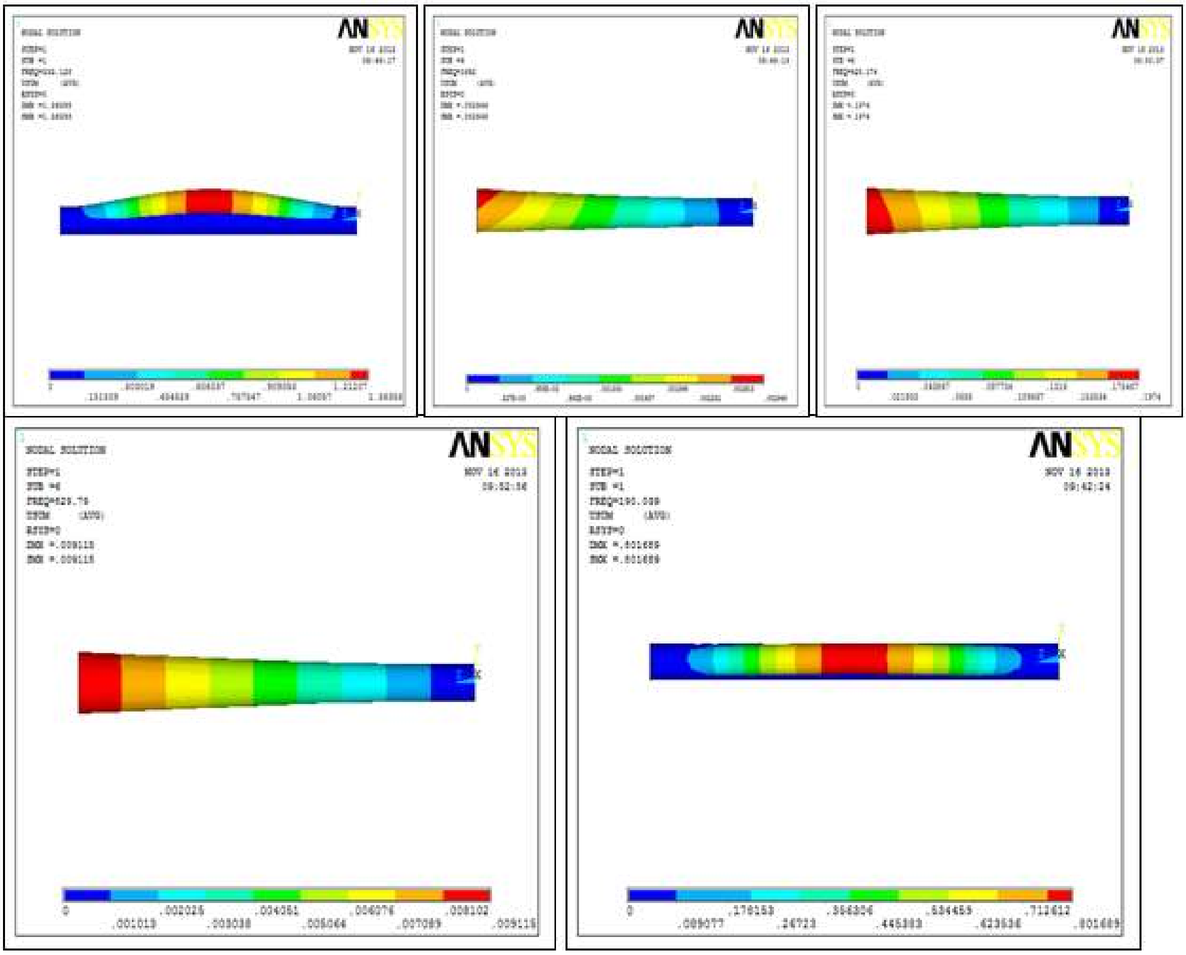

fig 7.4

Above fig showing the 1st mode of vibration of drive shaft for the E Glass, HS Carbon/Epoxy, HM Carbon/ Epoxy, polystyrene respectively.

VIII. Conclusion

The stress distribution and the maximum deformation in the shaft are the functions of the stacking of material. The optimum stacking of material layers can be used as the effective tool to reduce weight and stress acting on the drive shaft.

The design of drive shaft is critical as it is subjected to combined loads. The designer has two options for designing the drive shaft whether to select solid or hollow shaft. The solid shaft gives a maximum value of torque transmission but at same time due to increase in weight of shaft the 1st mode frequency decreases. Also shaft outer surface facing most of the stress coming on to it and the inner material layer experienced less stress, hence the inner layers increasing the weight of shaft and not utilized for stress distribution properly, that’s why the hollow drive shaft is best option.

The use of composite material reduces the weight of shaft significantly as the composite having lower density. The initial torque required to give rotation to the transmission system is large, as the weight reduces this surplus torque is utilized to propel the vehicle, at the same time inertial effect of rotating part decreases. Also the reduction in the weight of shaft increases the 1st modal frequency of bending, hence this shaft can be utilized for higher frequencies than the steel. The reduction in weight gives further advantage in the increase in the fuel economy of vehicle.

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