Dynamic Analysis of Heavy Vehicle Medium Duty Drive Shaft Using Conventional and Composite Material

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Abstract. The main highlight of this study is structural and modal analysis of single piece drive shaft for selection of material. Drive shaft is used for torque carrying from vehicle transmission to rear wheel differential system. Heavy vehicle medium duty transmission drive shaft was selected as research object. Conventional materials (Steel SM45 C, Stainless Steel) and composite materials (HS carbon epoxy, E Glass Polyester Resin Composite) were selected for the analysis. Single piece composite material drive shaft has advantage over conventional two-piece steel drive shaft. It has higher specific strength, longer life, less weight, high critical speed and higher torque carrying capacity. The main criteria for drive shaft failure are strength and weight. Maximum modal frequency obtained is 919 Hz. Various harmful vibration modes (lateral vibration and torsional vibration) were identified and maximum deflection region was specified. For single-piece drive shaft the natural bending frequency should be higher because it is subjected to torsion and shear stress. Single piece drive shaft was modelled using Solid Edge and Pro-E. Finite Element Analysis was used for structural and modal analysis with actual running boundary condition like frictional support, torque and moment. FEA simulation results were validated with experimental literature results.

1. Introduction
A propeller shaft, transmission drive shaft, driving shaft, drive shaft or cardan shaft is an automobile mechanical component. Conventionally it is manufactured using Steel material in two-piece and used for transmitting torque and rotation, at the same time it is also used to connect mechanical components of drive train that are not directly connected from transmission or engine to rear end of vehicle. This type of transmission drive shaft is known as propeller shaft. Two-piece drive shaft consists of two or more universal joints with jaw coupling which increases the total weight of drive shaft and decreases the fuel efficiency. Heavy vehicle truck transmission longitudinal drive shaft is subjected to shear stress, torsion, lateral vibration and torsional vibration. The strength and weight are two technical indexes for drive shaft failure.

Durk Hyun Cho et al. [1] the authors have studied the composite material single-piece drive shaft. The results shows that the shaft sustain for 107 cycles with dynamic load of + 500 Nm. M. Aleyaasin et al. [2] have investigated the problem of flexural vibration for cantilevered marine propeller shaft. Ercan Sevkat et al. [3] the authors have studied the problem of residual torsional properties of composite shafts. The composite shaft was studied on 4 different impact energy levels (5, 10, 20 and 40 J energy). Impact and without impact properties of shaft was compared for torsion. Balazs Trensceni at al. [4] have studied the driving comfort of heavy vehicle. The vehicle drivability performance is evaluated by driveline. Oscillations reduction, ease of gear shifting increases the drivability but it has some adverse effect on fuel economy. The paper highlights the importance of driveline torque measurements for drivability performance.
K. Solanki et al. [5] have studied the failure reason of AISI 304 stainless steel drive shaft. The main vibration reason for failure is low natural bending frequency. R.B. Ingle et al. [6] the research work highlights the composite material use in aerospace and aircraft industry in supercritical operating condition. The composite shaft made of carbon fibers in epoxy matrix, 16 layers with different stacking angles was used for analysis. The static and dynamic behaviour was investigated at high speeds (10000-65000) rpm. The vibration spectrum of composite shaft was observed in aerospace conical bearing. Ying-san WEI at al. [7] the authors have studied the propeller excited underwater noise of the submarine hull structure using numerical simulation method. The Helmholtz Integral Equation (HIE) was solved using Refined Integral Algorithm (RIA) and Boundary Element Method (BEM). The results shows that mainly thrust force excites the submarine axial mode and high frequency area appears. Thrust excitation was reduced for sound reduction of the submarine structure.

D.H. Cho et al. [8] the authors have studied the method to reduce the residual thermal stresses using co-curing operation. Aluminum composite shaft was prepared using aluminum tube and composite material. During bonding process residual stresses was generated. S. A. Mutasher [9] the research work present study of advanced hybrid shaft using ANSYS and FEM. The linear and nonlinear properties of materials were considered. The maximum torque transmitted through hybrid shaft is 295Nm. The numerical result was verified with experimental results. Rastogi N. [10] have design a automotive drive shaft using composite materials. The author have highlights the importance of composite material over conventional materials. Composite materials have high specific strength and low weight which is desirable for drive shaft vehicle application. Ashley R. Crowther et al. [11] the authors have studied the automatic transmission system for impulsive response for the abrupt change in mean torque excitation and system load change. Matrix element method was used for lumped mass model formulation. The model was reduced in nonlinear problem and numerical simulation was performed which provides good correlations.

Hak Sung Kim et al. [12] the authors have investigated the problem of thermal residual stresses for hybrid shaft. To eliminate the residual stresses a smart cure cycle of cooling and reheating was applied and this method effectively solved the stress problem. A.R. Abu Talib at al. [13] the authors have used carbon and glass fibers in an epoxy matrix to manufacture composite shafts. FEA method was used for the natural frequency analysis. The change in winding angle shows loss in natural frequency and stacking sequence of the material effect buckling strength. H. Baryrakceken [14] the research work concerned with the failure analysis of pinion shaft. Kumar et al. [15, 19] have studied the dynamic response and thermal analysis of heavy vehicle transmission gearbox system using FEA method. This result has signifies in design stage of transmission system.

Composite materials have higher specific stiffness to provide the required strength against less weight. Higher stiffness of composite material solves the problem of high strength requirement for drive shaft and less weight solves the problem of inertia. So composite material can be used as a one-piece drive shaft material without resonance. In this research work HS carbon epoxy and E-glass polyester has been used as a composite material for single-piece drive shaft analysis. The one-piece drive shaft of truck was specified for the study and the modeling of the drive shaft assembly was done using Pro-E. The weight of drive shaft was optimized to reduce the inertia and torsional vibration problem.

2. Designing of Single-Piece Composite Material Drive Shaft

Single-piece drive shaft was designed using the Solid Edge and Pro-E [16-17] software. FEA based analysis was done using Ansys 14.5 [18]. The result of this study provides the reference work for the structure optimization and performance evaluation of single-piece drive shaft aims at reducing vibration and strength problem. Free vibration study of heavy vehicle, single-piece composite material drive shaft was performed to evaluate the inherent natural frequency and vibration mode shape to prevent the resonance. For structure rigidity the natural bending frequency of drive shaft should be high. The structure analysis has evaluated the strength properties of drive shaft. The design model of automobile truck drive shaft consists of a single-piece shaft with universal joints at ends portion. Figure 1 shows the single-piece drive shaft with universal joint. The Ansys 14.5 program solver works on meshing concept of nodes and elements (nodes- 87718, elements- 453477). Figure 2 shows the
meshed finite element model of transmission drive shaft. Ansys 14.5 have high quality meshing facility.

![Figure 1. CAD Model of transmission driving shaft.](image1)

![Figure 2. FEM meshed model of driving shaft.](image2)

3. Problem Definition
The main objective of this research work is to replace conventional steel material two piece three universal joints drive shaft with composite material single-piece drive shaft. Higher strength and low weight are the two technical requirements for composite single-piece drive shaft. Steel SM45C, Stainless Steel as conventional material and HS-Carbon Epoxy, E Glass Polyester Resin were selected as composite material. Higher stiffness and specific strength of composite material solves the problem of strength requirement for drive shaft and less weight solves the problem of inertia and torsional vibration. For single-piece drive shaft the natural bending frequency should be higher. In literature [7, 10 and 11] various studies have recommended the replacement of conventional drive shaft using composite material single-piece drive shaft. In 1985 single-piece drive shaft was used for the Ford econoline van models. Drive shafts are used in automobiles, aerospace, cooling towers etc.

4. Assumptions and Advantage of Composite Material Drive Shaft
This research work highlights the use of composite material single-piece drive shaft for heavy vehicle truck application. Numerical simulation method is used for structural and free vibration analysis. In study of drive shaft it was assumed that the shaft is balanced, has circular cross section and rotates at constant speed. The nonlinear and damping effects were not considered. The advantage of composite materials has attracted the scientist worldwide. It has many applications in automobile fields. The drive shaft can be manufactured using composite materials. It has advantage of high specific strength and less weight, high torque carrying capacity, corrosion resistance, high damping. The advantage of composite material leads less fuel consumption and less noise, vibration. The fatigue life of composite material is high. Two composite materials HS-Carbon Epoxy and E Glass Polyester Resin were used for single-piece drive shaft study.

5. Material Properties and Selection of Boundary Conditions
One of the main features of composite material is damping property, which reduces the noise and vibration. Steel SM45C, HS carbon epoxy, E-glass polyester resin and Stainless Steel were selected as material for drive shaft analysis. Nonlinear effect of material properties were considered for structural and free vibration analysis. The geometric properties of the drive shaft are length of shaft 1250 mm, Outer Diameter-90 mm, inner diameter-83.36mm. Table 1 shows the material mechanical properties of steel and composite material. This paper highlights strength and vibration index base analysis for replacement of two piece drive shaft with single piece light weight conventional and composite material drive shaft. HS carbon epoxy composite material best suited for single-piece drive shaft having high specific stiffness, less weight and torsional stiffness.
The natural frequencies for HS carbon epoxy composite are (0-919.64) Hz. 0 Hz frequency shows rigid condition in modal analysis. Table 2 shows the boundary condition parameters. Four boundary conditions frictionless support, fixed support, rotational velocity and moment are applied. Fixed support boundary condition is applied on 2 faces at inner part of universal joint portion (figure 3). Universal joints fixed the drive shaft at two ends. One end is connected to transmission parts and another is connected to differential parts. To simulate the same environment the one end of single piece drive shaft is fixed and another end is supported by frictionless support on 8 faces (figure 4).

Rotational velocity of 1500rpm (157.08 rad/sec, figure 5) was applied for dynamic vibration analysis. The rotational motion of shaft generates a moment into whole body of drive shaft. This moment is applied on all 43 faces (figure 6) in opposite direction of rotational velocity. The moment effects observe the specific stiffness and torsional strength of single piece drive shaft. The boundary condition is applied for structural analysis and the result of structural analysis is imported for modal analysis to incorporate the deformation effect for natural frequency and mode shapes.

### Table 1. Material properties of conventional and composite material.

| Properties                  | Nonlinear Effects | Density (kg m^{-3}) | Young's Modulus (Pa) | Poisson's Ratio | Shear Modulus (Pa) |
|-----------------------------|-------------------|----------------------|----------------------|-----------------|--------------------|
| Steel SM45C                 | Considered        | 7600                 | 2.07e+011            | 0.3             | 7.9615e+010        |
| HS-Carbon Epoxy Composite   | Considered        | 1600                 | 2.1e+011             | 0.3             | 8.0769e+010        |
| E Glass Polyester Resin     | Considered        | 2100                 | 3.4e+010             | 0.366           | 2.433e+009         |
| Composite Stainless Steel   | Considered        | 7750                 | 1.93e+011            | 0.31            | 7.366e+010         |

### Table 2. Boundary condition applied.

| Object Name   | Fixed Support | Frictionless Support | Rotational Velocity | Moment |
|---------------|---------------|----------------------|---------------------|--------|
| Geometry      | 2 Faces       | 8 Faces              |                     | 43 Faces|
| Coordinate System |                |                      |                     |        |
| X Component   |               |                      | 157.08 rad/s (ramped)|        |
| Y Component   |               |                      | 0. rad/s (ramped)   | -245. N·m (ramped) |
| Z Component   |               |                      | 0. rad/s (ramped)   | 0. N·m (ramped) |
| Behaviour     |               |                      | Deformable          |        |

**Figure 3.** Fixed condition boundary condition applied. **Figure 4.** Frictionless support applied.
6. FEA Simulation Results and Discussion

Structural analysis was performed for stresses, strains and deformation performance evaluation of drive shaft. Inertia and damping effects was not considered for analysis. Rotational and moments values were applied in form of loading. The automobile drive shaft is subjected to torque transmission, no direct load value act on it. Rotational and moment effects caused failure of drive shaft. So only these two parameters were considered for structural and modal analysis. The result of this analysis evaluates the failure condition of drive shaft.

6.1 Structural Analysis of Steel SM45 C Material Driving Shaft

Steel SM45 C is used as conventional two-piece driving shaft material. The structural analysis simulation results are shown in figure (7, 8, 9, 10, 11 and 12). Table 3 shows the structural analysis results comparison for steel and composite material.

Figure 7 shows the shear stress distribution on XY plane. The analysis result shows that the shear stress variation is in permissible design limit (5.5325e6 Pa). The green color variation shows that the

Figure 7. Shear Stress distribution (XY plane).

Figure 8. Maximum principal Stress variation.

Figure 9. Total Deformation.

Figure 10. Strain Energy distribution.
steel SM45 C has high strength and rigidity to bear the torsional vibration and shear stresses. Figure 8 shows the maximum principal stress distribution in drive shaft. Principal stress variation \(2.1989 \times 10^7\) Pa is in safe limit. Figure 9 shows the total deformation in single piece drive shaft under loading conditions. The deformation is high \(0.05\) mm at the differential end of drive shaft. The yellow and red colour variation in shaft shows the high deformation zone. On design criteria base the deformation result is in safe zone. Figure 10 shows the strain energy distribution in drive shaft. The transmission end of drive shaft shows small variation of strain energy near constraining point of universal joint. Strain energy value is \(0.000031\) J for steel drive shaft.

6.2 Structural Analysis of HS Carbon Epoxy Composite Material Driving Shaft

Figure 11 explain the shear stress distribution on XY plane. The simulation result shows the shear stress distribution in single-piece HS carbon epoxy composite drive shaft. The maximum available shear stress for HS carbon epoxy composite material is \(1.2545 \times 10^6\) Pa which is very less in comparison to max. shear stress \(5.5325 \times 10^6\) Pa for steel material. The quantitative result shows that composite material have less shear stress generation due to loading and design is safe. Figure 12 shows the maximum principal stress distribution in single-piece drive shaft. The max. value of maximum principal stress is \(0.52064 \times 10^7\) Pa. Principal stress variation is within safe limit. Figure 13 shows the total deformation under loading conditions. The deformation is high at the transmission end of drive shaft. The maximum deformation value is \(0.01\) mm for HS carbon epoxy composite drive shaft. For the same loading conditions the deformation of steel shaft is \(0.05\) mm. The deformation result shows the suitability of HS carbon epoxy material for single piece drive shaft. Figure 14 shows the strain energy variation in drive shaft. The strain energy distribution is found at the constraining point of universal joint. Strain energy value is \(0.000029\) J.
6.3 Structural Analysis of E-Glass Polyester Composite Material Driving Shaft

E glass polyester resin composite material shows (-1.3252e6 to 1.6539e6) Pa maximum shear stress distribution (figure 15) on XY plane. The E glass polyester resin composite material shear stress value is less in comparison to steel SM45C (5.532e6) and more than HS carbon epoxy material (1.2545e6 Pa) (Table 3). Figure 16 shows the maximum principal stress variation in drive shaft. It varies from (-0.59956e6 to 1.2485e7) Pa. Figure 17 shows the total deformation in single piece drive shaft under loading conditions. The deformation is high at the transmission end of drive shaft. The deformation is 0.19 mm, which is maximum in all materials. Figure 18 shows the strain energy distribution in drive shaft. The maximum strain energy value is 0.000063 J for E glass polyester resin composite material.

6.4 Structural Analysis of Stainless Steel Single Piece Drive Shaft

Figure 15. Shear Stress distribution (XY plane). Figure 16. Maximum principal stress variation.

Figure 17. Total Deformation. Figure 18. Strain Energy distribution.

Figure 19. Total deformation
Stainless Steel is used as conventional two-piece driving shaft material. The structural analysis simulation results are shown in Table 3. Table 3 shows the comparison of structural result for steel and composite material. The structural simulation results conclude that HS carbon epoxy composite material is best suited for single-piece drive shaft and in conventional material Steel SM45 C shows high strength and rigidity for single piece drive shaft.

### 7. Modal Analysis

FEA based modal analysis was performed to find the natural frequencies and mode shapes. Natural frequency of a system depends on geometric and material properties. In all condition of modal analysis using different materials torque and speed boundary conditions remains same. Drive shaft rotates at maximum speed of 1500 rpm and transmits 245 Nm torque. Under external excitation resonance chances are more so it is necessary to find the natural frequency.

| Material                        | Type | Shear Stress (Pa) | Max. principal Stress(Pa) | Total Deformation (m) | Strain Energy (J) | Equivalent Elastic Strain (m/m) | Maximum Principal Elastic Strain(m/m) |
|---------------------------------|------|-------------------|---------------------------|-----------------------|-------------------|-------------------------------|--------------------------------------|
| Steel SM45 C                   | Min. | -5.145e6          | -3.3989e6                 | 0                     | 0                 | 0                             | -5.5131e-7                           |
|                                 | Max. | 5.532e6           | 2.1989e7                  | 5.0321e-5             | 3.106e-5          | 9.5587e-5                     | 9.8226e-5                            |
| HS Carbon Epoxy Composite      | Min. | -1.065e6          | -0.9313e6                 | 0                     | 0                 | 0                             | 0                                    |
|                                 | Max. | 1.2545e6          | 0.52064e7                 | 1.0458e-5             | 2.983e-5          | 2.2346e-5                     | 2.2973e-5                            |
| E Glass Polyester Resin Composite | Min. | -1.325e6         | -0.59956e6                | 0                     | 0                 | 0                             | 0                                    |
|                                 | Max. | 1.653e6           | 1.2485e7                  | 1.9792e-4             | 6.369e-5          | 6.983e-4                      | 5.6935e-4                            |
| Stainless Steel                | Min. | -5.2485e6         | -3.5698e6                 | 0                     | 0                 | 0                             | -3.9815e-7                           |
|                                 | Max. | 5.6524e6          | 2.8564e7                  | 5.5335 e-5            | 3.456e-5          | 10.434e-5                     | 10.703e-5                            |

Stainless Steel is used as conventional two-piece driving shaft material. The structural analysis simulation results are shown in Table 3. Table 3 shows the comparison of structural result for steel and composite material. The structural simulation results conclude that HS carbon epoxy composite material is best suited for single-piece drive shaft and in conventional material Steel SM45 C shows high strength and rigidity for single piece drive shaft.

Mode 8 $f_8=226.13$ Hz (Steel SM 45 C) Mode 10 $f_{10}= 919.64$ Hz (HS Carbon Epoxy)
Mode 8 $f_8=146.62$ Hz (E Glass Polyester resin)   Mode 8 $f_8=216.19$ Hz. (Stainless Steel)

**Figure 20.** Natural frequency and mode shape of drive shaft

The relation between critical speed and natural frequency is given as ($N_{cr} = 60 f_{nt}$). Figure 20 shows mode 8 having lateral vibration with bending effect. The bending frequency is 226.13 Hz (Steel SM 45 C) and critical speed is 13567 rpm. Mode 10 of Steel SM 45 C have torsional vibration at 919.64 Hz and deformation takes place at end points. HS carbon epoxy material mode 10 shows torsional vibration effect. For E-glass polyester resin first valid frequency is 48.127 Hz and critical speed is 2887 rpm. This critical speed is nearer to whirling critical speed of 2400 rpm. So E-glass polyester resin composite material has resonance problem. Stainless steel material mode 8 has large deformation at centre portion of drive shaft having stress concentration problem (Figure 20).

**Figure 21.** Natural frequency variation for conventional and composite materials

**Figure 22** FEA simulation result validation.
Figure 21 shows the variation of natural frequencies for conventional steel and composite materials. In conventional materials Steel SM45C and in composite materials HS carbon epoxy composite material shows the excellent material properties for the design of single-piece composite drive shaft to meet the stringent design requirements for automobiles. In order to avoid the whirling or resonance vibration the bending frequency should be higher than (2400-4000) rpm for trucks and vans and the transmission capability should be higher than 154 Nm. The HS carbon epoxy composite material fulfills these technical requirements. The bending natural frequency is 10930 rpm much higher than 2400 rpm, so it reduces the chances of whirling or resonance. The torque transmission capability of single-piece drive shaft was considered as 245 Nm. Simulation results of this study were validated with experimental results obtained from Trencséni & Palkovics [4]. Figure 22 shows validation graph for conventional material steel SM45C single piece drive shaft. 4 valid mode has been shown in graph. For mode 1, 2, 3 and 4 the difference of frequencies is 14.61 Hz, 6.77 Hz, 41.49 Hz and 61.43 Hz. The average difference between four valid mode frequency between FEA simulated and experimental result is 10.85%. It shows accurate FEA results.

8. Conclusion

The results of this research work have theoretical importance in design stage of single-piece drive shaft for heavy vehicles. The two-piece drive shaft design was replaced in single-piece composite material drive shaft. The structural and modal analysis was performed for four different materials two conventional and two composite materials. Frequency response graph (Figure 21) shows that Steel SM45C and HS carbon epoxy composite is suited for single-piece drive shaft. The research work concludes the following points-
1. The aim of selecting best suited material for single piece drive shaft was fulfilled. It was found that on technical index of strength and vibration Steel SM45C (conventional) and HS carbon epoxy (composite) materials were selected for single piece driveshaft.
2. Shear stresses, maximum principal stress, total deformation, strain energy, max. principal elastic strain and equivalent elastic strain were evaluated using structural analysis for all materials drive shaft. All the structural analysis results are in permissible limit for Steel SM45C and HS carbon composite, which ensures the strength of single-piece drive shaft.
3. HS carbon epoxy composite material shows maximum deflection of 0.1 mm and bending natural frequency is 182.17 Hz with critical speed of 10930 rpm. This speed limit is much higher than whirling critical speed.
4. The critical speed for all materials are- steel SM45 C- 4797 rpm (79.96 Hz), HS carbon epoxy composite-10930 rpm (182.17 Hz) and E-glass polyester resin composite-2887 rpm (48.12 Hz). The whirling critical speed for heavy vehicles vary (2400-4000) rpm which signifies that Steel SM 45C and HS carbon composite is best suited for single-piece drive shaft of heavy vehicle.

FEA based analysis tool Ansys 14.5 was used for structural and modal analysis. FEA results are in good agreement offering satisfactory results.

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