Analysis of Torsional Vibration Reduction on Automobile Cardan Shaft by using Composite Materials

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Abstract
The Cardan shaft is of interest because it transfers torsional loads from the gearbox to the rear axle for vehicle motion. Central to the entire discipline of the Cardan shaft is the concept of the dynamics of the Cardan shaft. This concept can be very complex because one head of the shaft is fixed to the gearbox, while the other end can move in the vertical plane when the vehicle is running on an uneven road. The Cardan shaft is twisted and bent at different rotational speeds. When the torsional oscillation frequency of the Cardan shaft coincides with one of its natural frequencies, it can induce resonance and causing structural damage. The paper presents the analysis of the Cardan shaft’s natural frequencies with two different materials: conventional sheet metal and composite material. The calculations can be used as the basis for designing the Cardan shaft in the vehicle powertrain system of the vehicles. These results further support the idea of using composite materials for the Cardan shafts in the automotive powertrain system, and composite materials for some other shaft parts in the vehicle.

Keywords: Cardan shaft, torsion vibration, composite material

1. Introduction
A driveline on automotive usually consists of a Cardan shaft, half shafts, transmission gears systems and bearings, as well as other components. For all-wheel-drive (henceforth, AWD) vehicles, the driveline includes a front Cardan shaft for the front axle, a rear Cardan shaft for rear axle (or more than one Cardan shaft is used). For front-wheel drive (henceforth, FWD) vehicles, the most usually is the Cardan shaft. In the Cardan shaft design, the bending and torsional natural frequencies should be higher than the specific frequencies corresponding to the maximum rotation speed of the shafts, to prevent the resonance caused by the rotating unbalance force. The natural mode frequencies of parts should be designed or tuned to avoid resonance [1]. Fuel efficiency and the weight of the vehicle are two of the most important parameters to be considered in automobile design. To reduce power loss in the powertrain, composite materials can be used to design Cardan shafts with less weight while maintaining the required strength and stiffness [2]. A researched by performing FEA analysis on two different composite materials are E-GLASS and E-CARBON reducing Von-Mises stress and weight compared to structural steel. This can be concluded that the composite material can be used in the Cardan shaft [3].
2. Composite materials selection

Figure 1 shows the Cardan shaft for the automobile. The Cardan shaft is used to connect the gearbox to the different rear axle, and to transfer power from the engine to differential automobile through universal joints assembly. Cardan shaft has to withstand high rotational speeds and has to change its length while transmitting the torque required by the vehicle. The second method used to identify the motion of the universal joints which is proportional to the angle between the driving and driven shafts. It also affects system vibrations. Constant velocity operation of Cardan shaft obtained if the axes of the input and output shafts are truly parallel. There are, however, torque and velocity variations in the elements of conventional Hookes joints which give rise to secondary rocking couples; these affect the support bearing of the input-output shaft. Joint angles should thus be as small as possible to minimize these effects. Due to the limited installation location of the driveline system, the use of composite materials is an effective solution in this case.

![Figure 1. Cardan shaft of the driveline for Automobile](image)

This research studies replacing the conventional steel materials with composite materials for Cardan shaft. This method is particularly useful in studying reduction in the allowable working stress on the Cardan shaft, obtaining a given life expectancy, and analysing different composite materials for best-used selection.

The objective of this research is to replace C45 carbon steel material of the Cardan shaft assembled two Hook joints with composite material for a single shaft. The material mechanical properties of C45 carbon steel and E-glass epoxy, kevlar epoxy composite material are shown in Table 1. E-glass epoxy is a composite material that has been used extensively in engineering.

| Mechanical Properties | Steel C45 carbon | E-glass Composite | Kevlar Epoxy Composite | E-carbon |
|------------------------|------------------|-------------------|------------------------|---------|
| Density (kg/m³)        | 7850             | 1580              | 1402                   | 1451    |
| Young’s Modulus (Pa)   | 2.0e+11          | 7.23e+10          | 9.571E+10              | 5.92E+10|
| Tensile Yield Strength, (Pa) | 2.5E+08 | 7.8E+08          | 2.5E+08                | 5.13E+08|
| Tensile Ultimate Strength, (Pa) | 4.6E+08 | 3.1E+07          | 4.6E+08                | 5E+07   |
| Poisson’s ratio        | 0.3              | 0.28              | 0.34                   | 0.3     |
| Shear Modulus (Pa)     | 7.679e+10        | 1.37E+10          | 3.57E+10               | 2.28E+10|
|Bulk Modulus (Pa)       | 1.67E+11         | 2.65E+10          | 9.97E+10               | 4.93E+10|

Figure 2 presents the parameters of the Cardan shaft. The base length is 1450 mm, while the outer diameter is 90 mm, and the inner diameter 78 mm.
3. Simulation results and discussion

3.1 Modal analysis

The finite element analysis used in this study was Ansys Workbench software. This method is particularly useful in studying the mode shape, deformation, stresses and strain value in the Cardan shaft [4,5]. To evaluate the modal frequency and mode shape to prevent resonance, a modal analysis of other materials of Cardan shaft. The modal analysis of the Cardan shaft used in this study includes the modes that must be verified to avoid mode coincidence and to have sufficient separation from vehicle body modes. In the operation, the Cardan shaft undergoes the excitations of both torque modulation and unbalance. Thus, both torsional and bending vibrations play a vital role in the study. For torsional vibrations, the analysis procedure is similar to the engine crankshaft system. When the rotational speed of a shaft is sufficiently high, the unbalance excitation frequency could be identical to the bending natural frequency of the shaft. Under this situation, resonance occurs, and the corresponding specific speed is referred to as the critical speed. Operation at critical speed is likely to lead to failures of the shaft and its system. Regarding an elastic shaft with two ends connecting to universal joints, it can be modeled as a simply-supported beam on the two ends. Its critical speed is as the following equation (1):

\[ f_n = 3.56 \sqrt{\frac{E I g}{W L}} \]  

in which \( E \) is the modulus of elasticity, \( I \) is the moment of inertia, \( g \) is the acceleration due to gravity, \( L \) is the length, and \( W \) is the weight of the Cardan shaft [1].

The boundary conditions including frictionless support, the fixed support, rotational velocity and moment were used to simulate the same Cardan shaft. The torsional moment is 320 Nm and is applied to all the body with the rotational velocity of 2200 rpm (230.308 rad/sec). The torsional moment and boundary conditions on the Cardan shaft are illustrated in Figure 3.

![Figure 3. The torsional moment and working boundary conditions of the Cardan shaft](image)

As shown in Figure 4, the mesh used in this study were 381312 nodes and 215054 elements.
The results of mode shape and maximum total deformation in four types of materials of Cardan shaft indicate that the highest natural oscillation frequency is in the 10th mode where the Kevlar Cardan shaft has the highest nature oscillation frequency at 1156.7 Hz. The remaining axes are the steel Cardan shaft (707.3), the E-glass Cardan shaft (609.87 Hz), the E-carbon Cardan shaft (894.72 Hz). It was also found that the deformation is equivalent to each mode shape. The deformation of E-carbon and Kevlar Cardan shaft is equivalent coincidentally.

3.2 Static analysis

From this data, we can see that the static analysis resulted in four types of materials of the Cardan shaft: maximum total deformation, maximum equivalent elastic strain, and minimum, maximum equivalent von-misses stress. It can be seen from the data in Figure 5 that the deformation of the E-glass Cardan shaft reached the highest point (2.9509m) and was at the smallest point (0.82062m) of the Kevlar Cardan shaft. The equivalent elastic strain maximum has the highest by 4.86 (m/m) of E-glass material, as shown in Figure 6.

As can be seen from Table 2, it reported the statistical comparison of the four types of materials, the steels Cardan shaft specifications showed 100% reduction in weight. The proportion of other materials slightly decreased; E-glass (76.4%), Kevlar (82.1%) and Carbon (81.5%).

| Materials   | Steel    | E-glass  | Kevlar  | Carbon   |
|-------------|----------|----------|---------|----------|
| Weight (kg) | 29.042   | 6.8444   | 5.1869  | 5.3682   |
| Reduction in Weight (%) | 100 | 76.4 | 82.1 | 81.5 |
| Max. total deformation (m) | 2.1953 | 2.9509 | 0.82062 | 1.3718 |
| Max. equivalent elastic strain (m/m) | 3.6275 | 4.8607 | 1.3834 | 2.2779 |
| Max. equivalent (Von-Mises) stress (pa) | 6.7057E+11 | 1.5803e+11 | 1.1978e+11 | 1.2398e+11 |

The minimum and maximum of equivalent (Von-Mises) stress reached the highest (6.71E+11 Pa) of steel material of the Cardan shaft, as shown in Figure 7.
Figure 7. Equivalent (Von-Mises) Stress (Pa)

Figure 8 compares the weight of C45 steel and composite E-glass, Kevlar, E-carbon materials of the Cardan shaft.

3.3 Dynamic analysis

The analysis of the dynamic was shown to have the Cardan shaft working conditions (see Table 3). The moments included the active torsional moment in the whole body of the Cardan shaft (320 Nm), resistance moment (125 Nm) which contains a phase angle of 30 degrees (0.5236 rad). The rotational motion velocity is 2200 rpm (230.308 rad/sec), and the acceleration inertial is 1.41 m/s².

| Materials       | C45 steel | E-glass | Kevlar | Carbon |
|-----------------|-----------|---------|--------|--------|
| Harmonic Maximum Total Deformation (m) | 2.35E-03 | 2.08E-04 | 1.22E-04 | 2.1922E-04 |
| Harmonic Maximum Equivalent Elastic Strain (m/m) | 6.88E-02 | 8.03E-03 | 2.89E-03 | 5.40E-03 |
| Harmonic Maximum Equivalent (von-Mises) Stress (Pa) | 1.36E+10 | 1.09E+09 | 2.74E+08 | 3.1674e+08 |

In this study, the Harmonic in Ansys Workbench software was used to analyze the deformation, stresses, and strain dynamics value in the Cardan shaft. The results, as shown in Figure 9, indicated that deformation of E-carbon of the Cardan shaft showed the highest, and so does the equivalent (Von-Mises) steel of the Cardan shaft (see Figure 10).
4. Conclusion
This project was undertaken to evaluate the use of composite materials. To analyze the Cardan shaft’s
natural frequencies with four different materials, the conventional sheet metal, the E-glass composite, Kevlar, and E-Carbon material were adopted. The investigation of the effectiveness of Kevlar composite materials for the Cardan shafts in the automotive powertrain system have shown that the Kevlar composite materials are the best specifications. The second major finding was that the static analysis was reduced in weight (82 %). Also, the total deformation was at 0.82062 m, and the equivalent elastic strain was at 1.3834 m/m. While the equivalent (Von-Mises) stress showed 1.1978e+11 (Pa) and was the smallest (see Table 2). Concerning the dynamic analysis, the results of the total deformation were at 1.22E-04 m, and the equivalent elastic strain was 2.89E-03 m/m. These experiments confirmed that the equivalent (Von-Mises) stress was at 2.74E+08 Pa, and is the smallest (see Table 3). These findings suggest that, in general, the composite is gradually deformed, if one want to replace steel by the composite in the automobiles, one should consult engineers. Because they have been improved with a solid surface that meets the demanding requirements of the body, chassis. These findings have significant implications for the understanding of how to reduce costs in the process as it has many options which it should help to give more style, size and color of the parts or components of the automobiles.

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