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Original Article

Design Development and Computational Studies on Propeller Shaft of Small Commercial Vehicle

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Abstract *- The demand for small commercial vehicles, viz. trucks, pickups, and cargo vans, is increasing exponentially. Mechanical elements present in these vehicles are chassis, steering, engine parts, propeller shaft, gearbox, clutch wheels and lamps. The reduction in weight of the vehicle enhances the fuel efficiency. 3D CAD layout helps the design engineers to optimize weight by considering various dynamic and static conditions of vehicles. Comprehensive details of aggregate parameters help the designer to finalize and optimize design dimensions. This research work focuses on propeller shaft design used in a commercial vehicle and calculates its detailed dimensions using a computerized digital code. This will help the designers overcome the current specification problem with conventional design methodology. The propeller shaft 3D part model is prepared using PTC Creo-7 parametric software. Maximum Shear and Equivalent (von Mises) stresses were obtained under subjective loading conditions using FEA software Ansys 2022 R2. The theoretical and simulation results were found in agreement with ± 10%.*

Keywords *- SCV, Propeller Shaft, CAD, FEA, PLM, ANSYS.*

1. Introduction

A drive shaft is a rotary member used to connect the gearbox and rear axle. It is used to connect the components with relative motion in between them[1]. A shaft that transmits torque while rotating is popularly known as a propeller shaft in automobiles. It connects the drive for the gearbox to the final drive.

The most preferably used material for a propeller shaft is high-strength SM45 steel [2]. The shaft is also made with composite material[3]. viz. Glass Epoxy/HS Carbon and HM Carbon/Epoxy shafts were utilized for propeller-shaft[4].

In this research paper, medium carbon steel was selected as a material for the propeller shaft because it has higher strength. There are three types of driveshaft which are popularly known as one-piece, two-piece and slip-in tube driveshaft [5]. In the case of two or multi-stage propeller shaft length of the rear propeller shaft is subjected to variation while the remaining propeller shafts are rigid members, i.e. do not change in length[6]

A universal joint is used at both ends of the shaft in order to transmit rotary motion by allowing it to bend in any direction. It helps to achieve desired articulation angle of the propeller shaft[7]. In this research work, one piece driveshaft was selected as the shaft length is less than 2 meter. Figure 1 represents the position of the propeller shaft in the rear-drive vehicle.

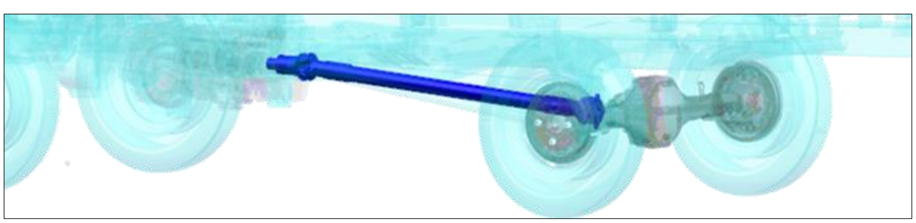
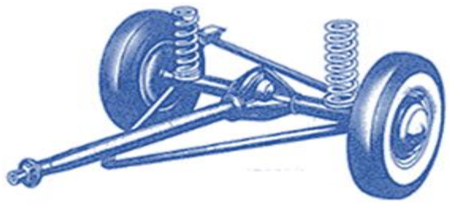


Fig. 1 Schematic layout of the driveline



(a) Torque tube drive

(b) Hotchkiss drive
Fig. 2 Schematic of the driveline

The most preferred drivelines in automotive applications are a) torque tube type and b) Hotchkiss drive (open driveline). The schematic of these drivelines is shown in Figure 2[8]. Hotchkiss drive is mostly preferred in small commercial vehicles.

1.1. Driveline Functions

The driveline or driveshaft's basic functions vary from one application to another. The four basic functions of the driveline are;

Torque: In the vehicle transmission system, the power source and driven member are inclined at an angle. In order to transmit the power drive shaft is used.
Rotation: The output shaft, also called the driven shaft, rotates at various speeds.

Angles: The universal joints used in a driveshaft must be capable of operating at fixed or varying angles of the intersecting shaft rotational axes.

Length changes: Most driveshaft installations require some means of compensating for or effecting shaft length changes. In a typical two-joint driveshaft, these length changes or axial movements may occur as follows
1. Between the universal joint centers
2. At one or both ends of the universal joint centers
3. Within one or both universal joints which have end motion capabilities.

Since the driveline is essentially a rotating power transmission element in a driveshaft system, it depends upon the driving and driven members for support. The dynamic characteristics of these supports can substantially influence the driveline in operating smoothly. These functions determine the dynamic operating characteristics of the driveline and their effects on the application's overall system. Evaluating these functions and considering their effects in selecting a driveline for a given application is important. In summary, the four basic functions that the driveline is expected to satisfy are torque, rotation, angles and length changes.

When the propeller shaft is operating, it is necessary that the torque transmitted by the engine should be low, and also the drive shaft should rotate at high speed. The drive shaft must also operate through constantly changing angles between the transmission, the differential and the axles [9]. When the vehicle is moving on the road having bumps, the wheels move up and down. The rear wheel movement causes the axle and differential to move vertically. This vertical movement affects the angle between the differential and the rotating shaft. The length of the drive shaft must also be capable of changing while transmitting torque. [10].

The propeller shaft design requires input parameter length of the driver shaft and torques transmitted to the engine. The next input parameter is the angle between the differential and the rotating shaft. It is necessary to redesign the propeller in different loading conditions per the customer's specifications. It is time-consuming and requires an entirely new design of the shaft. The novelty of this research is that the attempt is made to automate the process with an Excel spreadsheet.

2. Methodology

Design of propeller shaft for small commercial vehicle, considering the following steps.

- Concept workout
- IPTV (Incident Per Thousand Vehicle) data, i.e. field failure data consideration of similar design.
- Design Failure Mode Earlier Analysis (DFMEA)
- 3D CAD modelling design by using PTC Creo CAD tools.
- Vehicle layout check by using PLM JT by Team Centre visualisation mock-up.
- Design calculations data sheets using Microsoft Office Excel spreadsheet.
- Computer Aided Engineering (CAE) analysis using Ansys.
- Result and Conclusion.

Drive shaft parameters such as weight and design timeline can be optimised using exact methodology [11].

2.1. Design and Analysis

3D CAD modelling was initiated by considering IPTV data and DFMEA. The propeller shaft 3D CAD model was developed by using PTC Creo software. This parametric software feature enables editing parameters whenever required and updates results automatically. A hollow shaft with an outer diameter of 63.5mm and an inner diameter of 59.3mm was assumed. The length of 1460 mm was obtained through a 3D CAD vehicle package layout.

Table 1. Material properties of the propeller shaft

S. No.	Physical and Mechanical properties	Symbol	Units	Values
1	**Density**	ρ	kg/m^3	7850
2	**Modulus of elasticity**	E	Gpa	206
3	**Shear Modulus**	G	Gpa	80
4	**Ultimate strength**	S_{ut}	Mpa	625
5	**Yield strength**	S_{yt}	Mpa	530
6	**Poisson's ratio**	υ		0.3

2.2. Material Properties

The material for the propeller shaft is selected as per AISI 1045 medium carbon steel. AISI 1045 supports applications that require greater strength. Table 1 represents the material properties selected for manufacturing of propeller shaft.

2.3. Shaft Design Calculations

The propeller shaft for the small commercial truck (having a load capacity of less than 1 Ton payload) with engine torque of 120 Nm and max gear ratio of 5.5 is designed.

2.3.1. Design Torque

The propeller shaft torque was calculated based on the engine torque, overall gear ratio and factor of safety. It is assumed that the propeller shaft has 95 % transmission efficiency. The corresponding values of respective parameters are represented in Table 3.

$$T_t = T_e G_r \eta_t \tag{1}$$

$$T_t = 120 \times 5.5 \times 0.95$$

$$=627\ Nm$$

Where,

T_t = Design torque for propeller shaft (Nm)

T_e = Engine torque (Nm)

G_r = Gear ratio

η_t = Transmission efficiency

The following data table prepared in Excel represents the input and output parameters of propeller shaft design [12]. Table 2 represents the data spreadsheet of the propeller shaft design.

2.3.2. Mass of Propeller Shaft

$$m = \rho A L \tag{2}$$

$$= \rho\ x\ \pi 4 x\ (D_0{}^2 - D_i{}^2)$$

$$= 7850\ x\ \pi 4 (0.06352 - 0.05932) x\ 1.460$$

$$= 4.64\ \text{kg}$$

Where,

m = mass of hollow shaft (kg)

A = Area of hollow shaft (m^2)

L = Length of hollow shaft (m)

ρ = Density of medium carbon steel (kg/m^3)

D_o= Outer diameter of hollow shaft (m)

Di= Inner diameter of hollow shaft (m)

2.3.3. Torsional Buckling Capacity

For torsional and buckling capacity calculation, the shaft is classified as short and long shaft. Depending upon the following conditions, the classification is done.

$$\frac{1}{\sqrt{(1-\upsilon^2)}}\ X\ \frac{L^2 t}{(2r)^3} > 5.5\ r = \frac{ri + ro}{2}$$

$$r = \frac{ri + ro}{2}$$

$$\frac{1}{\sqrt{1 - 0.3^2}}\ X\ \frac{1.46^2 * 2.1}{(2 * 0.0614)^3} > 5.5$$

$$18.44 > 5.5$$

As the above condition is satisfied, it is short. The following formula is used for calculation (τ_{cr})

$$\tau_{cr} = \frac{4.39E}{\sqrt{(1-\upsilon^2)}} \text{X} \left(\frac{t}{r}\right)^2 \text{X} \sqrt{1 + 0.0257(1-\upsilon^2)^{\frac{3}{4}}}\ \text{X} \frac{L^3}{(rt)^{1.5}}$$

$$\tau_{cr} = \frac{4.39\ X\ 207\ X\ 10E}{\sqrt{(1-0.3^2)}} \text{X}\left(\frac{0.0021}{0.0614}\right)^2 \text{X} \sqrt{1 + 0.0257(1-0.3^2)^{\frac{3}{4}}}\ \text{X}\ \frac{1.46^3}{(0.0614 * 0.0021)^{1.5}}$$

$$\tau_{cr} = \frac{4.39E}{\sqrt{(1-\upsilon^2)}} \text{X} \left(\frac{t}{r}\right)^2 \text{X} \sqrt{1 + 0.0257(1-\upsilon^2)^{\frac{3}{4}}}\ \text{X} \frac{L^3}{(rt)^{1.5}}$$

T_{cr} =1764 Gpa

T_b=21.92 X 10^6 Nm

as $T_b > T_p$

The design of the propeller shaft is safe.

Table 2. The computerized excel data spreadsheet for theoretical calculations

Single piece Propeller Shaft Design Calculation Sheet					
Engine Speed, rpm	1000	Drive shaft length, mm	1460	Max operating Torque, Nm (eq.1)	627
Engine Max Torque, Nm	120	Drive Shaft Slip, mm	50	Mass ,kg(eq.2)	4.64
Max Gear Ratio	5.5	Drive shaft Outer dia mm	63.5	Maximum Shear stress, MPa (eq.3)	52.1
Min Gear Ratio	1	Drive Shaft thickness, mm	2.1	Max Von-Mises stress, MPa (eq.4)	104.2
Transmission Efficiency	95%	Drive Shaft Standout, mm	45	Total deflection, mm	0.921
RA Inclination,deg	3.6	Fatigue limit of DS	1226		

2.3.4. Maximum Shear Stress

$$T_t J = \tau_{max} r \quad (3)$$

$$J = \pi\,(D_0 4 - D_i 4)/32$$

$$= 3.82\times 10^{-7}\tau_{max}$$

$=52.10\ Mpa$

Where,
J = Polar moment of inertia (m^4)
τ_{max} = Maximum shear stress (MP_a)
r = outer radius of propeller shaft (m)

2.4. Maximum Von -Mises Stress

$Maximum$ von$-mises\ stress$

$=[T_t\ xD_o][2\ x\ I] \quad (4)$

$=[T_t\ x\ D_o][2\ x\ \pi 64(D_0 4 - D_i 4)]$

$=104.21\ MPa$

Where, I = Moment of inertia (m^4)

2.4.1. Critical Speed
Critical speed = N_{Cr} (rpm)
$N_{Cr} = 60$ x F_{nb}

$$N_{Cr} = \frac{60}{2\pi}\ \frac{r^2}{l^2}\ \sqrt{\frac{EI}{\rho A}}$$

F_{nb} = Natural bending frequency
I_x = moment of inertia
$I_x = \pi r^3 t$

Simplification after substitution of these given values gives

$N_{Cr} = 18{,}90{,}000$ x $\frac{\sqrt{{d_o}^2 + {d_i}^2}}{l^2}$
$N_{Cr} = 6693$ rpm

2.5. Modelling and Simulation

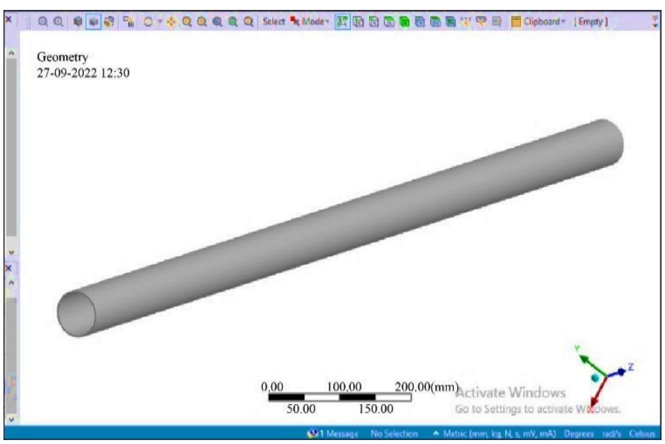


Fig. 3 3D CAD model of propeller shaft before meshing

Table 3. Shear and equivalent stress for different element sizes of meshes

Element Type	Solid 185	Solid 185	Solid 185	Solid 185
Element size in mm	10	8	6	5
No of Nodes	23166	36456	66132	92352
No of Elements	14208	19663	34000	47280
Max (von-Mises) Stress in Mpa	96.349	96.361	96.499	96.598
Max Shear Stress in Mpa	52.547	52.841	52.921	52.975
Total deflection in mm	0.994	0.993	0.990	0.990

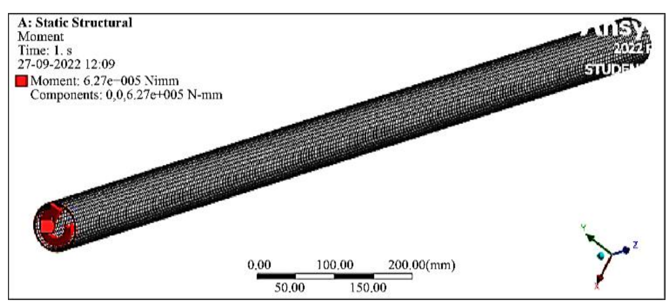
FEM helps to find approximate solutions for partial differential and integer equations [13]. Static structural simulation of propeller shaft was performed using Ansys workbench project. Engineering material AISI 1045 is selected using the inbuilt library. Then geometry is imported into the mechanical modeler. Figure 3 represents the 3D parametric model of the propeller shaft.

2.6. Meshing

The number of simulation iterations depends upon the convergence of load and displacement results with optimum values of nodes and elements [14]. The meshing was performed using Solid 185 element. Solid 185 is defined by eight nodes having three degrees of freedom. It has capabilities such as stress stiffening, plasticity, large deflection and strain. Solid 185 is available in homogeneous and layered structural solid form. [15] An automatic mesh refinement method was adopted for meshing. Linear element order was preferred over quadratic. Element size was varied from 10 mm to 5mm. Mesh refinement was carried out till results were converged. Table 2 represents the number of nodes and elements for converged results.

2.7. Boundary Conditions

The Propeller shaft's right end side, connected to the rear axle, is fixed to the drive end, and the left end, connected to the gearbox, is subjected to a torque load of 627 Nm, which is coming from the transmission as shown in Figure 4



(a)

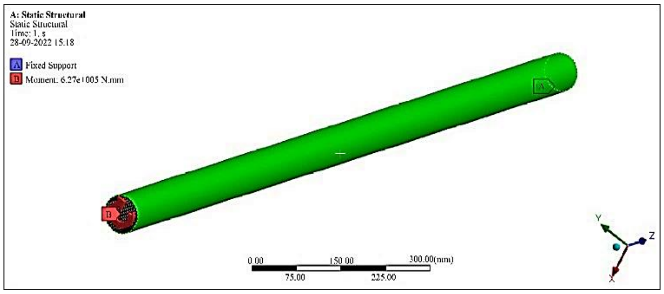


Fig. 4 Boundary conditions of propeller shaft a) fixed support b) Moment

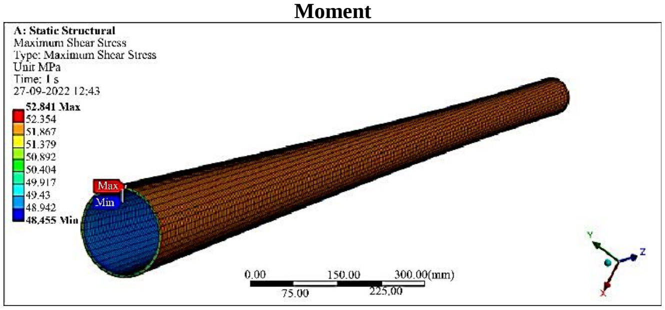


Fig. 5 (a) Maximum shear stress

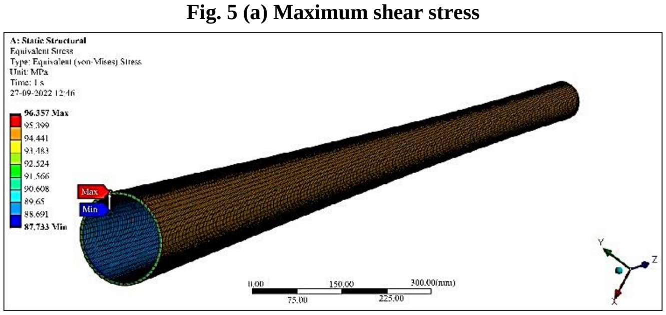


Fig. 5 (b) Equivalent (Von-Mises) stress

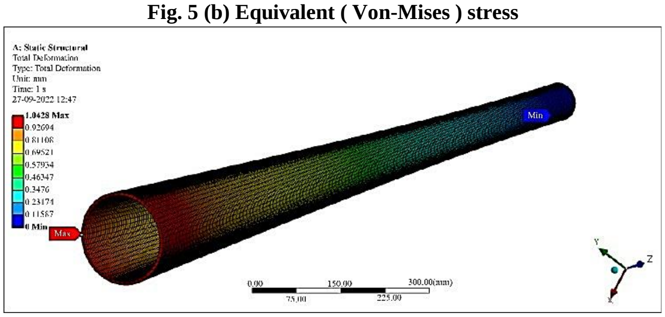


Fig. 6 Total deformations of the propeller shaft

Table 4. Theoretical and simulation results of the propeller shaft

Results	Analytical	Simulation	% Error
Mass ,kg	4.64	4.6357	0.09%
Maximum Shear stress, MPa	52.1	52.841	1.42%
Max Von-Mises stress, MPa	104.21	96.598	7.21%
Total deflection, mm	0.92	0.99	7.49%

Structural Analysis was performed, and values of maximum shear stress 52.841Mpa and equivalent (von Mises) stress 96.357 Mpa were obtained.

Figure 5a and 5b represents the maximum shear stress and von Mises stress, respectively.

Figure 6 represents the total deformation of the propeller shaft under the given loading condition mentioned in Figure 4.

3. Results and Discussion

The analytical and simulation results are tabulated for mass, max shear, von-mises stress and deflection. Table 4 shows the comparative results of analytical and simulations, which were found in agreement within ± 10%.

4. Conclusion

- The developed methodology will drastically reduce the time required for propeller shaft design.
- The database created will eliminate the repetitive calculations for key parameter changes.
- Behavior of the propeller shaft under different loading conditions can be visualized using Ansys simulation.

The analytical and simulations were found in agreement within ± 10.

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