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Design and Analysis of Drive Shaft for Heavy Duty Truck

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***Abstract* - In automobiles the drive shaft is used for the transmission of motion from the engine to the differential. An automotive propeller shaft, or drive shaft, transmits power from the engine to differential gears of rear wheel-driving vehicle. The power from Transmission shaft should be transmitted to the Rear axle of the vehicle. The axis of the Transmission and the connecting member of Rear axle are at an angle, which changes with the variation in load or the road condition. To facilitate the power transmission at a variable angle a Propeller shaft is used. With respect to the geometrical construction the Propeller shafts are categorized into single piece two-piece and three-piece propeller shafts. In 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. The variation in the length of rear propeller shaft is allowed using a splined shaft. Generally length of the propeller shaft is decided after freezing the remaining aggregates.**

In present work an attempt has been made to design a driveshaft for heavy duty truck on the basis of maximum torque transmitting capacity, maximum shear stress produced & critical speed requirement as design criteria followed by virtual simulation which uses Finite Element Analysis Software for evaluating the product performance.

Keywords-Driveshaft, Max.OperatingTorqueTransmission,CriticalSpeed, FEA.

1. INTRODUCTION

Drive shafts as power transmission tubing are used in many applications, including cooling towers, pumping sets, aerospace, trucks and automobiles. In metallic shaft design, knowing the torque and the allowable shear stress for the material, the size of the shaft's cross section can be determined. Metallic drive shaft has the limitations of weight, low critical speed and vibration characteristics.

When the length of steel drive shaft is beyond 2000 mm, it is manufactured in two pieces to increase the fundamental natural frequency, which is inversely proportional to the square length and proportional to the square root of specific modulus. [2]

Major features of the Drive shaft include its high resistance to dynamic load variations, large deflection angles and uniform load distribution throughout the axial displacement range, low rotational diameter, low weight, and versatile flange connections. These features provide an ideal base for standardized drive train design and new power transmission concepts. [2]

Heavy Duty Trucks (HDT) need high load carrying capacity, consequently it is technically specified to suit customer need. HDT uses variety of transmission system as 12-speed,9 speed,6speed etc. depending on application of vehicle where the engine and axles are separated from each other, as on four-wheel-drive and rear wheel-drive vehicles, it is the propeller shaft that serves to transmit the drive force generated by the engine to the axles. For its usage, the optimal shaft is a short, bar-like product. The longer the bar, the more liable it is to sag and sagging is further promoted when rotation is applied. Sagging causes vibration and results in an increase in noise, to such an extent that the shaft is likely to break when the critical speed is exceeded. The propeller shaft is naturally designed not to break when used within the service limits expected of use. Defining the length of the propeller shaft is an important task in the production of any vehicle. The power is transmitted from Gearbox to differential by means of propeller shaft. Depending on the length of the vehicle there is a necessity to make the propeller shaft in stages. The orientation of the propeller shaft is a critical factor defining the length of the propeller shaft. In case of multistage propeller shaft the intermittent pieces are supported by center bearings which are mounted on the bracket of cross member [2]. In case of two or multi stage propeller shaft length of the rear propeller shaft change in length. The variation in the length of rear propeller shaft is allowed using a splined shaft [1].

Where the engine and axles are separated from each other, as on four-wheel-drive and rear wheel drive vehicles, it is the propeller shaft that serves to transmit the drive force generated by the engine to the axles. The basic function of a driveshaft is to transmit power from one point to another in a smooth and continuous action. In automobiles, trucks and construction equipment the drive train is designed to send torque through an angle from the transmission to the

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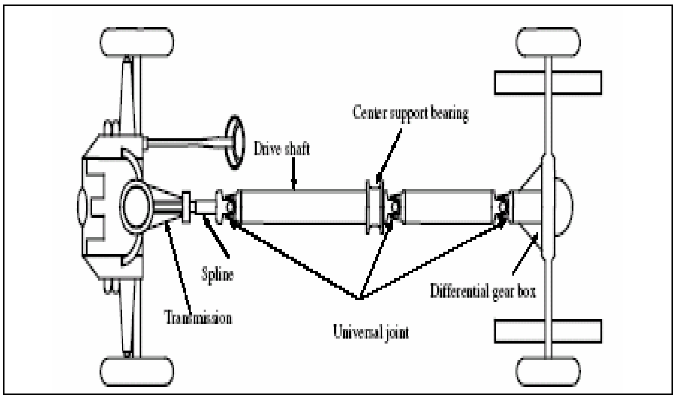
axle (or auxiliary transmission).The driveshaft must operate through constantly changing relative angles between the transmission and axle. It must also be capable of changing length while transmitting torque. The axle of a vehicle is not attached directly to the frame, but rides suspended by springs in an irregular, floating motion. This means the driveshaft must be able to contract, Expand and change operating angles when going over bumps or depressions. This is accomplished through universal joints. Which permit the driveshaft to operate at different angles, and slip joints which permit contraction or expansion to take place [4]

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The torque capability of the drive shaft for HDT should be larger than 8000 Nm and the fundamental bending natural frequency should be higher than 4000 rpm to avoid whirling vibration. Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminum is normally lower than 3800 rpm when the length of the drive shaft is around 2 m, the steel drive shaft is usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. The two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency. [3]
The Diagram below shows general arrangement of power transmission components.[3]
It is the arrangement showing 2 piece Drive shaft with center bearing.When single piece Drive shaft is used all arrangement remains same except that center bearing is eliminated using single driveshaft for power transmission.



2. DESIGN OF A DRIVE SHAFT

2.1 Specification of the Problem

The torque transmission capability of the drive shaft for HDT should be larger than 7000 Nm (Tmax) and fundamental natural bending frequency of the drive shaft should be higher than 4000 rpm (Nmax) to avoid whirling vibration. Here outer diameter of the shaft is taken as 115 mm and length L of the drive shaft considered is 2000 mm. The drive shaft of transmission system was designed optimally to the specified design requirements The specifications of the drive shaft of an automotive transmission are same as that of the steel drive shaft for optimal design. [5]

2.2 Assumptions [2]

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 steel material is linear & elastic; hence, Hooke’s law is applicable for the material.
6. Acoustical fluid interactions are neglected, i.e., the shaft is assumed to be acting in a vacuum.

2.3 Selection of Cross-Section [2]

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.

2.4 Design Requirement & Specifications: [1]

SR. NO.	Name	Notation	Unit	Value
1	Max. Torque	T_{MAX}	Nm	7500
2	Max.Speed Of Shaft	N_{MAX}	RPM	3000
3	Length of Shaft	L	mm	2000

Presently, steel (SM45C) is used for making automotive drive shafts. The material properties of the steel (SM45C) are given in Table below. The steel drive shaft should satisfy three design specifications such as torque transmission capability, buckling torque capability and bending natural frequency.

Mechanical properties	Symbol	Units	Steel
Young's Modulus	E	MPa	210000
Shear Modulus	G	MPa	80000
Poisson's Ratio	υ		0.3
Density	ρ	Kg/m^3	7600
Yield Strength	Sy	N/mm^2	550
Shear Strength	Ss	N/mm^2	710

A. Torque Transmission Capacity

1. Starting Torque, (Nm) =
   Max. Engine Torque x 1^{st} Gear Ratio

Where Starting Torque is the torque required by propeller shaft to transmit the power from transmission to rear axle drive. It is the maximum torque sustained by propeller shaft in 1^{st} Gear Ratio of gear box.
This Max.Torque is taken for calculating max.shear stress which should be less than material shear strength for safety of material.

2. I-M.I., mm^4 = Moment Of Inertia
   = $(\Pi/64)(Do^4 - Di^4)$

3. J-POLAR M.I., mm^4
   $=(\Pi/32) \times (O.D.^4 - I.D.^4)$

4. Z-Section Modulus, mm^3
   = (Π/16) x ((O.D.4-I.D.4) / O.D.)

5. Torsional Shear Stress/mm^2
   = (Starting Torque x D) / (2xJ)

Design Criteria for material selection,

Torsional Shear Stress < Shear Strength of material

If Torsional Shear stress is exceeding Shear strength of material then next Diameter of shaft is chosen.

B.Critical Speed Calculation

Critical Speed, RPM = (30/Π) x SQRT (g / δmax)

Where, δmax is maximum static deflection of drive shaft.

Max.Deflection, δ, mm = $(5 \times M \times g \times \cos\Theta \times L^3) / (384 \times E \times J)$ by Rayleigh Reitz Method
Where M is mass of tube.

Design Criteria-Maximum speed of propeller shaft should not exceed 75% of critical speed of shaft to avoid vibration.[6]
To increase critical speed of shaft to meet design criteria max.static deflection of shaft should be minimized by minimizing weight or reducing length of shaft or using two piece shafts.

3. Design Analysis- FEA of Propeller Shaft Assembly.

- Virtual Product Development (VPD) is an approach that takes a design at the earliest concept stage and fully evaluates design specifications and usage scenarios, and then uses this information to guide the development process. Across industries, VPD enables companies to leverage resources by optimizing product designs leading to improved performance, reduced need for real-world prototypes, verifiable quality improvements, and minimized operational problems and failures. Virtual simulation uses Finite Element Analysis software for evaluating the product performance.
- A solid model of the propeller shaft is created in CATIA. The geometry is imported in Altair HYPEMESH software to carryout meshing. The propeller tube is modeled with 2D shell elements & the solid parts like flange, yoke, spider & slip joint is modeled using second order tetrahedral elements. Maximum design torque is applied at one end of the shaft & other end is held fixed at ALL DOF (Degrees of Freedom). Linear static analysis is carried out using MSC Nastran. Sol101 analysis sequence is used and maximum stresses in various parts are predicted.
- Using the static stresses the fatigue life of propeller assembly is calculated for pulsating loads using FEMFAT/MSC Fatigue software. The parameters like surface finish, survival probability, material stress-life curves are given as input to fatigue code. The predicted fatigue life is compared with target life cycles. The design meeting the strength requirement is taken ahead for building prototype.
- Modal analysis of the assembly is carried out using NASTRAN SOL103 sequence for predicting the natural frequencies of the system. First natural frequency of the propeller assembly should be more than 1.4 times the engines excitation frequency.

Finite element analysis process involves following steps.

1. PRE-PROCESSING

Preprocessing is carried out in Altair Hypermesh Software. Following steps involved in preprocessing.

- Geometry import & cleanup.
- Component collector creation.
- Material & property definition.
- 2D shell meshing of propeller tube & 3D meshing of solid parts.
- Joints creation using 1D rigid RBE2 elements.
- Applying boundary conditions.
- Preparation of analysis Deck for Nastran.

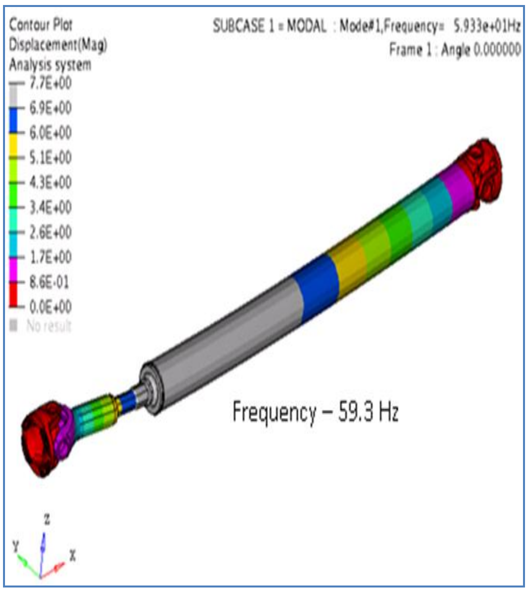
2. SOLUTION

- Applying boundary conditions.
- Running NASTRAN SOL101 solution sequence for static analysis.
- Running NASTRAN SOL103 solution sequence for modal analysis

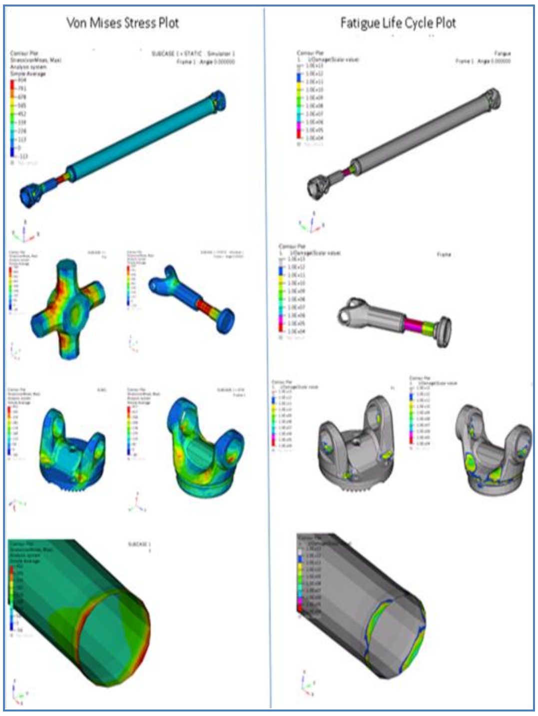
3. POST PROCESSING

In this part results are analyzed and animations are applied for visualization of the behavior of the component in the actual practice in all respects e.g. stresses displacement. Displacements and stress plots using Altair Hyperview.

Mode shape Plots for Propeller Shaft assembly



Stress Plots & Fatigue Life Plots of Propeller Assembly



CONCLUSION

- Proposed single piece propeller assembly meets the frequency target.
- Stresses in single piece assembly are within material acceptable limits.
- Single piece propeller assembly meets the fatigue life cycle target.
- CAE has benefited to reduce the weight of single piece assembly design compared to two piece design which gives cost benefit also.

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