

Interaction of Gear-Shaft Dynamics Considering Gyroscopic Effect of Compliant Driveline System

Yawen Wang and Junyi Yang
University of Cincinnati

Xuan Li
Chongqing University

Guohua Sun and Teik Lim
University of Cincinnati

ABSTRACT

Due to the design of lightweight, high speed driveline system, the coupled bending and torsional vibration and rotordynamics must be considered to predict vibratory responses more realistically. In the current analysis, a lumped parameter model of the propeller shaft is developed with Timoshenko beam elements, which includes the effect of rotary inertia and shear deformation. The propeller shaft model is then coupled with a hypoid gear pair representation using the component mode synthesis approach. In the proposed formulation, the gyroscopic effect of both the gear and propeller shaft is considered. The simulation results show that the interaction between gear gyroscopic effect and propeller shaft bending flexibility has considerable influence on the gear dynamic mesh responses around bending resonances, whereas the torsional modes still dominate in the overall frequency spectrum. The splitting of bending resonance peaks is observed in the dynamic bearing force spectrums, which indicates that the gyroscopic effect of gear and shaft is not negligible if accurate evaluation of the system responses is desired. This study provides an understanding of the interaction between hypoid gear pair and propeller shaft when gyroscopic effect of the compliant driveline structure is included.

CITATION: Wang, Y., Yang, J., Li, X., Sun, G. et al., "Interaction of Gear-Shaft Dynamics Considering Gyroscopic Effect of Compliant Driveline System," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(2):2015, doi:10.4271/2015-01-2182.

INTRODUCTION

Automotive rear axle gear noise problem has received attention in the past few decades. Although many experimental work and numerical simulation have been done in the past to investigate the nature of axle whine noise generation [1, 2, 3, 4], it is still not fully understood how component flexibility and system dynamics could affect radiated noise of the driveline system. In order to predict the noise radiation more precisely and solve axle whine noise problem during the design process, an accurate and realistic driveline system model is the key.

It is well recognized that gear transmission error is the primary source of gear whine noise and the dynamic response of the meshing gear pair due to gear transmission error can be transmitted through shaft-bearing structure to cause the vibration of the whole structure. Considering minimizing the transmission error requires much more efforts and cost, it is more reasonable to tune the system parameters for noise reduction purposes. Many researchers investigated in the effect of system dynamics on gear vibration. For example, Hua, et.al [5] proposed a shaft-bearing model for computing the effective support stiffness of spiral bevel geared rotor system and compared the dynamic responses of different shaft-bearing configuration. Yang, et.al [6, 7] studied the effect of time-varying bearing stiffness and

housing flexibility on the hypoid geared rotor system responses. Wang, et.al [8] studied the effect of torque load on mesh and dynamic characteristics of hypoid geared system.

Most previous studies neglect the gyroscopic moments and shaft dynamics to reduce the model complexity and computational cost. However, it has been shown the importance of gyroscopic effect on parallel axis gear transmission systems in some cases [9, 10]. The gear gyroscopic effect on hypoid geared system is studied by Tao [11], and it is found that the bending and torsional moment of inertia of the gear bodies are important factors to determine the importance of gyroscopic effect. The effect of shaft dynamics on the gear vibration has been studied by Yang [12]. In his study, the propeller shaft is modeled by Euler-Bernoulli beam elements and the gyroscopic moments of the shaft and gear bodies are neglected. Because the shaft dynamics including the rotordynamic effect and the gyroscopic effect of the gear bodies can both affect the lateral motions of the gears, it is necessary to study the coupling effect due to the gyroscopic moments and shaft vibration. No prior study has been done to take both of them into consideration in the driveline system model. Thus, one of the goals of the current work is to address this gap in the literature.

In this paper, a lumped parameter model of the propeller shaft is developed with Timoshenko beam elements, which includes the effect of rotary inertia, shear deformation and gyroscopic moments. The propeller shaft model is then coupled with a nonlinear hypoid gear pair representation using the component mode synthesis approach. The gyroscopic effect of the gear bodies is also considered. Dynamic analysis applying the proposed model with gyroscopic moments of the gear bodies only, propeller shaft coupling effect only and both are performed to determine the severity and impact of the gyroscopic effect and shaft dynamics. Finally, conclusions obtained from this study are presented and suggestions for future experimental and numerical investigations are given.

DYNAMIC FORMULATION

Propeller Shaft Model

The propeller shaft is modeled as two hollow beams with two different cross sections as shown in Fig. 1. Only the bending flexibility of the shaft is considered in the coupling with geared rotor system. The torsional flexibility is considered separately as a spring between engine inertia and pinion inertia of moments. The finite element model of the propeller shaft is built by applying Timoshenko beam finite rotating shaft element, in which the rotary inertia, shear deformation and gyroscopic moment of the beam are considered. The element matrices can be found in Ref [13].

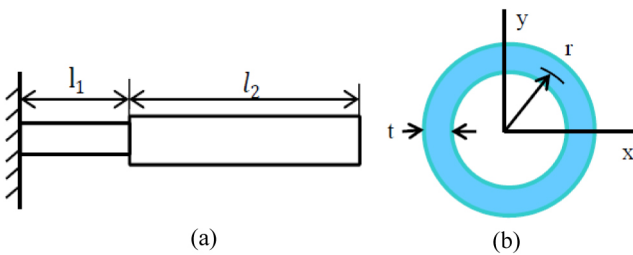


Figure 1. Propeller shaft model a) beam with two different cross sections; b) cross section dimensions.

Because the full shaft FE model contains thousands of nodes, it is difficult to directly apply it to geared rotor system model. Thus, a fixed-interface CMS method, which is known as Craig-Bampton method is adopted here to condense the shaft model. The size of the mass and stiffness matrices of reduced shaft model is determined by the degrees of freedom of retained nodes and truncated set of normalized modes, which is usually much smaller than the size of original matrices. In this case, the retained node is obviously at the end of the propeller shaft, which is going to interface with the geared rotor system model. The equations of motion of the shaft can be written as

$$\begin{bmatrix} [M^{CC}] & [0] \\ [0] & [M^{II}] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}^C\} \\ \{\ddot{u}^I\} \end{Bmatrix} + \begin{bmatrix} [K^{CC}] & [0] \\ [0] & [K^{II}] \end{bmatrix} \begin{Bmatrix} \{u^C\} \\ \{u^I\} \end{Bmatrix} = \begin{Bmatrix} \{F^C\} \\ \{F^I\} \end{Bmatrix} \quad (1)$$

where the coupling coordinates and interior coordinates are noted by superscript C and I, respectively. The physical coordinates $\{u\}$ can be represented by transformation matrix and modal coordinate $\{x\}$

$$\begin{Bmatrix} \{u^C\} \\ \{u^I\} \end{Bmatrix} = [\Phi] \begin{Bmatrix} \{x^C\} \\ \{x^I\} \end{Bmatrix} \quad (2)$$

The transformation matrix which map the physical coordinates of the housing into the modal coordinates can be obtained by

$$[\Phi] = \begin{bmatrix} [I] & [0] \\ [\Phi^C] & [\Phi^N] \end{bmatrix} \quad (3)$$

where $[\Phi^C]$ is matrix of constraint modes and $[\Phi^N]$ is matrix of normal modes. The constraint modes $[\Phi^C]$ can be computed by

$$[\Phi^C] = -[K^{II}]^{-1}[K^{IC}] \quad (4)$$

Finally, the condensed mass and stiffness matrices of the housing can be obtained by

$$M_s = \Phi^T M \Phi \quad (5a)$$

$$K_s = \Phi^T K \Phi \quad (5b)$$

$$G_s = \Phi^T G \Phi \quad (5c)$$

Similarly, the load vector can be obtained using

$$F_s = \Phi^T f \quad (5d)$$

Modal damping model is applied to the shaft and the truncated modes are selected to cover the frequency up to 2k Hz.

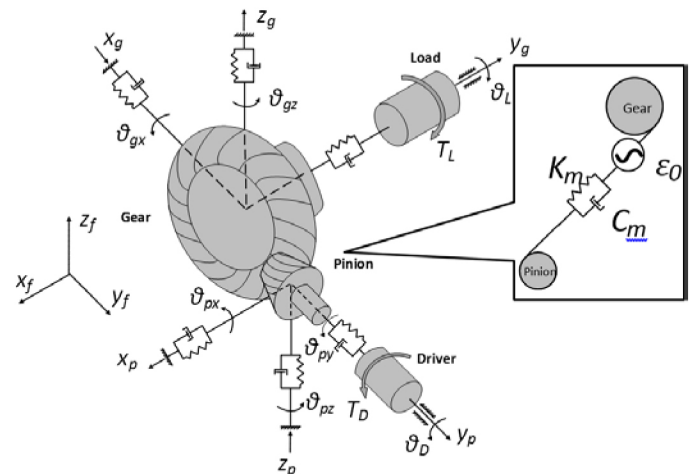


Figure 2. Lumped parameter model of hypoid geared rotor system

Gear Dynamic Model

The 14-DOF lumped parameter model of the hypoid geared rotor system is similar to the model used in Luo's study [11]. The equations of motion of the geared rotor system in matrix form can be written as