DEVELOPMENT OF A SEMI-EMPIRICAL FRICTION MODEL IN AUTOMOTIVE DRIVESHAFT JOINTS

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ABSTRACT—High speed and sport utility vehicles with large joint articulation angle demand lower friction in automotive driveshaft joints to meet noise and vibration comfort levels. Thus a more thorough understanding of internal friction characteristics and mechanisms is required. In this paper, a friction model in automotive driveshaft joints was developed through the use of test data from an instrumented Constant Velocity (CV) joint friction apparatus with actual driveshaft assemblies. Experiments were conducted under different realistic operating conditions of oscillatory speeds, CV joint articulation angles, lubrication, and torque. The experimental data was used to develop a physics-based semi-empirical CV joint internal friction model as a function of different CV joint operating parameters. It was found that the proposed friction model captures the experimental results well. Also the friction model estimates the generated axial force (GAF) in tripod CV joints well, which is the main source of force that causes vehicle vibration problems.

KEY WORDS : Constant velocity joints, Automotive driveshaft, Friction model, Friction coefficient

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1. INTRODUCTION

Constant Velocity (CV) joints are a standard design for driveshaft in front-wheel-drive passenger cars. It is well known that CV joints exhibit superior vibration performance compared to the universal joints as they eliminate uneven rotating torque via their ability to self-center. Each driveshaft is composed of two types of CV joints, namely fixed (outboard) and plunging (inboard) types connected via a shaft. Their primary function is to transmit the engine torque to the wheels with a constant velocity form. In this research, the emphasis is on a class of plunging CV joints called tripod CV joints, which have been favored due to their noise and vibration advantages as they offer lower plunging resistance, compared to ball-type joints (Schmelz et al., 1992).

Current research in modeling CV joint effects on vehicle performance assumes constant empirical friction coefficient values (Hayama, 2001). Such models, however, are long known to be inaccurate, especially under dynamic conditions, which is the case for CV tripod joints. High speed and sport utility vehicles with large joint articulation angles, demand lower plunging friction inside their driveshaft joints to meet noise and vibration requirements. Thus more in depth understanding of their internal friction characteristics is required.

The main goal of this paper is to develop a physics-based internal friction model of tripod CV joints that can be readily applied during new vehicle development. This model will replace current practices of using empirical fixed friction coefficient values. In order to build the joint friction model, a prototype well-instrumented CV joint friction apparatus was used to measure the internal friction behavior of actual CV joints (Lee, 2007). The apparatus is capable of measuring key performance parameters, such as friction and wear under different realistic vehicle operating conditions of oscillatory speeds, CV joint articulation angles and torque variations. Also, Hertzian contact analysis in a CV joint was used to get contact parameters, and the contact
results were subsequently incorporated in the friction model. Next, the friction behavior in CV joints in terms of sliding and rolling friction was investigated by measuring the slip to roll ratio, and subsequently incorporated in the proposed CV joint friction model. In addition, the proposed friction coefficient model was used to develop a model for the Generated-Axial-Force (GAF), which is a practical design variable as is the undesirable force that is seen at a vehicle wheel shaft. Based on both the friction coefficient model and GAF model, one can readily establish a better understanding of CV joint friction and use these models for designing automotive driveshafts with improved performance.

2. APPARATUS AND MEASUREMENT

The friction test apparatus and instrumentation was designed and developed to directly measure the internal friction inside CV joints. Basically, the apparatus uses actual automotive driveshaft assemblies with tripod CV joints, and consists of a dynamic sliding/height adjustment mechanisms and a static torque generator. This apparatus is capable of conducting controlled experiments to measure the key performance parameters, such as internal friction forces inside of a CV joint, under different realistic operating conditions using the actual CV joints. A unique feature of the apparatus is that an actual CV joint is retrofitted with a three-axis piezoelectric force transducer for in-situ measurement of the internal CV joint friction and normal forces. The overall experimental setup, including triggering, motion control of the linear actuator, recording of the experimental data and oscilloscope displays were carried out by a master program of Labview program (Lee, 2007).

In order to calculate the internal friction coefficient under any CV joint conditions, one needs to find a universal equation to cover all articulation angles and rotational phase angles. This is accomplished by introducing a coordinate transformation matrix based on Euler angles representing articulation angle $\beta$, and rotational phase angle $\varphi$. The components and directions of the three force components measured with the tri-axial force sensor installed inside the CV joint are depicted in Figure 1. Force component $F_x$ represents the normal force $P$ and is directly related to the applied torque. Force components $F_y$ and $F_z$ represent the axial and vertical friction forces respectively, which are the source of the total combined friction force $Q$. Using the defined coordinates of the tri-axial forces, one can obtain the individual Euler transformation matrix as illustrated in Figure 1. By multiplying each individual transformation matrix in sequence, a global transformation matrix that relates the measured internal forces to the global forces in accordance with the housing coordinate can be obtained. Thus, one can readily get the following equation which calculates the net friction coefficient along the housing groove at any rotational and articulation position in the CV joints.

$$\mu = \left[ \sin(\varphi - 90^\circ) \sin \beta \right] F_x + \left[ \cos(\varphi - 90^\circ) \sin \beta \right] F_y + \left[ \cos(\varphi - 90^\circ) \sin(\varphi - 90^\circ) \right] F_z$$

$$\mu = \left\{ \begin{array}{l}
\left[ \cos(\varphi - 90^\circ) \sin(\varphi - 90^\circ) \right] F_x + \left[ - \sin(\varphi - 90^\circ) \sin \beta \right] F_y + \left[ \cos(\varphi - 90^\circ) \sin(\varphi - 90^\circ) \right] F_z \\
\left[ \cos(\varphi - 90^\circ) \sin(\varphi - 90^\circ) \right] [-1 + \cos \beta] F_z
\end{array} \right\}$$

3. CHARACTERIZATION OF FRICTION

3.1. Slip to Roll Ratio

Characterization efforts to investigate the friction mechanisms in a CV joint were endeavored. In idealistic cases, a CV joint should only experience rolling motion without any sliding or slipping. However, sliding friction occurs due to kinematic effects at various articulation angles as well as micro-slips in the contact zone. The slip to roll ratio between the roller and housing is a very important issue since: (a) at $\beta=0^\circ$, the generated axial force (GAF) is zero, presumably because the slip to roll ratio is zero, which means that all friction is due to rolling friction, (b) as the CV joint angle increases, the GAF and the possibility of “shudder” increases. Based on the above argument, the slip to roll ratio must increase with increasing articulation angle, and this is experimentally investigated. In order to measure the slip to roll ratio, video recording was performed by using the CV joint apparatus where part of the housing was cut open to expose the internal rolling motion of the roller. After a typical test, the video was played back, and the slip to roll ratio was calculated by counting the grids during the rolling motion and comparing it to the linear distance traveled. Thus, the relationship between the slip ratio (%) and articulation angle $\beta$ is approximately linear, described by the following simple relationship:

$$\text{Slip Ratio} (\%) = 0.585 \beta$$

This relationship was subsequently incorporated in the friction model to represent the portion of pure sliding and rolling friction.

3.2. Sliding Friction Coefficient

The measurement of pure sliding friction coefficient was conducted in the presence of two different types of CV joint greases, called grease A and grease B (see properties in Table 1), using a versatile pin-on-disk tribometer. Specifically, 412-H modified steel disks were procured under the