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Energy dissipation mechanism and experiment of particle dampers for gear transmission under centrifugal loads

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ABSTRACT

As a passive means of vibration reduction, particle damping is mainly applied to the horizontal or vertical steady field. However, it is seldom applied to centrifugal fields. Under high speed and heavy loading, the vibration of tooth surfaces of gear transmissions becomes more severe shortening gear service life and augmenting noise. Under centrifugal loading, the particle system exhibits different characteristics, for example, particles are extruded at the end farthest from the center. We investigated gears with drilled via holes filled with damping particles. Using the discrete-element method, we developed an energy dissipation model for the particle system accounting for friction and inelastic collisions. Energy dissipation and damping characteristics of this system were analyzed. Experiments were also conducted with the gear system having different particle filling rates. The results show that this filling rate is an important parameter associated with particle damping in a centrifugal field. An unsuitable filling rate would significantly reduce damping effectiveness. With changes in rotation speed and load, the gear transmission system has different optimal filling rates. The results provide guidelines for the application of particle damping in centrifugal fields of gear transmissions.

Introduction

With the development of gear transmission towards use at high speeds and under heavy-duty loads, the vibration of tooth surfaces becomes ever more severe. It not only shortens the service life of the gear, but also causes heavy noise. In gear transmissions, the behavior resulting from the time-varying mesh stiffness (Wan et al., 2013; Yu et al., 2015) is the crucial factor that leads to vibration of the tooth surfaces and gear-system noise.

The main measures to reduce vibration and noise of the gear system can be divided into active and passive vibration controls. Active vibration control optimizes the parameter settings of the gear such as modification of the gear teeth. For gear transmission, the drawback is that determining the parameters is complex, and meeting strict requirements of high precision, high efficiency, and heavy loading is difficult. For these reasons, active vibration control is expensive.

Particle damping (Friend and Kinra, 2000; Papalou and Masri, 1998; Saluena et al., 1999; Shah et al., 2011) is a passive technique through which a high level of mechanical damping can be achieved. Indeed, vibration reduction can be done more effectively and simply. The particles in the enclosure space dissipate the energy of the mechanical system through friction and inelastic collisions (Dragomir et al., 2012; Lu et al., 2011a; Nayeri et al., 2007; Bai et al., 2009). Aside from vibration reduction, particle damping possesses several advantages including a wide frequency domain of application (Lu et al., 2013; Panossian, 1992) and good adaptability to temperature variation (Guyomar and Badel, 2006; Li and Darby, 2006).

In designing the gear, several holes are often drilled through the web to reduce weight. In the process of gear meshing, single-teeth meshing and double-teeth meshing alternate. The sequence of vibrational transfer is teeth surface→lightening hole→axle→bearing→bearing pedestal→gearbox. Filling particles into the lightening hole can effectively reduce the vibration, because the lightening hole is closest to the vibration source and is situated at a vital link in the transfer sequence.

Particle damping is mainly applied to the horizontal or vertical steady field. However, under centrifugal loading, the particle system shows different characteristics. For example, particles are extruded at the end farthest from the gear center and the change in load causes different motions. In brief, the energy dissipation

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mechanism of particles and the characteristics of particle motion under centrifugal loading provide important guidance in the application of particle damping.

In this paper, a theoretical analysis of the gear and particle system was performed. The numerical simulation is combined with actual gear vibration experiments. Using discrete element method (Friend and Kinra, 2000; Saeki, 2005; Lu et al., 2011b; Zhang et al., 2014), we studied the damping mechanism induced through inelastic collisions and friction between particles under centrifugal loading. A procedure is presented to calculate the energy dissipation of particle damping in a centrifugal field. The role of centrifugal loading on the natural frequency and other modal parameters of the gear system is analyzed. The influence of particle filling rate on gear vibration is detailed.

Model description

Discrete element model of particles under centrifugal loads

At present, simulation methods used to model particle damping mainly include the regression analysis method (Hu et al., 2008a), restoring force surface method (Jiang and Chen, 2007), power input method (Zhou et al., 2007), and neural networks (Tanrikulu, 2009). Although these general models or empirical-based studies have yielded many new insights, they are essentially phenomenological, and results are difficult to extrapolate beyond their respective experimental constraints. Recently, the discrete element method (DEM) (Cundall and Strack, 1979; Malone and Xu, 2008), which take into account the interaction between particles, has been used to perform studies of particle dampers (Hu et al., 2008b; Lu et al., 2010, 2013; Saeki, 2005).

The basic principle of DEM can be divided into three steps. First, dividing the object of focus into small independent units; second, based on the interaction between particles units and Newton's second law, the stress and displacement of all particle units at each time can be calculated using dynamic or static relaxation iteration method; and third, updating the position of all particle units (Xu et al., 2013). By tracking and calculating the micro-motion of each particle unit, the macroscopic motion of the whole particle system can be obtained. The basic assumption of DEM is that the velocity and acceleration are constant during any time step.

Control model of gear in centrifugal field

The simplified model (Fig. 1) comprises a gear equipped with particle damper in the lightening hole, in which a certain number of particles are placed. The equation of motion for the primary system is written as

$$M_e\ddot{X} + C_e\dot{X} + K_eX = \sum F + M_e g_x, \qquad (1)$$

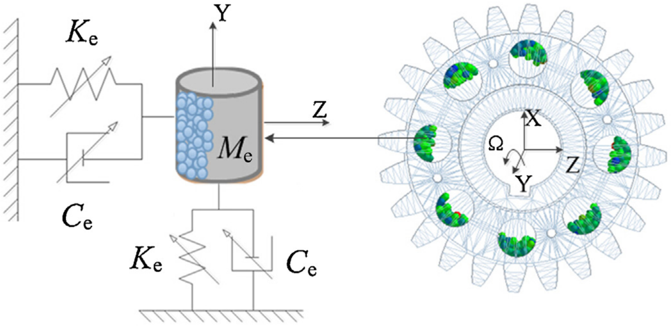

Fig. 1. Equivalent model (left) and diagram (right) of gear with particle damping. The gear with particle system can be regarded as a damper (equivalent model (left)).

Table 1
Values for the main parameters of the gear and particle damping system.

Gear	Material	Modulus, *m* (mm)	Number of teeth, *z*	Pressure angle, *α* (°)	Tooth width, *b* (mm)
Driving gear	^{45}Cr	4.5	24	20	20
Driven gear	^{45}Cr	4.5	24	20	20

where X, $\dot{X}$, and $\ddot{X}$ are the displacement, velocity, and acceleration, respectively; M_e, C_e, and K_e are the equivalent mass, the coefficient of damping, and the coefficient of stiffness, respectively, for the gear transmission system; g_x refers to the acceleration of gravity; and $\sum F$ is the contact forces acting on the gear by the particle units and provides the link between the particles and primary system. The main parameters of the gear transmission system are listed in Table 1.

Three types of gear model were considered having a range of rotary velocities up to 1000 rpm. Three particle damper models with different equivalent masses are shown in Fig. 2. The mass of the dampers are

$$\begin{aligned} M_1 &= 0\,\text{kg}, \\ M_2 &= 0.031365\ \text{kg}, \qquad (2) \\ M_3 &= 0.06273\ \text{kg}. \end{aligned}$$

For each model, an analysis of the modes ANSYS (ANSYSY Co., USA) was performed using the software. The fundamental frequency under different rotational speeds was obtained. The fundamental mode of gear model (a) in Fig. 2 under different rotation speeds is given in Fig. 3.

Based on the data obtained by finite-element analysis for each model, the curves of the fundamental frequency *f* under

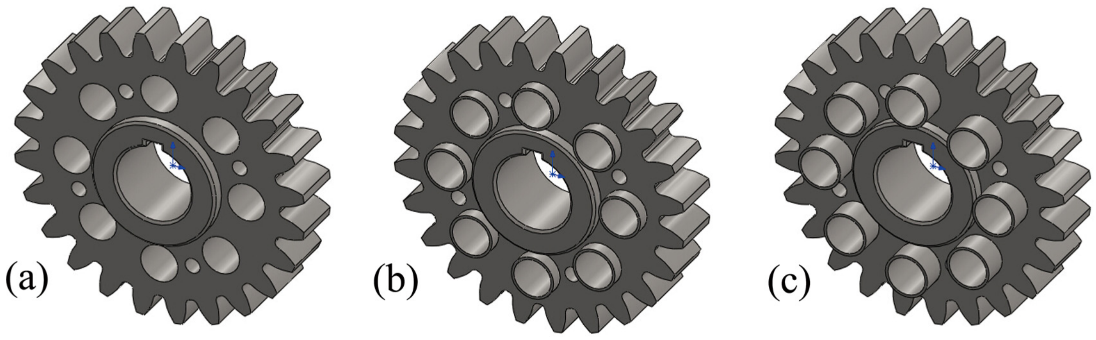

Fig. 2. Three different damper models.