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Modeling of automotive driveline system for reducing gear rattles

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ABSTRACT

A nonlinear torsional model for a driveline system with 4 degrees of freedom is proposed for studying gear rattle if a car is at idle. The time-varying meshing stiffness of geared teeth, gear backlash, and the damping from oil film are included in the model. The dynamic responses of the driveline system, such as clutch angular displacement, meshing force and relative displacement between geared teeth, are calculated using the presented model. The influences of stiffness and damping of a clutch on gear rattle of geared teeth in a generic transmission are investigated. Based on the calculation and analysis results, a design guideline to select clutch's stiffness and damping is developed to reduce gear rattle for a car at idle. Taking a generic driveline system of a passenger car as an example, the developed method is experimentally validated by comparing the baseline clutch and revised clutch, in terms of the measured noise inside engine compartment and cab and vibrations at transmission housing.

1. Introduction

Vibro-impacts in manual transmission (MT) are critical concern to automotive manufacturers in view of the noise, vibration and reliability [1–3]. Gear rattle is one of the major sources of noise and vibration in automotive MT, which is characterized by backlash induced by vibro-impacts between meshing gears [4–7]. The fluctuations of engine rotational speed and torque cause the torsional vibration of a transmission and then generate separations of geared teeth. The teeth separation may cause gear rattle noise and discomfort of the passengers [8]. The way to reduce gear rattles in automotive driveline systems has received much attention in recent years [9].

Nonlinear models used for analyzing vibration and noise generated from geared pairs are proposed in Refs. [10–15]. A nonlinear model considering the gap of the geared pairs is proposed and the influence of some critical parameters, such as excitation frequency, load ratio and damping ratio, on the stability of the geared pairs is carried out in Ref. [10]. It is concluded that the noise from geared pairs can be reduced by increasing load ratio or increasing friction forces and resistance torque, while this will increase the power consummation.

The optimization methods for reducing gear rattle noise are presented at Refs. [11–13]. Dynamic responses of geared pairs under different loads are estimated [11], and the calculated results in time domain is compared with the generic gear rattle [12]. A nonlinear model for analyzing dynamic response of geared pairs considering time-varying meshing stiffness,

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transverse contact ratio and total contact ratio of gears is proposed in Ref. [14]. A generic torsional powertrain model with 6 degrees of freedom (DOF) for loaded gear rattle analysis is developed to examine nonlinear responses of the rattling gears. The rattling of the geared pairs at 1st, 2nd and 5th gears are analyzed [15]. It is shown that analyses of both the linear and nonlinear characteristics of the system are required to gain a full understanding of the driveline system.

Experimental studies on the gear rattle noise of automotive transmissions are carried out in Refs. [16–20]. A single-stage gear transmission is designed and applied on a gear rattle noise test bench. The measured relative angular displacement is used to evaluate the sequence of meshing gear teeth along the path of contact under rattling conditions. The variation effect of tooth backlash on rattle noise is measured using the test bench [16]. An active internal gearbox structure is developed and is experimentally evaluated for suppressing vibrations at the geared pair caused by error excitation of the transmission [17]. A method for active vibration control of a shaft at transverse direction is proposed [17]. It is concluded that both noise levels and the vibration at gearbox housing at the first and second meshing frequencies are substantially reduced using the active control method. An analytical model including the hysteretic friction in the clutch springs and the oil squeeze effect between the impacting teeth of the meshing gears is proposed in Refs. [18–20]. The influence of damping effects caused by the oil in the gap between two geared teeth on gear rattle is investigated. A qualitative comparison between the effects of the oil and those of the hysteretic friction in the clutch on the rattle level is given in Ref. [20]. The influence of oil damping on reducing impact amplitudes of geared pairs is experimentally studied.

An effective way to reduce gear rattle of a transmission in a driveline is to optimize parameters of a clutch [19–30]. The parameters of a clutch include its torsional stiffness, end-stops at different stages and friction damping. Since the relation between the torque and the angular displacement for a clutch is nonlinear, a piecewise linear model with two or three stages is used to represent the nonlinear relation. A graph of torque versus angle with piecewise multi-stage is characterized by stiffness and end-stops at different stages. The works in Refs. [1,21–30] studied the relations of design parameters for a clutch and gear rattle of a transmission. Wu et al. [1] proposed a dynamic model of a driveline including nonlinear characteristics of clutch stiffness and damper, time-varying gear meshing stiffness, gear backlash at gear box and at differential, and drag torques. The simulation results show that under the creeping condition, clutch stiffness changes greatly between the first- and the second-stage, and this sudden change leads to serve gear rattle. A clutch with three-staged stiffness is thus proposed to reduce the gear rattle. The relations between the clutch parameters and the rattle noise of a transmission on a commercial vehicle are studied [21,22] and it is found that optimization of a pre-damper for a clutch is an effective way to reduce rattle noise. A method for elimination of gear rattle is proposed in Ref. [23]. It is found that maximizing the hysteresis of clutch is an effective method to absorb the torsional vibration transferred to transmission from engine and reduce gear rattle.

A nonlinear mathematical model of a driveline including multi-stage clutch dampers, such as asymmetric end-stops and pre-loads, is proposed and the transient and start-up transient dynamic responses of a driveline at time domain are studied in Refs. [24–27]. A measure index of gear rattle is defined, the methods for reducing gear rattle are suggested, and influences of three generic clutch dampers on gear rattles are given. The influence of a designed clutch with multi-staged stiffness on gear rattles under several engine operations are investigated [27]. A linear time-invariant model with six DOF for a driveline is presented and then a numerical analysis is used to study the gear rattle [28]. The dynamic characteristics of vibro-impacts of a geared pair are studied by examining gear meshing forces in a high frequency range. The influences of various system parameters on the vibro-impacts are examined using a nonlinear system model.

The dynamic performance of a clutch is investigated in [29]. A lumped parameter model with 5 DOF is proposed for a clutch, and the stiffness and damping of a clutch are modeled using visco-elastics and dry friction elements, respectively. The hysteresis behavior is validated using experiment data in Ref. [30].

Based on the above reviewing of existing references, it is clear that although some modeling and experiment methods are available for optimizing clutch parameters to reduce gear rattle at idle, most of the researches use simple model. Very few researchers investigate relations between gear rattle of a generic transmission and the clutch parameters if the vehicle is at idle, during which no load is applied to the geared pairs but the gear rattle is easy to occur. Therefore, the chief objectives of this article are: i) to develop experimental and calculation methods to reduce gear rattle of a generic transmission at idle, ii) to disclose relations between clutch's nonlinear stiffness and end-stops at the first stage and gear rattle of a generic transmission, and iii) to measure gear rattle by installing redesigned clutch and comparing the gear rattle with that of using baseline clutch.

Taking a generic driveline of a passenger as a studying example, an analytical method for determining clutch parameters to reduce gear rattle of a transmission at idle is presented in this paper. Firstly, a nonlinear torsional model with 4 DOF of the driveline is proposed and is used for analyzing gear rattle if the car is at idle. The nonlinear characteristic of clutch stiffness and damping, time-varying gear meshing stiffness and oil squeeze effect of a geared pair are included in the model. A performance measure is defined to evaluate gear rattle. The influences of the clutch parameters on gear rattle are investigated. The angular displacement of clutch's driving and driven plate and the meshing forces of the geared teeth at transmission are calculated, in order to investigate the influence of range of end-stops of clutch at first stage on meshing forces if the transmission is unloaded. The meshing forces are measures of gear rattle severity. Based on calculations, the design method for determining nonlinear characteristics of clutch torque versus angular displacement is proposed. Secondly, based on the trouble shooting of gear rattle for a generic transmission when the car at idle, the gear rattles are estimated using the proposed model and the favorable clutch parameters are proposed. A new prototype of the clutch is fabricated based on the proposed clutch parameters, and its effectiveness for reducing gear rattle is validated by comparing the measured vibrations and noises with those of baseline clutch. The measured vibrations and noises include the second torsional vibration angle between flywheel and primary shaft of a transmission, the vibrations at transmission housing and the noise inside the cabin.