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Analysis of start-up transient for a powertrain system with a nonlinear clutch damper

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ABSTRACT

The transient vibration phenomenon in a vehicle powertrain system during the start-up (or shut-down) process is studied with a focus on the nonlinear characteristics of a multi-staged clutch damper. First, a four-degree-of-freedom torsional model with multiple discontinuous nonlinearities under flywheel motion input is developed, and the powertrain transient event is validated with a vehicle start-up experiment. Second, the role of the nonlinear torsional path on the transient event is investigated in the time and time – frequency domains; interactions between the clutch damper and the transmission transients are estimated by using two metrics. Third, the harmonic balance method is applied to examine the nonlinear characteristics of clutch damper during a slowly varying non-stationary process in a simplified and validated single-degree-of-freedom powertrain system model. Finally, analytical formulas are successfully developed and verified to approximate the nonlinear amplification level for a rapidly varying process.

1. Introduction

The engine start-up (or shut-down) process is receiving attention recently for both conventional internal combustion (IC) engines [1–4] and hybrid electric vehicles [5–9]. Transient torsional vibration phenomena are more noticeable for reasons related to the enhancement of fuel consumption efficiency. First, downsizing of the IC engine, including fewer cylinders and light-weighting, has led to higher torque fluctuations. Second, the IC engine in some modern vehicles frequently starts up and shuts down [5–9]. The engine instantaneous firing frequency passes through the natural frequencies of the powertrain torsional modes, creating a vibration amplification and thus human discomfort. Such instantaneous frequency driven problems have been studied primarily for a linear single-degree-of-freedom (SDOF) mechanical system [10–14]. However, the transient vibration in a multi-degree-of-freedom powertrain system is yet be analyzed because of multiple discontinuous nonlinearities in the clutch damper and the transmission [15,16]. Therefore, this article intends to develop powertrain system models and examine the non-stationary process using numerical, experimental, and semi-analytical methods.

The effect of a multi-staged clutch damper on the stationary periodic vibro-impacts processes (such as gear rattle) has been studied [16–20]. In addition, the discontinuous nonlinearities, such as piecewise linear stiffness, hysteresis, and preload, have been studied in the frequency and time domains under harmonic excitation with a time-invariant excitation frequency [21–27]. For the non-stationary process with an instantaneous excitation frequency, the transient envelope of the

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vibratory response is normally used to evaluate the severity of the transient amplification. For instance, Sen et al. [13,14] utilized the Hilbert transform [28] to find the transient envelope of a nonlinear SDOF system with a clearance; Markert and Seidler [29] and Hok [30] analytically found the transient envelope in the closed form of a linear SDOF system. However, the effects of the discontinuous nonlinearities on the transient envelope have not been adequately studied in depth.

2. Problem formulation

Based on the void seen in previous studies, a simplified powertrain system of a conventional vehicle with a clutch damper and manual transmission is considered as shown in Fig. 1(a). A four-degree-of-freedom (4DOF) nonlinear torsional model with instantaneous motion input $\bar{\theta}_0(\bar{t})$, $\dot{\bar{\theta}}_0(\bar{t})$ will be developed where a bar over a symbol indicates a dimensional parameter. Specific objectives are as follows: 1. Develop a new nonlinear 4DOF powertrain model excited by the flywheel motion and validate it by using a vehicle start-up experiment; 2. Estimate the role of the multi-staged clutch damper on $\bar{\theta}_{01}(\bar{t})$ (where $\bar{\theta}_{01}(\bar{t}) = \bar{\theta}_0(\bar{t}) - \bar{\theta}_1(\bar{t})$ is the relative torsional displacement between the flywheel and the clutch hub) and study its interaction with transient gear rattles in the

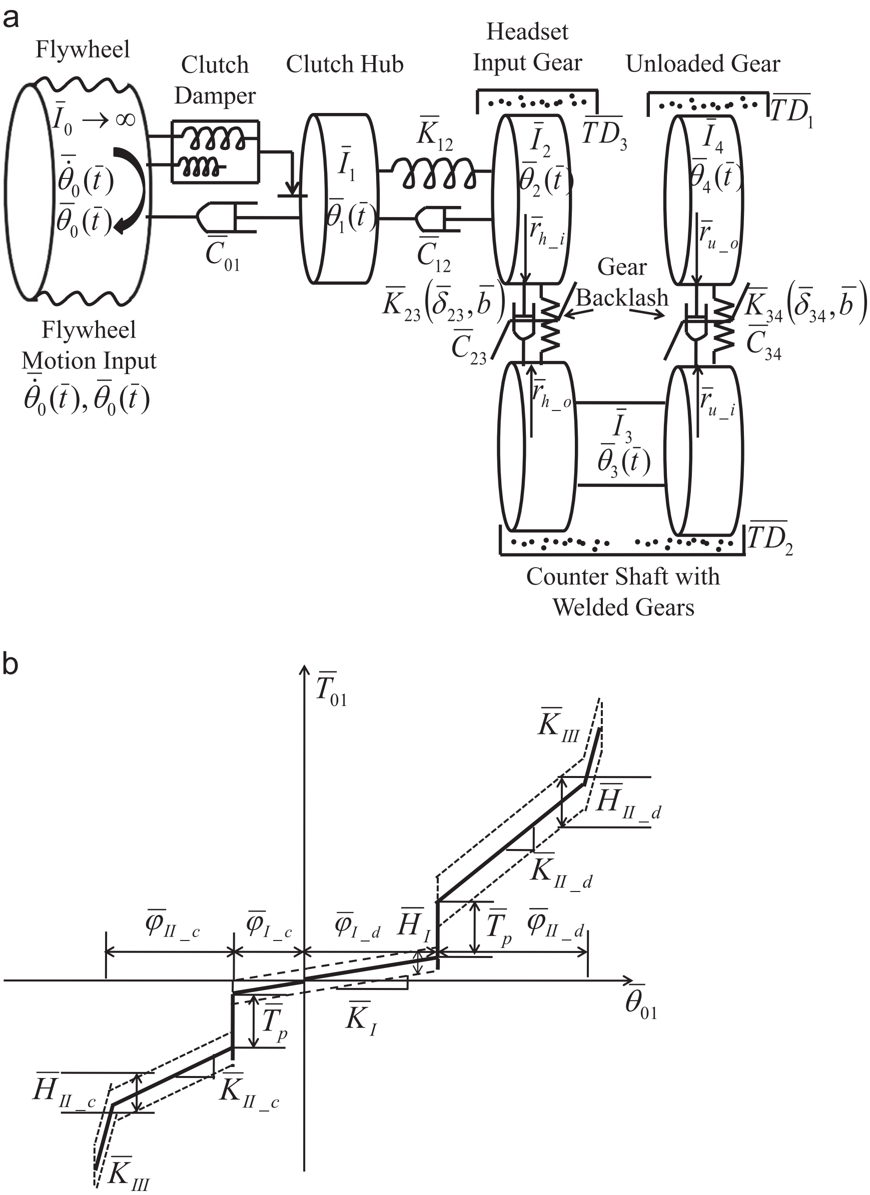

Fig. 1. Example case. (a) 4DOF nonlinear powertrain model given motion input from the flywheel; (b) Asymmetric nonlinear characteristics of a multi-staged clutch damper.