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On the effect of multiple parallel nonlinear absorbers in palliation of torsional response of automotive drivetrain

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ABSTRACT

Torsional vibrations transmitted from the engine to the drivetrain system induce a plethora of noise, vibration and harshness (NVH) concerns, such a transmission gear rattle and clutch in-cycle vibration, to name but a few. The main elements of these oscillations are variations in the inertial imbalance and the constituents of combustion power torque, collectively referred to as engine order vibration. To attenuate the effect of these transmitted vibrations and their oscillatory effects in the drive train system, a host of palliative measures are employed in practice, such as clutch pre-dampers, slipping discs, dual mass flywheel and others, all of which operate effectively over a narrow band of frequencies and have various unintended repercussions. These include increased powertrain inertia, installation package space and cost. This paper presents a numerical study of the use of multiple Nonlinear Energy Sinks (NES) as a means of attenuating the torsional oscillations for an extended frequency range and under transient vehicle manoeuvres. Frequency–Energy Plots (FEP) are used to obtain the nonlinear absorber parameters for multiple NES coupled in parallel to the clutch disc of a typical drivetrain configuration. The results obtained show significant reduction in the oscillations of the transmission input shaft, effective over a broad range of response frequencies. It is also noted that the targeted reduction of the acceleration amplitude of the input shaft requires significantly lower NES inertia, compared with the existing palliative measures.

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1. Introduction

Attenuation of torsional oscillations in automotive powertrains has recently received increased attention owing to a plethora of noise, vibration and harshness (NVH) concerns. These include clutch in-cycle vibration referred to in industry as "whoop" [1–3] and transmission rattle [4–7]. The underlying cause of these phenomena is the transmitted engine order harmonics [8] to the clutch and transmission systems, which are exacerbated through the modern high output power-to-light weight ratio concept, driven by the key objective of fuel efficiency. Light weight components are subjected to flexible structural dynamics, exacerbated by increased power torque fluctuations as the result of enhanced power, particularly with diesel engines. Furthermore, downsized engines with fewer cylinders and lower operating speeds exhibit increased torsional oscillations produced by discrete torque pulses through combustion process and cyclic inertial variation [9,10]. Other new technologies such as stop–start or cylinder deactivation, also developed for improved fuel efficiency and reduced emissions, cause transient intermittency which also leads to the generation of drivetrain vibration [11].

To mitigate the emergent NVH concerns, various palliative measures have been developed, including tuned vibration absorbers such as clutch pre-dampers, the Dual Mass Flywheel (DMF) [12,13] and DMF with Centrifugal Pendulum Vibration Absorbers (CPVA) [14,15]. Numerous studies have reported on the working principle of DMF and its design, including studies of DMF with: radial springs [16], Magneto-Rheological (MR) dampers and arc helix springs [17]. These are primarily meant to mitigate transmission gear rattle. For clutch in-cycle vibration, a Diehl-fix which is essentially a lumped mass-damper is attached to the clutch lever of a mechanical-type clutch [18]. These palliative measures are

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Nomenclature

A	Acceleration
C_d	Aerodynamic drag coefficient
c_1, c_2	Damping coefficient
F	Frequency Coefficient of rolling resistance
f_2	Speed dependent coefficient of rolling resistance
F_z	Normal load
J_2, J_3, J_N	Component inertia
k_2, k_3, k_N	Stiffness
r_w	Wheel radius
S	Vehicle frontal area
T_{RES}	Resistance torque
V	Vehicle longitudinal velocity
Z	Modal damping ratio matrix

Greek Symbols

ζ	Damping ratio
θ	Angular motion
ρ	Air density
Φ	Modal matrix
ω	Natural frequency

Abbreviations

AEAAR	Area of Effective Acceleration Amplitude Reduction
CPVA	Centrifugal Pendulum Vibration Absorber
CWT	Continuous Wavelet Transform
EO	Engine Order
FEP	Frequency-Energy Plot
FWD	Front Wheel Drive
LNM	Linear Normal Mode
NNM	Nonlinear Normal Mode
PSD	Power Spectral Density
SMF	Solid Mass Flywheel

invariably costly, only effective over a narrow band of frequencies and add to the mass of the powertrain system as well as increase the package space [19]. Furthermore, these devices are tuned to counteract/filter out some specific range of frequencies. Thus, they exclude the broad band response of internal combustion engines, which aside from the usual engine order (EO) vibrations include elastodynamic responses due to the increasing use of components of low elastic moduli [20] as well as broad band powertrain response to impulsive actions [21–23].

Therefore, there is a need for vibration absorbers which would act over a broader range of frequencies with limited prior tuning. The Nonlinear Energy Sinks (NES) are passive absorbers which operate on the principle of Targeted Energy Transfer (TET). The energy of mechanical vibrations is transferred, in a nearly irreversible manner, from its source (usually a linear primary system) to a recipient (a secondary system; NES), where it is either absorbed, redistributed or dissipated [24].

Vakakis et al. [25] and Gendelman et al. [26] have studied TET in two- and three-degree-of-freedom engineering systems. These were impulsively excited. It was concluded that 1:1 stable sub-harmonic orbits are responsible for energy transfer. Vakakis et al. [27] studied the activation of Nonlinear Normal Modes (NNMs) to describe the interaction of nonlinear absorbers with linear primary systems. Jiang et al. [28] studied, theoretically and experimentally, the steady state passive nonlinear energy pumping in coupled oscillators. Panagopoulos et al. [29] examined the transient resonant interactions of finite linear chains, coupled with an essentially nonlinear attachment. The study presented an alternative approach, allowing simultaneous resonant interactions between the NNMs of the nonlinear absorber and the normal modes of the linear system. McFarland et al. [30] conducted experimental studies of nonlinear energy pumping occurring at a single fast frequency. Kerschen et al. [31] performed studies on linear systems coupled with grounded and ungrounded nonlinear attachments to understand the dynamics of the individual absorbers and their effectiveness. It was highlighted that for both attachments the energy pumping is governed through 1:1 resonance captures. However, the grounded attachments do have limitations in application in certain fields due to the required stiffness and weight.

There have also been studies with regard to the use of different types of stiffness nonlinearity (e.g. non-smooth and non-polynomial [32,33]). Similarly, studies have been conducted on primary systems, coupled to multiple nonlinear attachments, where it was reported that the efficiency of energy transfer is substantially improved when compared with single attachments [34,35]. The above-mentioned studies were conducted on translational systems subject to transient excitations, where it was demonstrated that NES can engage in the suppression of broad band vibration responses.

A dearth of studies exists concerning applications of rotational NES which are necessary to attenuate powertrain NVH concerns which are largely of torsional oscillatory nature, such as gear rattle. In this regard, Viguie et al. [36] examined the implementation of NES to stabilise drill-string systems. The study mainly focused on friction-induced vibrations, which is similar to another clutch NVH phenomenon, referred to as take-up judder [37–39] caused by stick–slip friction of the lining material during clutch engagement. Viguie et al. [36] observed that the NES is able to eliminate limit cycle instabilities. Therefore, their findings can apply to problems such as clutch take-up judder. There are potential applications for NES in tackling a variety of vehicular powertrain NVH issues, which as yet remains untapped.

Recently, Haris et al. [40] showed that nonlinear vibration absorbers can be effective in attenuating torsional vibrations of vehicular driveline system over a broader range of frequencies. However, it was also shown that the efficiency of the NES is highly dependent on the amplitude and frequency of the applied input under various engine transient manoeuvres. Thus, a single NES may not be sufficient to act across the whole spectrum of excitation frequencies.

The majority of studies presented in the literature in the subject area of Targeted Energy Transfer are concerned with the incorporation of nonlinear vibration absorbers (NES) to reduce vibrations in translational systems, with the exception of a few studies only analysing the performance of rotational systems equipped with NES. To the best knowledge of the authors no previous attempt has been made on examining the potential of incorporating (multiple parallel) rotational NES(s) to attenuate torsional vibrations in automotive drivelines. Thus, the implementation of multiple parallel NES to attenuate the broad spectrum of encountered torsional NVH phenomena is the subject of the current study. The driveline system considered is a Front Wheel Drive (FWD) transaxle configuration, powered by a three-cylinder engine. A reduced order drivetrain model is developed and validated both in temporal and spectral domains against measured response of the vehicle under test conditions. Then, the model is modified to incorporate multiple parallel NES. Significant vibration attenuation at the dominant Engine Orders (EO) is noted.

2. The drivetrain model

A transaxle FWD powertrain system with a 3-cylinder engine with a Solid Mass Flywheel (SMF) is considered in the current study. It incorporates a 5-speed manual transmission and a clutch equipped with a clutch pre-damper. A two-degree-of-freedom linear model is used to represent the drivetrain system, comprising the clutch assembly, the transmission, differential and the axle half-shafts (Fig. 1).

The clutch assembly has the inertia J_2, coupled to the transmission input shaft with the inertia J_3. The engine is not included in the model, but the measured oscillatory motion of the flywheel is used as an input

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