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Development of a scientific torsional system experiment containing controlled single or dual-clearance non-linearities: Examination of step-responses

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ABSTRACT

The chief goal of this paper is to propose a new laboratory experiment that exhibits the step-response of a torsional system containing one or two controlled clearances. This work is motivated by the disadvantages of prior large-scale experiments which utilize production vehicle drivelines and their components with significant real-life complexities. The conceptual and physical design features, which include sizing, modal properties, excitation, and instrumentation, are discussed with the goal of creating a controlled experiment. Like prior literature, a step-down torque excitation is selected and all analyses are performed on the acceleration signals to observe vibro-impact in the time domain. Typical measurements (for both the single and dual-clearance configurations) exhibit rich non-linear behavior, including the double-sided impact regime and a time-varying oscillatory period. Additionally, new measurements are compared to predictions from simple reduced order non-linear models to verify the feasibility of the proposed experiment. Finally, the utility of this experiment is demonstrated by comparing its measurements to a prior large-scale experiment that accommodates a production vehicle clutch damper with multiple stages. The hardening and softening effects in both experiments are discussed in the context of double and single-sided impacts as well as the oscillatory periods that vary with time.

1. Introduction

Most torsional systems in vehicles and machinery contain one or more discontinuous non-linear features by design or otherwise [1–9]. Such non-linear elements include clearances (e.g. backlashes between gears), multi-staged torsional springs, pre-load and stopper features (e.g. torque transmission devices), and multi-staged dry friction components. Of this group, the clearance or gap element is the most fundamental as it is required to assemble components without interference while providing space for lubrication. Presence of such clearances in multi-degree of freedom systems induce conditions for vibro-impact phenomena, depending on the value of mean and alternating loads. Gear rattle [4,9,10] and vehicle driveline clunk [4–8] are common physical manifestations of such systems as evident from many noise and vibration issues in the ground vehicle industry. While several researchers have developed non-linear simulation models, they often include many

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simplifications and/or incorporate assumed or empirical parameters. There is clearly a need for a scientific experiment that could yield physical insight, accurate parameters, and benchmark time domain data for the validation of non-linear simulation models. Therefore, it is the chief goal of this article and as such a new laboratory experiment with controlled clearance element(s), while being distinctly different from the prior experimental studies [4–8], will be proposed.

2. Problem formulation

Couderc et al. [4] proposed a system-level rotating experiment to better understand gear rattle during engine run-up. Their experiment accommodates several production components, such as a clutch damper and vehicle transmission, while containing several clearances spread across multiple locations. Likewise, a different type of experiment must be considered to study vehicle driveline clunk, typically induced by a sudden change in the mean operating point of the driveline (often known as a tip-in or tip-out event) [4–8]. The simplest way to implement such excitation in a laboratory setting is to apply a step-down torque under vibratory conditions, which is essentially free vibration about a static equilibrium. Few system-level experiments that employ the step-response method have been proposed in the literature [5–7]. Common features across all test rigs [5–7] include the following: i) Production vehicle driveline components are often utilized; ii) The systems are made positive-definite to achieve vibratory conditions (i.e. at least one torsional component is fixed to ground); iii) Two or more clearance elements are present; and iv) A step-down torque is applied via a variable mass-drop from a torsion arm. Although these experiments [5–7] provide much needed system-level insight, it is also necessary to study non-linear dynamics at the component-level. For example, consider the experiment recently proposed by Krak et al. [8], which has been developed to provide parameter estimation for a clutch damper under dynamic conditions. This particular experiment [8] accommodates one or two production clutch dampers and is excited by a step-like torque like the clunk experiments [5–7]; however, the external torque is supplied by a pneumatic actuator rather than a mass-drop due to the relatively high torque capacity of the device.

These aforementioned large-scale experiments [4–8] have the following intrinsic benefits: i) Interactions between multiple non-linear features are maintained; ii) System and component-level dynamics can be studied under realistic boundary conditions; iii) Real-world type excitation is more easily achieved; and iv) Parameter estimation has greater fidelity [11]. However, there are also several inherent disadvantages, such as increased cost (e.g. labor, hardware, instrumentation, and laboratory space), a higher degree of complexity, and, most important, a lack of controllability. The latter two are largely due to the use of production components, which can contain multiple (known and unknown) non-linear features while being subject to variations in assembly and manufacturing. Therefore, the goal of this paper is to address this critical need by proposing a more controlled and scientific version of prior large-scale experiments [5–8]. Accordingly, the following specific objectives are defined: 1) Develop a new controlled laboratory ("bench-top") experiment that exhibits the step-response of a torsional system that contains one or two clearance non-linearities located at different locations (to allow single and dual-clearance cases); 2) Verify the feasibility of the proposed experiment by comparing typical measurements with predictions from simple, low-dimensional non-linear models and 3) Demonstrate the utility of the proposed experiment (denoted X1) through comparative studies between a single-clearance configuration and to a large-scale laboratory experiment (denoted X2 in this paper) [8].

3. Conceptual design considerations

First, it is assumed that clearance non-linearities (with torsional stiffness $k(\theta)$, where θ is the relative angular displacement) can be described by a general piecewise linear form as illustrated in Fig. 1. Here, $\Phi(\theta)$ is the elastic torque transmitted through the clearance, subscripts I and II denote stages (where stage I is the clearance), k_j is the torsional stiffness (linear) of stage j, and Θ_j is the angular transition from stage j to $j+\mathrm{I}$. For the sake of simplicity, the clearance is assumed to be symmetric about $\theta = 0$ and static stiffness values are known (and valid under dynamic conditions) while ignoring contact mechanics. Accordingly, $k(\theta)$ and $\Phi(\theta)$ are defined by the following expressions where sgn is the triple valued sign function and Ξ is the unit-step function:

$$k(\theta) = k_{\mathrm{I}} + (k_{II} - k_{\mathrm{I}})\Xi(|\theta| - \Theta_{\mathrm{I}}), \tag{1}$$

$$\Phi(\theta) = k_{\mathrm{I}}\theta + \mathrm{sgn}(\theta)(k_{\mathrm{II}} - k_{\mathrm{I}})(|\theta| - \Theta_{\mathrm{I}})\Xi(|\theta| - \Theta_{\mathrm{I}}). \tag{2}$$

Next, the proposed experiment (in its dual, single, and no-clearance configurations) is conceptually described by the non-linear models illustrated in Fig. 2. Here, J is the torsional inertia, k is the torsional stiffness (linear), h is the Coulomb friction coefficient, T is the external torque, subscripts $\{A, B, C\}$ are coordinate and element indices, and $\{\theta, \dot{\theta}, \ddot{\theta}\}$ are the angular displacement, velocity, and acceleration, respectively (see Appendix A for a full list of symbols). The dual-clearance configuration (denoted X1-2 and shown in Fig. 2a) is a three degree of freedom (3DOF) positive-definite system that contains two clearance non-linearities ($k_{AB}(\theta_{AB})$ and $k_C(\theta_C)$) and has the following set of governing equations: