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Examination of super-harmonics in a multi-degree of freedom nonlinear vibration isolation system: Refined models and comparison with measurements

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ABSTRACT

A multi-degree of freedom vibration isolation experiment consisting of a powertrain, three powertrain mounts including a dynamic load sensing hydraulic mount, a sub-frame, and 4 bushings is examined in both time and frequency domains. Since the hydraulic mount exhibits nonlinear phenomena, super-harmonics are observed in motion, pressure and interfacial force measurements when the system is sinusoidally excited. Refined indirect force estimation methods are proposed with a focus on the super-harmonics. This includes the development of a quasi-linear fluid system model with embedded spectrally varying and amplitude-sensitive parameters. The reverse path spectral method is employed using the measured relative motion and upper chamber pressure in the nonlinear hydraulic mount. The relevant transfer functions (with effective parameters for both rubber and hydraulic paths) are used to estimate the interfacial forces. Up to six harmonics of the fundamental excitation frequency are examined, and the contribution of each path is clarified. The proposed quasi-linear fluid system model including super-harmonics extends prior work on indirect force estimation methods and successfully predicts the interfacial forces in the multi-degree of freedom vibration isolation system. The quasi-linear fluid system model, however, seems to be inadequate in estimating the sub-harmonic responses.

1. Introduction

There is a large body of literature on transfer path analysis, and frequency or impulse response type methods have been employed to estimate interfacial or path forces in mechanical systems or structures [1–8]. For instance, the internal forces are estimated by Yap and Gibbs [1] by using the mobility method; Leclere et al. [2] employed an inverse transfer function method. Carne et al. [3] and Tao et al. [4] estimated the force excitation by utilizing the frequency response function and using the velocity amplitude (and phase), respectively. Further, the deconvolution technique, singular value decomposition, and Tikhonov filter approaches have been utilized to identify and assess path properties such as stiffness and damping [5–7]. Nevertheless, the literature is primarily limited to the frequency domain methods for linear time-invariant systems, though Gunduz et al. [8] have employed a sub-system method to predict interfacial forces in the time domain.

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In practice, some vibration isolation paths are inherently nonlinear, though they might co-exist with parallel linear paths [9]. Even though an estimation of their interfacial properties is critical to dynamic design and durability studies, only a few prior articles have addressed this topic. For instance, Yoon and Singh [10,11] examined the internal force transmission paths of a nonlinear hydraulic mount when connected to a rigid base. Super-harmonics were observed when the mount was excited by a sinusoidal displacement in a non-resonant test. This article will extend such prior studies [10–12] by focusing mainly on the super-harmonic terms that are generated in a multi-degree of freedom vibration isolation system under sinusoidal force excitation. Both experimental and analytical studies, including comparisons of several estimation methods, will be presented with respect to vertical excitation motion only.

2. Problem formulation and preliminary results

Fig. 1 illustrates an experimental setup of a multi-degree of freedom system based on the source-path-receiver system. It was previously described in [12]. Fig. 2 displays two mechanical system models of a system which contains both mechanical and fluid paths. This type of parallel system has been introduced by Gunduz et al. [8] and Inoue et al. [9], though they focused only on the linear system. The differences between the systems of Fig. 2(a) and (b) are due to a dynamic load sensing hydraulic mount which is marked with dotted lines [10–14]. For example, this hydraulic mount is simply assumed as a Voigt model in the two degree of freedom (2DOF) system in Fig. 2(a). However, the 3DOF system includes a fluid inertia effect. Here, the symbols are designated as follows: m_E, mass of the powertrain; m_S, mass of the sub-frame; c_{HF}, damping coefficient of the hydraulic mount at the front side; c_{HR}, damping coefficient of the dynamic load sensing hydraulic mount; m_{ie}, effective mass of

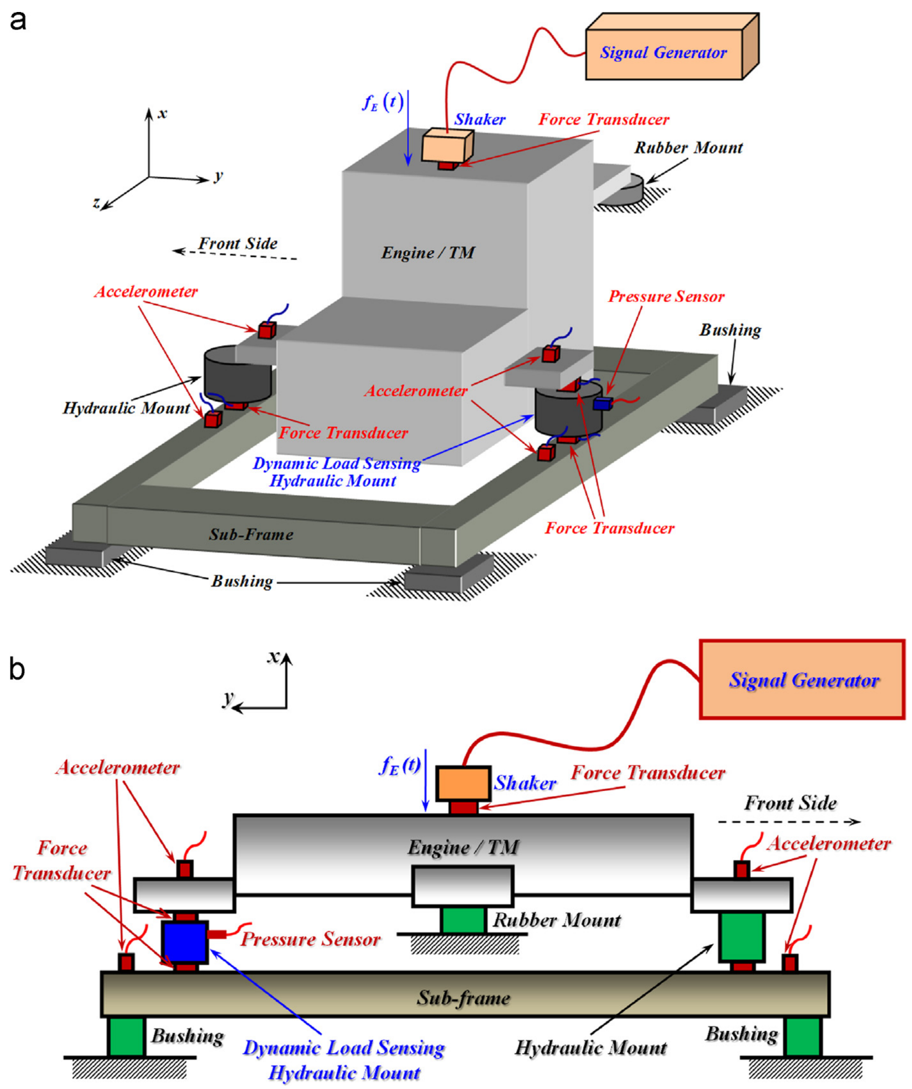

Fig. 1. Multi-degree of freedom vibration isolation experiment with a load sensing hydraulic mount; (a) powertrain and sub-frame assembly with instrumentation; and (b) front view laboratory experiment with focus on the vertical motions.