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A concept for semi-active vibration control with a serial-stiffness-switch system

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A B S T R A C T

This work deals with a new semi-active vibration control concept with a serial-stiffness-switch system (SSSS), which can be seen as one and a half degree-of-freedom system. The proposed switched system is mainly composed of two serial elements, each of which consists of one spring and one switch in parallel with each other. This mechanical structure benefits from a specified switching law based on the zero crossing of velocity in order to realize vibration reduction. In contrast with conventional ways, the new system is capable of harvesting vibration energy as potential energy stored in springs, and then applies it to vibration reduction. In this paper, the concept is characterized, simulated, evaluated, and proven to be able to improve the system response. The equivalent stiffness and natural frequency of the switched system are mathematically formulated and verified.

1. Introduction

Vibration is mostly unwanted when it creates uncomfortable noise, results in danger, and wastes energy. As a result, vibration control has always been of interest to researchers. Passive, active and semi-active vibration control systems have been mainly studied in the past decades. In these systems, system stiffness plays an important role on the system response such as the response time and the working frequency range of the system. Semi-active control not only requires less external energy acting as control energy and performs more stable than active control, but also works over a larger frequency range and performs more flexible than passive control. So, semi-active control systems are of high interest and applied in many engineering areas [1–6]. The variable components can be mass, stiffness or damping, applied for semi-active control, see Liu [1]. This research focuses on variable stiffness systems.

Variation of stiffness can be continuous or switched. The concept of continuous stiffness variation applied to vibration control was introduced by Chen [7]. It is used for motion control of large space structures by means of its bending and torsional varying stiffness. Afterwards, continuous variable stiffness systems have been documented and realized by different smart materials such as piezoelectric actuator, shape memory alloy and magnetorheological fluids [8–11], different mechanical structures [12,13], and control strategies [14–16].

A switched variation of the system stiffness usually uses high and low stiffness states, which are realized by connecting or disconnecting two parallel elastic elements. One is always connected and the other can be connected or not connected to system components. As a result, two values of stiffness are produced in the system. When one elastic element is disconnected from the mass, free vibration occurs in the elastic element and stored energy will be dissipated by damping

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finally. Switched stiffness systems, owning the advantages of simple physical structure and high speed response, have also attracted significant interest, as documented in Winthrop [17]. A basic structure of this form of vibration control system is illustrated in Fig. 2(a) and (b), and proposed by Onoda et al. [18] and Ledezma-Ramirez et al. [19].

In order to realize vibration reduction, the control strategy for the switching between two stiffness values, based on the maximal vibration energy dissipation per vibration cycle, is proposed and further improved by Onoda et al. [18] and [20], respectively. This control scheme is applied to the vibration suppression of truss structures. Ledezma-Ramirez et al. [19,21] documented that the above mentioned switching stiffness control strategy is applied to shock isolation and could outperform a linear passive system, if the damping in the isolator is light. Leitmann et al. [22,23] proposed a control logic based on the Lyapunov stability theory for vibration attenuation. This control strategy aims to not only accomplish the task of maximizing the vibration energy dissipation, but also prove the stability of the controlled system. In Liu et al. [24,25], the stiffness on-off control based on an on-off controllable damping is presented for vibration isolation and verified to have better isolation performance than conventional variable damping ways. Winthrop [17,26] documented the detailed development related to variable stiffness, proposed an analytical solution method for vibration control system with switching stiffness and designed a tool for the selection of switching stiffness applied to a specified system. Time delay control between two different stiffness states is very important for switched system and studied in [27,28].

The switching between two stiffness values has been practically explored by means of many different structures. Onoda et al. [18] developed a variable stiffness member structure, which consists of a piezoelectric actuator, a variable-length member and an outer element. The actuator is installed inside the member. The clamping or release of the member and outer element is realized by the piezoelectric actuator. As a result, axial stiffness of the member can be varied. Choi et al. [29] proposed a hollow composite beam filled with electrorheological fluids for the construction of switching stiffness system. With the combination of the control logic developed by Leitmann et al. [22], the switching stiffness could be obtained. In Clark [30] an electrical shunt circuit of a piezoelectric actuator is designed for vibration control in a mechanical system. High and low stiffness states are carried out between open-circuit and short-circuit of the actuator. Yong et al. [31] documented a smart spring system applied to the vibration reduction in helicopter blade. This vibration control system consists of two parallel springs and a piezoelectric actuator. Supplying voltage to the actuator disconnected one of springs from the system and finally two stiffness values are produced. In Liu et al. [25], two magnetorheological fluid dampers are placed in series with two springs. The switching stiffness can be produced through the on-off state of semi-active dampers. Ledezma-Ramirez et al. [32] presented a switching stiffness device for shock isolation. Based on the concept of magnetic levitation, an electromagnetic element is applied to achieve the switching stiffness. Greiner-Petter et al. [33] built a switching fluid-mechanism, which uses two serial magnetorheological fluids valves and two serial springs. This system could provide four different stiffness values through the on-off states of two fluid valves. In Scheidler et al. [34] the switching stiffness is realized by a magnetostrictive transducer as a magnetostrictive spring, which can be controlled in real-time by a variable magnetic field. Xiang et al. [35] put forward a method for rapidly switching between pneumatic and hydraulic modes of operation through two valves for the improved stiffness characteristics of McKibben muscles.

In most of the above mentioned switching stiffness systems, during a vibration reduction process there still exist unavoidable time instants, where elastic elements release potential energy stored by themselves, and drive the mass to move again. This is the intrinsic property of an elastic element, but this results in an oscillating system response to some extent. In order to further reduce this adverse effect of elastic elements on vibration control, this research documents how elastic elements affect system response and then introduces a new type of vibration control system. The new system does not dissipate energy into heat, but stores the kinetic energy as potential energy in elastic elements.

This paper is outlined as below. In Section 2, a brief description of how elastic elements are affecting the system response in passive and traditional semi-active control systems is provided and then a new vibration reduction idea is proposed. Following is the mathematical formulation for the novel concept in Section 3. Then numerical analysis of the new system in open-loop operation is executed in Section 4. The equivalent stiffness and natural frequency of the system are mathematically formulated and the spectral analysis for system response by means of FFT (Fast Fourier Transformation) is performed to verify the mathematical derivation. In Section 5, a switching law, applied to the new system, is proposed. The total vibration control system is numerically analyzed and evaluated. Finally, the conclusions related to the new system are drawn in Section 6.

2. Problem statement and vibration reduction idea

For the sake of simplicity, all elastic elements through the work are denoted as springs. First, a passive single-degree-of-freedom (SDOF) model is taken for explanation, as sketched in Fig. 1(a). The equation of motion is given by

$$m\ddot{x} = F - d\dot{x} - kx, \tag{1}$$

where $x(t)$ is the mass displacement and m, k and d are mass, stiffness and damping parameters of the system, respectively. The force $F(t)$ represents the external disturbance and is considered to be a pulse in this case. The objective of vibration control as understood here is to achieve vibration reduction, which moves a mass back to its equilibrium position $x{=}0$. Multiplying Eq. (1) with the velocity $\dot{x}$ results in the mechanical power balance