Semi-passive piezoelectric structural damping based on a pulse-width modulation switching circuit

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Abstract

Studies in the past focused on the implementation of semi-passive damping techniques that could significantly reduce structural vibration. Recently, the performances of these damping techniques have been enhanced by artificially increasing the voltage amplitude delivered by the piezoelectric patches with an external voltage source. To maintain the stability of this damping method, an adaptive voltage source must be used. To satisfy this requirement, this study proposes an enhanced semi-passive damping technique based on pulse-width modulation. The proposed method allows the waveform of the piezoelectric voltage to adapt to the vibration velocity. Thus, this method can maintain its stability with a constant voltage source and simultaneously exhibit superior performance. This study consists of a theoretical part and an experimental proof-of-concept demonstration of the proposed damping technique.

Keywords: Electrical interface; Piezoelectric transducer; PWM; Structural damping

1. Introduction

A piezoelectric transducer connected to a shunt circuit is attached to the host structure in semi-passive structural vibration suppression applications. By using piezoelectric electromechanical coupling, the vibration energy of the host structure is converted into an electrical energy and then dissipated into the shunt circuit, which can then damp structural vibrations. This method has been widely implemented because of simple configuration and compact size of these components. Moreover, the technique requires no heavy amplification for active vibration control [1].

With the large intrinsic capacitor of the piezoelectric element considered, an impedance matching shunt circuit is required to maximize the generated power. The shunt circuit can be optimized by a passive network but fails to adapt to environmental variation [2, 3]. The switching shunt circuit was proposed to address this problem and has been widely used in recent years [4-7]. In switching shunt circuits, the switches are operated synchronously with the vibration of the host structure to optimize the power flow. An external voltage supply can also be connected to the piezoelectric material to enhance vibration suppression. Several switching shunt circuit topologies and corresponding switching laws were proposed. Efficient switching shunt-damping techniques include synchronized switch damping on a voltage source (SSDV) [8] and velocity-controlled switch damping (VSD) [9]. In SSDV, the switching shunt circuit is only turned ON during extreme displacement to shift the phase of the voltage across the piezoelectric element. In VSD, the switching shunt circuit is turned ON or OFF according to the polarity of the vibration velocity of the host structure. In both techniques, an external voltage source is connected to enlarge the voltage amplitude across the piezoelectric element and optimize the dissipated power. In theory, the vibration can be cancelled completely if the external voltage is properly set in both SSDV and VSD.

Despite the efficiency of both SSDV and VSD, these techniques require a dynamic voltage source to ensure the stability of the control system. However, a fast dynamic voltage source is practically difficult to implement. In addition, audible re-injected noises may be generated in SSDV and VSD systems. Lallart et al. proposed blind switch damping (BSD) to reduce these noises [10]. BSD adopts a periodic switching law and modulates the voltage across the piezoelectric element at high frequencies. With the modulation, BSD can decrease the re-injected harmonic noise. However, the performance of BSD is determined by the switching frequency of the carrier. BSD exhibits a poor damping performance at high switching frequencies; thus, the switching frequency is difficult to set in the
ultrasonic frequency range in BSD.

A full bridge (Fig. 1) is used for the shunt circuit, and the pulse-width modulation (PWM) switching law is applied in this study. The PWM shunt method can efficiently reduce audible noises and ensure the stability of the control system with a constant voltage source in wideband vibration. The performances, disadvantages, and system requirements of the PWM piezoelectric switching shunt technique are evaluated. The electromechanical model, electrical circuit, and energetic analysis are introduced in the following section. The experimental identification method of the parameters used in this model is described in the subsequent section. Experimental damping results are then presented and discussed.

2. Switching control strategy

The system consists of a piezoelectric patch bounded on a host structure, which mainly operates at the approximate first natural frequency. Fig. 2 shows that the system can be modeled by a simple spring, mass, and damper system, with \( M \) as the mass, \( D \) as the damping coefficient, the spring coefficient \( K \) as the device stiffness, and \( u \) as the free-end displacement. The spring represents the ideal compliance, the mass is the energy storage element, and the damper indicates the internal mechanical losses.

The governing equation of piezoelectric elements can be represented as Eqs. (1) and (2).

\[
F_p = K_p^0 u + \alpha v_p
\]

where \( F_p \) is the external force exerted on the piezoelectric element, \( I \) is the outgoing current generated from the piezoelectric element, \( K_p^0 \) is the short circuit stiffness, \( \alpha \) is the force-voltage coupling factor, \( C_p \) is the static capacitance of the piezoelectric element, and \( u \) is the displacement of the system. According to dynamics equation, the differential governing equation of this electromechanical system can be expressed as Eqs. (2) and (3):

\[
M \ddot{u} + D \dot{u} + Ku + \alpha V_p = F_M.
\]  

The base acceleration \( \dot{\gamma} \) can be regarded as force excitation to the dynamic system \( F_M = -M \dot{\gamma} \). Eq. (3) becomes the standard dynamic equation for a spring-mass-damper system if the last term \( -\alpha V_p \) is not considered. However, for systems using the piezoelectric device as the beam, the application of an electrical voltage to the device terminals can affect the mechanical system and consequently, the device current. This coupling can harvest energy from the mechanical system and damp the structure.

The electric equivalent circuit of the host structure with the shunt circuit is illustrated in Fig. 3. In this figure, \( \dot{u} \) represents the velocity of the host structure at a particular location, which can also be regarded as the current in the equivalent circuit. The voltage \( v_p \) denotes the voltage across the piezoelectric element.

According to the equivalent circuit analysis, the dissipated energy in the switching circuit can be expressed as

\[
E = \alpha \int \dot{u} v_p dt.
\]  

Generally, the velocity \( \dot{u} \) is caused by external disturbance. The electromechanical ratio \( \alpha \) is determined by material properties, sensor placement, and shape. According to Eq. (4), the piezoelectric voltage \( v_p \) should be in phase with the velocity, and the voltage amplitude should be sufficiently large to cancel the vibration, thereby obtaining the largest dissipated energy. The switching circuit is primarily aimed at changing the phase of the piezoelectric voltage \( v_p \), and the external voltage is used to increase the piezoelectric voltage amplitude.

In large-band vibrations, the velocity can be expressed as