A new adaptive resonance frequency of piezoelectric components used for vibration damping

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Abstract: This paper describes two methods for vibration damping in a broad band frequency range using a piezoelectric patch. The first method, applied to an adaptive device, uses a bias (static voltage control), which applies stresses or releases stresses in a piezoelectric component to modify its mechanical characteristics and thereby its resonance frequency. The second method is based on a semipassive approach [synchronized switch damping (SSD)], developed to control structural vibration damping using a piezoelectric component. Attenuations of 10 and 4.8 dB in vibration velocity have been obtained using the adaptive frequency and SSD methods.

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1. Introduction

Vibration damping has become a priority research area in a number of industries including car manufacturing, aerospace, and sports equipment manufacturing. Faced with this diversity of potential applications, various damping methods have been designed based on piezoelectric materials. These components (patch, piezofiber composite, and thick or thin layer) are bonded on or embedded in the structure and are used as sensors, actuators, or combined sensors and actuators. When the structure vibrates, the piezoelectric components are stressed and respond by creating an electric field based on the piezoelectric effect. Electrical energy degradation or transfer leads to control and vibration attenuation.

A complex system integrating at least one sensor, a control unit, and a feedback actuator is required for active vibration control. External power sources and amplifiers are additionally required for the control unit and actuators.

Passive techniques are more adaptable because of their simplicity and compactness. The piezoelectric component is connected to a specific electrical system incorporating a dissipative shunt ([Hagood and Flotow, 1991](#)). The most effective method is the tuned shunt, in which a circuit incorporating an inductor (L) and a resistor (R) in series is connected to a piezoelectric component capacitor (C_0). Optimum damping is achieved by tuning the electrical resonance to the frequency of the unwanted structural mode. This method gives good results but has several

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Table 1. Resonance frequency, coupling coefficient and the vibration damping for different static voltage applied.

Static voltage applied	−5 V	0 V	5 V
Resonance frequency	350 Hz	400 Hz	450 Hz
Coupling coefficient k^2	52%	48.7%	44%
Attenuation (dB)	10 dB	7.6 dB	4.4 dB

disadvantages:

- (1) Multimodal damping requires the use of complex shunt circuits (Wu, 1998).
- (2) At low frequency modes, the optimum inductance is very high and may reach tens or hundreds of henry.

Several semipassive or active-passive techniques had been proposed to overcome these drawbacks. In the active-tuned solid state piezoelectric absorber developed by Davis and Lesieutre (1998), a passive capacitive shunt circuit is used for electrically adjusting the effective stiffness and consequently the resonance frequency of the piezoelectric components. In the approach suggested by Morgan and Wang (2002), an arrangement comprising an adaptive tuning inductor, a negative resistance, and a coupling creates a system with multimodal damping capacity.

More recently, switched shunt techniques have been developed, which introduce a nonlinear approach by modifying piezoelectric component properties or boundary conditions in synchrony with structural movement. The state-switching method proposed by Clark (2000) is a variable stiffness technique, in which piezoelectric components are periodically maintained in the open-circuit state, then switched and maintained in the short-circuit state in synchrony with structural movement. In a rather different way, Cunefare *et al.* (2000) successfully adapted the earlier work of Larson *et al.* (1998) on the state-switching concept to vibration damping and has proposed the state-switching absorber (SSA) (Cunefare *et al.*, 2000).

Richard *et al.* (1999) suggested previously the synchronized switch damping (SSD) technique, which is the approach considered in this paper. The SSD technique (Richard *et al.*, 2000) involves modifying the voltage on a piezoelectric component bonded to the structure a simple switch actuated for short periods in synchrony with structural movement. This switch connects the piezoelectric component to a small inductor (SSDI). The process involves a phase shift between the piezoelectric component strain and the resulting voltage; this causes energy dissipation. The SSD method offers several advantages: it is unaffected by environmental changes because of its self-adaptive broad band behavior, it does not require a large tuning inductor at low and very low frequencies, it achieves multimodal damping without the need for complex circuitry and it only requires a very low power supply for switch control. The adaptive resonance frequency and the SSD methods are described in Sec. 2 of this paper. Section 3 then describes the experimental setup and results.

2. Anechoic termination principle

2.1 Adaptive resonance frequency of the piezoelectric component absorber

To obtain a smart panel broad band frequency range, it would be necessary to use various piezoelectric components with different resonance frequencies. This could be achieved by integrating piezoelectric components into the various dimensional specifications and/or mechanical characteristics.

To make this panel type more flexible, we can conceivably modify the resonance frequency of the piezoelectric component without radically changing these physical properties.

The adaptive resonance frequency method involves changing the stiffness of the system by modifying the electric conditions and thus varying the resonance frequency (Table 1).

Fig. 1. Experimental device for adaptive resonance frequency of piezoelectric components.

Stiffness can be changed by applying a static voltage to the piezoelectric component. It can be increased or decreased based on the piezoelectric component polarity and the static voltage.

The experimental device shown in Fig. 1 is a piezoelectric component, specifically a 50 mm diameter MURATA Ceramitone VSB50EW-0701B buzzer, connected to a spectrum analyzer (4194A HP). The control bias allows a static voltage to be applied the piezoelectric component. Impedance analysis yields the variation in this component's characteristic parameters (resonance and antiresonance frequency, quality factor, and coupling factor) with respect to static voltage.

Figure 2(a) illustrates the admittance spectrum variation for the piezoelectric component with respect to static voltage.

Figures 2(b)–2(d) illustrate the resonance and antiresonance frequencies (f_0, f_1), the coupling factor k^2 , and the mechanical quality factor Q for the piezoelectric component with respect to applied voltage (–5 to 5 V).

We note that the resonance and antiresonance frequencies in Fig. 2(b) increase with respect to the static voltage. This variation causes the specific characteristics of the piezoelectric component to be modified. Increasing flexibility of the piezoelectric component with respect to

Fig. 2. Admittance modulus (a) and mechanical proprieties of piezoelectric component with respect to static voltage [(b)–(d)].

Fig. 3. Experimental device for vibration damping.

negative voltage leads to decreasing resonance frequency. Conversely, the positive voltage stiffens the piezoelectric component and leads to increasing resonance frequency.

Figure 2(c) illustrates the variation in electromechanical coupling coefficient with respect to voltage. Increased voltage reduces the coupling coefficient and this reduction is caused by greater stiffness according to Eq. (1). The coupling coefficient is approximately 10% for the voltage used in this experiment (5 V).

$$k^2 = \frac{f_1^2 - f_0^2}{f_1^2}. \quad (1)$$

The mechanical quality factor for the piezoelectric component remains practically constant for all applied voltages. Figure 2(d) illustrates this variation; this parameter is conventionally calculated from the bandwidth of the real part of the admittance.

These results show that the first bending mode resonance frequency for the piezoelectric component is controlled and this enables the first bending mode frequency to be adjusted for the excitation frequency.

2.2 The nonlinear technique

The principle involves intermittently switching piezoelectric components to a specific shunt circuit (resistor R_s and inductor L_s) to discharge the piezoelectric component capacitance each time the strain [or displacement $u(t)$] reaches a maximum. The SSDI device is used to control the piezoelectric component voltage. A specific analog processing box detects the voltage $V(t)$ extremum and actuates the switch control. An oscillating capacitance discharge is induced through the inductor. Pulse ω_s of this oscillation is directly related to the piezoelectric component blocked capacitance C_0 and L_s based on the equation

$$\omega_s = \frac{1}{2\pi\sqrt{L_s C_0}}. \quad (2)$$

If the switching control pulse width t_s is equivalent to the half-oscillation period, the voltage $V(t)$ is precisely reversed at each maximum value. The voltage is then distorted, resulting in a magnification and a quasi- $\pi/2$ phase between the voltage $V(t)$ and the displacement $u(t)$. The piezoelectric effect causes the voltage to exert a force, which is invariably opposed to the speed. This method is described in another paper (Faiz *et al.*, 2006 Guyomar *et al.*, 2006).

3. Experimental setup

The experimental setup shown in Fig. 3 comprises a 3 m long, 28 mm internal diameter brass pulse tube. A loudspeaker fitted to one end of this tube generates a tone sweep acoustic wave (200–800 Hz). An active end featuring a piezoelectric buzzer (50 mm diameter MURATA Ceramitone VSB50EW-0301B buzzer) is connected to the other end of the pulse tube. A vibrometer laser monitoring the vibration velocity is positioned 1 m from the buzzer terminals, which are connected to a SSDI-type controller for switched nonlinear processing of the piezoelectric voltage.

Figure 4 illustrates the vibration velocity with and uncontrolled (SSD on, SSD off) of the buzzer in three cases: voltage static = −5, 0, and 5 V.

Fig. 4. The vibration velocity is plotted with the uncontrolled (SSD off) and then the controlled (SSD on) buzzer termination in three cases: voltage static = -5, 0, and 5 V.

The buzzer resonance frequency is successively 350 Hz when the static buzzer voltage $V = -5$ V, 400 Hz when $V = 0$ V, and 450 Hz when $V = 5$ V. This adaptation frequency and the SSD on control ensure satisfactory attenuation at different frequencies.

For the controlled buzzer when the applied static voltage is -5 V, the maximum vibration velocity is one-fifth of the case without control. This corresponds to a 10 dB attenuation of the vibration velocity. This attenuation is specified in Fig. 4.

4. Conclusion

Both the SSD control and adaptation resonance frequency methods offer to be high performance in relation to solving vibration damping problems. High attenuation is obtained for different resonance frequencies (10–4.4 dB).

The control device described in this study is simple, lightweight, and compact. It requires only little energy to control a resonance frequency. Moreover, the SSDI-related device can be self-powered using vibration energy to start and continue the damping function.

The ongoing aim of current research into acoustic control architecture is to extend this technique to associate various skin panels on a large surface. One of the main advantages of the proposed technique is its potential for high performance at low frequency using a very low profile, thin, lightweight panel device. Another research aim is controlling large panels combining a number of piezoelectric patches designed for different modes.

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