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Letter to the Editor

Beam vibration control via rubber and piezostack mounts: experimental work

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1. Introduction

Many types of passive mounts have been developed to support static load and isolate unwanted vibration of flexible structures systems. The rubber mount is one of most popular and effective passive mounts applied for various vibrating systems. It is generally known that the rubber mount shows efficient vibration isolation performance in the non-resonant and high frequency excitations [1]. However, it cannot have a favorable performance at the resonant frequency excitation. In order to overcome the drawback of the rubber mount, various types of active mount systems have been proposed. One of potential active mounts is to utilize smart material actuators such as electro-rheological fluids [2,3], shape memory alloys [4] and piezoelectric materials [5–8].

As well-known, the piezoactuator is featured by fast response time, small displacement and low power consumption. Using these salient features, vibration control performance of various systems subjected to small magnitude and high frequency resonant excitations can be effectively accomplished. However, control performance of the piezoactuator mount only may be deteriorated at the non-resonant and low frequency excitations due to low material damping and small deformation. Thus, several types of so-called hybrid mounts are being actively studied in order to achieve favorable vibration control performance in wide frequency excitations. For example, efficient vibration isolation performance has been achieved by activating the ER fluid for the large amplitude and low frequency excitations, while activating the piezoactuator for the small magnitude and high frequency excitations [9]. More recently, Ichchou et al. [10] proposed a piezo-rubber mount, and experimentally demonstrated its efficacy by utilizing an adaptive control law.

In this work, both passive rubber mount and active piezostack mount are adopted in order to achieve superior vibration control performance of a flexible beam structure. The rubber element is

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adopted to support the imposed static load (the weight of the beam structure) and obtain efficient vibration isolation performance in the non-resonant frequency domain. The piezostack mounted on the rubber element (we call it hybrid mount) is adopted to achieve efficient vibration control of resonant modes in the relatively high frequency domain. In order to achieve this goal, a simple sliding mode controller is designed and experimentally implemented. Vibration control performances such as acceleration and displacement of the beam structure are evaluated and presented in both frequency and time domains.

2. System construction

Fig. 1 shows the configuration of a flexible beam structure supported by two rubber mounts and one hybrid mount. The rubber element integrated with the piezostack at l_2 has exactly same dimensions and properties of the rubber mounts positioned at l_1 and l_3. In order to identify damping and stiffness properties of the rubber mount shown in Fig. 2(a), the dynamic stiffness is measured as shown in Fig. 2(b). The dynamic stiffness can be expressed by $k_d(\mathrm{j}\omega) = k_r + \mathrm{j}\omega b_r$. Here, k_r is the static stiffness, b_r the damping constant, and ω the excitation frequency. From the curve fitting shown in Fig. 2(b), the values of k_r and b_r of the rubber mount are evaluated by 62 kN/m and 40 N s/m, respectively (refer to Ref. [11] for the measurement details).

The piezostack actuator used in this work is a bipolar type. The relationship between input voltage and output displacement is measured and shown in Fig. 3(a). It is clearly observed that it exhibits a typical hysteresis phenomenon. This requires a robust feedback control scheme to achieve a desirable vibration or position control performance. It is also shown that the piezostack can produce the displacement of 10 μm by applying voltage of 250 V. The piezostack actuator is connected to the rubber mount through the intermediate mass as shown in Fig. 3(b). The intermediate mass acts like a reaction mass for efficient force generator of the piezostack actuator. The spring constant k_p of the piezostack is experimentally evaluated by 66 MN/m. The actuating force $f_a(t)$ of the piezostack actuator by input voltage $V(t)$ is given by $f_a(t) = \alpha V(t)$. Here, α is a proportional constant which is function of piezostack properties such as strain constant. In this work, α is evaluated by 2.4 N/V. The control objective is to reduce the vertical vibration $y(x, t)$ of the beam structure by applying an appropriate control voltage to the piezostack actuator.

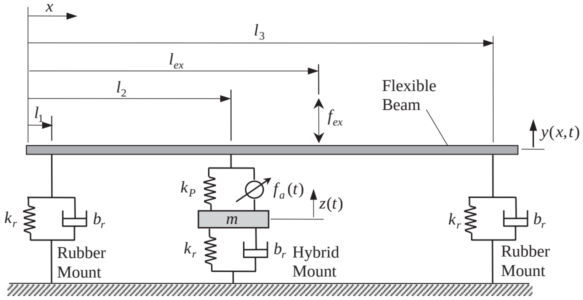

Fig. 1. Vibration control system supported by rubber and hybrid mounts.

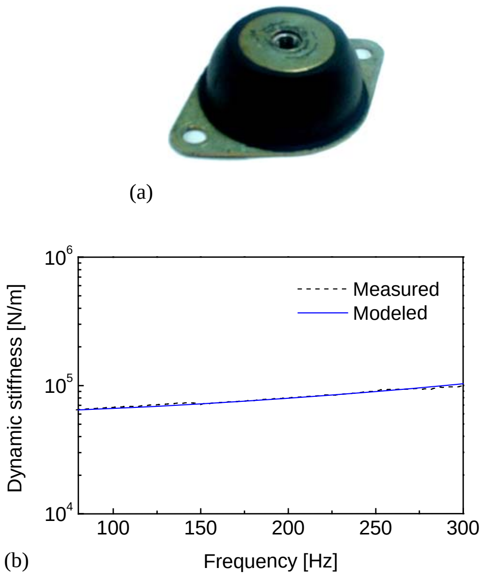

Fig. 2. Rubber mount: (a) photograph; (b) dynamic stiffness.

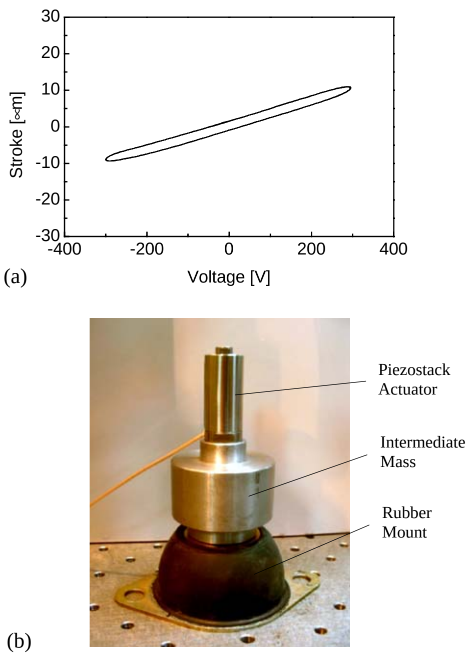

Fig. 3. Piezostack actuator on rubber mount: (a) piezostack performance; (b) photograph.

3. Control results

In order to determine dominant vibration modes of the beam structure, the acceleration responses are measured at the location of l_2 and presented in Fig. 4. Fig. 4(a) has been obtained by installing three rubber mounts ($l_1 = 50\,\text{mm}$, $l_2 = 650\,\text{mm}$, $l_3 = 1450\,\text{mm}$), while Fig. 4(b) by installing two rubber mounts (l_1, l_3) and one hybrid mount (l_2) without control voltage. It is clearly seen from two cases that the third and fourth modes are dominant for the transverse deflection of the beam. In addition, we see that two dominant frequencies are different from each other. This, of course, is due to the different dynamic properties between the rubber mount (l_2) and the piezostack hybrid mount (l_2). In this work, two dominant modes shown in Fig. 4(b) are chosen as control modes.

Among numerous control strategies, a sliding mode control scheme which is known to be robust to the hysteresis and external disturbance [12] has been adopted in this work. As a first step, the sliding surface is defined as follows: $s(t) = \mathbf{G}\mathbf{x}(t)$. Here, $\mathbf{G}(= [g_1 \quad g_2 \quad g_3 \quad g_4 \quad g_5 \quad g_6])$ is the sliding surface gradient, and $\mathbf{x}(t)$ are state variables to be controlled. The existence condition of the sliding mode motion is given by $\frac{1}{2}(\mathrm{d}/\mathrm{d}t)s^2(t) \leqslant -\eta|s(t)|$. Here, η is a strictly positive constant. This condition allows the state variables $\mathbf{x}(t)$ converge to the sliding surface $s(t)$. The sliding mode controller which satisfies the existence condition of the sliding mode motion is obtained by $f_a(t) = -(\mathbf{GB})^{-1}(\mathbf{GAx}(t) + k\,\mathrm{sgn}(s(t)))$. Here, $\mathbf{B}$ is the input matrix, $\mathbf{A}$ the system matrix, k the feedback gain, and $\mathrm{sgn}(\cdot)$ the sign function (refer to Ref. [11] for the details of $\mathbf{A}$ and $\mathbf{B}$ matrices). Once the actuating force $f_a(t)$ is determined via the sliding

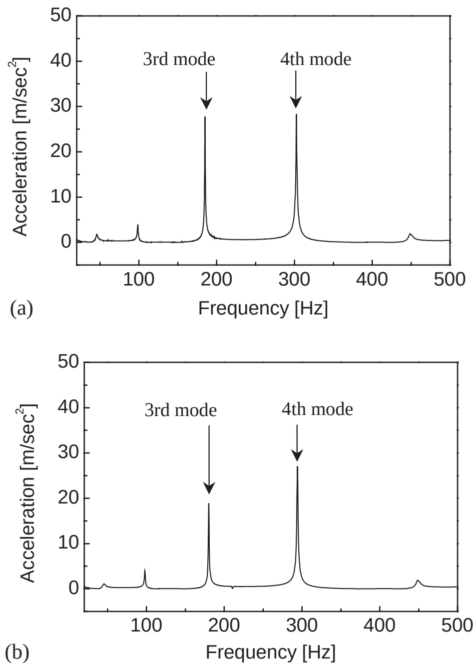

Fig. 4. Measured acceleration response at l_2: (a) with three rubber mounts; (b) with two rubber mounts and one hybrid mount (without control voltage).

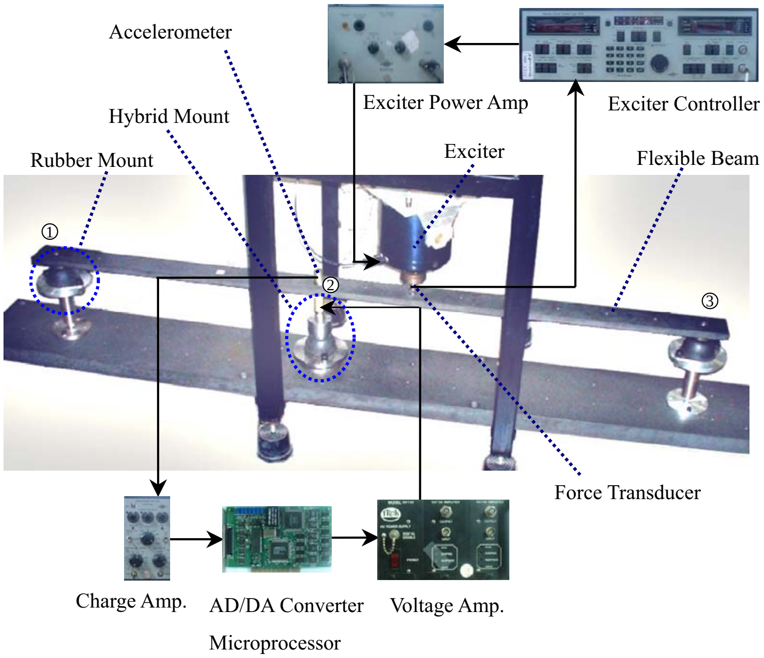

Fig. 5. Experimental set-up.

mode controller, the control voltage $V(t)$ to be applied to the piezostack actuator is obtained by the relationship of $f_a(t) = \alpha V(t)$. It is noted that since all of control variables $\mathbf{x}(t)$ are not available from the direct measurement, the Luenberger observer [13] has been used in this experiment.

In order to implement the sliding mode controller, an experimental set-up is established as shown in Fig. 5. The dimension of the steel beam used in this experiment is 1500 mm(length) $\times$ 60 mm(width) $\times$ 15 mm(thickness). The flexible beam is excited by the electromagnetic exciter, and the excitation force and frequency are regulated by the exciter control. Accelerometers are attached to the beam, and their positions are denoted by ① ($x = l_1$), ② ($x = l_2$), and ③ ($x = l_3$). The accelerometer at position ② is used for the feedback signal as shown in Fig. 5. The velocity signal at this position is obtained by installing integrator circuit. The velocity signal is then fed back to the microprocessor via an A/D (analog to digital) converter. The state variables required for the sliding mode controller are then estimated by the Luenberger observer. The control voltage is applied to the piezostack via a D/A (digital to analog) converter and a voltage amplifier which has a gain of 20. The sampling rate in the controller implementation is chosen by 12.5 kHz.

Fig. 6 presents the displacement responses of the beam structure at the positions of l_1 and l_2. Time responses are obtained at the fourth resonance frequency (294 Hz). We clearly see that the displacements are substantially reduced by activating the piezostack actuator. Fig. 7 presents the acceleration responses of the beam at l_1 and l_2. The excitation force amplitude is set by 1 N. It is clearly observed that acceleration levels at the resonances are substantially suppressed by activating the controller associated with the hybrid mount. It is noted that control performance has not been deteriorated in the non-resonant region.

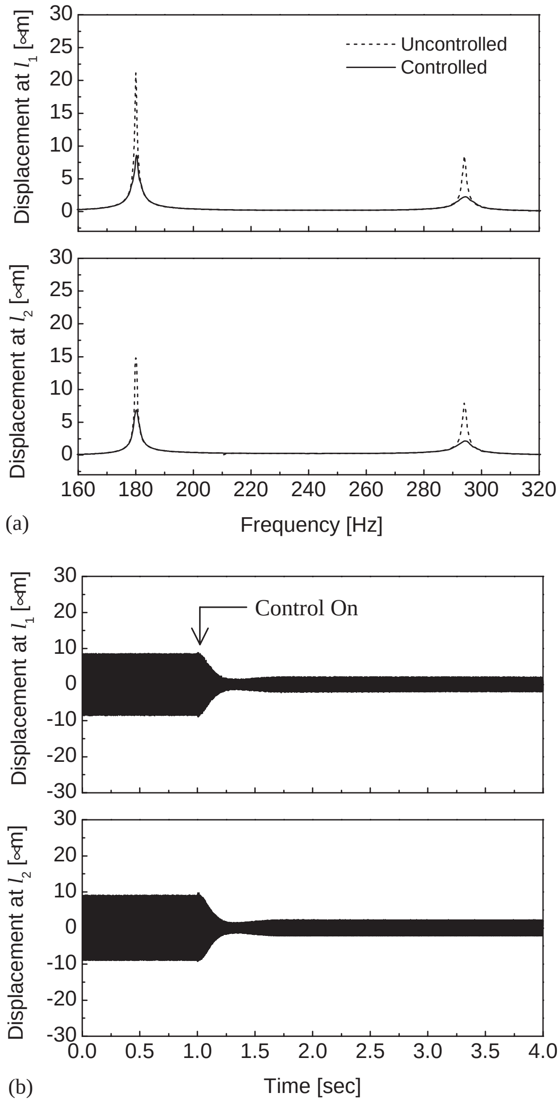

Fig. 6. Displacement responses with rubber and hybrid mounts: (a) frequency responses; (b) time responses at the fourth mode.

4. Concluding remarks

After identifying dynamic properties of the rubber mount and the piezostack actuator, a sliding mode controller was designed and experimentally realized. It has been shown that the imposed vibrations such as acceleration of the beam structure are substantially reduced at target resonances by activating the proposed hybrid piezostack mount without performance deterioration in the non-resonant region. The optimal location

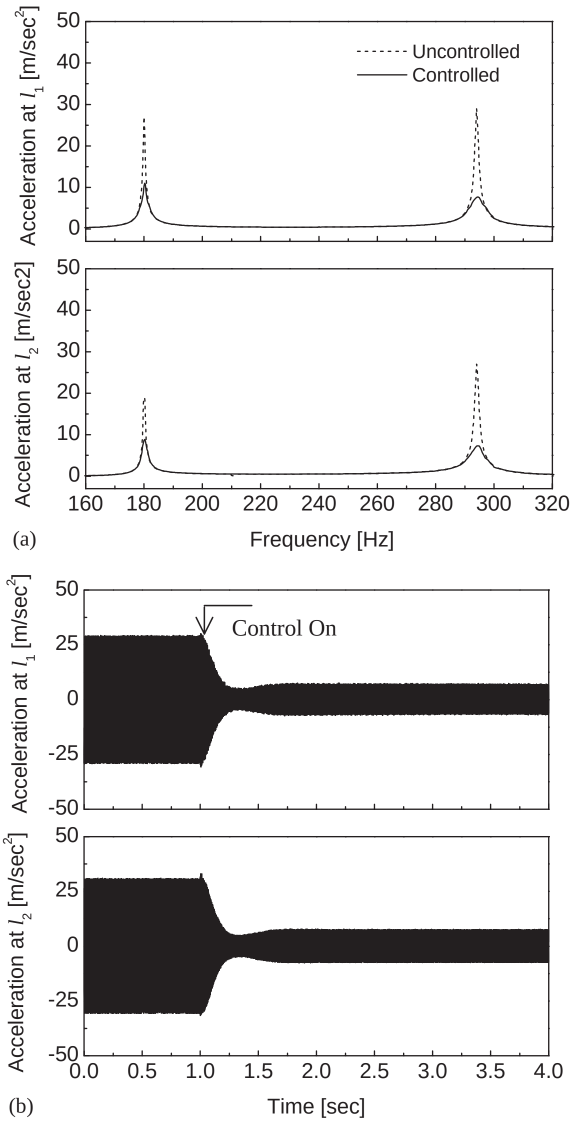

Fig. 7. Acceleration responses with rubber and hybrid mounts: (a) frequency responses; (b) time responses at the fourth mode.

for the piezostack hybrid mount based on modal analysis is remained as a future research work.

Acknowledgements

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References

[1] Y. Yu, S.M. Peelamedu, N.G. Nagathan, R.V. Dukkipati, Automotive vehicle engine mounting systems: a survey, *American Society of Mechanical Engineers Journal of Dynamic Systems, Measurement and Control* 123 (2001) 186–194.

[2] S.B. Choi, Y.K. Park, C.C. Cheong, Active vibration control of intelligent composite laminate structures incorporating an electro-rheological fluid, *Journal of Intelligent Material Systems and Structure* 7 (4) (1996) 419–441.

[3] S.B. Choi, Vibration control of a flexible structure using ER dampers, *American Society of Mechanical Engineers, Journal of Dynamic Systems, Measurement and Control* 121 (9) (1999) 134–138.

[4] S.B. Choi, C.C. Cheong, Vibration control of a flexible beam using SMA actuators, *Journal of Guidance, Control, and Dynamics* 19 (5) (1996) 1178–1180.

[5] A. Baz, S. Poh, Performance of an active control system with piezoelectric actuators, *Journal of Sound and Vibration* 126 (2) (1988) 327–343.

[6] H.S. Tzou, Distributed modal identification and vibration control of continua: theory and applications, *American Society of Mechanical Engineers Journal of Dynamic Systems, Measurement and Control* 113 (1993) 494–499.

[7] T. Ushijima, S. Kumakawa, Active engine mount with piezo-actuator for vibration control, SAE Technical Paper Series 930201, 1993.

[8] T. Kamada, T. Fujita, T. Hatayama, T. Arikabe, N. Murai, S. Aizawa, K. Tohyama, Active vibration control of frame structures with smart structures using piezoelectric actuators (vibration control by control of bending moments of columns), *Smart Materials and Structure* 6 (4) (1997) 448–456.

[9] S.H. Choi, Y.T. Choi, S.B. Choi, C.C. Cheong, Performance analysis of an engine mount featuring ER fluids and piezoactuators, *International Journal of Modern Physics B* 10 (23) (1996) 3143–3157.

[10] M.N. Ichchou, B. Jemai, L. Bellon, L. Jezeguel, Active rubber mount by means of piezoelectric actuators, experimental work, *Smart Materials and Structures* 10 (5) (2001) 1095–1099.

[11] S.H. Kim, Vibration Control of a Beam Structure using a Hybrid Mount, MS Thesis, Inha University, 2003.

[12] D.W. Park, S.B. Choi, Moving sliding surfaces for high-order variable systems, *International Journal of Control* 72 (11) (1999) 960–970.

[13] C.T. Chen, *Linear System Theory and Design*, Oxford University Press, Oxford, 1999.