DOI: 10.3901/CJME.2010.0*.***, available online at www.cjmenet.com; www.cjmenet.com.cn

Vibration Control of a Composite Beam Using Self-sensing Semi-active Approach

JI Hongli, QIU Jinhao*, and ZHU Kongjun

The Key Laboratory of Aircraft Structural Mechanics and Control of Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Received February 10, 2009; revised July 18, 2010; accepted August **, 2010; published electronically ****, 2010

Abstract: Structural vibration control was an active research area for the past twenty years because of their potential applications in aerospace structures, civil structures, naval structures, etc. Semi-active vibration control methods based on piezoelectric actuators and synchronized switch damping on inductance (SSDI) techniques attract the attention of many researchers recently due to their advantages over passive and active methods. In the SSDI method, a switched shunt circuit is connected to the piezoelectric patch to shift the phase and amplify the magnitude of the voltage on the piezoelectric patch. The most important issue in SSDI method is to control the switching actions synchronously with the maximum vibration displacement or maximum strain. Hence, usually a displacement sensor is used to measure the vibration displacement or a collocated piezoelectric sensor is needed to measure the strain of the structure near the piezoelectric actuator. A self-sensing SSDI approach is proposed and applied to the vibration control of a composite beam, which avoids using a separate sensor. In the self-sensing technique, the same piezoelectric element functions as both a sensor and an actuator so that the total number of required piezoelectric elements can be reduced. One problem in the self-sensing actuator, which is the same as that in the traditional collocated piezoelectric sensors, is the noise generated in the sensor signal by the impact of voltage inversion, which may cause extra switching actions and deteriorate control performance. In order to prevent the shunt circuit from over-frequent on-and-off actions, a simple switch control algorithm is proposed. The results of control experiments show that the self-sensing SSDI approach combined with the improved switch control algorithm and effectively suppress over-frequent switching actions and gives good control performance by reducing the vibration amplitude by 45%, about 50% improvement from the traditional SSDI with a separate piezoelectric element and a classical switch.

Key words: piezoelectric elements, synchronized switch damping, semi-active control, vibration damping, self-sensing

1 Introduction

Piezoelectric materials are widely used as sensors and actuators in vibration and noise control of smart structures owing to their excellent frequency characteristics and capability in reciprocal conversion between the electric and mechanical strain energy. Vibration control using piezoelectric materials has received much attention in recent years. The methods of vibration control can be mainly divided into three categories, passive, active, and semi-active. Among of these methods, the semi-active control which is called synchronized switch damping (SSD) has been attracting much attention in recent years because of several advantages: Compared with passive and active vibration control, it is not sensitive to the variation of the system parameters, and the control system is more compact.

The SSD method consists in a nonlinear processing of the voltage on a piezoelectric patch embedded in the structure. It is implemented with a simple electric shunt circuit, which is connected to the piezoelectric patch and switched synchronously with the structural vibration. This switched shunt circuit is used to process the voltage on the piezoelectric element. The switch is kept open for most of the time in a period of vibration and closed for a short duration (much shorter than the period of vibration) when the voltage reaches a maximum (corresponding to a maximum of the strain in the piezoelectric patch). Due to this process, a voltage magnification is obtained and a phase shift appears between the strain in piezoelectric patch and the resulting voltage, thus creating energy dissipation. Several SSD techniques, depending on the structure of the shunt circuit (short circuit, inductor, voltage sources depending on the SSD version), have been reported[1–5].

The most important issue in SSD methods is to drive the switch synchronously with the maximum vibration displacement or maximum strain. In the former studies, usually displacement sensors or additional piezoelectric patches, which are bonded at the same place on the structure, were used to measure the strain[6–8]. However,

---

* Corresponding author. E-mail: qiu@nuaa.edu.cn

This project is supported by National Natural Science Foundation of China (Grant No. 50775110), Aeronautical Science Fund of China (Grant No. 20091552017), and Jiangsu Provincal Graduate Innovation Program of China (Grant No. CX08B_048Z)

sometimes there are difficulties in using these sensors for switch control, due to phase difference and interference between the sensor and actuator. The self-sensing technique, in which the same piezoelectric functions as a sensor and an actuator, is an ideal solution for these problems.

The self-sensing technique was originally proposed for active control[9–10]. Due to the true collocation of the sensor and actuator, a velocity feedback system using a self-sensing actuator is unconditionally stable. A great number of researches on self-sensing methods of piezoelectric actuators have been conducted in active control, and the use of a bridge circuit connected to a piezoelectric actuator is a common approach[11–12]. However, the high sensitivity of the bridge circuit to variations in the parameter values is a serious drawback of this technique. According to ANDERSON, et al[13], a mere 1% variation in piezoelectric capacitance can make active self-sensing control system unstable because of the imbalance of the bridge circuit. These self-sensing approaches have been investigated intensively for the active vibration control[14–15]. But very few studies have been reported on application of self-sensing in semi-active vibration suppression with piezoelectric actuators. MAKIHARA, et al[16], proposed a novel self-sensing method for semi-active vibration control based on a Kalman filter.

In this paper, a simple self-sensing semi-active approach based on SSDI technique is proposed and applied to the vibration control of a composite beam. The self-sensing technique proposed in this study is easy to implement because the strain extrema are detected directly from the voltage signal of the self-sensing piezoelectric actuator. In the semi-active approach, the control of switching actions in the shunt circuit is critical to the control performance. An improved switch is proposed in this study to prevent the system from over-frequent switching actions due to the noise in the sensor signal.

2 Mechanical Model of the Beam

The structure used in the experiment is a composite beam with two embedded piezoelectric patches as shown in Fig. 1. The one end of beam is clamped at a mini-shaker which is used to drive the vibration and piezoelectric patches are bonded on its surface close to the clamped end. The beam is 300 mm long, 50 mm wide and 1.2 mm thick. It is assumed that the structure acts as pure Euler-Bernoulli beam. In this study, control of the resonant vibration at the first nature frequency is considered. Hence, the amplitude of the first mode is dominant and the high-order modes can be neglected. That is, at the first resonant frequency, the structure can be simplified to a single-degree-of-freedom system, represented in Fig. 2. The equation of motion can then be expressed in the following form:

$$M\ddot{u} + C\dot{u} + K_E u = F_e + F_p , \tag{1}$$

where M is the modal mass, C is the modal damping coefficient, K_E is the modal stiffness, and F_e and F_p are modal force due to excitation and the piezoelectric patch, respectively. M, K_E, and F_e and F_p can be derived from the equation of motion of the beam, but C must be estimated experimentally. F_p can be expressed in the form $F_p = -\alpha V$, where minus sign is to express the direction of force.

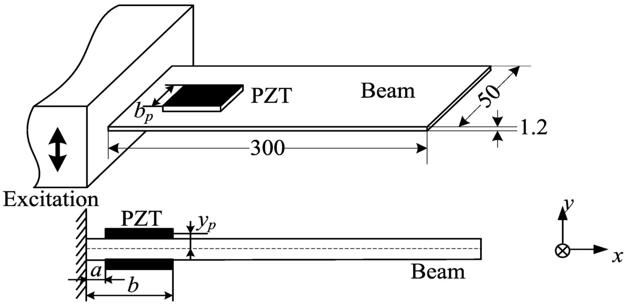


Fig. 1. Schematic representation of the system

The following energy equation is obtained by multiplying both sides of Eq. (1) by the velocity and integrating over the time variable:

$$\int F_e \dot{u} \mathrm{d}t = \frac{1}{2} M \dot{u}^2 + \frac{1}{2} K_E u^2 + \int C \dot{u}^2 \mathrm{d}t + \int \alpha V \dot{u} \mathrm{d}t . \tag{2}$$

The provided energy is divided into kinetic energy, potential elastic energy, mechanical losses, and transferred energy. The transferred energy $\int \alpha V \dot{u} dt$ corresponds to the part of the mechanical energy which is converted into electrical energy. For a certain vibration level, maximization of this energy leads to minimization of the mechanical energy in the structure. However, as the vibration level is reduced, the absolute value of this energy may decrease. Hence the objective of all the SSD control approaches is to maximizing this energy in a given vibration level.

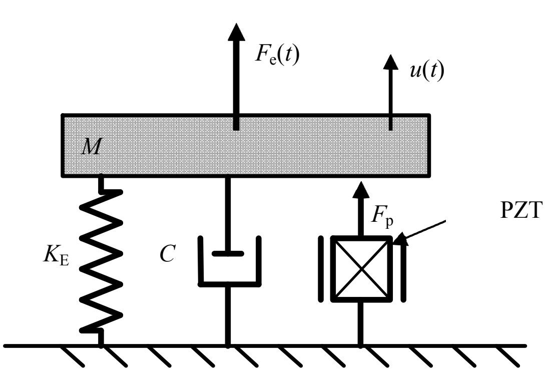


Fig. 2. Diagram of the electromechanical model

3 Control System

3.1 Principle of the synchronized switch damping on inductor (SSDI)

The schematic diagram of a SSDI control system is shown in Fig. 3. In the SSDI, a shunt circuit is connected to the piezoelectric element. The circuit is composed of a switch and an inductance *L*. The switch is in open state for most of the time except when a voltage extremum occurs (it corresponds to the strain extremum because the voltage is proportional to the strain). At this time, the switch is closed. Since the piezoelectric element and the inductor constitute a *L*-*C* resonance circuit, fast inversion of the voltage on the piezoelectric element is achieved by appropriately controlling the closing time and duration of the switch. The duration of the closed state t_i is half the period of the *L*-*C* circuit. The period of the *L*-*C* circuit is chosen to be much smaller than that of the mechanical vibration. Normally it is roughly between 1/20 and 1/50 of the mechanical vibration period[17].

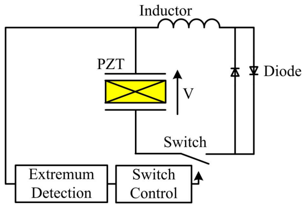


Fig. 3. Schematic diagram of a SSDI control system

If there is no shunt circuit connected to the piezoelectric element, the generated voltage *V* on the piezoelectric patch is proportional to the actual displacement *u* as shown in the Fig. 4. In half of the vibration cycle the mechanical energy is converted to electrical energy. In the other half of the cycle, the electrical energy is converted back to mechanical so that the net converted energy is zero. In the SSDI, the shunt circuit is not only used to shift the phase of the voltage on the piezoelectric patch, so that the force generated by the voltage is always opposite to the velocity $\dot{u}$ of the vibrating structure, but also amplify the voltage. So during a whole vibration cycle, the mechanical energy is always converted in electrical energy. The dissipated energy E_t during a period of single-mode vibrations (provided that the switch actions take place at the strain extremum) is given by Eq. (3):

$$E_t = \frac{4\alpha^2}{C_0} \square \frac{1+\gamma}{1-\gamma} u_M^2 \ , \tag{3}$$

where u_M is the displacement amplitude of voltage, C_0 is the capacitance of the piezoelectric patch, and $\gamma \in [0,1]$ is the voltage inversion coefficient, which is defined as the ratio of the voltages after and before inversion. The value of γ depends on the quality factor of the resonance circuit.

Since the shunt circuit is switched at the maximum strain of the piezoelectric actuator, the strain signal is essential for switch control in a SSDI control system. JI, et al[18], studied the relationship between the switching delay and the control performance. The results show that the best control performance is achieved when the circuit is switched at every strain extremum in single-mode vibration control so that the voltage on the piezoelectric actuator is reversed twice in a period of vibration. The control performance deteriorates as the switching delay increases. Usually, a displacement sensor or an additional piezoelectric patch is used to measure the strain indirectly. However sometimes there are difficulties in using these sensors for switch control. For example, phase difference can be induced between the voltage of the piezoelectric actuator and the sensor output if the sensor is not placed at an appropriate position. When a piezoelectric sensor is located too near to the actuator, a noise can be induced in the sensor signal due to the local mechanical coupling. In this study, a self-sensing technique, in which a single piece of piezoelectric element plays the roles of both the traditional sensor and actuator concurrently, is proposed for SSDI.

Fig. 4. Diagram of the electromechanical model

3.2 Self-sensing technique

The self-sensing technique has been widely used in active control of structural vibrations. It has attracted much attention because of its advantages. Due to the true collocation of the sensor and actuator, a structure controlled with collected velocity feedback is unconditionally stable at all frequencies. The total number of piezoelectric elements for sensors and actuators can be reduced. The key issue in self-sensing is to separate the sensor signal caused by mechanical strain of a piezoelectric element from the control signal applied to the same piezoelectric element. Usually a bridge circuit is used by many researchers to achieve the objective. However, the high sensitivity of the bridge circuit to variations in the parameter values is a serious drawback of this technique.

In this paper, a new self-sensing technique is proposed for semi-active vibration control. In SSDI approach, the key issue is to detect the extrema of strain in the piezoelectric actuator. Self-sensing in SSDI means detecting the extrema based on the actuator voltage signal without using a displacement sensor or an additional piezoelectric element. Since there is no externally applied signal to the piezoelectric actuator, self-sensing technique is easier to realize in semi-active vibration control than in active vibration control. As discussed above, the voltage on the piezoelectric element is proportional to its strain if there are no switching actions. The voltage can be divided into two components[19]: one being an image of the strain and the other being a rectangular waveform as shown in Fig. 5, when the switch works. Since the voltage component due to switching actions keeps constant between two switching actions, the voltage on the piezoelectric element can be used to detect the strain extrama.

Fig. 5. Decomposition of the voltage signal in SSDI techniques

The voltage on the piezoelectric element is converted to digital signal. When the voltage values at there consecutive sampling points, t_0, t_1 and t_2, are V_0, V_1 and V_2, then the strain in the piezoelectric patch reaches an extremum at t_1 if the voltage values satisfy

$$(V_0 - V_1)\cdot(V_1 - V_2) < 0 . \tag{4}$$

When a strain extremum is detected, a switch control signal is generated to inverse the voltage on the piezoelectric patch. Fig. 3 shows schematic view of the switched voltage on the piezoelectric patch. Hence in the self-sensing technique, extremum detecting algorithm is the same as that in a system using external sensors, but the number of piezoelectric patches can be reduced.

3.3 Improved switching algorithm

The main problem in using Eq. (4) for extremum detection is the noise in the voltage signal. If the noise level is high enough, some detected extrema are induced by the noise, not the strain. That is, more than two extrema can be detected from the voltage signal in a period of single-mode vibration. This may lead to over-frequent on-and-off actions of the switch and low control performance.

In order to prevent over-frequent on-and-off actions of the switch, an improved switch control algorithm is proposed in this study. The improved algorithm turns switch to inactive state for a certain period, τ, after each switching action so that no switching actions can occur in this period even if extrema are detected. It can prevent the switch from over-frequent on-and-off actions and consequently increase the stability and control performance of the control system. Hence a switching signal is generated only when the following condition is satisfied in addition to Eq. (4):

$$t_1 - t_1' > \tau , \tag{5}$$

where t_1' is the time of the previous switching point. Parameter τ should be smaller than half the period of vibration to be controlled.

As shown in the experimental results later, the above algorithm is effective in increasing the control performance because the sensor noise in the self-sensing actuator is generated by the switching actions. If the switch can be kept inactive at the subsequent extrema induced by a switching action, the problem of over-frequent switching actions can be solved in the self-sensing SSDI approach. In a general case, the above algorithm may not work effectively because it may prevent the switching from actions at real extrema of displacement or strain. In that case, it can be combined with other algorithms, e.g., with a displacement threshold criteria. That is, in addition to the above condition, switching actions only take place when displacement satisfies

$$|u| > u_M, \tag{6}$$

where u_M is the displacement threshold for switching action. The displacement threshold in a real system should be adjusted automatically according to the vibration level and control state as shown in Ref. [18].

3.4 Experimental setup for control

The schematic of the experimental setup is shown in Fig. 6. One end of the beam is clamped and the other is free. The piezoelectric patches are located near the clamped end, where the maximum strain is induced. The geometrical parameters and physical properties of the piezoelectric patches and the beam are listed in Tables 1 and 2. The detailed configuration of the composite beam is given in[4–5]. In the experiment, the beam is excited at the first resonance frequency of the beam, which is 11 Hz.

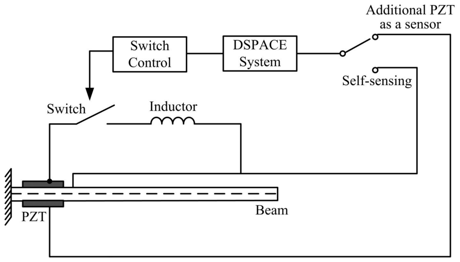


Fig. 6. Schematic of the experimental setup

Table 1. Material properties of the piezoelectric patch

Material properties	Values
Elastic modulus E/GPa	59
Poisson ratio v	0.345
Density ρ /(kg • m^{-3})	7.4×10^3

Thickness h/mm	0.2
Piezoelectric constant d_{31}/(mm • V^{-1})	-2.6×10^{-7}
Capacitance C_p/ nF	141

For comparison purpose, control experiments using both self-sensing technique and a separate sensor were carried out. In the control experiments by using self-sensing technique, the top piezoelectric patch is used as a self-sensing actuator. In the control experiments by using a separate sensor, the top piezoelectric patch is used as an actuator and the bottom one is used as a sensor. The SSDI control system is implemented in a digital signal processing (DSP) environment based on the dSPACE board DS1103. The voltage signal from the piezoelectric patch is converted to digital and sent to the DSP system. The extrema of the voltage signal are detected using Eq. (4). When the classical switch control algorithm is used, a switching signal is generated at each detected extremum. However, when the improved switch control algorithm is used, a switching signal is generated only when both Eqs. (4) and (5) are satisfied. Control experiments were carried out using the different combinations of the two sensing approaches and the two switch control algorithms and their results are compared.

Table 2. Material properties of the composite beam

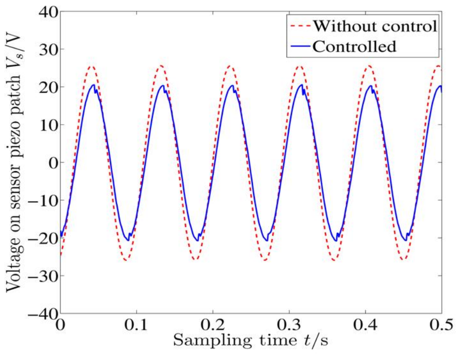
Material propertie	Value
Elastic modulus E_1/GPa	16.5
Elastic modulus E_2/GPa	35.2
Poisson ratio v	0.109
Shear modulus G/GPa	12.5
Density ρ /(kg • m^{-3})	1.8×10^3
Thickness h/mm	1.2

4 Results and Discussion

4.1 Results of the SSDI control using a separate sensor

First, experiments using a separate sensor and the classical switch were performed. The voltage on the sensor piezoelectric patch is shown in Fig. 7 (a). Since the voltage on the sensor piezoelectric patch is proportional to the strain, it can be used to evaluate the control performance. The amplitude of voltage on the sensor piezoelectric patch is reduced from 25.7 V to 19.2 V. It means that the strain amplitude or displacement amplitude of vibration has been reduced by 25 percent.

The voltage on the actuator piezoelectric patch is shown in Fig. 7 (b). Although the maximum voltage has become smaller, its phase has shifted 90° so that the force produced by the voltage is always opposite to the velocity of vibration. It can also be found from the voltage on the actuator piezoelectric patch that two or more switching actions occur at most of the strain extrema. The extra switching actions can be attributed to the noise in the voltage signal of the sensor piezoelectric patch as shown in Fig. 7(a). It is not difficult to understand that the noise in the sensor signal is induced by the sudden change of voltage on the actuator piezoelectric patch, which induces a sudden change of the local strain around the actuator piezoelectric patch. Since the sensor piezoelectric patch and actuator piezoelectric patch are located at the same position, the strain change is reflected in the voltage signal of the actuator piezoelectric patch. The spectrum of the sensor signals with and without control is shown in Fig. 8. The reduction of sensor voltage is 2.354 dB.



(a) Voltages on the sensor piezoelectric patch

(b) Voltages on the actuator piezoelectric patch

Fig. 7. Voltages on the sensor and actuator piezoelectric patches using a separate sensor and the classical switch

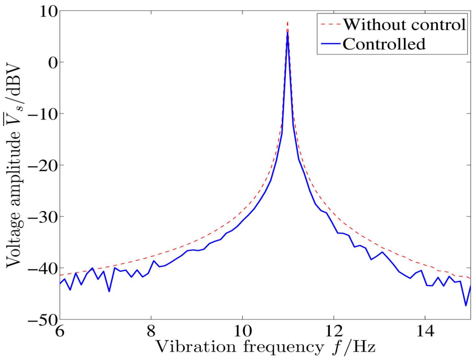
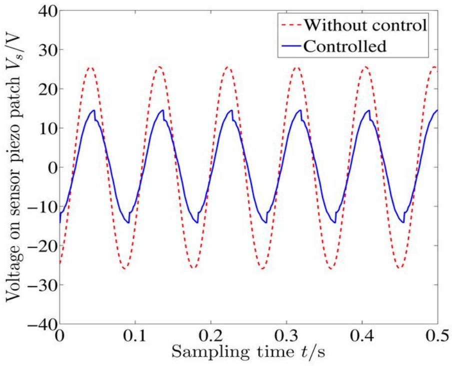


Fig. 8. Spectrum of the sensor voltage using a separate sensor and the classical switch

Next, control experiments using a separate sensor and the improved switch were performed. The voltage on the sensor piezoelectric patch is shown in Fig. 9(a) and the voltage on the actuator piezoelectric patch is shown in Fig. 9(b). The inactive period τ is set to 0.002 5 s. Figure 9 (b) shows that excessive switching actions have been prevented and that not only the phase of the voltage on the actuator piezoelectric patch has been shifted by 90°, but also its amplitude has been amplified to 18 V due to the suppression of unnecessary switching actions.



(a) Voltages on the sensor piezoelectric patch

(b) Voltages on the actuator piezoelectric patch

Fig. 9. Voltages on the sensor and actuator piezoelectric patches using a separate sensor and the improved switch

The sensor signal in Fig. 9(a) shows that the sudden change of voltage in the sensor piezoelectric patch induced by the voltage inversion in the actuator piezoelectric patch still exists, but better control is achieved due to suppression of unnecessary switching actions. Fig. 10 shows the spectrum of the sensor voltage with and without control. The amplitude of the sensor voltage is reduced by 5.74 dB using a separate sensor and the improved switch, which is better than that achieved using the classical switch.

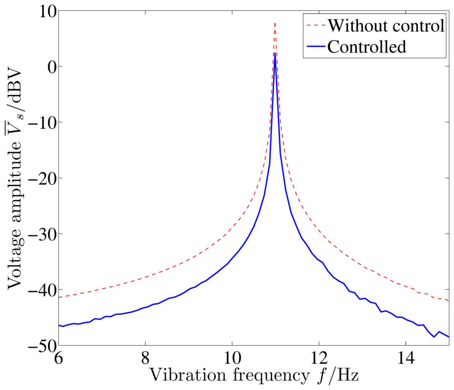
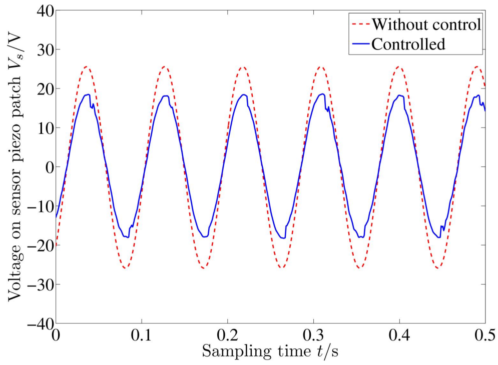


Fig. 10. Spectrum of the sensor voltage using a separate sensor and the improved switch

4.2 Results of the SSDI control using a self-sensing actuator

In the experiments of SSDI control using the self-sensing technique, the top piezoelectric patch was used as a self-sensing actuator. The bottom piezoelectric patch was only used as a sensor for the evaluation of control performance. The voltage on the sensor piezoelectric patch is shown in Fig. 11(a) and the voltage on the self-sensing actuator is shown in Fig. 11(b) when using the classical switch. The amplitude of voltage on the sensor piezoelectric patch is reduced from 25.7 V to 16.6 V. The sensor voltage with control in Fig. 11(a) is very similar to that in Fig. 7(a), but a little better control performance is achieved due to fewer excessive switching actions with the self-sensing actuator. It means that the self-sensing actuator gives better quality of sensor signal than the separate piezoelectric patch sensor does. Fig. 12 shows the spectrum of the sensor voltage with and without control. The amplitude of the sensor voltage is reduced by 3.194 db using a self-sensing actuator and the classical switch, which is better than that achieved using a separate piezoelectric patch sensor.



(a) Voltages on the sensor piezoelectric patch

(b) Voltages on the actuator piezoelectric patch

Fig. 11. Voltages on the sensor and actuator piezoelectric patches using self-sensing technique and the classical switch

The voltage on the sensor piezoelectric patch is shown in Fig. 13(a) and the voltage on the self-sensing actuator is shown in Fig. 13(b) when the self-sensing technique is combined with the improved switch. The inactive period τ is set to 0.002 5 s. The amplitude of voltage on the sensor piezoelectric patch is reduced from 25.7 V to 12.7 V. Fig. 13(b) shows that all the unnecessary switching actions have been prevented and that the amplitude of actuator has been amplified to 18.5 V due to the suppression of unnecessary switching actions, which is the same as that in the case using a separate sensor.

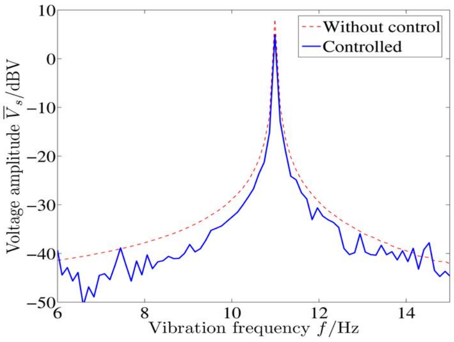
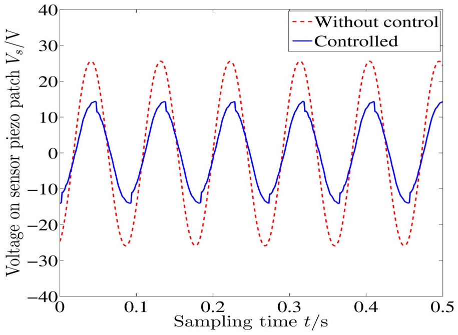


Fig. 12. Spectrum of the sensor voltage using self-sensing technique and the classical switch



(a) Voltages on the sensor piezoelectric patch

(b) Voltages on the actuator piezoelectric patch

Fig. 13. Voltages on the sensor and actuator piezoelectric patches using self-sensing technique and the improved switch

Fig. 14 shows the spectrum of the sensor voltage with and without control. The amplitude of the sensor voltage is reduced by 5.77 db using a self-sensing actuator and the improved switch, which is the same as that achieved using a separate piezoelectric patch sensor.

From the above experimental results, we can conclude that the self-sensing technique proposed in the study is effective when it is applied to SSDI control. By using the self-sensing technique, the number of piezoelectric patch can be reduced. Since no extra hardware or software is required in the self-sensing technique, it is easy to implement and can easily be applied to the self-powered SSDI control systems, which have been proved possible in the former studies[20].

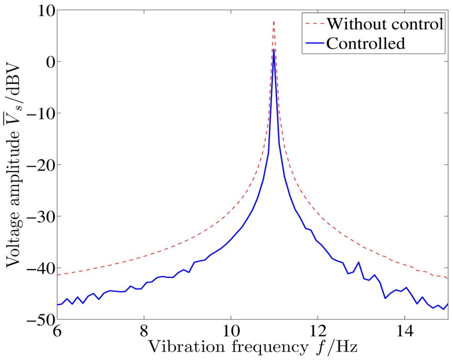


Fig. 14. Spectrum of the sensor voltage using self-sensing technique and the improved switch

5 Conclusions

(1) A self-sensing semi-active vibration control approach based on a self-sensing piezoelectric actuator and the semi-active synchronized switch damping on inductance (SSDI) method is proposed and applied in the vibration control of a composite beam.

(2) The self-sensing actuator functions as both a sensor for detection of strain extrema and an actuator for vibration suppression so that no external displacement sensor or additional piezoelectric element is needed for measurement of the displacement or strain.

(3) An improved switch, which can prevent the shunt circuit from over-frequent on-and-off actions, is also proposed to improve the control.

(4) The experimental results show that the self-sensing SSDI approach gives better control performance than the traditional SSDI using an additional piezoelectric element as a sensor when they are combined with a classical switch, and the same control performance when they are combined with the improved switch.

References

[1] CLARK W W. Semi-active vibration control with piezoelectric materials as variable stiffness actuators[C]//*Proceedings of SPIE International Symposium on Smart Structures and Materials*: Passive *Damping and Isolation*, Newport Beach, USA, 3672, 1999: 2 623–2 629.

[2] RICHARD C, GUYOMAR D, AUDIGIER D, et al. Enhanced semi passive damping using continuous switching of a piezoelectric device on an inductor[C]//*Proceedings of SPIE International Symposium on Smart Structures and Materials*: *Damping and Isolation*, Newport Beach, USA, 3989, 2000: 288–299.

[3] BADEL A, SEBALD G, GUYOMAR D, et al. Piezoelectric vibration control by synchronized switching on adaptive voltage sources: Towards wideband semi-active damping[J]. *Journal of*

Acoustics Society American, 2006, 119(5): 2 815–2 825.

[4] JI Honhli, QIU Jinhao, BADEL A, et al. Semi-active vibration control of a composite beam using an adaptive SSDV approach[J]. *Journal of Intelligent Material Systems and Structures*, 2009, 20(3): 401–412.

[5] JI Hongli, QIU Jinhao, ZHAO Yongchun, et al. A study on semi-active vibration control using piezoelectric elements[J]. *Journal of Vibration Engineering*, 2008, 21(6): 614–619. (in Chinese)

[6] LEFEUVRE E, GUYOMAR D, PETIT L, et al. Semi-passive structural damping by synchronized switching on voltage sources[J]. *Journal of Intelligent Material Systems and Structures*, 2006, 17(8/9): 653–660.

[7] RICHARD C, GUYOMAR D, AUDIGIER D, et al. Semi-passive damping using continuous switching of a piezoelectric device[C]//*Proceedings of the SPIE Smart Structures and Materials Conference*: *Passive Damping and Isolation*, San Diego, 1998, 3672: 104–111.

[8] ONODA J, MAKIHARA K, MINESUGI K. Energy-recycling semi-active method for vibration suppression with piezoelectric transducers[J]. *AIAA Journal*, 2003, 41(4): 711–719.

[9] QIU Jinhao, HARAGUCHI M. Vibration control of a plate using a self-sensing actuator and an adaptive control approach[J]. *Journal Intelligent Material Systems and Structures*, 2006, 17(8/9): 661–669.

[10] QIU Jinhao, TANI J, HARAGUCHI M. Suppression of noise radiation from a plate using self-sensing actuators[J]. *Journal Intelligent Material Systems and Structures*, 2005, 16(11/12): 963–970.

[11] DOSCH J J, INMAN D J. A self-sensing piezoelectric actuator for collocated control[J]. *Journal Intelligent Material Systems and Structures*, 1992, 3(1): 166–185.

[12] DONGI F, DINKLER D, KROPLIN B. Active panel flutter suppression using self-sensing piezoactuators[J]. *AIAA Journal*, 1996, 34(6): 1 224–1 230.

[13] ANDERSON E H, HAGOOD NW, GOODLIFFE J M. Self-sensing piezoelectric actuation: analysis and application to controlled structures[C]//*Proceedings of 33rd AIAA/ASME/ASCE/AHS/ASC Structures*, *Structural Dynamics and Materials Conference*, CP-2465, AIAA, Washington, DC, 1992: 2 141–2 155.

[14] LAW W W, LIAO W H, HUANG J. Vibration control of structures with self-sensing piezoelectric actuators incorporating adaptive mechanisms[J]. *Smart Materials and Structures*, 2003, 12(5): 720–730.

[15] OSHIMA K, TAKIGAMI T, HAYAKAWA Y. Robust vibration control of a cantilever beam using self-sensing actuator[J]. *JSME International Journal Series C-Mechanical Systems Machine Elements and Manufacturing*, 1997, 40(4): 681–687.

[16] MAKIHARA K, ONODA J, MINESUGI K. Novel approach to self-sensing actuation for semi-active vibration suppression[J]. *AIAA Journal*, 2006, 44(7): 1 445–1 453.

[17] BADEL A, GUYOMAR D. Nonlinear semi-passive multimodal vibration damping: an efficient probabilistic approach[J]. *Journal of Sound and Vibration*, 2006, 294: 249–268.

[18] JI Hongli, QIU Jinhao, ZHU Kongjun, et al. Multi-modal vibration control using a synchronized switch based on a displacement switching threshold[J]. *Smart Materials and Structures*, 2009, 18(3): 1–8.

[19] JI Hongli, QIU Jinhao, BADEL A, et al. Semi-active Vibration control of a composite beam by adaptive synchronized switching on voltage sources based on LMS algorithm approach[J]. *Journal of Intelligent Material Systems and Structures*, 2009, 20(3): 939–947.

[20] GUYOMAR D, JAYET Y, PETIT L, et al. Synchronized switch harvesting applied to selfpowered smart systems: piezoactive microgenerators for autonomous wireless transmitters[J]. *Sensors and Actuators A*, 2007, 138: 151–160.

Biographical notes

JI Hongli, born in 1983, graduated from Nanjing University of Aeronautics and Astronautics, China, in mechanical engineering in 2007, and work toward her PhD degree in aerospace engineering, Nanjing University of Aeronautics and Astronautics, China. Her current field of interest focuses on vibration damping, noise suppression and energy harvesting.
Tel: +86-25-84891123; E-mail: jihongli@nuaa.edu.cn

QIU Jinhao, born in 1963, is currently a professor in Nanjing University of Aeronautics and Astronautics, China. He received his master degree in mechanical engineering from Nanjing University of Aeronautics and Astronautics, China. He obtained his PhD in mechanical engineering from Tohoku University, Japan. His research interests are in the field of smart material and systems: vibration control, noise isolation, energy harvesting, piezo-transformers and non-linear/hysteretic modeling of these materials.
Tel: +86-25-84891123; E-mail: qiu@nuaa.edu.cn

ZHU Kongjun, born in 1971, is currently an associate professor in Nanjing University of Aeronautics and Astronautics, China. He received his PhD degree on functional materials from Kochi University, Japan, in 2005. His main research interests include hydrothermal synthesis of functional ceramics powder, preparation of biomaterials and fabrication of lead-free piezoelectric ceramics.
Tel: +86-25-84891123; E-mail: kjzhu@nuaa.edu.cn