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SEMI-A VIBRATION SUPPRESSION OF AIRCRAFT PANEL USING PIEZOELECTRIC ACTUATOR WITH SYNCHRONIZED SWITCH DAMPING TECHNIQUE

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Abstract

Owing to low power consumption and easy implementation, semi-active vibration control methods were more and more applied to solve kinds of structural vibration problems. Among these semi-active treatments, Synchronized Switch Damping (SSD) technique was proved to be an effective method. Compared with the passive ways, this control system possessed good immunity against structural dynamic properties shift due to environmental changes. They were also compact, lightweight which was convenient to apply to specific structure with weight or size restriction. In this study, the principle of SSD technique was introduced. An electromechanical coupling equation of this technique was proposed by employing a state space representation. Then, the mathematical model of SSDI technique was verified by using Matlab/Simulink software. Finally, an experiment was carried out on an aircraft panel which was fixed on a progressive wave tube under acoustical load. Experimental results showed that the vibration amplitude of this aircraft panel was attenuated to 75% of its original at its first resonant frequency when SSD technique was enabled. It was also found that the damping efficiency decreased with the vibration level increasing.

1 General Introduction

Acoustical fatigue damage may occur to aircraft panel structure due to the strong vibration. In order to eliminate these potential risks, vibration control methods should be applied to these panel structures. For the past two decades, several vibration control approaches were developed to suppress these undesirable vibrations. These methods could be roughly classified as three catalogues, which are passive, active and semi-active ways. Usually, these treatments are expected to be a compact, lightweight, intellectual and modular system. Passive methods, such as tuned mass damper (TMD) or constraint layer, have been widely applied due to its good reliability and stability. Despite the simplicity and effectiveness of passive methods, many drawbacks have also been occurred. Usually, they are sensitive to the environmental changes leading to an off-tune problem. Once the structure dynamic properties changes, the control system would need to be re-tuned. Moreover, it is usually heavy and bulky, which is unacceptable in aeronautic field. Active control can suppress the vibration efficiently meanwhile achieving broadband control. But its power consumption would be large and the spill-over problem could be induced for high frequency control. Semi-active control approaches possesses partial advantages of passive and active controls. Usually, these control strategies are hysteretic or nonlinear in nature. By using small amount of external energy, these methods can change the structural dynamic properties by altering the control state thus achieving damping purposes on the target structure.

In kinds of semi-active control treatments, synchronized switch damping (SSD) techniques are proved to be an effective treatment. Generally, the switch in the circuit is intermittently switched leading to a non-linear voltage processing in these techniques. The piezoelectric force induced by the voltage on bonded piezo-elements always shows an opposite sign with the structure velocity which leading the vibration suppression on the structure. In this paper, the principles of three typical SSD techniques were introduced. The mathematical model of synchronized switch damping on inductor (SSDI) was presented by using a state space representation. Considering the tradeoff between the power consumption and control effectiveness, SSDI technique was employed to suppress the fundamental modal vibration response of the aircraft cabin panel which was exposed to intense acoustical pressure loads. Based on the experimental results, it was found that the vibration levels of the open and closed loop systems differ by up to 25% (for sinusoidal excitation).

2 Principles of SSD technique

The structure coupled with piezoelectric elements is often described by a model of a single degree of freedom as shown in Fig.1. Here, m is the structure mass, c is the damping coefficient and k_E is the short-circuit stiffness. Furthermore, F is an external force exerting on the structure, C_0 is the natural capacitance of the piezoelectric elements on the structure, u is the displacement of the structure and V is the voltage between two electrodes of the piezoelectric element. This electromechanical coupling system can be generally formulated according to Eq. (1). Here, i is the outgoing current from the piezoelectric elements and α is the force factor related to the piezoelectric material.

$$\begin{gathered} m\ddot{u} + c\dot{u} + k^E = F - \alpha V \\ i = \alpha\dot{u} - C_0\dot{V} \end{gathered} \tag{1}$$

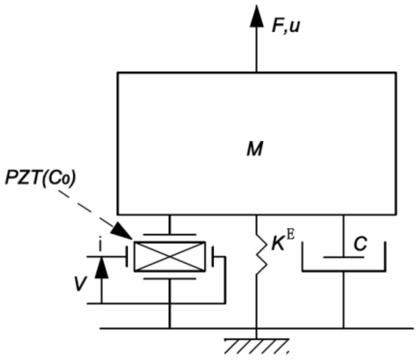
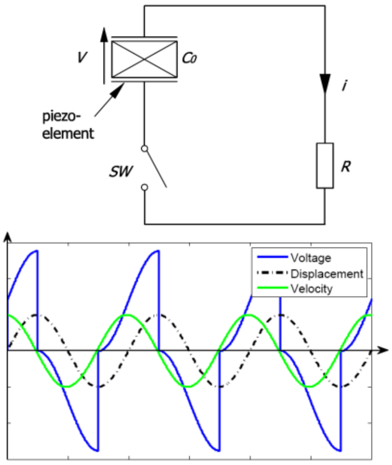
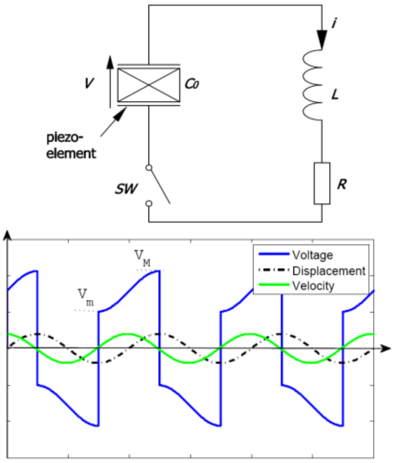


Fig.1 An electromechanical model.

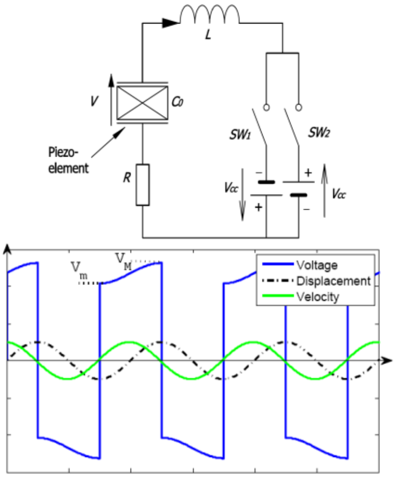
In SSD techniques, the switch in the circuit is intermittently switched leading to a non-linear voltage processing. The piezo-force induced by such voltage always shows an opposite sign with the structure velocity leading the vibration suppression on the structure (for sinusoid excitation case). There are three typical SSD techniques which are SSDS, SSDI and SSDV respectively [1-3]. Fig.2 lists their circuits and corresponding waveforms. The inversion factor, which defined by a ratio between the voltages before-and-after inversion, is closely related to the damping capability of SSD techniques. Normally, higher inversion factor brings to better damping effect. Therefore, SSDV technique could show the best control ability among these three techniques, while the performance of SSDS is the worst since the inversion factor in SSDS is zero as shown in Fig.2. However, SSDV technique needs a voltage source to enhance the inversion factor, which increases the power consumption. Moreover, the added voltage source could induce ‘instability’ problem. Considering the tradeoff between control efficiency and power consumption, SSDI technique was chosen to suppress the vibration of the aircraft cabin panel in this paper.



a) SSDS circuit and its waveforms



b) SSDI circuit and its waveforms



c) SSDS circuit and its waveforms

Fig 2. SSD circuits and their waveforms Mathematical modeling of SSDI technique

3 Mathematical modeling of SSDI technique

In SSDI technique, when the SW switch is closed, the circuit becomes a LCR oscillator, thus the voltage on the piezoelectric elements C_0 yields:

$$V = L\frac{di}{dt} + Ri \qquad (2)$$

Combining Eq. (1), the mathematical model of SSDI technique can be represented as follows by adopting the state space method:

$$\dot{\mathbf{x}}(\mathrm{t}) = \mathbf{A}\mathbf{x}(\mathrm{t}) + \mathbf{B}\mathbf{f}(\mathrm{t}) \qquad (3)$$

In this equation, the state vector x(t) is chosen as:

$$\mathbf{x}(\mathrm{t}) = [u \quad \dot{u} \quad V \quad i] \qquad (4)$$

The state matrix **A** can be divided by 4 blocks given in Eq.(5):

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_2 \\ \mathbf{A}_3 & \mathbf{A}_4 \end{bmatrix} \qquad (5)$$

Where $\mathbf{A}_1 = \begin{bmatrix} 0 & 1 \\ -k/m & -c/m \end{bmatrix}$, $\mathbf{A}_2 = \begin{bmatrix} 0 & 1 \\ -\alpha/m & 0 \end{bmatrix}$, $\mathbf{A}_3 = \begin{bmatrix} 0 & \alpha/C_0 \\ 0 & 0 \end{bmatrix}$. According to the state of the switch (open or close), $\mathbf{A}_4$ has two forms. That is, when switch is close, $\mathbf{A}_4 = \begin{bmatrix} 0 & -1/C_0 \\ 1/L & -R/L \end{bmatrix}$; When switch is close, the current flows through PZT equals to zero thus $\mathbf{A}_4 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$. The **f**(t) is the force exerting on the structure and the input matrix $\mathbf{B} = \begin{bmatrix} 0 & 1/m \\ 0 & 0 \end{bmatrix}$. Based on the state space model, a simulation work is carried out by using Simulink software. The simulation model is shown in Fig. 3. The system parameter used in this simulation is obtained from a cantilever beam which are listed in Table.1 and the parameter identification method can be found in reference^4. In this model, a max/min detector is used to pick up the extreme moments of the displacement and send a signal to switch the alternative state matrix.

The simulation results are shown in Fig. 4. The excitation frequency is set to 22.5Hz which is the structural natural frequency under open-circuit condition. The simulation lasts for 6 seconds. The SSDI control was not enabled in the first 3 second until the structural vibration gets to its stable state. After 3 seconds, the SSDI control was conducted. From Fig.4, it could be seen that the vibration was damped meanwhile the piezoelectric voltage increased at the switch closing instant. The response signals between 4 and 4.1 second were detailed as shown in Fig.4. It can be noticed that the voltage was inverted at each displacement extremes. The current is zero in most of the time but only appears during the voltage inversion. During each switch closing, the current sign does not change and the extreme value of the current occurs when the voltage drops to zero.

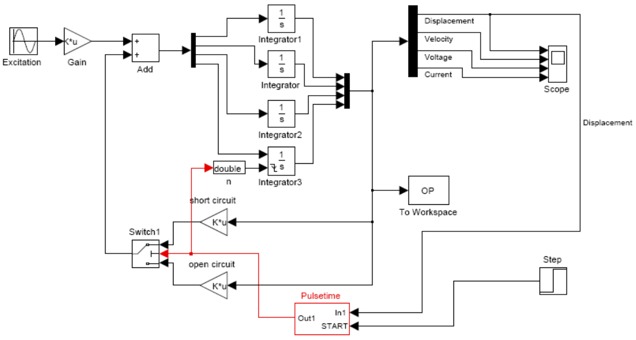


Fig 3. Simulink model of SSDI

Table. 1 System properties.

Parameter	Sym	Value (Unit)
Mass	m	0.135 kg
Damping coefficient	c	$0.2548\ N/m^{-1}s^{-1}$,
Damping ratio	ζ	0.00067
Stiffness	k	$2650\ N\cdot m^{-1}$
Open circuit frequency	ω_E	22.25 Hz
Short circuit frequency	ω_D	22.3 Hz
Quality factor	Q_M	73.9
Resistance	R	300 Ω
Inductance	L	0.09 H
Capacitance	C_0	44.5 nF
Ratio of volt. and disp.	λ	$1.6\times10^4\ V\cdot m^{-1}$
Force factor	α	$7.2\times10^{-4}\ N\cdot V^{-1}$

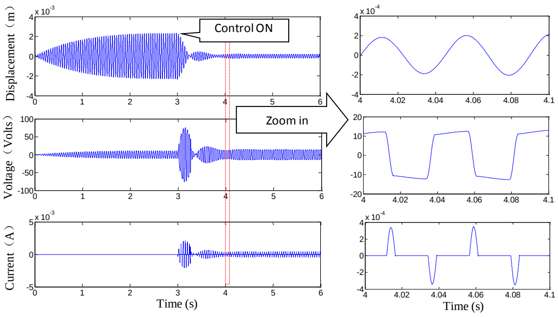


Fig 4.Simulation results

4 Experiments

An experiment was carried out to show the feasibility of SSDI technique for vibration control on aircraft panel structure. The control target was to suppress the first natural mode of the cabin panel whose mode shape shown in Fig. 5. Figure 6 showed the experimental setup. The aircraft panel was fixed on a progressive tube and excited under acoustical load at its first resonant frequency (126Hz). The PZTs were bonded on the surface of the panel and their locations were showed in Fig.6. The dimension of PZT is 48mm×24mm×0.5mm. The displacement of the panel was sensed by a laser sensor at the geometric center of the panel. The control system was developed by using Matlab/simulink software and then builds on dSPACE 1104 board to implement the SSDI algorithm. The control system can detect the extreme moment of the panel displacement and send a pulse signal to enable the switch for a short duration at these instants.

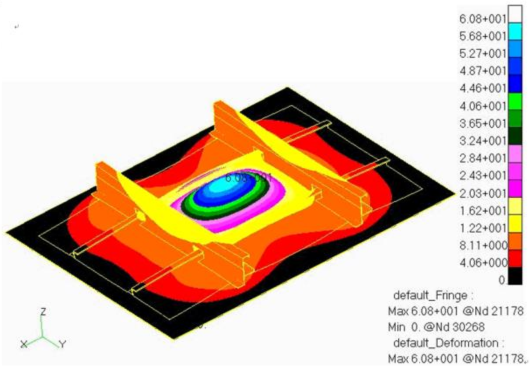


Fig 5. The first mode shape of the panel

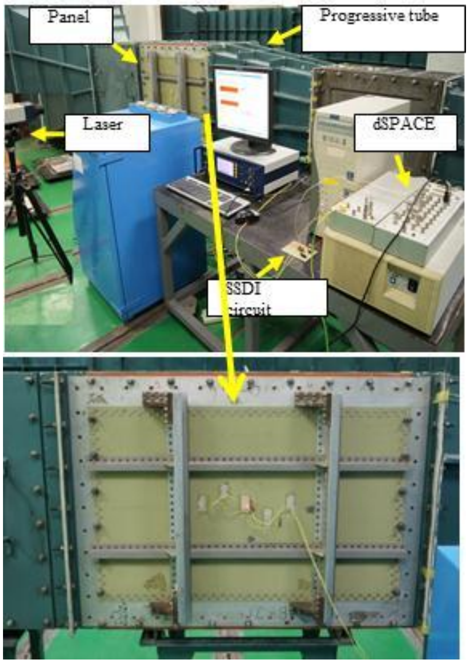
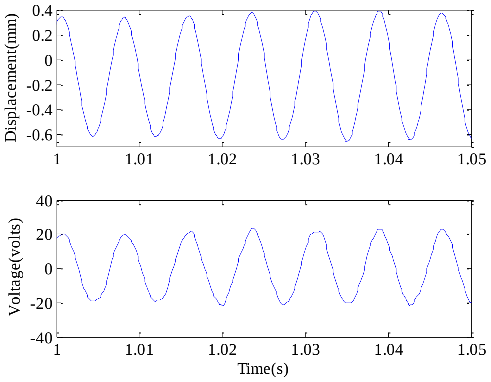


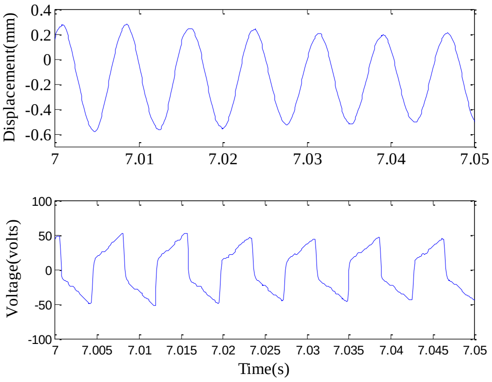
Fig 6. Experimental setup

Fig.7 shows the experimental results. From Fig.7a, it could be noticed that the piezoelectric voltage is in phase with the panel displacement when the SSDI control was off. When the control was conducted (as shown in Fig.7b), the piezoelectric voltage was inverted at each displacement extreme moment. However, the inversion factor was about 0.5 (it is usually more than 0.7 in SSDI technique) which limits the SSDI control performance. It could be attributed to the high resistance of the inductor which was made from thin copper wire. In order to get a better damping effect, a coil with smaller resistance should be used in SSDI circuit. However, it would inevitably increase the weight and size of the inductor.

It was also found that the damping efficiency was not constant but decreased with the sound pressure level increasing (namely vibration level increasing) as shown in Fig. 8. According to reference[5], the control efficiency of SSDI technique is only related to structural and electric properties, but not the excitation level. However, this conclusion was established on linear assumption. When vibration level is high, structural (or piezoelectric elements) nonlinear property could be induced. The experiment was forced to stop when the SPL is 138dB since the PZT was cracked to pieces due to the strong vibration level.



(a) Without control



(b) With control

Fig 7. Experimental results (the sound pressure level was 119dB).

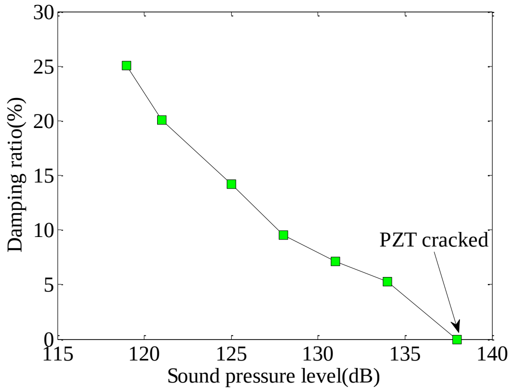


Fig 8. Control efficiency under different acoustical loads

5 Conclusions

The purpose of this research is to show the feasibility of applying SSDI technique on aircraft panel structure. The theoretical analysis shows that the SSDI technique damps the structural vibration by converting the mechanical energy to electrical energy, and finally dissipated it in the circuit as heat. Thus, the control system can avoid the instability problem. The experiment shows that SSDI technique can suppress the vibration of the panel structure. But, it should be pointed out that the control efficiency decreased with the vibration level increasing. Moreover, the results indicate that the PZT patch is not suitable for high-level vibration control due to their poor flexibility. The future work will focus on adopting SSDV technique to enhance the control effect. Meanwhile, piezoelectric patch such as micro fiber composite will be considered instead of the fragile PZTs.

References

[1] Richard C, Guyomar D, Audigier D, Ching G. Semi-passive damping using continuous switching of a piezoelectric device, *Proc. SPIE: Smart Structures and Materials*, *Passive damping and isolation*, Vol.3672, Newport Beach, CA, pp: 104-111, 1999.

[2] Richard C, Guyomar D, Audigier D, Bassaler H. “Enhanced semi-passive damping using continuous switching of a piezoelectric device on an inductor, *Proc. SPIE: Smart Structures and Materials, Damping and Isolation*, Vol.3989, Newport Beach, CA, pp: 288-299, 2000.

[3] Petit L, Lefeuvre E, Richard C, Guyomar D. ”A broadband semi passive piezoelectric technique for structural damping, *Proc. SPIE: Smart Structures and Materials,Damping and Isolation*, Vol.5386, Bellingham, WA, pp:414-425, 2004.

[4] Lallart M, Harari S, Petit L, et al. Blind switch damping(BSD): A self-adaptive semi-active damping technique. *J. Sound Vib.* Vol 328, pp:29-41, 2009.

[5] Badel A, Sebald G, Guyomar D, et al. Piezoelectric vibration control by synchronized switching on adaptive voltage sources: Towards wideband semi-active damping. *J. Acoust. Soc. Am.* Vol 119, pp: 2815–2825, 2006.

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