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Velocity-Controlled Switching Piezoelectric Damping based on Maximum Power Factor Tracking and Work Cycle Observation

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ABSTRACT

Piezoelectric switching shunt damping was popular in the recent year due to the wide bandwidth and good performance. This research found the ideally best piezoelectric switching damping based on the power factor and work cycle observation. The best work cycle of the piezoelectric damping should be rectangular and the power factor should be equal to 1. However, the best work cycle is difficult to achieve due to the stability problem. To alleviate this problem, the Schmitt trigger circuit is used as the control strategy between the detected velocity and the controlled piezoelectric voltage to obtain and good performance at the same time.

Keywords: piezoelectric damping, semi-active, semi-passive, energy cycle, switching damping, power factor

INTRODUCTION

Piezoelectric passive shunt damping is widely adopted in vibration suppression [1, 2]. Compared to active control, passive shunt damping is easier to accomplish as it does not need heavy amplification [3]. Figure 1(a) shows the equivalent circuit model of the piezoelectric shunt damping configuration. However, the typical passive shunt damping only has good performance in relative small bandwidth. On the other hand, the semi-active shunt damping has larger control bandwidth and does not need heavy power supply, thus the semi-active shunt damping is the most popular technique in recent years. There were several proposed semi-active control methods, such as state-switched absorber [4] and synchronized switching damping (SSD) techniques [5, 6], which could improved the conventional method..

However, there are two significant problems of the semi-active damping to be addressed. The first problem is the semi-active damping has poorer performance than the typical passive damping although the semi-active damping is more adaptive. The second problem is the analysis of the semi-active damping is not easy due to the nonlinearity. This paper introduced the concept of the power factor correction usually used in power electronics to design the semi-active damping. We will use the concept of "work cycle" (or energy cycle) [6, 7] to analyze the performance of the shunt circuit. Both these two methods make the analysis more intuitive. Based on the analysis, the best topology of the semi-active damping was found and proposed in this paper. This new technique is called velocity-controlled switching piezoelectric damping (VSPD). The VSPD system will be demonstrated both in theoretical analysis and simulated verifications. The sensing circuit and the control criterion will be also detailed here.

1. THE CONCEPT OF THE VELOCITY CONTROLLED SWITCHING DAMPING

When the piezoelectric layer attached on a structure, the equivalent circuit can be expressed as a current source i_m with an ideal transformer and a parallel capacitor, which is shown in Figure 1. The equivalent current source represents the mechanical velocity, and the ideal transformer coupled the energy between mechanical regime and the electrical regime. Considering the simple case that the current source is sinusoidal at the specific frequency, the vibration power is the function of the velocity i_m, the piezoelectric voltage v_p and their phase difference θ. More specifically, the power generated from the piezoelectric layer can be expressed as:

$$P_m = \frac{n i_m v_p}{2} \cos\theta \quad (1)$$

Equation (1) describes the power at point “A” in Figure 1. If the mechanical current source (mechanical velocity) is assumed as a constant, the power is decided by the piezoelectric voltage v_p and the phase angle θ. The piezoelectric voltage v_p and the phase angle θ are mainly decided by the piezoelectric shunt network. When the impedance of the shunt circuit is zero (short circuit), the piezoelectric voltage is zero. There is no power flow out of the piezoelectric layer. When the impedance of the shunt circuit is infinite (open circuit), the mechanical current and the piezoelectric voltage have the 90 degree phase difference. There is also no power flow out of the piezoelectric layer. It should be noted that these two critical cases both cannot obtain any power/energy from the piezoelectric layer but the fundamental reasons are not the same.

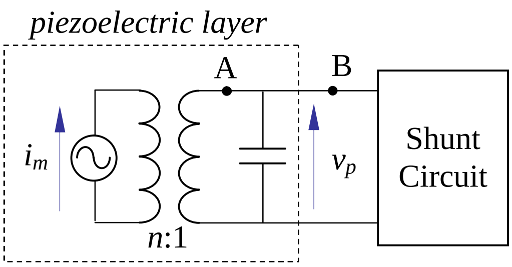


Figure 1. Equivalent circuit of the piezoelectric shunt damping

Based on the simple observation of equation (2), the innovative semi-active damping is proposed and show in the Figure 2. To obtain the largest power out from the piezoelectric layer, the large piezoelectric voltage v_p and zero phase difference (θ =0) are both required. To have zero phase difference between the velocity and the piezoelectric voltage, the velocity is detected at point “A” to control the phase of the piezoelectric voltage. Second, the dc voltage source is used to increase the piezoelectric voltage. Accordingly, the piezoelectric layer is possible to generate larger power flowing to the shunt circuit from the vibration. The damping factor can be thus increased. The piezoelectric voltage is followed the velocity, and thus this innovative damping technique is called velocity-controlled switching damping (VSPD).

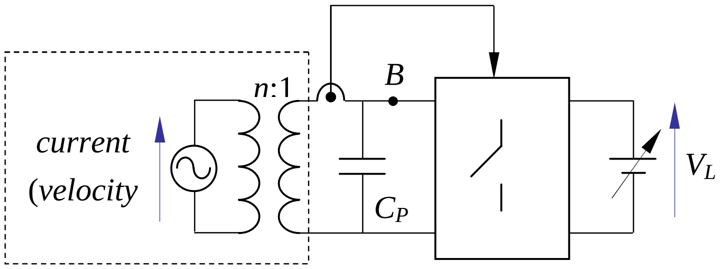


Figure 2. The basic thinking of the velocity-controlled switching piezoelectric damping

The implemented circuit of the VSPD is shown in Figure 3. To put the mechanical current and the piezoelectric voltage in phase, four switches are used to change the phase of the piezoelectric output voltage. The piezoelectric sensor with current amplifier is used to detect the mechanical current (velocity) of the piezoelectric layer. When the mechanical current is positive, the switch L1 and R2 is ON and the switch L2 and R1 is OFF (Figure 4(a)). The piezoelectric voltage is thus positive in this stage. When the mechanical current is negative, the switch L1 and R2 is ON and the switch L2 and R1 is OFF (Figure 4(b)). The piezoelectric voltage is thus negative in this stage. Accordingly, the mechanical current and the piezoelectric voltage become in phase. The ideal waveforms are shown in Figure 5. It should be noted that this methodology is not only for the specific frequency but working for a wide frequency range. The bandwidth of the VSPD is mainly depended on the sensing observability of the piezoelectric sensor and the sensing signal conditioner itself. Actually, the wider bandwidth is the key advantage of the semi-active control compared to the passive shunt circuit.

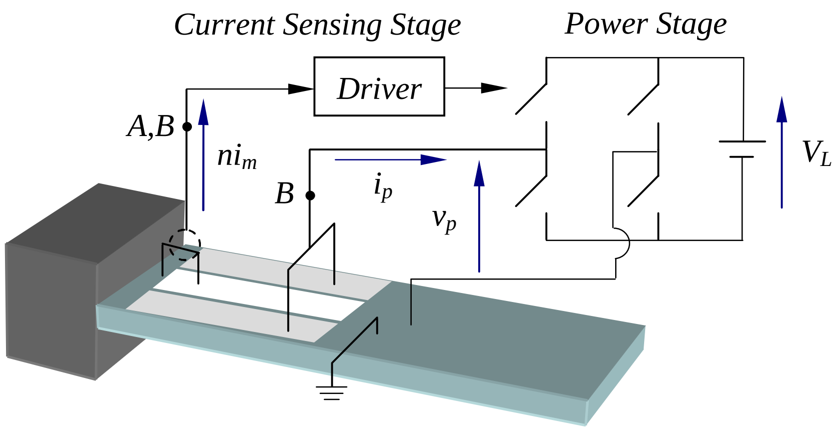
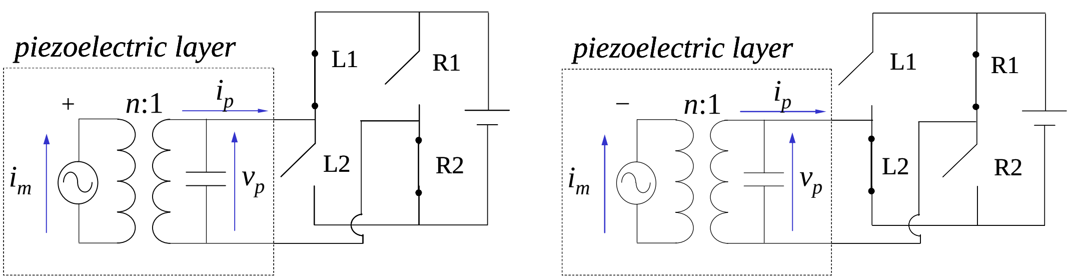


Figure 3. The implemented circuit topology of the VSPD system



(a) **(b)**

Figure 4. The operating principle of the VSPD: (a) The positive current state (b) The negative current state

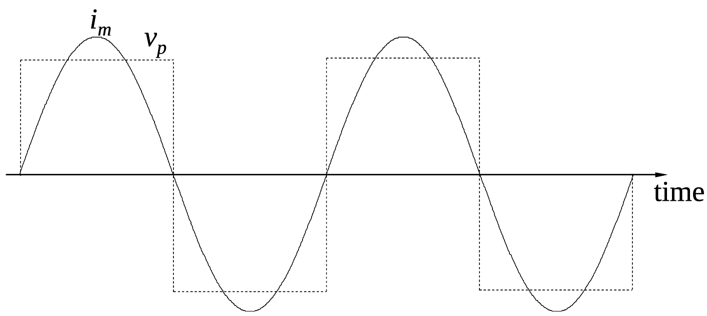


Figure 5. The ideal waveform of the velocity and the piezoelectric voltage in the VSPD

2. THE WORK CYCLE OF THE VSPD SYSTEM

The semi-active control such as the VSPD is a nonlinear control method essentially, and is not easy to analyze. To make the analysis more intuitive, the "work cycle" (or energy cycle) is used to analyze the switching shunt circuit. The work cycle is the trace on piezoelectric charge-voltage plane. To get the work cycle, piezoelectric charge and piezoelectric voltage should be obtained from the waveforms of the mechanical current and the piezoelectric voltage. The observing point of interest is point "A" because the power there represents the power generated from the mechanical part. At point "A", the average power out of the piezoelectric layer in a period can be expressed as:

$$P_r = \frac{1}{T}\int_0^T i_m(t)v_p(t)dt \tag{2}$$

,where T represents the period of the vibration. The real energy flows out of the piezoelectric layer is the key issue in the damping design. The larger the power flows out of the piezoelectric layer, the larger the vibrating energy loss on the piezoelectric layer or said larger loss factor. The energy flows out in one vibration cycle can be expressed as:

$$E_r = P_r T = \int_0^{q_m(T)} v_p(t)dq_m(t) \tag{3}$$

,where $q_m(t)$ represents the equivalent charge. The integration in Equation (3) also stands for the area on the charge-voltage plane on the energy flow out of the piezoelectric layer.

On the other hand, it mentioned that the phase difference between the velocity and the piezoelectric voltage is the key to design the shunt damping. Nevertheless, the phase difference on the charge-voltage plane is the key parameter of interest. With phase difference, a portion of power generated from the piezoelectric layers flows into the shunt circuit will flow back to the piezoelectric layer, and the situation corresponding to the power factor smaller than 1. The definition of the power factor is the ratio between the delivered real power and the apparent power, and is thus enclosed between 0 and 1. However, equation (2) only has the information of the real power, but no information of the apparent power. To obtain the apparent power P_a, the velocity and the piezoelectric voltage are put in phase:

$$P_a = \frac{1}{T}\int_0^T i_m(t)v_p(t-t_0)dt \tag{4}$$

,where t_0 is the time delay between the piezoelectric voltage and the velocity at the fundamental frequency. The area of the work cycle, i.e. the corresponding energy form, can be written as:

$$E_a = P_a T = \int_0^{q_m(T)} v_p(t - t_0) dq_m(t) \quad (5)$$

According to the definition of the power factor,

$$PF = \frac{P_r}{P_a} = \frac{E_r}{E_a} \quad (6)$$

In summary, there are two work cycles on the charge-voltage plane. One cycle tracks for the real power and the other cycle tracks for the apparent power. The areas of the work cycles represent the corresponding energy flows out in one vibration period and the area ratio between the two work cycles represents the power factor.

The typical resonant shunt damping circuit shown in Figure 6 is examined by the work cycle first. It is known that the resonant shunt damping have good performance only when the inductor-capacitor electrical resonant frequency matches with the mechanical resonant frequency of the structure. When the mechanical and electrical resonant frequencies are mismatch, the work cycles are shown in the Figure 7(a). It can be seen that the power factor of this case is poor. However, when the mechanical frequency and the electrical resonant frequency are close to each other, the areas of the apparent work cycle and the real work cycle are almost equal (Figure 7(b)). Specifically, good power factor leads to good performance due to the power does not flow back to the piezoelectric layer. Typical resonant shunt damping circuit uses the inductor to compensate the contribution of the piezoelectric intrinsic capacitance, but only at resonant frequency. This is the underlying reason that the resonant shunt damping only has good performance with small bandwidth near the resonant frequency. Most importantly, the work cycle observation is really an effective way to examine the damping performance.

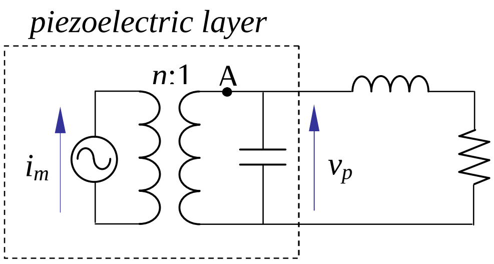
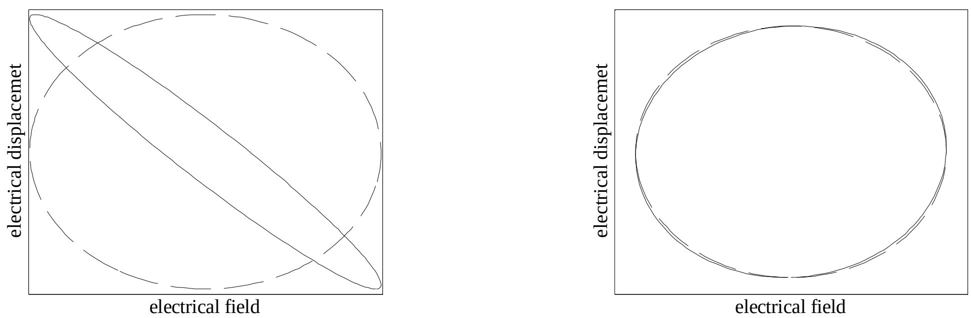


Figure 6. The piezoelectric resonant shunt damping



(a) (b)

Figure 7. The work cycle of piezoelectric resonant shunt damping (a) mismatches the resonant frequency (b) matches the resonant frequency (solid line: the apparent work cycle; dotted line: the real work cycle)

There are three conclusions we can get from the work cycles analysis to evaluate the performance of a damping circuit..

1. The maximum power transfer out of the piezoelectric layer, can be describe as maximum area of

the real work cycle, which is actually squared shape on the charge-voltage plane.
2. The best damping performance occurs when the areas ratio of two work cycles equal to one, and the corresponding power factor should also be one.
3. In the whole controllable bandwidth, the power factor should be always equal to 1 in all frequencies within the bandwidth.

Actually, the VSPD technique can fit all these three requirements well. The work cycle of the VSPD is rectangular because of the waveforms of the velocity and the voltage are sinusoidal and square respectively (Figure 5). The rectangular work cycle will have the maximum area under the same physical limitations. Furthermore, the power factor of the VSPD is equal to one in all frequencies range due to the piezoelectric voltage always follow the phase of the velocity. The ideal work cycle of the VSPD is shown in Figure 8. The work cycles of the apparent power and the real power are both square and overlapping well even though the frequency varies. In other words, the VSPD system has the optimal energy cycle, namely, the best semi-active damping. From the viewpoint of power electronics, the VSPD is actually a power factor correction circuit to force the power factor to be one.

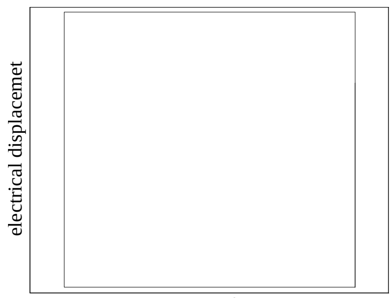


Figure 8. The work cycles (the apparent work cycle and the real work cycle overlapping) of the VSPD

STABILITY PROBLEM

Different from the passive shunt damping or some semi-active control methods, the dc voltage source is used in the VSPD to increase the damping performance. However, the ideal case is that the energy is always flows out of the piezoelectric layer to the dc source. However, when the vibration amplitude is very small, the energy may flow from the voltage source to the piezoelectric layer and excite vibrations on the structure. In practice, the velocity of the structure is in the transient state, the velocity always getting smaller gradually. Therefore, the VSPD technique will become unstable if the constant voltage source is applied. To ensure the energy flow in proper direction, the dc voltage should be adaptive to the vibration level. Larger vibration level needs larger control gain i.e. the large dc voltage level; while smaller vibration level only needs smaller control gain. In addition, the interfacing circuit of the mechanical current (velocity) sensor may cause extra phase delay in the high frequency range. However, the control gain is a constant in all frequency range. The gain margin cannot be large enough in the high frequency range and may exhibit stability problem. According to this viewpoint, the dc voltage level should roll-off in the high frequency range, and should be should be tunable adaptive to the vibration level. More specifically, the control gain in the high frequency range and in the small vibrating condition should be small enough to avoid the problem of the instability.

There are two major parameters varying the control gain, and they are the duty cycle of the switching stage and the dc voltage level. In general, the dc voltage is more difficult to vary in real-time because another dc/dc converter circuit has to include into the circuit and increase the complexity of the system. Varying the duty cycle of the switching cycle is relatively much easier to tailor the control gain and the energy delivered.. To vary the duty cycle with the magnitude of the vibration level, the sensing signal is compared with a threshold voltage to obtain the pulsing control signal with a ordinary comparator circuit. The threshold voltage is set according to the minimum allowable vibrating velocity. When the velocity is smaller than this level, the damping control circuit is actually off. When the velocity exceeds the corresponding level, the switching stage starting to work and the damping control is applied to the structure. The larger the vibration velocity is, the larger the duty cycle will be and more energy is damped in a energy cycle. Figure 9 shows this concept in detail. It should be noted that the duty cycle would not vary linearly. The duty cycle is decided by the relationship between vibration velocity and the threshold voltage. For the case the velocity and the threshold voltage is crossing:

$$\theta = \sin^{-1}\frac{V_T}{xI_m} \tag{7}$$

where V_T is the threshold voltage and x is the gain of the sensing interface circuit. Equation (7) has two solutions between 0 and π, which are named as θ_1 and θ_2. The duty cycle of the half period can be derived as

$$d = \frac{|\theta_1 - \theta_2|}{\pi} \tag{8}$$

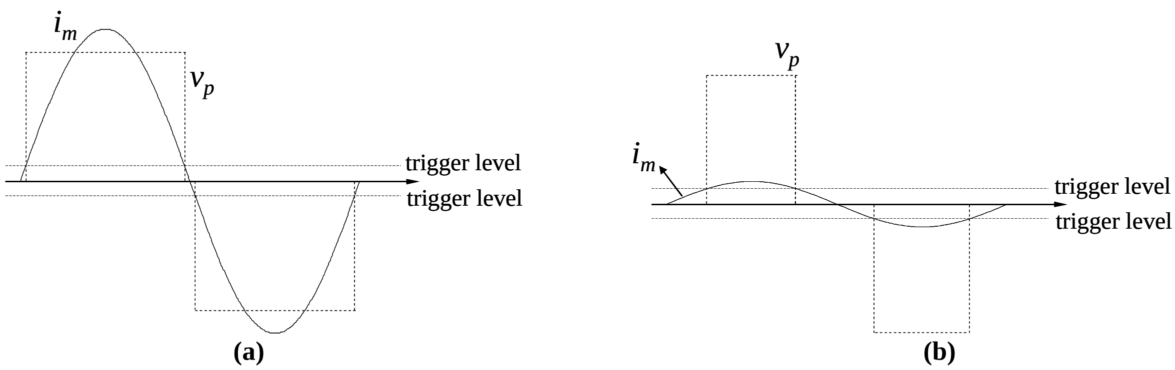


Figure 9. The duty cycle variation between different threshold voltage and (a) large velocity (b) small velocity

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In addition, the velocity signal is separated to two parts by the diodes. After passing through a Schmitt trigger comparator with a predefined threshold level, the pulsing control signal can be obtained to control the switching stage. The circuit schematic is shown in Figure 10.

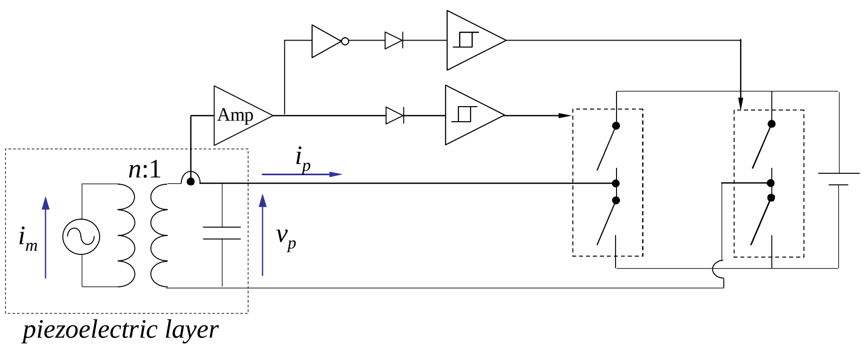

Figure 10. The duty cycle variation between trigger level and (a) large velocity (b) small velocity

THEORATICAL ANALYSIS

When the piezoelectric voltage and the current are in phase, the mechanical current source can be equivalent to deliver energy to a pure resistor load. According to Fourier theory, the first harmonic of the square wave is:

$$V_p = \frac{4}{\pi} V_{dc} \sin(\pi d) \tag{9}$$

The equivalent resistance can then be derived with Ohm's law as

$$R_{eq} = \frac{4V_{dc} \sin(\pi d)}{\pi n I_m} \tag{10}$$

To connect the VSPD system to the structure, the single-mode governing equation of the structure with piezoelectric layers is written as

$$M\ddot{x} + D\dot{x} + Kx = F + nV_p \tag{11}$$

$$q = nx + CV_p \tag{12}$$

,where *M*, *D*, *K*, *F*, *x* are mass, damping, stiffness, external force and the displacement respectively. Based on equation (12), the piezoelectric sensing equation at short circuit state, i.e. $V_p = 0$, can be obtained as

$$I_m = \dot{q}\big|_{V_p=0} = n\dot{x} \tag{13}$$

This relationship describes the fact that the mechanical current is the velocity at the short circuit state. Furthermore, apply the Ohm's law to equation (13),

$$V_p = -R_{eq} I_m = -R_{eq} n\dot{x} \tag{14}$$

Substituting equations (10, 14) into equation (11), the governing equation of the structure with the VSPD can be derived as

$$M\ddot{x} + (D + n\frac{4V_{dc}}{\pi I_m})\dot{x} + Kx = F \tag{15}$$

It can be observed that the larger external dc voltage level V_{dc} and larger coupling factor *n* lead to larger damping coefficient in equation (15). However, the damping coefficient has upper bound which is limited as the critical damping situation. This is the underlying reason that the control voltage cannot be too large, or the system may enter into the over-damping state. Moreover, it should be noted that the damping coefficient is also function of the mechanical current. If the control voltage is a constant, the damping coefficient will increase as the mechanical current decreases. Therefore, the VSPD may become unstable in the case of the small vibration level. To avoid the over-damped situation, the external voltage should be tunable. Equation (15) explains that the VSPD system is possible to be designed in the critical damping situation with a tunable control voltage source. This conclusion is the same as the problem of the stability we mentioned in the last section.

The damping ratio ζ can be obtained from equation (15):

$$\zeta = \frac{2\zeta_0 \omega_0 + n\frac{4V_{dc} \sin(\pi d)}{\pi I_m}}{2\omega_0} \tag{16}$$

,where ζ_0 and ω_0 are the damping ratio and the natural frequency of the uncontrolled structure. The critical damping is the critical case where the damping ratio is equal to 1. The system is stable only when the damping ratio smaller than 1, which implies:

$$V_{dc}\sin(\pi d) \le \frac{\pi(1-\zeta_0)\omega_0}{2n} I_m \tag{17}$$

Equation (17) is the criterion for setting the control gain. If equation (17) is asserted, higher control gain means better performance but smaller stability margin. Smaller control gain has larger stability margin but poor performance. It mentioned that the external voltage is fixed in this paper, but the duty cycle is nonlinearly varied with the mechanical current accordingly.

According to the theoretical model, the cantilever beam (160mm*40mm*0.3mm) is used as the testing structure. The external voltage source is set at the 2 Volt. The gain of the interface circuit is set as 100, and the threshold level is set in 2V.The simulated result is shown in Figure 12. The performance of the VSPD is compared with the synchronized switching techniques in Figure 12. The result shows that the VSPD system indeed has better performance than the synchronized switching technique.

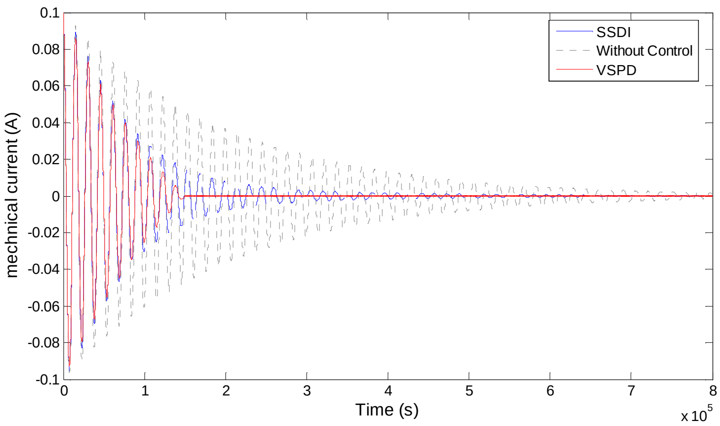

Figure 12. the damping of the VSPD and the SSDI

CONCULSION

The velocity controlled switching damping technique is proposed, modeled and verified in this paper. The concept of the power factor correction and the work cycle analysis are detailed to analyze the damping performance. The best damping circuit as the VPSD proposed here in equivalent to a power factor correction circuit in whole bandwidth of interest, and also should have the rectangular work cycle on charge-voltage plane. However, the stability problem should be taken into consideration carefully, especially in the case of the small vibration level.

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