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Blind switch damping (BSD): A self-adaptive semi-active damping technique

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ABSTRACT

Much attention was given to the control of vibrations for smart structures equipped with piezoelectric elements in the nineties. Active control has shown its efficiency, however, necessitating important power requirements and complex signal processing. To bypass these drawbacks, semi-passive control schemes have been proposed. In the semi-passive approach, the piezoelectric element is intermittently switched from open circuit to a specific circuit synchronously with the structure motion. Such systems are simpler than active control methods and require low power supply (they can even be self-powered), but necessitate a deterministic approach.

In this paper, a novel semi-passive method is proposed for a piezoceramic actuator coupled with a switching resistor/inductor shunt. This method, named BSD (for *blind switch damping*), has the advantage of being independent from the structure vibrations and does not need any model of the smart structure. This technique also exhibits low requirements in terms of power supply. In the BSD technique, the piezoelectric element can be either switched on a short circuit or the piezovoltage magnitude can artificially be increased by switching on piecewise constant or adaptive voltage sources, making the approach semi-active.

Experimental measurements carried out on a simple structure (clamped-free smart beam) show good agreements with theoretical predictions, exhibiting damping performances similar to previously proposed semi-passive and semi-active methods.

1. Introduction

Limiting vibrations of structures has become an intensive research field. Such an interest comes from the necessity of preserving structure integrity, as cracks, delaminations or more general damages that generally occur for high vibration levels. In this domain, piezoelectric elements are good candidates for damping issues, as they provide high power densities as well as high coupling coefficients, limiting the amount of needed active material [1].

Typically, the simplest way for creating a damping effect consists in connecting the piezoelectric insert in series with an inductance and a resistor, thus shaping an oscillating electrical network that dissipates a part of the converted energy [2,3]. Although the implementation of this method is almost straightforward, the unrealistic inductance values (from tens to

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hundreds of Henry) makes the purely passive technique barely envisageable. Moreover, such a technique needs a fine tuning of the electrical frequency to the mechanical frequency, making this method very sensitive to mechanical drifts, and is limited to monomodal control as well.

Active methods were first proposed in order to efficiently control the vibrations of a structure [4]. Such techniques are efficient, multimodal and robust on a wide frequency band, but necessitate complex signal processing as well as high power requirements for energy exchanges, although different strategies have been developed in order to reduce external energy consumption [5,6]. Such techniques also require a full feedback system. Some self-sensing methods have been developed in order to reduce the number of piezoeletric elements [7–9], but control units and amplifiers are still necessary. Therefore active control is rapidly limited, especially for on-board damping units, where integration issues play a great role.

Recently, it has been shown that semi-passive and semi-active methods based on nonlinear treatments of the output voltage of piezoelectric actuators offer an interesting trade-off of the two previously mentioned techniques [10–12]. Such control laws allow simple but efficient, cost-effective and robust vibration damping methods. The *state switched absorber* proposed by Larson et al. offers an effective control of the structure parameters, such as stiffness or dynamic mass [13–16]. Among other nonlinear methods, the *synchronized switch damping* technique proposed by Guyomar et al. has been proved to be an extremely efficient method for vibration damping purposes [17–24]. This method consists in connecting the piezoelectric element in a synchronous fashion with the structure motion on an electrical network for a very short time. This network can either be a short circuit (SSDS), an inductor (SSDI) or voltage sources (SSDV and adaptive SSDV). Although this method is adaptive and effective for controlling a particular mode, it requires additional treatment for multimodal vibration control [25–27].

The purpose of this paper is to present new semi-passive and semi-active methods for controlling vibrations of a structure. These techniques, named BSD (for *blind switch damping*) consist in connecting the piezoelement on an electrical network for a very short time and independently to the structure motion (contrary to other semi-passive and semi-active approaches), thus providing a fully adaptive and broadband way for damping. Three methods derived from these principles are exposed. The first one consists in connecting the piezoelectric insert on a short circuit, leading to the semi-passive method called *blind switch damping on short-circuit*. For the second and third ones, the electrical network is intermittently an inductance in series with voltage sources and a short circuit. The piezoelectric material is connected from time to time to the short-circuit, and then to the voltage sources. These latter can either be tuned to the displacement magnitude or to the value of the piezovoltage before switching, leading to the semi-active methods *blind switch damping on piecewise constant voltage sources* (BSDVp) and *blind switch damping on adaptive voltage sources* (BSDVa), respectively. Therefore such a treatment shapes a voltage whose envelope is in phase with the speed (as the connection on short-circuit performs a low-cost differentiation operation), thus creating a friction effect that leads to vibration damping.

This paper is organized in three parts. First, the objectives, principles and performances of the three control laws are developed in Section 2. This part is composed as follows: first the smart structure modeling is presented in Section 2.1 and the basic theory of the BSD is developed in Section 2.2; theoretical developments are then exposed in Section 2.3 for the BSDS technique and in Section 2.4 for BSDVp and BSDVa techniques; last, a discussion on the performances of each method compared to current semi-passive methods conclude this part. The second part of this paper concerns an application on a clamped-free smart beam (Section 3), aiming at validating previously exposed theoretical results. Finally, Section 4 concludes the study.

2. Blind switch damping (BSD): basic theory and modelling

2.1. Smart Structure modelling

Lumped model analysis of smart structures has received considerable attention since the seventies and the formulation presented by Alik and Hughes [28], based on the variational principle using the concept of virtual work, is widely referenced. It allows writing the dynamic behavior and observation equations of a structure with m modes and p piezoelectric patches as

$$M\ddot{u} + C\dot{u} + K^E u = FI_d - \alpha V \tag{1}$$

$$I = \alpha^t \dot{u} - C_0 \dot{V} \tag{2}$$

where u is the $[m, 1]$ displacement vector at a particular location of the structure; M, C and K^E are, respectively, the $[m, m]$ diagonal and positive matrices of mass, damping and stiffness when all the piezoelectric element are in short circuit; α is the $[m, p]$ electromechanical coupling matrix; V is the $[p, 1]$ piezoelectric element voltage vector; I is the $[p, 1]$ current vector; C_0 is the $[p, p]$ diagonal capacity matrix; F is the [1,1] external force F applied on the structure; I_d is an $[m, 1]$ identity matrix.

In an open circuit or when the sensor voltage is monitored with a voltage amplifier, the current is null, therefore Eq. (2) becomes

$$V = C_0^{-1} \alpha u \tag{3}$$

For clarity reasons, the model used in this paper is based on one piezoelectric element and has one degree of freedom. Indeed, a mechanical model based on only one degree of freedom gives a good description of vibrating structure behavior near a resonance. When one mode is excited with one patch short-circuited, inserting Eq. (3) in Eq. (1) leads to the transfer function linking the displacement U to the driving force F:

$$\frac{U}{F}=\frac{1}{-M\omega^2+\mathrm{j}C\omega+K^E} \tag{4}$$

with ω the angular frequency and

$$u=U\mathrm{e}^{\mathrm{j}\omega t} \tag{5}$$

2.2. Basic theory of blind switch damping (BSD)

The aim of the blind switch damping (BSD) is to create a damping effect without any knowledge of the structure characteristics. The method consists in switching the piezoelectric element on an electrical network for a very short time thanks to a digital switch. The switch is closed many times per period, independently from the structure characteristics, contrary to classical semi-passive or semi-active damping techniques. The time period between two consecutive switching events, noted τ, can be defined by

$$\tau=\frac{T}{n},\quad n\in\Re^+ \text{ and } n\gg 1 \tag{6}$$

with T the structure natural period and n the number of switches per period.

The switching time is very short compared to the open-circuit time period therefore the piezoelectric element is almost always in open circuit condition, with different initial conditions after every switch event.

Three techniques are proposed in this paper without any knowledge of the structure characteristics. The first one consists in switching on a short circuit (BSDS), the second method relies in intermittently switching on a piecewise constant voltage source (matched with the displacement magnitude) and a short circuit, and finally, for the third technique, on an adaptive voltage source (tuned to the instantaneous value of the controlled voltage) and a short circuit.

2.3. Blind switch damping on short circuit (BSDS)

The first proposed method consists in switching on a short circuit, as depicted in Fig. 1. When the switch is closed, the piezoelectric voltage is zero. Indeed, each time the switch S is closed a charge flow appears from point a to point b for a positive piezovoltage (resp. from point b to point a for a negative piezovoltage), cancelling the global charge on the piezoelement. Such a control thus shapes the piezovoltage as illustrated in Fig. 2.

Hence, the piezoelectric voltage can be expressed as:

$$V(t)=\frac{\alpha}{C_0}\left(u(t)-u\left(\frac{iT}{n}\right)\right)\quad \text{for } \frac{iT}{n}\leq t<\frac{(i+1)T}{n} \text{ with } i\in\mathbb{N} \tag{7}$$

For large values of n and approximating the effect if the voltage V by its first harmonic, the piezoelectric voltage can be approximated by

$$V(t)\approx\frac{\alpha}{C_0}\frac{T}{\pi n}\dot{u}(t) \tag{8}$$

Consequently the motion equation becomes

$$M\ddot{u}+\left(C+\frac{\alpha^2}{C_0}\frac{T}{\pi n}\right)\dot{u}+K^E u=F \tag{9}$$

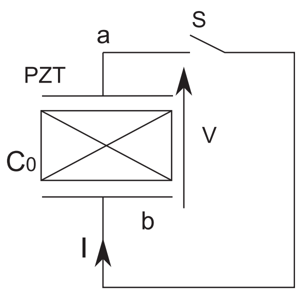

Fig. 1. BSDS basic circuit.

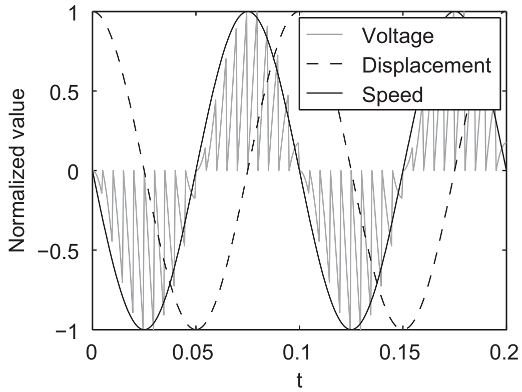

Fig. 2. BSDS control waveforms.

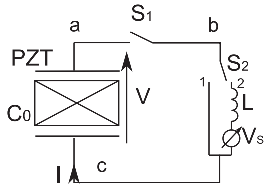

Fig. 3. BSDV basic circuit.

As shown in Fig. 2, this formulation clearly shows that the first harmonic of the controlled voltage is in phase with the speed, therefore creating a viscous friction effect, leading to an artificial increase of the damping coefficient C.

The transfer function linking the displacement U to the driving force F can then be expressed from Eq. (9) as

$$\frac{U}{F} = \frac{1}{-M\omega^2 + \mathrm{j}\left(C + \frac{\alpha^2}{C_0}\frac{T}{\pi n}\right)\omega + K^E} \tag{10}$$

In the case of an excitation at the resonance frequency, the expression of the attenuation A_{BSDS} is defined by the ratio of the BSDS transfer function with the short circuit transfer function:

$$A_{\mathrm{BSDS}} = \frac{1}{1 + \frac{1}{C}\frac{\alpha^2}{C_0}\frac{T}{\pi n}} \tag{11}$$

From this expression it can be seen that the additional attenuation is inversely proportional to the switching time period T/n. However, one has to keep in mind that the more this period decreases, better is the reconstructed speed. Consequently a trade-off appears between a good reconstruction of the speed and a significant damping.

2.4. Blind switch damping on voltage source (BSDV)

The aim of the BSDV is to improve the efficiency of the BSDS. The concept of this technique consists in increasing the voltage level which is very low in the case of the BSDS, in order to artificially enhance the energy conversion. In the case of such a control, the piezoelectric element is connected alternatively on a voltage source and a short circuit thanks to two switching networks as shown in Fig. 3.

The first network is a short circuit and the second is a tuneable voltage source V_S in series with an inductor. When the switch S_1 is closed and the switch S_2 is in position 1, the piezoelement is in short circuit condition, leading to the same effect than the BSDS (i.e. charge cancellation and low-cost differentiation). After the short circuiting, S_1 is opened and S_2 goes to the position 2. Consequently, at the next switching instant, S_1 is closed and S_2 is in position 2. The piezoelectric element is then connected to the voltage source V_S.

The role of the additional voltage source V_S is to increase the piezoelectric voltage magnitude, thus magnifying the damping effect. Indeed, the voltage source value V_S has the same sign than the piezoelectric voltage but a greater value. Fig. 4 shows the corresponding waveforms of the piezovoltage using the BSDV technique.

Thanks to the use of an inductance L, the voltage is inverted with respect to the reference V_S. However, due to internal losses in the inductance, the voltage inversion across the voltage source V_S is not perfect and characterized by the inversion

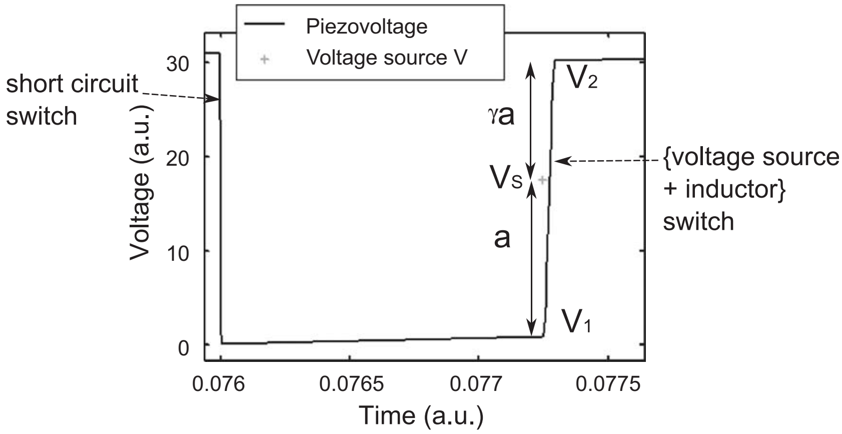

Fig. 4. BSDV voltage inversion.

coefficient γ ($0 \le \gamma \le 1$), leading to

$$V_2 = V_1 + \gamma(V_S - V_1) + V_S \tag{12}$$

With the voltage V_1 given by

$$V_1 = \frac{\alpha}{C_0}\left(u\left(\frac{(2i+1)T}{n}\right) - u\left(\frac{2iT}{n}\right)\right) \tag{13}$$

Assuming $n \gg 1$ leads to the expression of V_1 as a function of the speed:

$$V_1 \approx \frac{\alpha}{C_0}\frac{T}{n}\dot{u}\left(\frac{(2i+1)T}{n}\right) \tag{14}$$

Hence using Eq. (12) the expression of the voltage yields

$$V(t) \approx \frac{\alpha}{C_0}\frac{T}{n}\dot{u}(t) \quad \text{for } \frac{2iT}{n} \le t < \frac{(2i+1)T}{n} \text{ (short circuit switching)} \tag{15}$$

$$V(t) \approx \gamma\left(V_S - \frac{\alpha}{C_0}\frac{T}{n}\dot{u}(t))\right) + V_S \quad \text{for } \frac{(2i+1)T}{n} \le t < \frac{2iT}{n} \text{ (voltage source switching)}$$

The voltage source can be tuned in several ways. In this paper, two voltage control strategies will be investigated:

- the voltage source is proportional to the displacement magnitude, and has the same sign than the piezoelectric voltage (blind switch damping on piecewise constant voltage sources—BSDVp);
- the voltage source is proportional to the instantaneous piezovoltage (blind switch damping on adaptive voltage sources—BSDVa).

2.4.1. *Blind switch damping on piecewise constant voltage sources (BSDVp)*

It is proposed here to tune the voltage source to the displacement magnitude U_M as

$$V_S = \beta\frac{\alpha}{C_0}U_M\,\mathrm{sgn}(V) \tag{16}$$

with β the dimensionless tuning coefficient between the displacement magnitude and the absolute value of the reference voltage V_S.

As the voltage after a short circuit switching event roughly gives the derivative of the displacement (for large values of n), the voltage source value can be approximated by

$$V_S \approx \beta\frac{\alpha}{C_0}U_M\,\mathrm{sgn}(\dot{u}) \tag{17}$$

Applying such a control thus shapes the voltage waveform as shown in Fig. 5.

It is besides assumed in the following developments that the displacement is sinusoidal. Assuming $\beta \gg 1$ and $n \gg 1$ leads to the expression of the controlled voltage from Eq. (15):

$$V(t) \approx 0 \quad \text{for } \frac{2iT}{n} \le t < \frac{(2i+1)T}{n} \text{ (short circuit switching)} \tag{18}$$

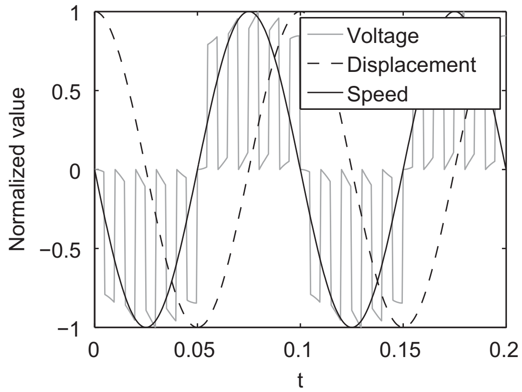

Fig. 5. BSDVp control waveforms.

$$V(t) \approx (1+\gamma)V_S \approx (1+\gamma)\beta\frac{\alpha}{C_0}U_M\,\mathrm{sgn}(\dot{u}(t)) \quad \text{for } \frac{(2i+1)T}{n} \le t < \frac{2iT}{n} \text{ (voltage source switching)}$$

Approximating the voltage V by its first harmonic (the higher harmonics being filtered by the host structure for high value of n) thus leads to

$$V \approx (1+\gamma)\beta\frac{\alpha}{C_0}\frac{2}{\pi}\frac{1}{\omega}\dot{u} \tag{19}$$

Therefore merging this expression with the equation of motion (1) yields

$$M\ddot{u} + C\dot{u} + K^E u = F - (1+\gamma)\beta\frac{\alpha^2}{C_0}\frac{2}{\pi}\frac{1}{\omega}\dot{u} \tag{20}$$

The transfer function is then defined by

$$\frac{U}{F} = \frac{1}{-M\omega^2 + \mathrm{j}\left(C\omega + \beta(1+\gamma)\frac{\alpha^2 2}{C_0\pi}\right) + K^E} \tag{21}$$

The expression of the attenuation A_{BSDVp} at the resonance frequency is therefore given by

$$A_{\mathrm{BSDVp}} = \frac{1}{1 + \beta(1+\gamma)\frac{1}{C\omega_0}\frac{2}{\pi}\frac{\alpha^2}{C_0}} \tag{22}$$

2.4.2. Blind switch damping on adaptive voltage sources (BSDVa)

While the previous subsection proposes to tune the voltage source to the displacement magnitude, a BSDV control using a voltage tuned to the value of the voltage just before the switching event is exposed in the following:

$$V_S = \beta V\left(\frac{2i+1}{n}T\right) \tag{23}$$

with β the dimensionless tuning factor.

Considering the expression of the piezovoltage after a short-circuit switch (15), the voltage source can be approximated for large value of n by

$$V_S \approx \beta\frac{\alpha}{C_0}\frac{T}{\pi n}\dot{u} \tag{24}$$

Consequently, for $\beta \gg 1$ and $n \gg 1$, the value of the voltage yields

$$V(t) \approx 0 \quad \text{for } \frac{2iT}{n} \le t < \frac{(2i+1)T}{n} \text{ (short circuit switching)} \tag{25}$$

$$V(t) \approx (1+\gamma)V_S \approx (1+\gamma)\beta\frac{\alpha}{C_0}\frac{T}{n}\dot{u}(t) \quad \text{for } \frac{(2i+1)T}{n} \le t < \frac{2iT}{n} \text{ (voltage source switching)}$$

Such a control thus shapes the control waveforms as depicted in Fig. 6. One can note that the envelope of the voltage is much closer to the speed than in the BSDVp case, thus dramatically decreasing the harmonic reinjection.

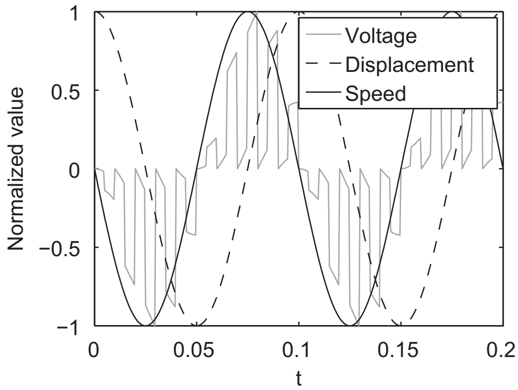

Fig. 6. BSDVa control waveforms.

Considering the first harmonic assumption, the value of the voltage can be approximated as

$$V \approx (1+\gamma)\beta \frac{\alpha}{C_0} \frac{T}{\pi n} \dot{u} \tag{26}$$

Thus, with the BSDVa control technique, the motion equation yields

$$M\ddot{u} + C\dot{u} + K^E u = F - (1+\gamma)\beta \frac{\alpha^2}{C_0} \frac{T}{n\pi} \dot{u} \tag{27}$$

The transfer function in that case is therefore given by

$$\frac{U}{F} = \frac{1}{-M\omega^2 + \mathrm{j}\left(C + \beta(1+\gamma)\frac{\alpha^2}{C_0}\frac{T}{n\pi}\right)\omega + K^E} \tag{28}$$

Consequently the attenuation A_{BSDVa} at the resonance frequency can be expressed as

$$A_{\mathrm{BSDVa}} = \frac{1}{1 + \beta(1+\gamma)\frac{1}{C}\frac{T}{n\pi}\frac{\alpha^2}{C_0}} \tag{29}$$

2.5. Performance discussion

This section aims at pointing out the advantages and drawbacks of the BSD techniques compared to existing methods like synchronized switch damping (SSD). In addition as well, a comparison between the three investigated BSD techniques is proposed.

Compared to the SSD technique [17], the BSD is less interesting in terms of damping. The attenuation is typically two times less in the case of the BSDVp for equivalent control parameters.

However, contrarily to the SSD technique, the BSD technique allows a control of the reinjected harmonics. Fig. 7 compares the reinjected harmonics on the voltage when one mode is excited and controlled by the SSD and BSDVa techniques.

In the case of synchronized switch damping, the control generates a crenel function that therefore contains odd harmonics of the fundamental frequency (i.e. resonance frequency), that can interact with higher modes. In the case of the BSD control, the technique can be seen as a modulation of the piezovoltage by a crenel function with a frequency n/T. Thus the harmonics of the controlled voltage appear to be at $kn/T \pm \omega_0$. As the number of switch per period n is user-defined, these harmonics are thus managed by the user. As shown in Fig. 7, the frequencies of the reinjected harmonics are not in the same place for $n = 20$ or 50. Therefore, if a mode of the structure has a frequency which is excited by reinjected harmonics, changing n allows shifting the reinjected harmonics and therefore avoids an excitation of the structure. Moreover, as $n \gg 1$, these harmonics are far beyond the significant modes and thus do not interact with major modes of the structure.

As well, the pseudo-frequency of the electrical network LC_0 has to be much higher than in the case of the SSD control. This leads to a dramatic reduction of the required inductance compared to SSD control, thus allowing a better integration of the system on silicium.

Energetically speaking, the command of the BSD is quite simple (much simpler than the SSD command) and does not require heavy computation as active control. As well, a charge flow only appearing during a switch event, no energy is

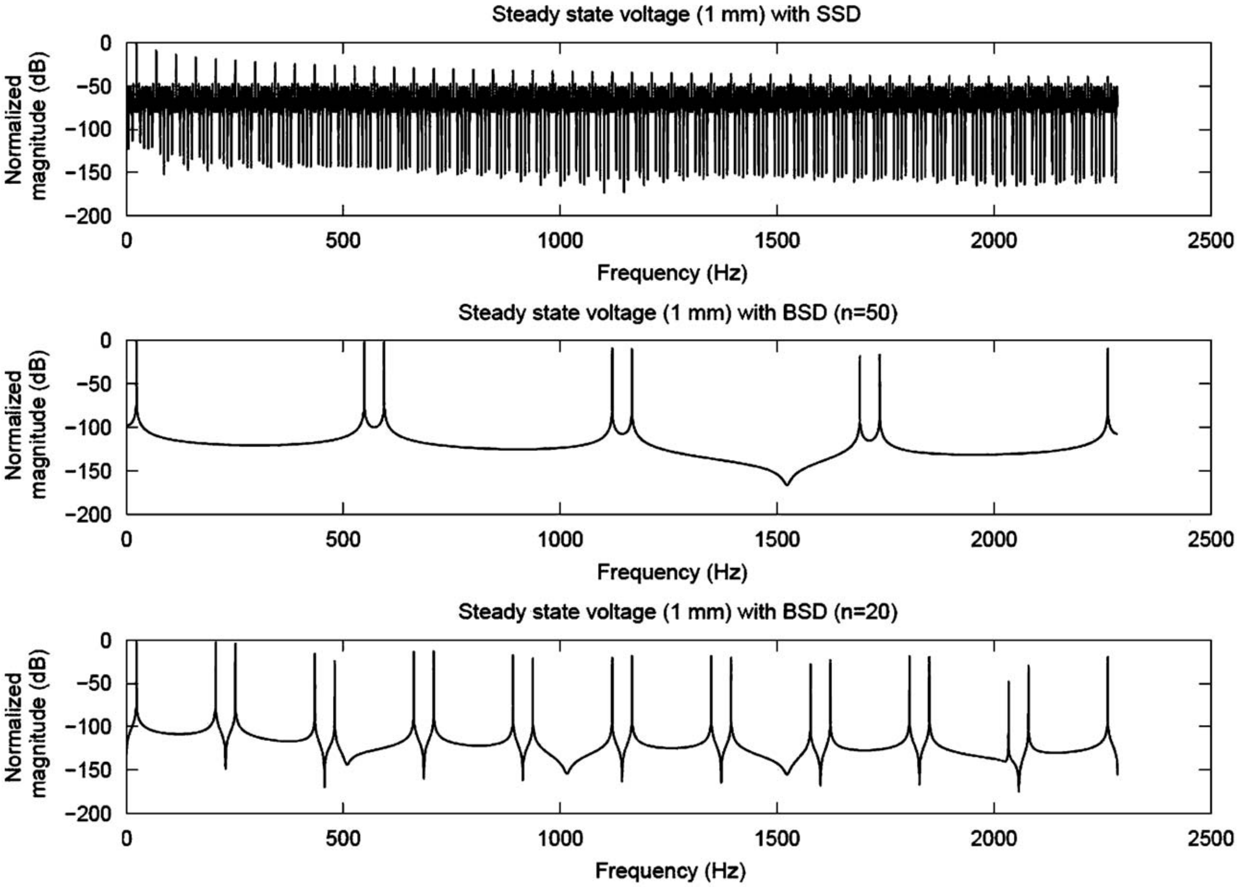

Fig. 7. SSD and BSDVa reinjected harmonics comparison.

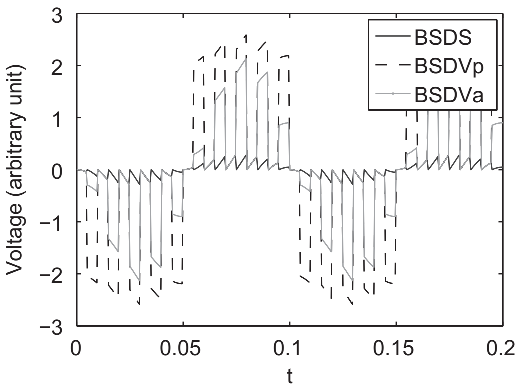

Fig. 8. BSDS, BSDVp and BSDVa waveform comparison.

needed when the piezoelectric element is in open circuit. Moreover, most of the energy in active control is dissipated by the actuator, while the BSDV technique can operate in energy supply/energy recovery basis using for example the synchronous electric charge extraction technique described by Lefeuvre et al. [29] while BSDS technique does not require any external energy supply for the control. The energy transfer during a voltage source switching can beside be optimized using for example a PWM inverter. As well, the inductance in the switching network allows a reduction of the applied voltage by a factor $(1+\gamma)$, thus limiting the required voltage of the external source.

The most interesting of the three presented techniques seems to be the BSDVa. Indeed, the BSDS, while being semi-passive, cannot achieve high damping. The BSDV requires a fast adaptive voltage but is more efficient than the BSDS.

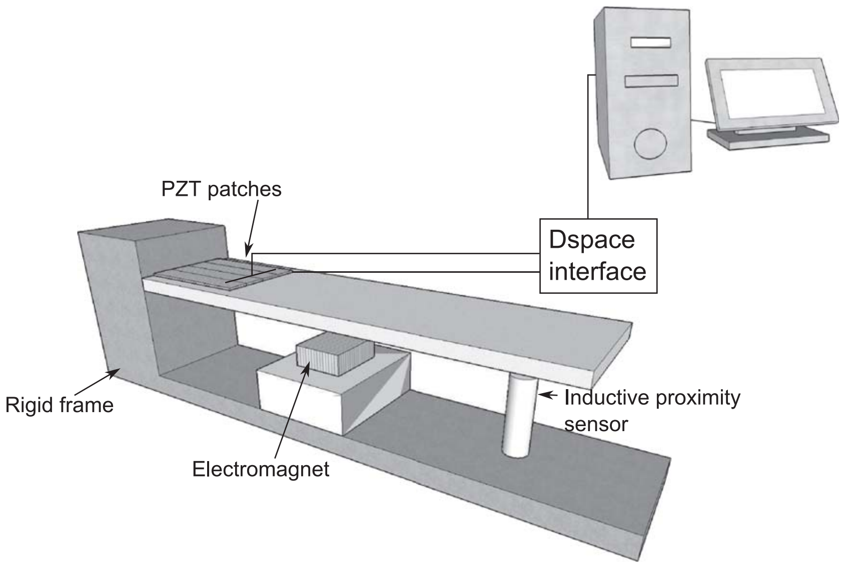

Fig. 9. Experimental set-up.

Table 1
Experimental parameter identification.

Dynamic mass M	52.4 g
Structural damping coefficient C	$0.09\,\mathrm{N\,s\,m^{-1}}$
Open circuit stiffness K^D	$1080\,\mathrm{N\,m^{-1}}$
Force factor α	$-0.989\,\mathrm{mN\,V^{-1}}$
Clamped capacitance C_0	52 nF

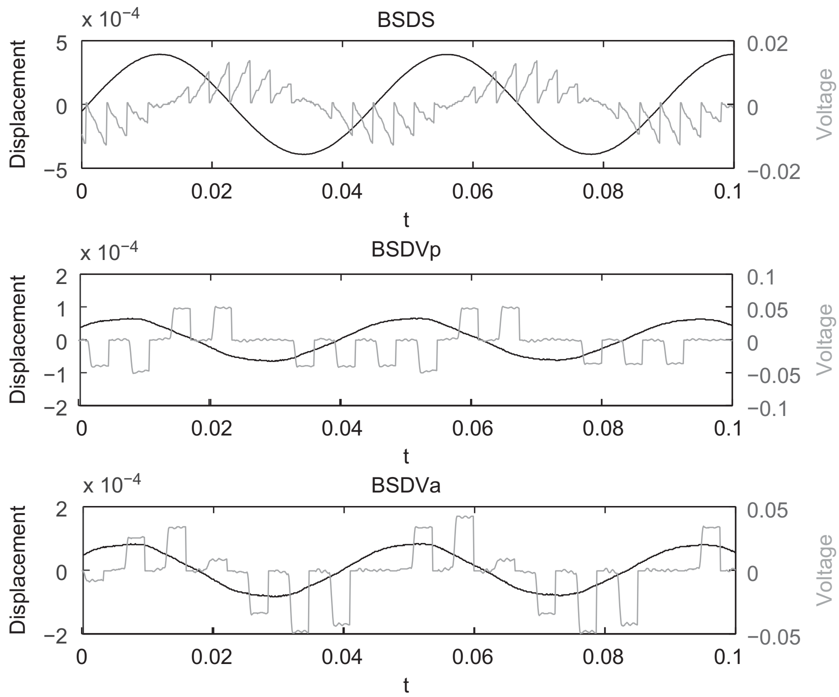

Fig. 10. Experimental displacement and voltage waveforms.

Moreover, the BSDVp requires an additional sensor to have the value of the magnitude of the displacement, while the BSDVa is self-sensing. The BSDVa also limits the harmonics of the piezovoltage, as the envelope is much closer to the speed than the BSDVp (Fig. 8). Actually, the BSDVp has an envelope that is equal to the sign of the speed. Therefore, there is more energy wasted in harmonics than in the BSDVa case. As well, while the damping effect of the BSDVa increases with the number of switch per period (parameter n), the damping effect of the BSDVp is constant whatever n (as long as $n \gg 1$). As the dissipated energy in the switching circuit also increases with n, the figure of merits given by the damping over the required energy is more interesting for the BSDVa than for the BSDVp. For all these reasons, the BSDVa seems to be the most interesting of the three techniques presented in this paper.

3. Experimental results

This section aims at experimentally verifying the concept of the blind switch damping. The principle of the method is tested with an excitation on one mode of the structure. The mode chosen in order to validate the method is the first mode. Further work will aim to control many modes of structure submitted to large bandwidth excitation.

3.1. Experimental set-up

The experimental set-up is presented in Fig. 9.

It consists of an instrumented cantilever beam. Hard PZT patches (type NAVY III) are bonded near the clamped side and are connected to the real-time interface *DSpace*® in order to apply the BSD control law. An inductive proximity sensor is

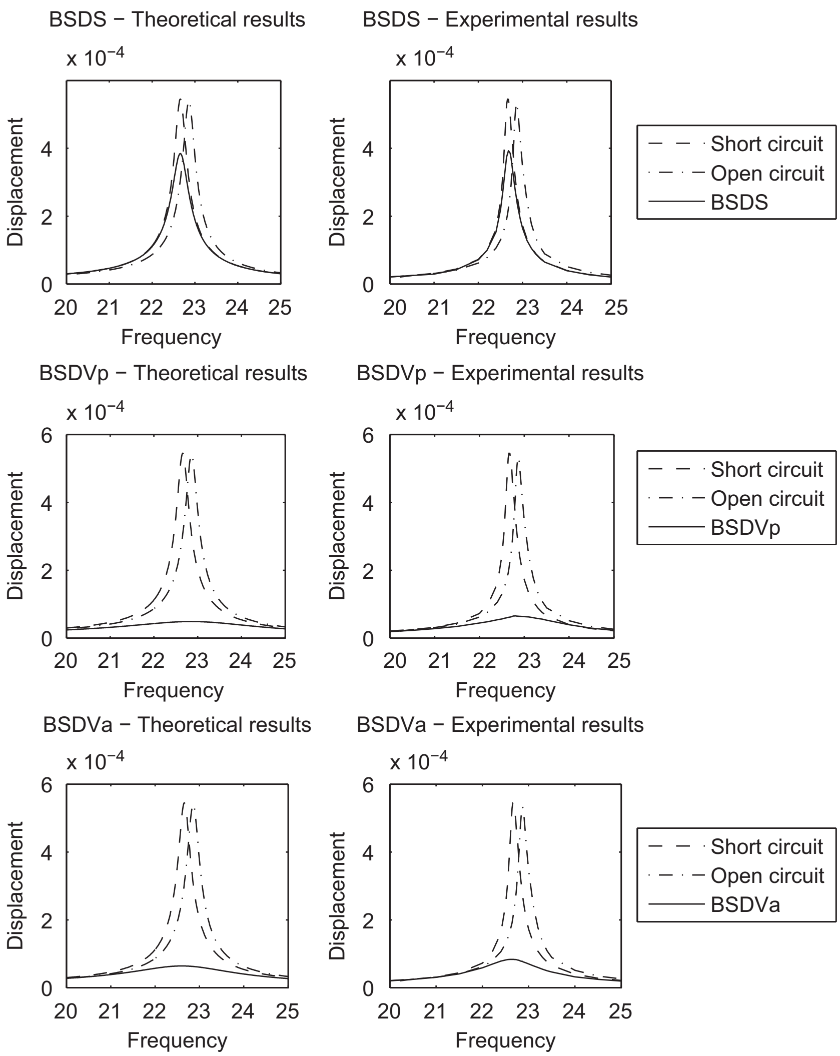

Fig. 11. Theoretical prediction vs. experimental results.

used in order to measure the displacement, but is not necessary for the control, except for the BSDVp. The excitation is realized thanks to an electromagnet in swept sine around the first frequency of the structure.

First, the model of the smart structure is identified near its first mode. The parameter identification for the structure is given in Table 1. M, C, K^E, α and C_0 are calculated as

$$\alpha = \lambda C_0$$

$$K^E = \alpha\lambda \frac{f_{sc}^2}{f_{oc}^2 - f_{sc}^2}$$

$$M = \frac{K^E}{4\pi^2 f_{sc}^2}$$

$$C = 4\pi\xi M f_{oc} \tag{30}$$

with f_{sc} and f_{oc}, respectively, defined as the short circuit and open circuit resonance frequencies, ξ the open circuit damping coefficient, λ open circuit piezoelectric voltage to the structure free end displacement ratio and C_0 the clamped capacitance of the piezoelectric element. The tuning coefficient β is chosen so that the term $\beta(1+\gamma)$ is equal to 11 and 18 for the BSDVp and BSDVa, respectively.

3.2. Experimental results and discussion

The first set of measurements consists in measuring the displacement magnitude around the resonance frequency of the structure. The switching parameter value n is fixed and set to 7. This value, as shown thereafter, gives a good trade-off between BSDS and BSDVa damping abilities and speed reconstitution, while ensuring the BSDV stability. Typical

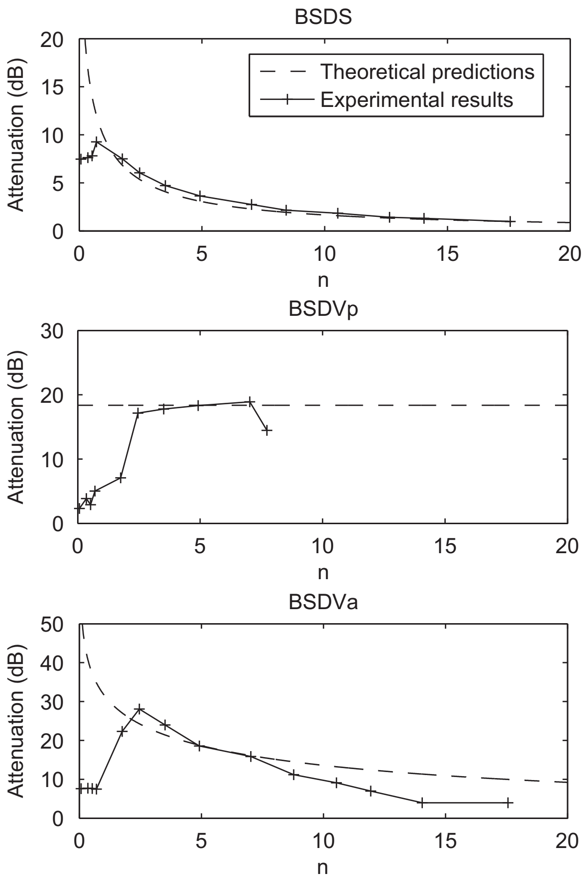

Fig. 12. Attenuation as a function of the switching coefficient n.

waveforms are depicted in Fig. 10[1] and experimental results as well as theoretical predictions in Fig. 11. This figure shows that experimental results are in good agreement with theoretical predictions.

As expected, the BSDS, although needing no power except the command, presents limited damping capabilities (−2.85 dB). The voltage increase of the BSDVp and BSDVa leads to an enhancement of the damping (respectively, −18.42 and −16.28 dB for the BSDVp and BSDVa), artificially increasing the conversion abilities.

Fig. 12 compares the attenuation of the three techniques with the number of switch per period n. The attenuation is defined by

$$\text{Attenuation} = -20\log 10(A) \tag{31}$$

As expected, the damping is a decreasing function of n for both BSDS and BSDVa techniques, while the damping effect is quite constant for the BSDVp on a given range of n. However, due to its frequency contents (odd harmonics of the vibration frequency), the BSDVp approach presents stability issues for high values of the switching coefficient n. In conclusion, in the case of the BSDVp, the choice of the value of n depends on the stability, whereas in the case of the BSDS or BSDVa, this choice is justified by the trade-off between damping and speed reconstruction.

4. Conclusion

This paper proposed a new and original control law for vibration damping purposes, based on a periodic switching of a piezoelement. This approach is independent from the electromechanical structure characteristics, thus allowing a very large frequency band operation and a good robustness facing environmental drifts. The proposed control law presents a very simple command that can be very easily implemented. As well, the technique can rely on an energy injection/recovery basis that makes the system requiring relatively low power.

Compared to the semi-passive synchronized switch damping (SSD) method, the proposed technique allows a control of the reinjected harmonics, although the damping effect for equivalent parameters is lower with the blind switch damping.

Experimental measurements have been carried out, confirming that the BSD method allows an effective damping of vibrations. Further work will aim to show the efficiency of the proposed method when the structure is submitted to a large bandwidth excitation.

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[1] Actually in this case the voltage is opposed to the speed due to the negative value of α; this speed and voltage opposition has no consequences on the efficiency of the technique.

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