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SEMI-PASSIVE VIBRATION CONTROL: PRINCIPLE AND APPLICATIONS

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***Abstract* – This paper presents the semi-passive vibration control technique and its applications to vibration damping, energy harvesting and health monitoring. This concerns systems including a piezoelectric actuator embedded or bounded on a host structure. A nonlinear process of the piezoelectric voltage leads to large enhancements of dissipated or harvesting energy on the mechanical vibration. After the principle explanations, the different experiments held in the laboratory are presented. In every case, large enhancements are obtained through this nonlinear shaping of the piezoelectric element voltage.**

Keywords**:** *piezoelectric, application, energy harvesting, vibration damping, nonlinear.*

1. INTRODUCTION

The semi-passive vibration control relies on an optimization of the electrical energy generated on a piezoelectric insert bonded on a vibrating structure. The piezoelectric element is able to extract the mechanical energy from the vibrating structure by converting it into electrical energy. Degradation or transfer of this energy results in control and reduction of the vibration. For active vibration control, a complex system built with at least a sensor, a control unit and a feedback actuator is necessary. In addition, external power sources and amplifier are needed for the control unit and the actuators. The passive techniques are more easily integrated due to their simplicity and their compactness. The piezoelectric elements are connected to a specific electrical network consisting of a dissipative shunt [1]. The most effective method is the tuned shunt where a circuit made with an inductor (L) and a resistor (R) in series is connected to the capacitance (C_0) of the piezo-elements. Optimal damping is obtained by tuning the electrical resonance on the frequency of the wanted structural mode. This method leads to good results but has the few following disadvantages: For low frequency modes, the optimal value of the inductor is very large and requires active circuitry. Moreover it is sensible to environmental factors such as temperature, acoustic load, which cause drifts of the structure resonance frequencies. Once detuned, the shunt circuit looses its damping performance. Finally, multimode damping requires the use of complex shunt circuits [2-4]. More recently, switched shunt techniques have been developped introducing a non-linear approach by using a modulation of the piezoelement properties or boundary conditions synchronously with the structure motion. They are also based on a discontinuous dissipation or transfer of the mechanical energy. The state switching method proposed by Clark [5] is a variable stiffness technique in which piezoelements are periodically held in the open circuit state then switched and held in the short-circuit state, synchronously with the structure motion.

The method discussed in this paper was previously developed for damping applications [6]. It is known as SSD for Synchronized Switch Damping. It consists in a non-linear processing of the voltage on a piezoelement bonded on the structure [6, 7, 8]. It is implemented with a simple switch driven during short periods synchronously with the structure motion. The switch connects the piezoelement to a circuit, which can be a simple short circuit (SSDS) [6], a small inductor (SSDI) [7] or voltage sources (SSDV) [9, 10]. Due to this process, a voltage magnification is obtained and a phase shift appears between the piezoelement strain and the resulting voltage, thus creating energy dissipation. This method offers several advantages: It is insensitive to environmental changes due to its self-adaptive broadband behavior, it does not require a very large tuning inductor for low and very low frequencies, multi-modal damping is achievable without complex circuits and only a very low external power is required for the switch control.

2. SSD PRINCIPLE

When driven by a mechanical excitation, a piezoelectric transducer develops a voltage in phase with the mechanical strain or displacement. In the proposed approaches shown schematically on Fig. 1, this voltage can be forced to zero (SSDS) or can be reversed (SSDI) each time a maximum of the voltage is reached. It is simply obtained by closing a switch device (mosfet transistor) for a very brief period of time, and synchronized by an extremum detector. If forcing the voltage to zero with a short-circuit is straightforward, the voltage inversion is obtained by an oscillating discharge of the piezoelement capacitance with a small inductor and re-opening the circuit after exactly half an oscillation period. [6,7]. As a result of this treatment, the voltage is greatly magnified and time shifted nearly in quadrature with the strain or displacement, as it is shown in Fig. 2.

Now, if the state equation for a piezoelectric material is considered, it appears that a stress T develops driven by the electric field E and therefore by the voltage V In the state equation (1) for a piezoelectric material, c^E is an elastic coefficient, e is the piezoelectric constant and S and T the mechanical strain and stress.

$$T=c^E S-e\ E \qquad (1)$$

Depending on the piezoelement geometry and coupling used, either axial or lateral strains and stresses as well as the proper elastic and piezoelectric coefficients have to be considered. For frequencies lower than the piezoelement resonances, equation (1) can be expressed as a function of the displacement u, the piezo voltage V and the mechanical force F, leading to equation (2) where t is the thickness between electrodes, L is the length in the direction of the considered strain and A the aera of the piezoelectric element.

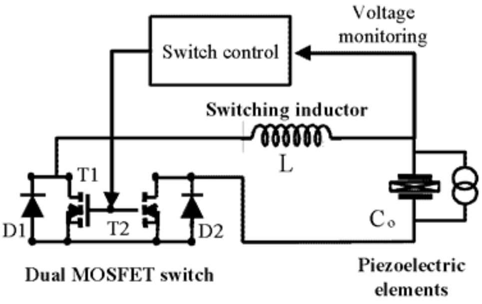

Fig. 1: The electronic circuit used for the SSDI damping technique. The inductor can be replaced by a simple short-circuit

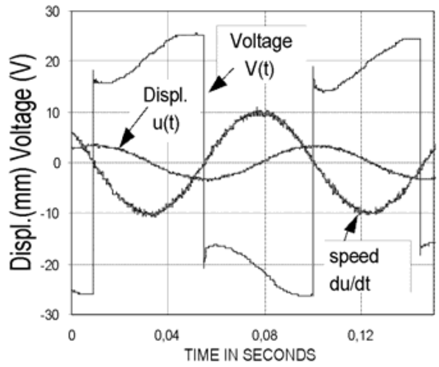

Fig. 2: The voltage on the piezoelectric elements and the transducer strain or displacement versus time for the SSD technique with an inversion inductor

$$\frac{F}{A}=c^E\frac{u}{L}-e\ \frac{V}{t} \qquad (2)$$

$$F=K^E u-\alpha.V \qquad (3)$$

where $K^E=c^E.\frac{A}{L}$ and $\alpha=e.\frac{A}{t}$ are respectively the short-circuit elastic constant and a global piezoelectric voltage coefficient.

Multiplying both terms of equation (3) by the speed and integrating over the time leads to the energy equation balance (4):

$$\int F.\dot{u}\,dt=\int K^E u.\dot{u}\,dt-\int \alpha.V.\dot{u}\,dt \qquad (4)$$

The left term corresponds to the mechanical energy provided to the piezoelement by the host structure. The first integral of the right term corresponds to the elastic energy. For a periodic signal this term vanishes except for the mechanical losses of the piezoelement.

The second integral corresponds to the energy converted by the switching process. This energy can be either degraded into heat, or transferred on a capacitance leading respectively to damping or energy harvesting applications

Without switching and without losses, the open-circuit piezoelectric voltage V(t) is in phase with the strain and therefore participates in the stiffness of the transducer and only corresponds to reactive electrostatic energy. With the switching process on, it generates a component of the stress in quadrature with strain and acting as force leading to energy transfer and damping. Clearly the switching integral is optimized and the SSD effect very performant if the voltage is exactly in opposition with the speed. The generated piezo force is therefore opposed to the speed and nearly constant, thus very similar to dry friction (V and therefore the corresponding force is roughly proportional to the sign of the speed).

The energy defined by the cycle is given [7] by:

$$E_S=4.k^2.K^E.U_M^2.\frac{1+I}{1-I} \qquad (5)$$

U_M is the displacement amplitude, I is the inversion process coefficient (I=1 is ideal inversion and I=0 corresponds to the short-circuit case). The importance of this coefficient is illustrated on Fig. 3 showing the induced piezo force αV as a function of u. The area of the cycle is larger with the SSDI process (plot 3) compared to SSDS (plot 2) and open circuit (plot 1).

Finally k is the global electromechanical coupling factor of the structure. Enhancing this figure is a key parameter for improving the transferred energy and consequently the system performance. The main advantage of the SSD technique is its simplicity. The piezoelectric transducer is used both as a sensor, allowing to synchronize the switch sequence on the voltage, and an actuator generating the damping dry friction alike force.

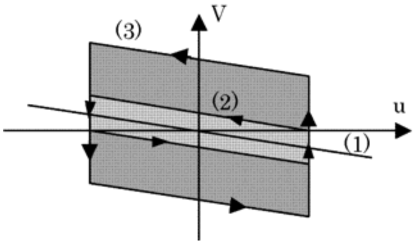

Fig. 3: switching energy cycles for open-cicuit case (1), SSDS voltage process (2) and SSDI (3)

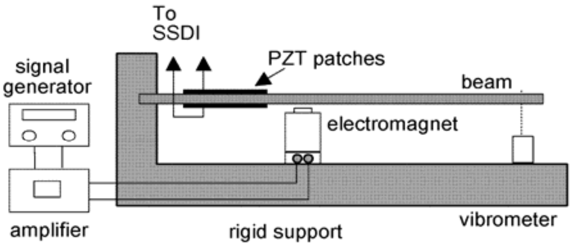

Fig. 4: Cantilerver beam experimental setup.

3. VIBRATION DAMPING APPLICATIONS

The basic configuration for demonstrating the performance of the proposed technique for vibration damping is illustrated on Fig. 4. The considered structure is a cantilever beam that could be excited either on the first bending mode or on the first two modes simultaneously. The beam is equipped with PZT patches bonded close to the clamped end since according to equations (3) and (4) the piezoelement have to be ideally stressed by the structure to extract energy. The SSD device shown on Fig. 1 is simply connected on the PZT patches wired in parallel. Fig. 5 shows the first bending mode resonance around 13 Hz. The tip deflection is plot as a function of the frequency for various configurations. Open and short circuit configurations correspond to the natural damping of the structure. The resonance frequency shift illustrates the stiffness variation characterizing the piezoelectric effect. It is also representative of the global electromechanical coupling of the beam. The performance of the passive technique with a matched resistor [1, 6] is given for comparison.

Clearly, SSDS and SSDI allow a very significative resonance amplitude reduction (12dB in this case) In the later case the resonance is barely visible.

Finally to illustrate the broadband possibilities of the proposed technique, a SSDI controller has been used with a PZT patch (ACX QP10N) bonded on a plate [9]. Many modes are visible on Fig. 6 obtained during a frequency sweep. Clearly SSDI offers a wide band damping possibility.

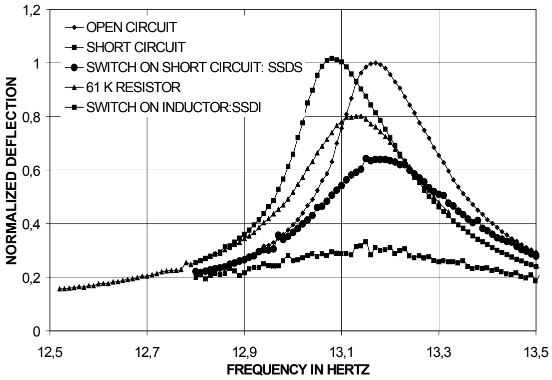

Fig. 5: Aluminum cantilever beam resonance for various control configurations.

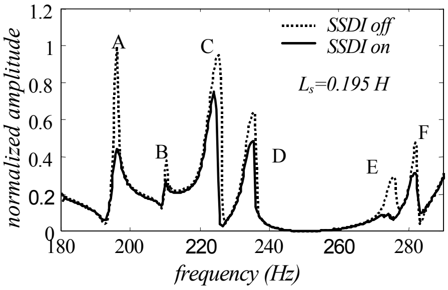

Fig. 6: vibration amplitude spectrum of a plate (measured close to the PZT patch. L_S is the inversion inductor.

Variation of the damping performances for the various modes is due to the variation of the electromechanical coupling coefficient due to the PZT patch position relatively to the considered mode. The vibration damping that can be achieved for a given mode can be expressed by a damping coefficient similar to those defined for mechanical losses. It is obtained from equation (5) and from the expression of the elastic energy in the structure. For SSDI it is given by:

$$tg\delta_{SSDI} = \frac{4k^2}{\pi} . \frac{1+I}{1-I} \tag{6}$$

This coefficient is intimately related to the coupling coefficient. This can be understood since the power conversion of the patch is fully exploited in this technique. Usual configuration allows an inversion coefficient I ranging between 0.4 and 0.8. SSDS case corresponds to I=0.

4. ENERGY HARVESTING OPTIMIZATION

The proliferation of transducers and sensors integrated in many systems raises the problem of wires installation for power supplies and data transmission. This explains the growing interest in miniature electrical generators enabling to feed, for instance, a wireless transducer and a small infrared or radio data transmitter [11].

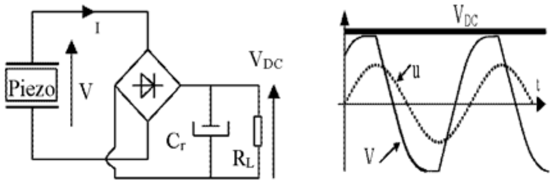

Fig. 7: Standard electrical circuit and waveforms

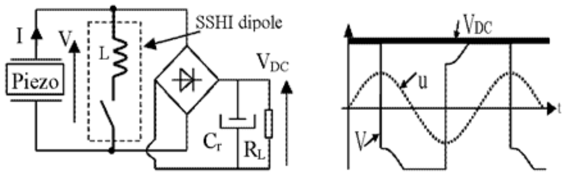

Fig. 8: SSHI dipole inserted in parallel with the piezoelement and the load and the corresponding waveforms

In this field, piezoelectric micro-generators are of major interest due to their solid state nature facilitating their integration. For a low consumption system placed on a vibrating structure, the extraction of electrical energy using an embedded piezoelectric device is particularly well adapted to create an autonomous electrical power supply.

The standard circuits used for harvesting electrical energy using a piezoelectric element are composed of a diodes rectifier and a filter capacitor, in order to provide a DC voltage to the load. This standard circuit is represented in Fig. 7. The electric load is modeled as a resistor having equivalent energy consumption. Considering a single vibration mode, the mechanical displacement *u* is supposed purely sinusoidal in steady state operation. In this condition, the open circuit voltage delivered by the piezoelectric element *V* is sinusoidal too. But the electrical circuit connected to the piezoelectric element changes the waveform of *V*. Indeed, the piezoelectric element is in open-circuit only when the rectifier bridge is blocking, that is to say when the absolute value of *V* is lower than V_{DC}. Theoretical displacement and voltage waveforms corresponding to this case are also shown on Fig. 7. It is assumed that the voltage on the load remains constant, which is realistic if the capacitance C_r allows a filtering time constant larger than a vibration period.

The solution proposed to enhance piezoelectric energy reclamation from mechanical vibrations, is derived from the semi passive technique that has been previously described It is called SSH for synchronized Switch Harvesting technique [12][13]. As illustrated on Fig. 8, it consists in adding a switching device connected in parallel with the piezoelectric element and the rectifier input.

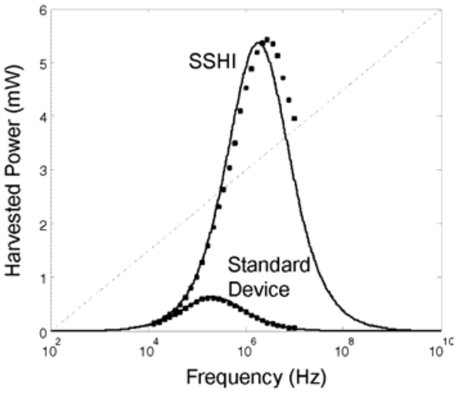

Fig. 9: Experimental and theoretical results showing the harvested power as a function of the load impedance for standard and SSHI energy harvesting. Solid lines stand for simulation and dots for experiments [13].

For a given vibration amplitude, the SSH dipole increases and shifts the voltage waveform leading to a voltage in phase with the speed. The energy balance represented by equation (4) is still valid and therefore the switch induced energy term given by equation (7) is optimized. This energy is represented by the area defined by the periodic cycles shown in Fig. 3:

$$E_S = \int \alpha . V . \dot{u} \, dt \qquad (7)$$

Except for the losses of the device due to the transistor switch and the inversion inductance, E_S corresponds to the harvested energy.

The optimized voltage corresponds on the mechanical side to an optimized force that allow to increase the mechanical work of the piezoelement for a given vibration amplitude, and therefore to an increased extracted power flow. However, as usual, the power flow also depends on the load connected to the electric generator. There is generally a matched load for which this power flow is optimized. Fig. 9 illustrates both experimentally and theoretically this point, showing the extracted power as a function of the load resistor for both standard and SSHI configurations. It appears that for a given vibration amplitude, power can be increased by nearly a factor 10 using SSHI depending on the host structure.

With resonant structure having a strong electromechanical coupling, for which the displacement amplitude does not remain constant with the load, the harvested power tends to the same limit using a standard energy harvesting circuit or the SSHI circuit. This is due in particular to the strong damping effect of the SSHI technique. However, for powers lower than this maximum, the SSHI technique strongly reduces the required quantity of piezoelectric material comparatively to standard systems. SSHI technique presents a very interesting compromise between harvested power and piezoelectric material quantity. Therefore, the global cost of the system could be significantly reduced.

5. AUTONOMOUS WIRELESS TRANSMITTER FOR HEALTH MONITORING NETWORK

With the growing use of sensors for the health monitoring in various structural and mechanical systems, the powering and communication network of these sensors become a critical factor. Opportunely, the permanent decreasing electrical power requirement for electronic circuits allows now the use of autonomous micropower piezoelectric generators exploiting the structural vibrations. Global or partial wireless networks are then feasible, such as several self-powered transmitters communicating with a central receiver.

Our goal was to implement an energy harvesting system for powering a single integrated wireless transmitter using our SSH (Synchronised Swtich Harvesting) method.

This self-powered system (piezoelements coupled with a RF transmitter) has two main functions: The generation of an identifier code to the central receiver and the generation of a Lamb wave for the health monitoring of the host structure (see Fig. 10). A damage index [14] can be derived from the variation between the transmitted wave spectrum and a reference spectrum. The interest of this method is its very low energy requirement. The piezoelements cumulate the SSH energy harvesting function and the Lamb wave generation ability.

In the monitoring network described in Fig. 10, only the transmitters are self-powered. The central receiver does not require self-power since it is outside of the vibrating device.

The functions of the autonomous wireless transmitter device (AWT) are as following:

- Energy Harvesting
- Identifier code emission: in case of wireless network, each transmitter must be identified.
- Lamb Wave Generation: acoustic emission used to control health of the host structure.

Reflected lamb wave can then be recorded and sent to the central recorder in order to compare it with reference data and to detect aging or defects in the structure. The micro-controller manages the energy balance and control lamb wave emission and RF information transmission.

The AWT has been evaluated on a 300x50x3 mm^3 composite cantilever beam. Four 33x12X0.3 mm^3 piezoelements are used for the energy harvesting and for the wave lamb generation. All the electronic components of the AWT are chosen for their low consumption ability. Piezoelectric materials are soft PZT material type Navy II (P188, Saint Gobain Quartz). Furthermore, additional piezoelectric patches were bonded on the free end of the beam in order to check the lamb waves emissions. A pulse stress disturbance is applied to the cantilever beam. When sufficient energy has been stored, the sleep mode of the controller is ended. It was set a threshold of 5V in the storage capacitance. Then the RF transmission is achieved followed by the lamb wave emission as depicted in Fig. 11. Recording the voltage on the storage capacitor gives the energy balance after the different steps. The results are as following:

Harvested energy : 6 mJ .(equivalent to 5V on the storage capacity).

Energy used for RF transmission : 0.5mJ, for an single information coded on 8 bits.

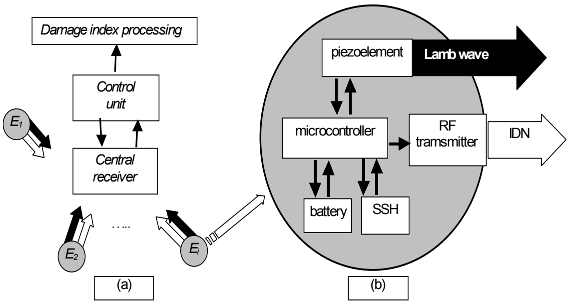

Fig. 10. Health monitoring network (a) and single Autonomous Wireless Transmitter (b)

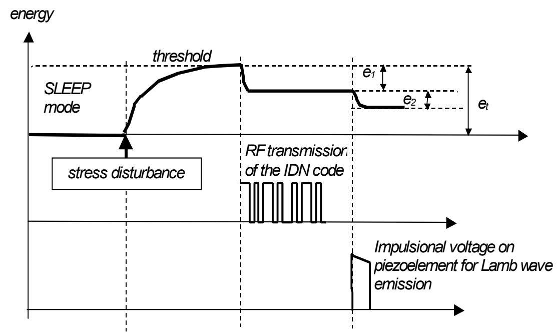

Fig. 11. The AWT transmission protocol and the energy balance: et is the global harvested energy, e1 is the outgoing energy for the RF transmission and e2 is the outgoing energy for the Lamb wave emission.

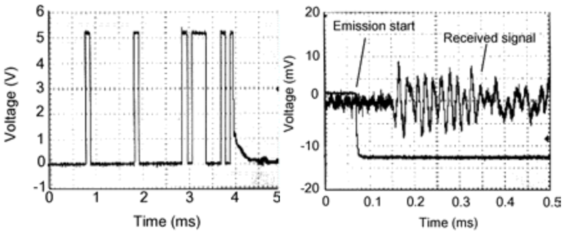

Fig. 12. (left) RF received signal for one octet and (right) Lamb wave emission. Signal received on the free end of the beam

Lamb wave emission : very small, less than 50 µJ.
Finally the complete sequence can be achieved with 4 RF transmission and 4 lamb waves emissions (one for each piezoelectric patch). A total of 2mJ is required for these operations, which represents only one third of the initial stored energy.
It should be noticed that a higher capacity corresponds to a higher stored energy, but requires a longer time of charge.

6. CONCLUSION

SSD technique that was initially developed as a vibration damping method is a very general principle. It is demonstrated that the non-linear processing of the piezovoltage allows a drastic increase of the electromechanical power conversion taking place in a piezoelectric patch. One of the main technical limitations that have been encountered is the loss in the switch and in the inversion inductance, which limits the induced voltage magnification and therefore the conversion performance. The application of the technique was successful for various applications where performance is related to better energy conversion in the piezoelements. Interesting figures are a nearly ten-fold potential power increase for a given piezoelectric micro-generator working out of resonance, a 10 to 20 dB vibration reduction on simple structure, with very good performances in low frequency without the need for bulky inductances.
The harvested energy showed to be ten times higher using SSD than standard harvesting system. In order to show the performance of the technique, this was applied to the power supply of an Autonomous Wireless Transmission device. It is always difficult to predict the required energy for a specific operation such as RF emission or acoustic wave generation. Actually, except the radiated power, the internal consumption plays an important role. In the presented experiment, it was shown the harvested energy is sufficient to ensure automatic health monitoring process including energy management, RF transmission and acoustic wave generation thus showing the advantages of high-performance energy harvesting device

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