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A new Vibration Damping Method using a Semi-passive Control

D. Guyomar , C. Richard, D. Audigier

INSA – Laboratoire de Génie Electrique et Ferroélectricité– 69621 Villeurbanne cedex – France.

e-mail : lgef@ge-serveur.insa-lyon.fr

A new damping system, based on piezoceramics shunted with a specific time sequence, is presented. Unlike other passive devices, the dissipation does not occur in a resistance or in a resistor/inductor circuit. The basic idea is to adequately deform the piezo output voltage waveform in order to create a phase shift between the output voltage and the mechanical displacement. The voltage distortion is obtained by switching from short circuit to an open circuit configuration in a repetitive sequence synchronous with the motion. The switching removes periodically the electric charges from the piezoelectric elements, changes the mechanical overall stiffness and creates non-linearities, thus creating several dissipations mechanisms. Experiments have been run on a cantilever device equipped with ceramic plates and a switching network. The results show a damping level higher that what is achievable with a passive circuit approach. Furthermore, the proposed approach works over a large bandwidth thus leading to important reduction for transient vibration.

1. Introduction

The passive piezoelectric vibration damping technique consists in shunting a piezoelectric device, imbedded or bonded on the mechanical structure, on a simple resistor [1][2]. The piezoelectric elements stressed by the structure motion behave as electric generators transforming mechanical energy into electrical energy that can be removed from the system or degraded. As a consequence of the electric impedance mismatch of the resistive circuit and the piezoelectric electric generator output impedance equivalent to a capacitance, the resistor has to be frequency tuned. Moreover, in order to optimize the impedance matching and to optimize the energy transfer a tuning inductor can be added or simulated if practicable [3].

The inductor tuned circuit presents interesting damping performances but suffers from its narrow band behavior (second order) and consequently presents degraded damping performances in the transient regime. For low frequencies, typically lower than 20Hz, the coil element can be very bulky and heavy, thus adding another drawback. The resistive shunt exhibits a rather small damping ability and since the resistance has to be tuned to get optimal results at a fixed frequency, the damping efficiency is also narrow band. To overcome these drawbacks, a low consumption semi-passive technique has been developed allowing enhanced damping performances over a large frequency bandwidth.

The proposed device is designed to be powered, in the industrial phase, by flat batteries over a large time period. From a practical point of view, the piezo elements output voltage, which is an image of the displacement or stress, is switched to zero when the displacement reaches a predetermined threshold. As a consequence of this switching, the output voltage presents a phase lag in comparison with the displacement waveform thus creating a kind of controlled viscous damping. This type of control consequently needs a kind of sensor giving an image of the displacement. It could be a passive piezoelectric insert close to the semi-active ones or simply the main piezoelectric inserts.

The required power is only needed for driving the static switch and for the control circuit supply. It can therefore be maintained at a very low level with dedicated low consumption electronic circuitry.

In the core of this paper, a brief description of the experimental set-up consisting in a low frequency (11 Hz) vibrating structure and the chopping device are given. A comparison between resistive shunt and semi-passive shunt damping experiments show enhanced damping performances for the proposed device. A qualitative model is finally proposed to interpret the observed controlled damping effect.

2. Experimental

Experimental set-up.

A schematic of the experimental set up is shown on Figure 1. An epoxy cantilever (length: 400 mm., width: 50 mm, thickness: 5 mm), clamped at one end with a rigid structure, is designed to vibrate on the first flexural mode close to 10Hz. Eighteen piezoceramic inserts (20mm x 10mm x 0.5mm) are embedded in the polymer close to the clamped end where the stresses are maximum for the first flexural mode. Two sets of 9 piezoelectric ceramic plates are each distributed at a 2mm distance from the neutral fiber of the beam. The piezoelectric material is PZT P194 (Soft PZT) from Quartz & Silice (St. Gobain – France) and the polymer is Araldite D + HY 956 hardener from Ciba. All these inserts are connected electrically in parallel and are oriented in the stress field in order to maximize the electric charge output. The poling direction is perpendicular to the plate and the piezoelectric response is consequently mainly driven by the lateral coupling (k_{31} and d_{31} piezoelectric coefficients [4]).

On the first flexural mode, these ceramics generate an output voltage which is simply proportional to the displacement.

The monitoring of the cantilever flexural displacement is obtained with an optical laser vibrometer (OptoNCDT 1605 from Micro-Epsilon Messtechnic GmbH – Germany). The beam deflection along the vertical axis is measured close to the cantilever free end.

The cantilever vibrations are driven by an electromagnet that generates an alternative force on a ferromagnetic metal plate (50mm x 20mm x 0.2mm), embedded in the polymer and located as shown on Figure 1. The electromagnet is driven by a signal generator (HP 33120A) through an audio power amplifier (NF4505). It can generate sinusoidal, pulsed or continuous forces.

The signals from the piezoelectric elements and from the vibrometer are simply monitored on an oscilloscope (HP 54645). The signal processing for the command of the switch device is made with simple discrete components but an experimental base using a PC for this goal has also been implemented. Finally the driving force is controlled through the electromagnet current.

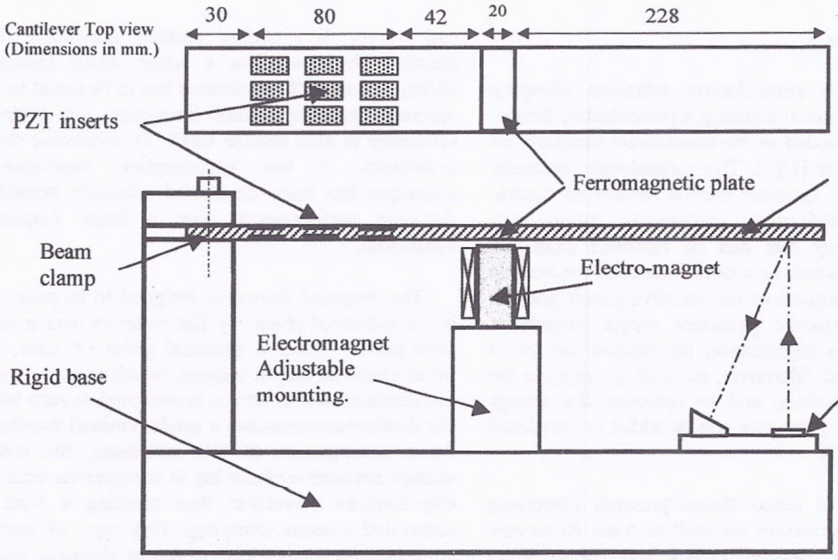
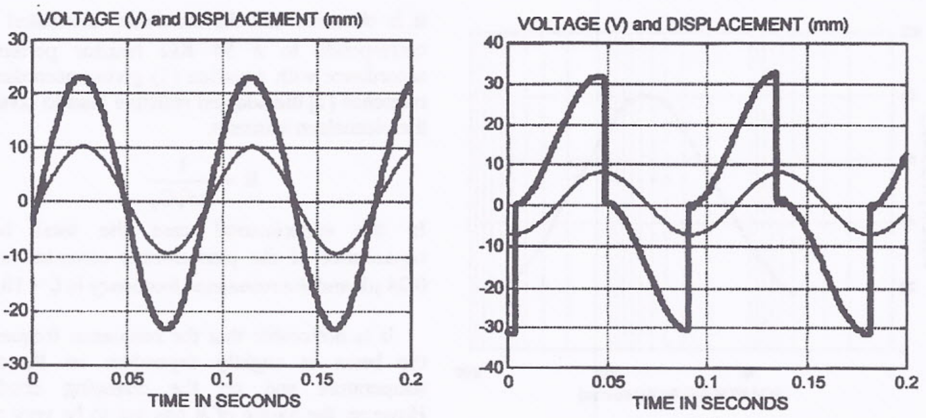


Fig. 1: Schematic view of the set up used for the vibration-damping experiments.



(a) *(b)*

Fig. 2.: The voltage (in Volts) on the piezoelectric elements (thick line) and the deflection (in mm) at the beam extremity (thin line) are given as a function of time. Fig 2a corresponds to the open circuit case and Fig 2b to the proposed switched regime.

The switching device.

For the low resonance frequency (11 Hz) corresponding to the cantilever first flexural mode, the ceramics output voltage is normally proportional to the beam flexural displacement (Figure 2 a).

The proposed electronic switching technique is implemented as follows: the piezoceramics are as an initial state, in an open circuit configuration; when the displacement reaches a threshold value (symmetrically positive and negative) the electronic switch forces the piezoelectric device to short-circuit; as the short circuit occurs, the output voltage undergoes a strong discontinuity and cancels over a short time period (typically shorter than 1ms); right after this period, the circuit is switched again to the open circuit configuration and the voltage varies again. Repeating continuously this process leads to an output voltage which is a time shifted image of the displacement (Figure 2.b). It is also noticeable that if the switching is properly controlled and with a very brief short-circuit period the output voltage amplitude is nearly twice the amplitude obtained without switching. The shunt impedance can be seen as changing alternatively from open to short circuit synchronously with the cantilever motion.

The switch itself consists simply in a pair of MOSFET transistors wired as shown on Figure 3. The command is very easy and little energy is needed. A symmetric structure is necessary to work properly on the positive and negative voltages.

In a general manner, the threshold value of the displacement or of the voltage that trigs the switching process can be either fixed or variable. It appears that best results are obtained for a threshold corresponding to the maximum and a minimum of the considered signal (displacement or voltage).

The switching process results in a distorted output voltage signal which presents a phase lag with the non processed signal and also a greater amplitude. Since the process is highly non-linear, high frequency harmonics are generated. This harmonics generation creates an extra damping by spreading the energy over different frequencies.

When the switching process takes place on maximum or minimum of the output voltage, this voltage is more or less an image of the displacement velocity and thus creates a damping quite similar to a newtonian viscous dissipation.

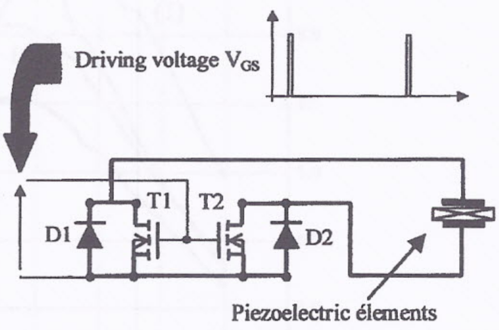


Fig. 3: The switch set up used to chop the voltage across the piezoceramics. T1 and T2 are usual NMOS transistors, D1 and D2 classical fast recovery diodes. The drive signal consists in pulses of short duration synchronized to the beam motion.

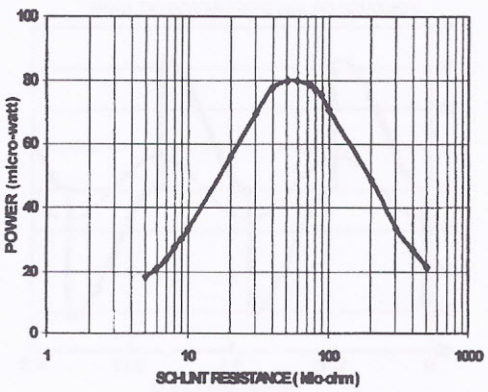


Fig. 4. :maximum electric power degraded by the resistive network as a function of the shunt resistance for a given excitation (0.2 N excitation force).

Classical resistive damping.

First experiments were aimed at establishing the damping ability of a dissipative network consisting in a simple adapted resistive load.

Figure 4 shows the maximum power dissipated by the resistive network as a function of the resistance for a given excitation level (approximately 0.2 N). This power is simply derived from the measured voltage across the resistor.

It is observed that the maximum dissipated power corresponds to a 54 KΩ resistor perfectly in accordance with equation (1) giving accordingly to reference [1] the adapted resistive load to connect to the piezoelectric inserts.

$$R = \frac{1}{2\pi f_r C_0} \qquad (1)$$

In the experimental case the total blocked capacitance of the piezoelectric ceramics is C_0 = 0.28 μF and the resonance frequency is f_r = 10.5 Hz.

It is noticeable that the resonance frequency of the beam is slightly dependent on R, on the temperature and on the clamping conditions. However the tuning of R has not to be very precise since it is only a kind of first order filter type. It is also observed that an inductor/resistor tuning approach is here impracticable since the proper inductor should be L=820H.

Vibration damping results.

A damping performance comparison between the resistive shunt and the proposed approach has been conducted with a steady harmonic type excitation. The results are given on Figure 5. Deflection measurements are made at the beam tip for a constant driving force (constant electromagnet driving current) with the frequency varying around the beam resonance frequency (# 11 Hz) corresponding to the first flexural mode.

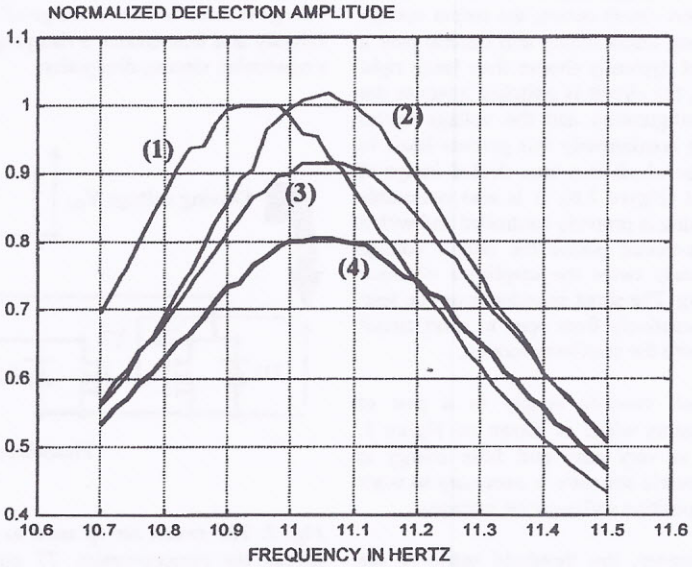


Fig. 5: Beam tip vibration amplitude as a function of the frequency. The deflections are normalized to the short circuit maximum amplitude. - (1): full time short-circuit configuration, (2) : full time open circuit configuration, (3): resistive shunt (R = 54 KΩ), (4): continuous switching configuration proposed.

Curve 1 and curve 2 correspond respectively to the displacement amplitude at the free end for the short and open circuit configurations.
It appears that the resonant frequencies associated with these two configurations are slightly different. As the piezo ceramics participate to the overall cantilever stiffness and since the piezo element stiffness is different for the open and short circuit configurations, the global cantilever stiffness and consequently the resonant frequency are affected by the electric boundary conditions applied to the piezoelectric inserts. The resonant frequency shift is quite small (0,1 Hz) because the global coupling factor is low. The natural resonance quality factor is close to 12 for the first flexural mode.
Curve 3 shows the damping due to resistive shunt for the adapted resistance of 54 KΩ. A 10% decrease of the maximum amplitude is observed on the resonance frequency.

Curve 4 shows the damping obtained with the proposed method when the switching is triggered both on the maximum and minimum of the displacement signal and with a 1 millisecond long short circuit. A 20 % amplitude decrease is reached.

Short-circuit duration influence

The short circuit duration influence on the damping ability was also investigated. In this case the short circuit was again triggered both on maximum and minimum of the displacement signal but the short circuit interval was made variable. Figure 6 compares the vibration amplitude as a function of the frequency for various short circuit times.

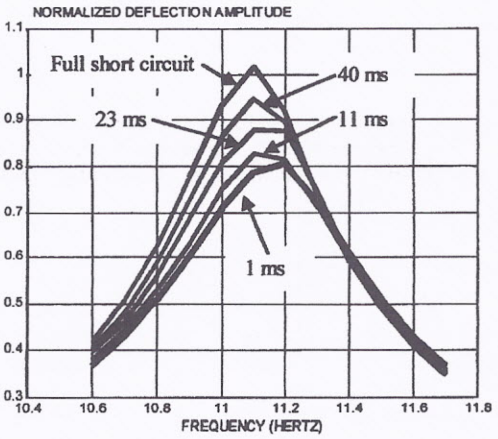


Fig. 6: Normalized beam tip deflection amplitude as a function of frequency for the switched regime with various short circuit intervals (1ms, 11ms, 23ms, 40ms and continuous short circuit) for a given constant excitation (electromagnet current).

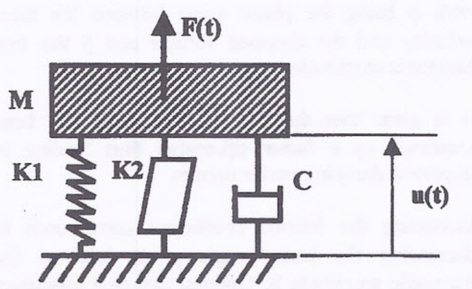


Fig. 7: spring mass model proposed. M is the inertial mass, K1 is the structure stiffness, K2 is the piezoelectric element and C is additional viscous damping.

It is observed that as the short circuit time increases the corresponding curve logically slightly shifts toward the full short circuit behavior. It is finally shown that best results are obtained with the smaller short circuit duration.

3. Model and discussion.

A basic spring-mass model illustrated in Figure 7 gives a qualitative understanding of the proposed semi-passive damping mechanism. The rigid mass M undergoes the action of the driving force F(t) and the restoring forces due to the initial spring (corresponding to the K1 stiffness of the non-damped oscillator) and the added spring (corresponding to the K2 stiffness of the piezo elements). In the general case, an extra force corresponding to the "natural" viscous force also acts on the mass.
In the low frequency regime, for wavelength much larger than the spring's length, the mass motion u(t) can be written:

$$M\frac{\partial^2 u}{\partial t^2}+C\frac{\partial u}{\partial t}+(K_1+K_2)u=-\alpha V(t)+F(t)$$

Where V(t) is the output voltage, and α is a coefficient related to the piezo material, C is an additional viscous coefficient corresponding to the mechanical losses of the structure itself.

As mentioned previously, the switching creates a time shift and a distortion of the output voltage (Figure 2). Clearly this process generates non-linear harmonics even for a narrow band driving force.
Taking a Fourier transform of the last equation and adopting the first harmonic approximation of V(t) leads to:

$$\{\ -\omega^2 M+(K_1+K_2)+j\omega(C+\alpha\beta\cos(\varphi))\ \}U(\omega)=F(\omega)$$

where the first harmonic V_1 of V is defined as

$$V_1=j\beta\cos(\varphi)U(\omega)$$

with φ being the phase angle between the mass velocity and the chopped voltage and β the first harmonic amplitude

It is clear that the friction coefficient has been increased by a factor $\alpha\beta.\cos(\varphi)$ thus leading to improved damping performances.

Increasing the friction coefficient corresponds to decreasing the phase angle φ or increase the harmonic amplitude β. Optimal damping efficiency is obtained for a switch sequence that maximize the $\beta.\cos(\varphi)$ product.

The damping performance is also a consequence of the α coefficient resulting of the global electromechanical coupling factor of the piezoelectric transducer attached to the structure. Increasing this electromechanical coupling can be obtained by either increasing the global coverage of the structure with piezoelectric elements (only discrete coverage was experimentally achieved here) or increasing the coupling factor of the piezoelectric element itself. For this purpose using piezoelements working in the 3.3 longitudinal mode instead of the 1.3 lateral one as in the experimental beam would certainly increase the resulting damping effect.

4. Conclusion

A new semi-passive approach of the vibration damping which consists in the continuous switching of a piezoelectric transducer embedded in the vibrating structure is proposed.

Switching the electrodes of piezo elements, imbedded in a polymer cantilever, from short to open circuit configuration leads to a resulting voltage on the piezo-elements which is distorted and shifted in the time domain from the beam deflection. When, the switching sequence, synchronous to the beam deflection signal, is adequately chosen, the damping performances of this device can be twice the one obtained with a classic adapted resistive shunt. Moreover the proposed approach is inherently a wide band technique.

This semi-passive method requires an external power supply for the logic circuits that control the switch device. It is estimated that this power consumption will be low enough to allow the use of batteries even on a long time period. A deflection sensor has been used for these experiments but it can be simply replaced by a sensing ceramic insert close to the main piezoelectric transducer or by the main piezoelectric transducer itself.

On going work aims at improving the actual damping performance using dual or multiple switches, reducing the power consumption and using alternative solutions to classical bulk piezoelectric ceramics.

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