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Passive self-tuning inductor for piezoelectric shunt damping considering temperature variations

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ABSTRACT

Piezoelectric shunt damping offers a passive solution to mitigate mechanical vibrations: the electromechanical coupling induced by piezoelectric patches bound to the vibrating structure allows the transfer of vibration energy to an electrical circuit, where it can be dissipated in a resistive component. Among the existing passive piezoelectric shunt circuits, the resonant shunt leads to significant vibration damping if it is tuned with enough precision. However, temperature may have a strong influence on electrical parameters such as the piezoelectric capacitance and the circuit inductance. As a consequence, a temperature variation can lead to a deterioration of vibration damping performance. This paper describes how inductive components can be chosen to minimize the mistuning of the resonant shunt when temperature evolves. More specifically, inductors are made of magnetic cores whose magnetic permeability varies with temperature, which counterbalances the variations with temperature of the mechanical resonance frequency and of the piezoelectric capacitance. Experiments show the benefits of adequately choosing the magnetic material of the inductor for vibration damping of a cantilever beam. The concept of a fully passive shunt adapting to temperature variations is hence validated.

1. Introduction

The direct and inverse piezoelectric effects allow piezoelectric materials to create an electromechanical coupling between mechanical and electrical domains. Since the nineties, vibration damping by bonding piezoelectric patches to lightweight mechanical structures has been studied. The electromechanical coupling enables transferring part of the mechanical energy to an electrical circuit, where it can be dissipated in a resistive component. The use of piezoelectric shunts, first proposed by Forward [1], stands as a relatively simple vibration damping solution. In 1991, Hagood and von Flotow [2] developed the concept of the resonant shunt, which is the electrical analog of a tuned mass damper [3], also called dynamic vibration absorber. Since then, different types of resonant shunts have been developed to damp a single mechanical resonance [4–7], as well as several resonances thanks to multi-branch shunts [8–11] or interconnected arrays of piezoelectric patches [12–14].

The resonant shunt provides a significant vibration damping around the electrical resonance angular frequency $\Omega_e = 2\pi f_e = 1/\sqrt{LC}$, where f_e is the electrical resonance frequency, L is the inductance and C is the capacitance of the piezoelectric patches. The literature is abundant on techniques to properly tune resonant shunts [6,15–19]. A commonly accepted result is that the electrical resonance frequency should be set sufficiently close to the mechanical resonance frequency. The main drawback of

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this technique is the need of a precise tuning of the electrical parameters to ensure the performance of the resonant shunt [6,17,20,21]. Temperature is one of the environmental parameters that have a significant impact on the resonant shunt tuning. Indeed, piezoelectric materials properties vary with temperature [22–24], especially the piezoelectric capacitance. Then, Park and Han [25] have shown that the degradation of resonant shunts performance when temperature evolves is mainly caused by variations of both the piezoelectric patches parameters and the inductance. Niederberger [26] has thus developed an autonomous switching shunt which can adapt to temperature variations, but the overall damping performance is limited to around 6 dB vibration reduction with the proposed setup. Other adaptive piezoelectric shunts have been proposed [27,28], but they are not autonomous passive solutions since they require external power supply.

The contribution of this paper is the validation of a fully passive resonant shunt that would remain correctly tuned in case of temperature variations. The resonant shunt is kept tuned by using a variable inductor that makes the electrical resonance frequency of the system evolve in the same manner as the mechanical resonance frequency. This principle has been recently proposed in Ref. [29], where a nonlinear mechanical system is damped with a fully passive but adaptive piezoelectric resonant shunt subjected to variations of the electrical current. The former principle is here extended to a case where temperature is the main parameter inducing variation of the equivalent inductance value.

The following section presents an electromechanical model to estimate the influence of temperature on damping performance of resonant shunts. A tuning condition of the resonant shunt is expressed. Then, the experimental setup is described in section 3. In the same section, the evolution with temperature of the mechanical resonance frequency and the piezoelectric capacitance are measured from room temperature to around 60 °C. As a consequence, inductive components, made by winding turns of conductive wire around magnetic cores, are designed by taking into account the temperature characteristics of the cores magnetic permeability. The influence of the air gap on the inductance value is highlighted, and the resulting inductive components are then characterized when subjected to temperature and electrical current variations. Finally, in section 4, practical validation in forced vibration at different temperatures is performed. Experiments highlight that it is possible to counterbalance the variations with temperature of the mechanical resonance frequency and of the piezoelectric capacitance with inductance variations, and so to mitigate the influence of temperature on damping performance. When the magnetic material of the inductor is adequately chosen to satisfy the tuning condition, the damping performance of the resonant shunt is maintained from room temperature to around 50 °C.

2. Electromechanical model for piezoelectric shunts

An electromechanical model of the shunted vibrating structure is derived from the governing equations of piezoelectricity. The case of the resonant shunt is studied, and the importance of its tuning is highlighted. The influence of temperature on the tuning condition is then expressed from linear variations of the involved quantities.

2.1. Governing equations

The piezoelectric effect allows some materials under stress to produce a potential difference between their electrodes. Conversely, these materials get under stress when subjected to an electrical field. These are called the direct and inverse piezoelectric effects, respectively. The 3D governing equations of the piezoelectric materials behavior is given in Ref. [30] by

$$\begin{aligned} \varepsilon_{ij} &= s^E_{ijkl}\sigma_{kl} + d_{kij}E_k, \\ D_i &= d_{ikl}\sigma_{kl} + \epsilon^{\sigma}_{ik}E_k, \end{aligned} \tag{1}$$

where ε_{ij}, σ_{kl}, E_k and D_i are the strain, stress, electrical field and electrical displacement variables, respectively. The s^E_{ijkl}, ϵ^{σ}_{ik} and d_{ikl} constants are the elastic compliance under constant electrical field, the electric permittivity under constant stress, and the piezoelectric constants which represent the electromechanical coupling, respectively. Under the assumption of a transverse isotropic piezoelectric material being polarized in the '3' direction and free in the other directions, Eq. (1) is simplified as

$$\begin{aligned} \varepsilon_{11} &= s^E_{11}\sigma_{11} + d_{31}E_3, \\ D_3 &= d_{31}\sigma_{11} + \epsilon^{\sigma}_{33}E_3. \end{aligned} \tag{2}$$

A thin patch of length $l_{\rm p}$, width $b_{\rm p}$ and thickness $h_{\rm p}$ is considered. The electrical field is supposed constant along the polarization direction, thus $E_3 = -V/h_{\rm p}$, where V is the voltage between the two electrodes of the patch. In the case of a one-dimensional mechanical model, if the considered wavelength is large enough compared to $l_{\rm p}$, the strain can be assumed uniform along the patch and expressed with the displacement U in the longitudinal direction by the relation $\varepsilon_{11} = U/l_{\rm p}$. We define $q_{\rm p}$ as the electric charge on an electrode, and $N_{\rm p}$ as the normal force applied to the patch. The electric charge $q_{\rm p}$ is linked to the electrical displacement by $q_{\rm p} = -l_{\rm p}b_{\rm p}D_3$. The longitudinal stress σ_{11} is supposed uniform along the cross-section $h_{\rm p}b_{\rm p}$, so the normal force is $N_{\rm p} = \sigma_{11}h_{\rm p}b_{\rm p}$. Hence, Eq. (1) can be transformed in

$$\begin{aligned} N_{\rm p} &= K^E_{\rm p}U - e_{\rm p}V, \\ q_{\rm p} &= C^{\varepsilon}_{\rm p}V + e_{\rm p}U, \end{aligned} \tag{3}$$