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Shunted piezoelectric patch vibration absorber on two-dimensional thin structures: Tuning considerations

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ABSTRACT

This paper investigates the flexural vibration control effects produced on a distributed two-dimensional thin structure by an electrically shunted piezoelectric patch tuned vibration absorber. The study highlights how the high modal overlap factors that characterise the response of thin two-dimensional distributed structures and the electro-mechanical, capacitive, stiffening and inertial, inherent properties of the piezoelectric patch transducer substantially influence the tuning of the electrical shunt and consequently the vibration control effects produced at frequencies near a given resonance frequency of the structure. In particular, the study shows that the classical approach considering a simplified two degrees of freedom equivalent model of the structure and shunted piezoelectric patch is inadequate to identify the optimal tuning parameters of the shunt. The study, also provides general guidelines for the dimensioning of the piezoelectric patch transducer and electrical shunt in order to maximise the electro-mechanical vibration absorption.

1. Introduction

This paper presents a simulation study on the control of flexural vibration in a thin rectangular plate two dimensional structure, which is equipped with a pair of collocated piezoelectric patches connected to a shunt composed by a resistor and an inductor in parallel. The initial results of this work were briefly reported in ref. [1], whereas this paper provides a detailed description of the mathematical model, which takes into account both the mechanical and electro-mechanical passive effects produced by the shunted piezoelectric patches, and the simulation results on the tuning and control effects of the shunted piezoelectric patches.

The idea of using shunted piezoelectric elements to control mechanical vibrations was first introduced experimentally by Forward [2] who considered the vibration control effects produced on a structure by a piezoelectric element connected with an inductive electrical shunt. About a decade later, Uchino [3] investigated experimentally the vibration control effects that would be produced by a piezoelectric patch connected to a purely resistive shunt. Few years later Hagood and von Flotow [4] further investigated the effects produced on a structure by a piezoelectric element connected to a series resistive-inductive shunt. They presented a seminal study showing that with a simple resistive shunt the piezoelectric transducer produces a viscoelastic damping effect while with a series resistive-inductive shunt the piezoelectric transducer produces a resonating vibration absorption effect. In this second arrangement, the resistive and inductive components of the shunt are

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selected to adjust the damping factor and natural frequency of the electromechanical absorber in such a way as it efficiently absorbs vibration energy near a resonance frequency of the hosting structure. Hagood and von Flotow presented two design approaches to find the optimal values of the resistive and inductive components of the shunt: one based on the classical "fixed-point" formulation developed by Den Hartog [5] for mechanical tuned vibration absorbers and the other based on a pole placement control methodology. Later on Wu [6] showed that a parallel resistive-inductive shunt can also be used to implement a piezoelectric vibration absorber, which would prove easier to tune since, with the parallel connection, the resistive and inductive components can be adjusted independently to find respectively the optimal damping factor and natural frequency parameters of the electromechanical vibration absorber. Forward [7] considered also the addition of a negative capacitive component in the shunt to reduce the inherent capacitive effect of the piezoelectric transducer and thus enhance the vibration absorption effect produced by the shunted piezoelectric element. This idea was further investigated by many authors, (for example see refs. [8–25]) who also recognised how the implementation of the negative capacitance may require a fully active shunt circuit. Additional fundamental theory on shunted piezoelectric elements was added over the years by many authors such as for example Hagood and Crawley [26], Hollkamp [27], Johnson [28], Davis and Lesieutre [29], Law et al. [30], Neubauer et al. [31] and Kozlowski et al. [32]. Also, detailed overviews of shunted piezoelectric elements for broad band vibration control can be found in refs. [33–36] for example.

Recent works [37–39] have proposed new approximated and exact expressions to tune the resistive and inductive components in the shunt such that the shunted piezoelectric patch tuned vibration absorber effectively absorbs vibration energy at frequencies near a given resonance frequency of the hosting structure. Nevertheless these studies refer to simplified two degrees of freedom models, one for the flexural natural mode of the hosting structure to be controlled and the other for the shunt electrical circuit, which are coupled via the piezoelectric transduction effect. In general, the spectrum of the response of distributed structures subject to broad band disturbances is characterised by multiple resonance peaks produced by the overlap of the second order resonant responses of the structure natural modes [40]. The frequency distribution of the resonance peaks depends on the wave-type (extensional, flexural, etc.) and on the type of structure (beam, plate, etc.) and is normally defined by the modal density factor $n(\omega)$, which gives the average number of natural frequencies per unit frequency interval (ω is the circular frequency in rad/s) [40–42]. At each frequency the response of the structure is thus characterised by the overlap of the modal responses that resonate at neighbouring frequencies. Normally a 3 dB bandwidth criterion is used to define the frequency band encompassing the second order modal responses that mostly influence the overall response at a given frequency. The amplitude of the 3 dB bandwidth depends on the sharpness of the resonance peaks of the second order modal responses. For instance, for a structure subject to viscous damping, which produces constant modal damping ratios ξ, the bandwidth tends to rise proportionally with frequency. Thus the number of modal responses that mainly contribute to the overall response of the structure at a given frequency is proportional to frequency, to the modal damping ratio and to the modal density factor. This effect is normally quantified with the so called modal overlap factor $M(\omega) = 2\omega\xi n(\omega)$ [40–42]. Analytical expressions for the modal overlap factor have been derived for various types of waveforms propagating in different types of structures. In general, flexural vibrations in thin two-dimensional structures are characterised by modal overlap factors that rise rapidly with frequency. The flexural response of thin plates or shells at each frequency is hence influenced by multiple modes. This is a rather fundamental property that characterises the flexural response of distributed two-dimensional structures, which, as will be discussed in this paper, becomes even more important when the structure is characterised by localised discontinuities as, for example, shunted piezoelectric patches bonded on the surface of the structure.

This study considers the flexural response of a thin rectangular plate equipped with a pair of collocated thin rectangular piezoelectric patch transducers, which are bonded on opposite side of the plate to form a symmetric laminate. The two transducers are connected to a shunt electrical circuit in counter–phase parallel architecture. The flexural vibration of the plate and shunted piezoelectric patches is derived from an analytical fully coupled electro-mechanical model that includes the passive stiffness and inertial mechanical effects of the piezoelectric patches. The shunt is composed by tuneable resistive and inductive electrical components connected in parallel, which, together with the capacitor formed by the piezoelectric transducers, produce a resonating electrical circuit that is effectively coupled to the flexural vibration of the plate and acts as a vibration absorber [4–6]. The effect of an idealised negative capacitance component connected in parallel to the shunt is also considered, which is added to reduce the inherent capacitance of the two piezoelectric transducers in such a way as to enhance the vibration absorption effect [7–25].

The aim of this study is to highlight how the multi-modal response of a distributed two-dimensional thin structure and the mechanical stiffness-inertia and electrical capacitive inherent effects of the piezoelectric transducers may substantially affect the tuning of the electrical shunt and consequently the vibration control effects the piezoelectric patch tuned vibration absorber may produce at frequencies near a resonance frequency of the hosting structure. This analysis is complemented with a parametric study, which provides general guidelines on how the dimensions of the piezoelectric patch (surface area and thickness) influence the tuning and therefore the vibration absorption effects produced by the shunted piezoelectric patch vibration absorber.

The paper is structured in six sections. Section two describes the plate with the piezoelectric patch shunt vibration absorber. Section three presents the analytical fully coupled model used to the derived the flexural response of the plate equipped with the shunted piezoelectric patch when it is excited by a uniform distribution of spatially uncorrelated random point forces that resemble the so called rain on the roof excitation field. Section four investigates how the multi-modal response of the plate structure and the mechanical and the electromechanical effects produced by the piezoelectric patches