Chinese Journal of Aeronautics, (2016), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Sound insulation performance of plates with interconnected distributed piezoelectric patches

Yi Kaijun [a], Li Lin [b,*], Mohamed Ichchou [a], Manuel Collet [a]

[a] *Tribology and System Dynamics Laboratory, Ecole Centrale de Lyon, Ecully 69130, France*
[b] *School of Energy and Power Engineering, Beihang University, Beijing 100183, China*

Received 29 January 2016; revised 17 June 2016; accepted 26 July 2016

KEYWORDS

Coincidence frequency;
Homogenization;
Piezoelectric material;
Sound transmission loss;
Wave propagation

Abstract This paper deals with the sound insulation performance of a thin plate with interconnected distributed piezoelectric patches. Piezoelectric patches are periodically bonded on the surfaces of the plate in a collocated fashion, and are interconnected via an inductive circuit network. This piezoelectric system is termed as piezo-electromechanical (PEM) plate in the paper. Homogenization methods are involved under a sub-wavelength assumption to analytically develop the dynamical equations for the PEM plate. The dispersion relationships and energy densities of the wave modes propagating in the PEM plate are studied; the sub-wavelength assumption is verified for the simulations in this paper. The coincidence frequency of the PEM plate is researched, and results show that the coincidence frequency of the PEM plate will disappear at certain circumstances; mathematical and physical explanations are made for this phenomenon. The disappearance of the coincidence frequency is used to optimize the value of inductance, for the purpose of improving the sound transmission loss of the PEM plate.

1. Introduction

The intensive uses of light plate-like structures in aerospace and transportation industries result in more serious vibration and noise issues for their higher dynamical sensitivities. To deal with these problems, techniques based on piezoelectric materials have been proposed and numerous papers have contributed to their developments and applications. In these applications, localized piezoelectric shunt techniques[1–8] and periodic distributed piezoelectric control techniques[9–34] have attracted a lot of attention. Among periodic distributed piezoelectric control techniques, two kinds of strategies can be found in the literature. The first one only uses separated shunted piezoelectric patches, and the second one interconnects all the distributed piezoelectric transducers via a circuit network.

The idea of using separated periodic shunted piezoelectric patches was proposed by Thorp et al.[10] They periodically placed shunted piezoelectric patches along rods to control

* Corresponding author.
E-mail addresses: yikaijun88@gmail.com (Y. Kaijun), feililin@buaa.edu.cn (L. Lin), mohamed.ichchou@ec-lyon.fr (M. Ichchou), manuel.collet@ec-lyon.fr (M. Collet).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.cja.2016.12.012
1000-9361

the longitudinal wave propagation. They found that at certain frequency ranges (namely the stop bands) no propagative longitudinal waves existed and these stop bands could be extended or relocated by tuning the shunting inductive/resistive circuits. Later, this concept has been extended to flexural beams[11,12] and plates.[13,14] Distributed shunted piezoelectric patches were also exploited to control energy flow in structures.[15–21] In Collet et al.'s work,[15] piezoelectric patches were distributed on a host beam to form a periodic piezo-composite beam; this functional beam was connected with a passive beam with identical parameters to the host beam. It was found that at the interface of these two different beams, total reflection or total absorption of certain types of waves incident from the passive beam could be achieved by tuning the shunting parameters. In another work of Collet et al.[17], an interface composed of a host plate and periodically distributed piezoelectric patches shunted with negative capacitance and resistance was designed. This semi-active interface was arranged between two passive plates to diminish energy translation from one passive domain to another one by trapping waves at their original domains or dissipating them. Its effectiveness was further verified by experiments in Tateo et al.'s work.[18,19] More recently, distributed shunted piezoelectric patches were successfully employed to focus waves by using gradient shunting parameters.[21] Along with the control of vibration and waves, periodic shunted piezoelectric patches were also used in the noise control domain. Casadei et al.[22] numerically and experimentally investigated the application of a periodic array of resistive–inductive (RL) shunted piezoelectric patches for the attenuation of broadband noise radiated by a flexible plate in an enclosed cavity. They demonstrated that the noise radiated by the plate was significantly attenuated. Zhang et al.[23] studied the sound transmission loss (STL) of a thin plate with periodically distributed piezoelectric patches shunted by an inductive circuit, and their results showed that the STL of the thin plate could be improved within the mass-law region and the coincidence region.

Interconnected distributed piezoelectric patches were mainly researched by Dell'Isola et al.[24–34] Firstly, they periodically distributed piezoelectric actuators in a truss and interconnected them by circuits. This integrated structure was called piezo-electromechanical (PEM) truss in their paper.[24] Research shows that there are waves in both the mechanical structure and the electric networks, and the maximum electro-mechanical coupling factor occurs when the speeds of the waves in these two mediums approach. Later, they extended this interconnected distributed configuration to beams and plates to build PEM beams[25,26,29,31,32] and PEM plates.[27,28,30,33,34] Results show that in these structures, internal resonances exist between the mechanical and electrical parts and multimode control effectiveness can be obtained by delicately designing the electric networks.[24,31–33]

However, previous works that used distributed piezoelectric techniques mainly focused on controlling vibration, associated sound radiation, or wave propagation in the structures, and few of research concerned the control of sound transmission especially by using interconnected distributed piezoelectric patches. In this paper, the sound insulation performances of a thin plate with interconnected distributed piezoelectric patches are studied. Firstly, the analytical dynamical equations for this PEM plate are established by using homogenization methods under a sub-wavelength assumption (Section 2). Then, the dispersion relationships and energy densities of wave modes propagating in the PEM plate are analyzed and the sub-wavelength assumption is verified (Section 3). At last, the coincidence frequency as well as the STL is studied (Section 4).

2. Model and dynamical equations

2.1. PEM plate model

Consider an infinite thin plate lying in $x-y$ plane; its upper and lower surfaces are periodically bonded with piezoelectric patches to constitute a piezoelectric composite plate, as shown in Fig. 1. A detailed configuration of one unit piezoelectric cell in this composite plate is illustrated in Fig. 2. The piezoelectric patches on both sides of the thin plate are respectively interconnected with their horizontal and vertical adjacent transducers via a circuit network shown in Fig. 3. In the circuit network, only inductors are used and they are all identical. The bonding surfaces of the piezoelectric patches are grounded, and the free electrodes are directly connected with the circuit network. For example, the free electrodes of the piezoelectric patches in the unit cells (m,n), $(m+1,n)$, $(m,n+1)$, and $(m+1,n+1)$ in Fig. 1 are respectively connected with the corresponding intersections (m,n), $(m+1,n)$, $(m,n+1)$, and $(m+1,n+1)$ in Fig. 3. The piezoelectric composite plate and the circuit network together construct a new functional system, which is called piezo-electromechanical plate in this paper, or PEM plate for short as in Refs. 30, 33

Assume that the wavelengths corresponding to the frequencies under consideration are much greater than the length of the unit cell. Under this sub-wavelength assumption, an analytical model is developed for the PEM plate. In the analytical model, an approximation method is employed to deal with the circuit network, which has been widely used in modelling of PEM structures,[29–33,35] and its effectiveness in characterizing the global dynamic behaviors of circuit networks has been experimentally demonstrated in Refs. 31, 35 The piezoelectric composite plate is homogenized through a well-validated method used in Refs. 21, 23, and after the homogenization, the composite plate can be treated as a homogeneous structure with equivalent dynamical parameters. The modelling process is introduced below, and for the sake of simplicity, a subscript comma is used to indicate the partial differential with respect

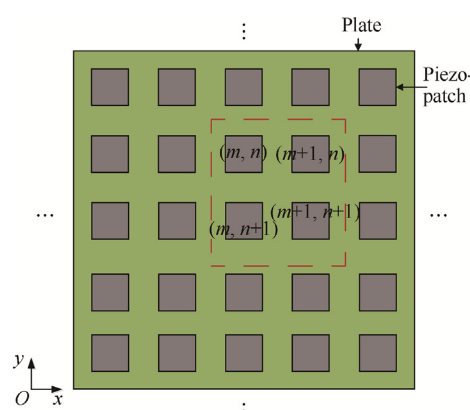

Fig. 1 Piezoelectric composite plate.