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Study of an hybridization gap in a one dimensional piezoelectric phononic crystal

S.A. Mansoura[a], B. Morvan[a], P. Maréchal[a], A.-C. Hladky-Hennion[b], B. Dubus[b].

[a] *LOMC, UMR 6294 CNRS, Université du Havre, 75 rue Bellot, 76600 Le Havre, France.*
[b] *IEMN, UMR 8520 CNRS, ISEN, 41 boulevard Vauban, 59800 Lille, France.*

Abstract

A one dimensional Phononic Crystals (PC) composed of a periodic stack including piezoelectric plates is studied. When the size of the pattern is a multiple of the wavelength, Bragg gaps appear based on interference mechanisms. In addition to this property, it is shown in this paper that the use of active piezoelectric plates allows opening hybridization gaps. These gaps are due to a coupling of an electrical resonance with the propagation of the acoustic waves. The electrical resonance is obtained by connecting inductances on the piezoelectric plates. Both experimental and analytical studies are conducted in this paper in order to study this phenomenon.
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Keywords: Phononic crystal; piezoelectric material; tunability; hybridization gap; ultrasonic waves.

1. Introduction

Phononic crystals (PC) are structures composed of periodic arrangements of a pattern along one or several dimensions that affects the propagation of elastic waves. If the size of the pattern is a multiple of the wavelength, Bragg gaps appear based on interference mechanisms. In the case of a stack of plates made of passive materials, only Bragg gaps are observable in the band structure of the PC [1]. In this paper, a 1D PC constituted of piezoelectric plates is considered. Previous works have shown the tuning properties of PC made of piezoelectric layers electrically connected to electrical capacitance loads [2]. In addition to Bragg gaps, it is shown in this paper that the use of active piezoelectric plates allows the opening of hybridization gaps. These gaps are due to a coupling of an electrical resonance with the propagation of the acoustic waves. The electrical resonance is obtained by connecting inductances on the piezoelectric plates. Recently, an experimental study [3] has shown the possibility to obtain variable mechanical coupling between a substrate and stubs by using piezoelectric disks shunted through an inductive circuit. In this paper an analytical expression of the dispersion relation is presented for a one dimensional PC including piezoelectric layers. The experimental transmission of the ultrasonic waves through the PC is then analyzed in the light of the theoretical band structure.

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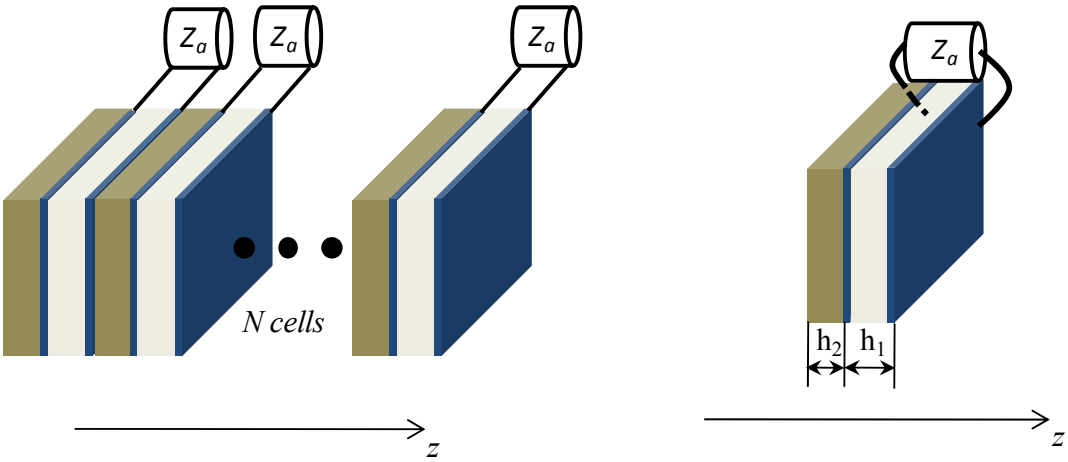
2. Dispersion relation

We consider the PC presented in Fig. 1(a). The structure is composed of a stack of alternating piezoelectric and passive plates. We study the propagation of longitudinal waves along the z axis on this structure which correspond to the thickness mode of the plates; the lateral dimensions of the plates are assumed to be much larger than the thickness. An electrical impedance Z_a is connected on each piezoelectric plate.



(a) (b)

Figure 1: (a) PC composed of passives and actives plates, an electrical impedance Z_a is connected to the electrodes of the piezoelectric plates. (b) Unit cell of the PC.

The densities of the active and passive plates are respectively $\rho^{(1)}$ and $\rho^{(2)}$. The solution of the equation of motion for the active layer is $u^{(1)}(z)$ and for the passive layer is $u^{(2)}(z)$. The expressions of the displacements are

$$\begin{cases} u^{(1)}(z) = A^{(1)}\cos(k^{(1)}z) + B^{(1)}\sin(k^{(1)}z) \\ u^{(2)}(z) = A^{(2)}\cos(k^{(2)}z) + B^{(2)}\sin(k^{(2)}z) \end{cases} \tag{1}$$

where $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ and $B^{(2)}$ are an unknown amplitudes. $k^{(1)} = 2\pi f / v_L^{(1)}$ is the wavenumber in the piezoelectric plate, and $v_L^{(1)}$ is the speed of the longitudinal waves in the piezoelectric material. $k^{(2)} = 2\pi f / v_L^{(2)}$ is the wavenumber of the passive plate, and $v_L^{(2)}$ is the speed of the longitudinal waves in the passive plate. The piezoelectric equations for the active plates are written by taking only the physical components on the z direction, the subscript "3" on the equations refers to the direction of propagation z.

$$\begin{cases} T_3^{(1)}(z) = c_{33}^D S_3^{(1)}(z) - h_{33} D_3(z) \\ E_3(z) = -h_{33} S_3^{(1)}(z) + \beta_{33}^S D_3(z) \end{cases} \tag{2}$$

where c_{33}^D is the elastic rigidity under constant electrical displacement, $S_3^{(1)} = \partial u_3^{(1)} / \partial z$ is the mechanical strain, E_3 is the electrical field along the thickness of the plate, h_{33} is the piezoelectric coefficient and β_{33}^S is the dielectric permeability at constant stress. According to the Gauss's law applied on the thickness of active plate, the electrical displacement D_3 is uniform along the direction of propagation. For the passive layers, the stress equation given in (2) is reduced to the classic Hooke's law $T_3^{(2)}(z) = c_{33} S_3^{(2)}(z)$,where c_{33} and $S_3^{(2)} = \partial u_3^{(2)} / \partial z$ are respectively the stiffness constant and the elastic deformation of passive layers.

The effect of the electric impedance load Z_a is taken on the expression of the electric displacement as follows

$$D_3(Z_a) = \frac{h_{33}}{\beta_{33}^S h_1.(1 + j\omega C_0 Z_a)}\left(u_3(h_1) - u_3(0)\right) \tag{3}$$

where $C_0 = h_1\beta_{33}^S / (j\omega S)$ is the clamped capacitance of the piezoelectric plate, and S the surface of the electrodes. The dispersion relation is obtained by applying the Bloch-Floquet relation (BFR) on the unit cell (Fig. 1(b)), the relation of continuity of the fields are written by using the Bloch function $X = e^{jkz}$, where k is the wave number in the structure.

$$\begin{cases} u_3^{(2)}(h_2) = u_3^{(1)}(0) \\ T_3^{(2)}(h_2) = T_3^{(1)}(0) \\ u_3^{(2)}(0) = X u_3^{(1)}(h_1) \\ T_3^{(2)}(0) = X T_3^{(1)}(h_1) \end{cases} \tag{4}$$

The application of the equations (4) gives a linear system where the only unknown are the amplitudes of the fields defined in equation (1). The dispersion relation is given by setting the determinant of the system to zero, this yields to the final equation

$$AX^2 + BX + C = 0 \tag{5}$$

where

$$\begin{cases} A = 1 - \alpha \sin(k^{(2)}h_2) \\ B = -2\cos(k^{(1)}h_1)\cos(k^{(2)}h_2) + \left(\gamma + \frac{1}{\gamma}\right)\sin(k^{(2)}h_2)\sin(k^{(1)}h_1) + \gamma\cos(k^{(1)}h_1)\sin(k^{(2)}h_2) \\ C = A \end{cases} \tag{6}$$

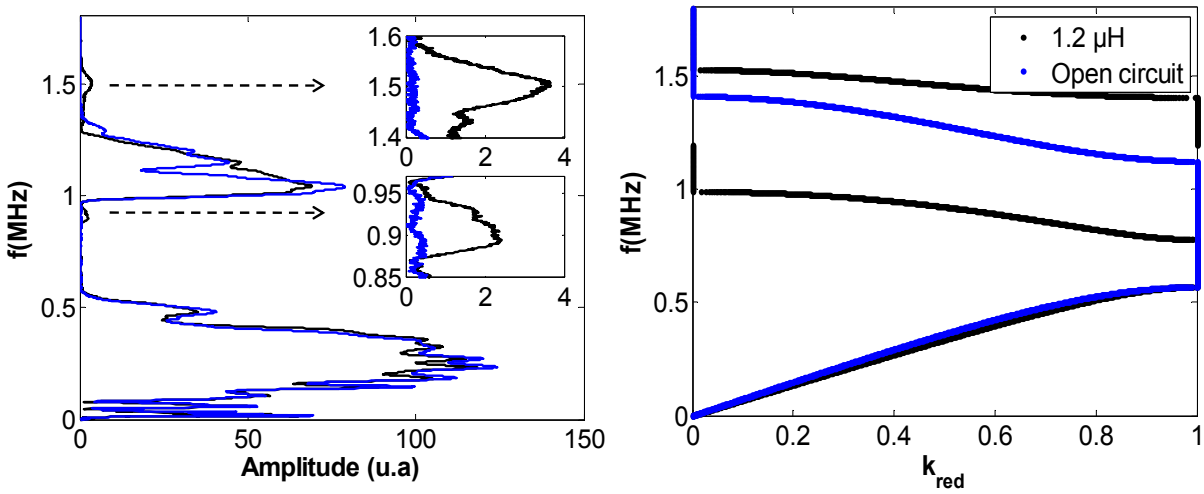
with

$$\begin{cases} \gamma = \dfrac{\rho^{(1)} v_L^{(1)}}{\rho^{(2)} v_L^{(2)}} \\ \alpha = \dfrac{h_{33}^2}{\beta_{33}^S\ c_{33}^D\ k^{(1)}\ h_1\left(1 + j\omega C_0 Z_a\right)} \end{cases} \tag{7}$$

Only wavenumber solutions of the equation (5) with positive real parts are considered.

3. Results

Experimental measurements of transmission are performed for the propagation of longitudinal waves through a PC. The PC is composed of 10 piezoelectric plates (Pz27) separated by 10 thin passive plates (PMMA). Two cases of electric boundary conditions are considered : piezoelectric plates in open circuit or connected to an inductance $L_a = 1.2$ µH. Fig 2 shows the opening of a new pass band around 0.9MHz. This corresponds to the electrical resonance frequency $f_0 = 1/(2\pi\sqrt{L_a C_0})$, where the clamped capacitance is estimated around 15 nF. A shift of another pass band in higher frequencies is also observed. The transmission amplitude through the PC shows two corresponding peaks at these pass-bands.



(a) (b)

Figure 2: (a) Transmission measurements on the PC, the piezoelectric plates in open circuit (bleu) or connected to an inductance L_a = 1.2 µH (black). (b) Dispersion curves calculated using the equation (5).

Table 1. Acoustical properties of the constituting layers.

Material	h (mm)	ρ (kg/m^3)	v_L (m/s)	*Z* (MRa)
PMMA	1.15	1140	2740	3.12
Pz26	1.11	7700	4530	34.9

h: thickness; ρ: density; v_L: longitudinal velocity; *Z*: acoustical impedance.

4. Conclusion

The transmission through a one dimensional PC including piezoelectric elements is studied analytically by using the Bloch-Floquet theorem. The case of an inductive load L_a connected to the electrodes of the piezoelectric elements is studied. The presence of the inductance modifies the bands structure and a new pass band is created at a frequency corresponding to the L_aC_0 electrical resonance. The measurements are in good agreement with the predicted dispersion curves. However, some differences are noted near the resonance of the thickness mode of the piezoelectric element. This could be due to the presence of lateral modes (guided Lamb waves) in the piezoelectric plate that are not taken into account in the model.

Acknowledgements

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