



# Effects of thermo-order-mechanical coupling on band structures in liquid crystal nematic elastomer porous phononic crystals

Shuai Yang<sup>a,b</sup>, Ying Liu<sup>a,\*</sup>

<sup>a</sup> Department of Mechanics, School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

<sup>b</sup> School of Civil Engineering and Architecture, Anyang Normal University, Anyang 455000, China



## ARTICLE INFO

### Article history:

Received 1 February 2018

Received in revised form 2 March 2018

Accepted 6 March 2018

Available online 5 April 2018

### Keywords:

Phononic crystal  
Absolute band gap  
Nematic elastomer  
Thermo-induced  
Band tuning

## ABSTRACT

Liquid crystal nematic elastomers are one kind of smart anisotropic and viscoelastic solids simultaneously combining the properties of rubber and liquid crystals, which is thermal sensitivity. In this paper, the wave dispersion in a liquid crystal nematic elastomer porous phononic crystal subjected to an external thermal stimulus is theoretically investigated. Firstly, an energy function is proposed to determine thermo-induced deformation in NE periodic structures. Based on this function, thermo-induced band variation in liquid crystal nematic elastomer porous phononic crystals is investigated in detail. The results show that when liquid crystal elastomer changes from nematic state to isotropic state due to the variation of the temperature, the absolute band gaps at different bands are opened or closed. There exists a threshold temperature above which the absolute band gaps are opened or closed. Larger porosity benefits the opening of the absolute band gaps. The deviation of director from the structural symmetry axis is advantageous for the absolute band gap opening in nematic state which constrains the absolute band gap opening in isotropic state. The combination effect of temperature and director orientation provides an added degree of freedom in the intelligent tuning of the absolute band gaps in phononic crystals.

© 2018 Elsevier B.V. All rights reserved.

## 1. Introduction

Propagation of elastic waves in periodic composites, which are called phononic lattices or phononic crystals (PnCs), has attracted more and more attention [1–5] in recent years. One important characteristic of PnCs is the existence of absolute band gaps (ABGs), particular frequency regions within which propagating elastic waves do not exist [6–11]. This distinct property determines potential applications of PnCs as frequency filters, beam splitters, sound or vibration isolators and elastic waveguides [12–14]. Along with more and more works on the clarification of band structures in different PnCs, band design and tuning have become active topics in acoustic fields. PnCs with tunable properties have been explored to control phononic properties upon the application of an external stimulus, such as temperature, light, electric and magnetic fields, and strain.

Lately, Bertoldi et al. [15,16] investigated deletion of existing band gaps and creation of new band gaps by using large deformation and microstructural elastic instability in periodic elastomers. The results show that propagation of acoustic waves is strongly

influenced by geometric pattern, material properties and loading conditions, particularly the deformation, which can be used to effectively tune band gaps and directionality of propagating waves. This gives additional opportunities for tuning and manipulating the location and presence of phononic band gaps. Moreover, dynamic characteristics of lattices constituted by piezoelectric and piezo-magnetic media have also been studied to understand the effects of magnetic and electric fields on the band structures in PnCs. Yeh et al. [17–19] investigated the elastic band structure of a two-dimensional electrorheological (ER) PnC by plane wave expansion (PWE) method. They found that acoustic characteristics of the system could be changed by the variation of the electric fields, which resulted in the variation of band gaps in the smart system.

As an active branch of smart materials, liquid crystal nematic elastomers (LCNEs) have been widely investigated for their potential applications in intelligent controlling [20–23]. Unlike traditional solids, LCNEs combine the physical properties of two subsystems, namely of network (like an elastomer) [24] and mesogenic units (liquid crystalline building blocks), which are light molecular materials used to form liquid crystalline phases [25]. One remarkable ability of LCNEs is that it exhibits large deformation under small forces, which is known as soft elasticity.

\* Corresponding author.

E-mail address: [yliu5@bjtu.edu.cn](mailto:yliu5@bjtu.edu.cn) (Y. Liu).

Moreover, LCNEs are susceptible to a variety of stimuli, such as temperature, light, electric and magnetic fields, and strain. These unique features render them useful in diverse applications including soft actuators, motors, tunable optical elements, microfluidic valves, and artificial muscles.

As one kind of thermal sensitive materials, temperature variation may cause significant variation of mechanical properties and geometries of LCNEs. Thermal sensitivity of LCNEs is always a hot topic due to its prospective applications. Tajbakhsh and Terentjev [26] studied spontaneous thermal deformation of LCNEs. They found that when a LCNE sample is heated or cooled, the director changes with spontaneous deformation. Stretch a NE sample along the director  $\mathbf{n}$  will increase the director order degree and the transition temperature,  $T_{ni}$ , that is, the critical temperature from nematic phase to isotropic one. Finkelmann et al. [27] found that due to anisotropy of LCNEs and the director order-mechanical coupling effect, the elastic modulus perpendicular to the director is different from the parallel one. The stress-strain relation and elastic modulus change with temperature. Recently, Huo et al. [28] investigated thermo-induced director order-mechanical coupling behavior of LCNEs. The constitutive model according to Clausius–Duhem inequality has been derived. Obviously, considerable researches have been focused on the thermal-mechanical interactions of LCNEs. The possibility of LCNEs as an intelligent band tuning material through temperature variation is worth of exploring.

In order to investigate acoustic properties of LCNEs, dynamic properties of solids should be known beforehand. Based on the linear theory of viscoelasticity, Terentjev et al. [29,30] studied the acoustic wave propagation through an elastic LCNE. Fradkin et al. [31] analyzed the spectral and polarization properties of acoustic waves propagating in LCNEs in the low-frequency (hydrodynamic) limit. Singh [32] studied reflection properties of homogeneous elastic waves from free surface of LCNE half-space. Zakharov [33] explored the properties of surface and edge waves in solids with nematic coating. Yang and Liu [34] studied the exotic properties of Rayleigh waves in LCNEs. The investigations had revealed unusual polarization effects of waves, which promises perspective applications as smart acoustic filters and polarizers.

Recently, Yang et al. [35] investigated wave dispersion in LCNE phononic crystals. The influence of intrinsic material parameters on the band structures in LCNE phononic crystals (PPnCs) has been discussed in detail. In the present discussion, the thermal-induced deformation of LCNE matrix is included. Unidirectional coupling algorithm is adopted to analyze the thermo-order-mechanical coupling response of LCNE porous phononic crystals (PPnCs), which has periodic distributed pores in the LCNE matrix. Firstly, a quasi-static approach is followed to consider finite deformations due to external temperature variations. Then, the elastic wave motion is superimposed on the deformed lattice and investigated by considering the Bloch boundary conditions. The variation of band structures due to the thermal-order-mechanical coupling of LCNEs are clarified. At last, the conclusion is given.

## 2. Thermal finite deformation of LCNEs

LCNEs are considered to be a thermal hyperelastic body that is initially in an undeformed state, denoted by  $\mathbf{C}_r$  with boundary  $\partial\mathbf{C}_r$  as the reference configuration, which is shown in Fig. 1. When the temperature changes slowly with the time, it deforms, with the region occupied by  $\mathbf{C}_t$  and boundary  $\partial\mathbf{C}_t$  at a given time  $t$ , which is called as current configuration. Let  $\mathbf{X}$  and  $\mathbf{x}$  be the position vectors of the material particle at the reference and current configurations, respectively, where  $\mathbf{x} = (\mathbf{X}, t)$ , and  $\Phi: \mathbf{C}_r \rightarrow \mathbf{C}_t$ , the deformation mapping. In this study, a unidirectional coupling approach is followed to consider the geometrical nonlinearity during the

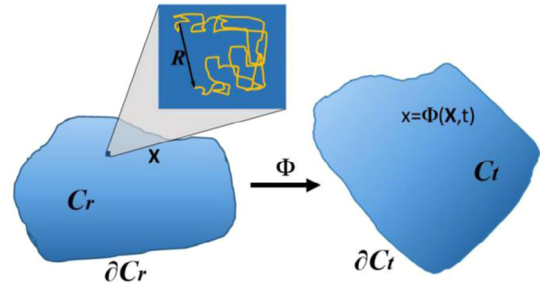


Fig. 1. Reference and current configurations.

thermo-induced deformation, as well as the linear wave propagation in the deformed structures. Firstly, the solids undergo large deformations due to the temperature variation. Then, the elastic wave motion is superimposed on the deformed body and studied based on the current configuration.

Microscopically, LCNE is a kind of elastomers whose networks are formed from polymers. They are similar except that they are in nematic phase and are characterized by an anisotropic distribution of molecular shapes. To be elastomers, the polymer chains must be long and flexible such that they adopt a Gaussian distribution of molecular shapes. They must be in fluid-like motion in local so that the entropy is maximized. Fluidity implies that such elastomers are capable of large deformation in response to molecular elongations, and in nematic case the director is readily redirected and shape variation due to director reorientation can also be achieved.

An anisotropic Gaussian distribution is completely characterized by its second moments. Here we consider uniaxial nematic elastomers. For the end-to-end vectors  $\mathbf{R}$  of chains in the network (shown in Fig. 1), there are only two moments, those parallel and perpendicular to the director  $\mathbf{n}$ , that is,

$$\langle R_{\parallel}^2 \rangle = \frac{1}{3} l_{\parallel} L, \quad \text{and} \quad \langle R_{\perp}^2 \rangle = \frac{1}{3} l_{\perp} L. \quad (1)$$

The appropriate effective step lengths are  $l_{\parallel}$  and  $l_{\perp}$ , which reflect the current nematic ordering in the network.  $L$  is the end-to-end arc length of a chain. A general frame-independent form of the step length tensor is given as:

$$\mathbf{l} = (l_{\parallel} - l_{\perp}) \mathbf{nn} + l_{\perp} \delta \equiv l_{\parallel} [(r - 1) \mathbf{nn} + \delta], \quad (2)$$

where  $\delta$  is the unit tensor. The ratio of step lengths,  $r = l_{\parallel}/l_{\perp}$ , named as anisotropic parameter, is the measure of anisotropy of the chain shape distribution, which is temperature dependent. The variation of  $r$  with respect to the temperature is the underlying origin of the variation of elastic responses. Terentjev et al. [36] studied the relationship between temperature and anisotropic parameter  $r$  theoretically and experimentally. Fig. 2 displays the relationship between  $r$  and the temperature. It is seen that the networks of polymer chains are elongated on cooling from the isotropic state I to nematic state N, or contracted on heating back to the isotropic state. When  $T/T_{ni} > 1$ ,  $r$  tends to 1 and LCNEs are reduced to isotropic viscoelastic materials.

Assume that LCNEs are in an initial state with anisotropic parameter  $r_0$ . Along with the variation of the temperature, it deforms and the anisotropic parameter is described as  $r_t$  in current configuration. A moderate generalization of classical rubber elasticity theory gives the free energy of a network strand by taking the log effect of the current anisotropic strand shape distribution function. The free energy is then averaged over the chance of encountering this strand (now possibly anisotropic) during the network formation. Multiplying by the number of strands per unit volume, the free energy density for LCNEs are then given as

Download English Version:

<https://daneshyari.com/en/article/8129897>

Download Persian Version:

<https://daneshyari.com/article/8129897>

[Daneshyari.com](https://daneshyari.com)