



Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Measuring the band structures of periodic beams using the wave superposition method

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ARTICLE INFO

Article history:

Received 16 September 2015

Received in revised form

30 June 2016

Accepted 4 July 2016

Handling Editor: G. Degrande

ABSTRACT

Phononic crystals and elastic metamaterials are artificially engineered periodic structures that have several interesting properties, such as negative effective stiffness in certain frequency ranges. An interesting property of phononic crystals and elastic metamaterials is the presence of band gaps, which are bands of frequencies where elastic waves cannot propagate. The presence of band gaps gives this class of materials the potential to be used as vibration isolators. In many studies, the band structures were used to evaluate the band gaps. The presence of band gaps in a finite structure is commonly validated by measuring the frequency response as there are no direct methods of measuring the band structures. In this study, an experiment was conducted to determine the band structure of one dimension phononic crystals with two wave modes, such as a bi-material beam, using the frequency response at only 6 points to validate the wave superposition method (WSM) introduced in a previous study. A bi-material beam and an aluminium beam with varying geometry were studied. The experiment was performed by hanging the beams freely, exciting one end of the beams, and measuring the acceleration at consecutive unit cells. The measured transfer function of the beams agrees with the analytical solutions but minor discrepancies. The band structure was then determined using WSM and the band structure of one set of the waves was found to agree well with the analytical solutions. The measurements taken for the other set of waves, which are the evanescent waves in the bi-material beams, were inaccurate and noisy. The transfer functions at additional points of one of the beams were calculated from the measured band structure using WSM. The calculated transfer function agrees with the measured results except at the frequencies where the band structure was inaccurate. Lastly, a study of the potential sources of errors was also conducted using finite element modelling and the errors in the dispersion curve measured from the experiments were deduced to be a result of a combination of measurement noise, the different placement of the accelerometer with finite mass, and the torsional mode.

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1. Introduction

Phononic crystals and elastic metamaterials are materials or structures that can be engineered to possess interesting properties that are not found in natural materials, such as negative effective stiffness, negative effective mass, and negative refraction [1–8], in certain frequency ranges. These unique properties give phononic crystals and elastic metamaterials the potential of being used

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for a wide variety of applications, such as vibration and sound isolation [9–13], wave guiding [9,13], acoustic cloaking [13,14], and acoustic lensing [15,16].

Phononic crystals are periodic and although elastic metamaterials can be non-periodic, many analyses assumed periodicity when only analysing a single unit cell for elastic metamaterials. Thus, they are studied based on classical wave characteristics of periodic structures or crystals [6] and share some similar characteristics with photonic crystals. A notable example is the presence of band gaps, which are regions of frequencies where no wave can propagate, that exist in both photonic and phononic crystals [6]. Many designs to utilise the band gaps in this class of materials for vibration isolation have been proposed in the literature. Among the proposed designs include lattices with inertia amplification [12], chiral lattices with internal resonators [17], beams or plates with local resonators [18–20], structures with periodic piezoelectric patches [21–23], and many others. The band gaps are commonly determined by calculating the band structure, also known as the dispersion curve, of the material using a variety of methods, such as plane wave expansion (PWE) [24–27], extended plane wave expansion (EPWE) [28–31], finite element (FE) [32,33], transfer matrix (TM) [34,35], and spectral element (SE) [36–38] methods.

Some studies, such as the ones performed by Airoidi and Ruzzene [23] and Bavencoffe et al. [39], have managed to measure the band structure from the response of a system by using laser velocimetry and then performing two-dimensional Fourier transforms. However, the method they used requires measurements with high temporal and spatial resolutions. It might also require post-processing of the data to remove the effects of wave reflection. Additionally, they did not manage to measure the band structure of the complex waves that characterises the attenuation within the band gaps. Junyi and Balint [40] have recently proposed an inverse method, known as the *wave superposition method* (WSM), to determine the band structure from a finite structure using a small number of data points. Their method allows the band structure to be calculated with simple equipment that are familiar to engineers, such as a shaker and accelerometers. This might encourage the adoption of elastic metamaterials and phononic crystals in engineering applications. Furthermore, WSM is capable of calculating both the real and imaginary parts of the band structure from a finite structure, which might be useful in the analysis of evanescent waves, as seen in [31].

In their paper [40], Junyi and Balint have only validated their method using analytical solutions of Timoshenko beams but in practice, the measured response of a system will contain noise and errors, for example, the noise in the accelerometer, manufacturing tolerances, and the accelerometers and force gauge having a finite area rather than a point. Therefore, the main objective of this study is to demonstrate that the technique is applicable in practice and discuss the issues while implementing WSM in a physical experiment. This is done by taking the required frequency response measurements of a beam and performing the calculations described in [40].

This paper is organised as follows. Firstly, the theory behind the wave superposition method from [40] will be briefly reviewed in the next section. Then, the experimental setup and properties of the beams studied will be described. In the next section, the results will be presented and discussed with emphasis on the issues related to this method. The relative displacement transfer function, which is the frequency response function of a point relative to that of a reference point, calculated from the measured band structure will be discussed. Finally, a study on the potential sources of error using finite element analysis is performed before concluding this paper.

2. Theory

2.1. Superposition of Bloch waves

This section will briefly describe the basic principles of the wave superposition method and the calculation of the band structure using a finite number of points. An elastic wave in an infinite 1D periodic structure can be described by a Bloch

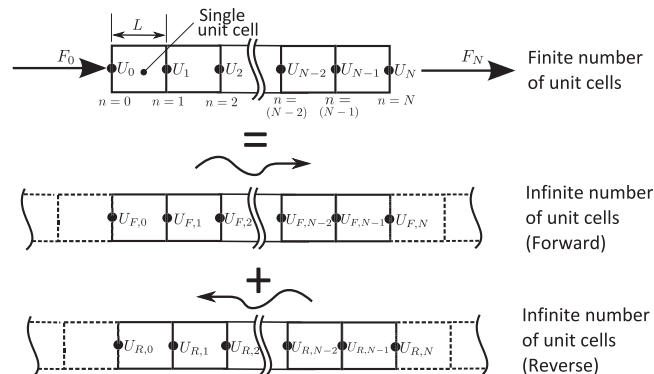


Fig. 1. Superposition of waves in a finite periodic structure.

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