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PHONONIC MATERIAL AS ULTRASONIC FILTERS IN NONDESTRUCTIVE EVALUATION MEASUREMENTS

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ABSTRACT

Passive ultrasonic filters have the potential to greatly improve nonlinear ultrasound measurement techniques. In this presentation, we designed, analyzed, and tested a phononic material with ultrasonic filtering properties. Finite element simulations show that the phononic material has a 2 MHz stop band. The structure's behavior was verified with a simulated frequency sweep and will be experimentally validated on an additively manufactured phononic material.

Keywords: phononic materials, stop bands, nonlinear ultrasound, ultrasonic filter

1. INTRODUCTION

Phononic crystals and materials exploit periodicity to control the frequency, temporal, and spatial properties of wave propagation [1]. In particular, the unit cell of a periodic structure can be designed such that propagating waves exist only at certain frequencies. Over certain frequency ranges where the periodicity constant is comparable to the wavelength, waves are forbidden to propagate; these frequency regions are called stop bands or band gaps. The unit cell's material properties, geometry, constituents, and size can be modified to shift the stop bands to desired frequencies [2]. The frequency range of these phononic materials can thus be tailored to suit a wide range of applications such as vibration isolation, seismic wave mitigation, elastic wave guiding, and enhanced nondestructive evaluation.

Nonlinear ultrasound (NLU) is a nondestructive evaluation technique which enables damage detection at the microscopic scale. Where conventional ultrasonic NDE methods detect damage on the macroscopic scale, a technique known as second harmonic generation is sensitive to features such as dislocations and precipitates that evolve during the early stages of damage accumulation [3]. Nonlinear ultrasound measures the amplitudes of both the fundamental and second harmonic frequencies (Fig. 1). The ratio of these measurements can be correlated with microstructure properties. This technique has the potential to predict remaining component life well before failure occurs. However, extraneous nonlinearities at the second harmonic can occur in NLU measurements that obscure second harmonic generation due to material defects. These difficulties require careful calibration of equipment and hinder NLU in situ applications.

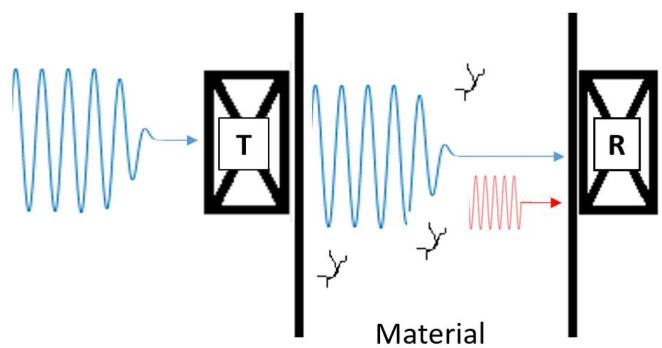

FIGURE 1. SCHEMATIC OF NLU. MICROSCOPIC DEFECTS GENERATE SECOND HARMONIC FREQUENCIES (RED) OF THE FUNDAMENTAL FREQUENCY (BLUE).

Here we explore the idea of using a phononic material as a passive mechanical filter to improve contact longitudinal NLU measurements. Mostavi et al. recently employed this technique with phononic superlattices to improve NLU measurements using immersion [4]. By introducing a phononic material after the transmitting transducer that has a stop band tuned to the second harmonic frequency of NLU measurements, any waves generated at the second harmonic, caused by e.g. the testing process or contact between transducer and sample, would be strongly attenuated in the phononic filter. In this way, the measured second harmonic wave on the receiving end would be generated purely from the material nonlinearity. To study this

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concept, we design a phononic material that has a stop band in the MHz range using finite element method simulations, fabricate the phononic material using additive manufacturing, and experimentally validate its transmission behavior over the relevant frequency ranges.

2. PHONONIC MATERIAL DESIGN

We designed a phononic material with a stop band in the MHz frequency range using an iterative process. We iteratively conduct an eigenfrequency analysis of phononic unit cells using finite element method (FEM) modeling with COMSOL Multiphysics. To conduct an eigenfrequency analysis, we model the unit cells with 3D periodicity. The wavenumber, k, was swept only in the x direction through the length, a, of the unit cell to find the dispersion relation that consists of the propagating modes. We then analyze the modes surrounding any resulting stop band, to determine how to modify the geometry in order to change the modal stiffness or modal mass, which will in turn shift the mode in the frequency domain in the desired direction. Further, we incorporated constraints of a suitable fabrication process into the phononic material design. Note that since only k_x was swept in this eigenfrequency study, only directional stop bands are extracted from the simulation.

To start, we took a slightly modified unit cell from a previous study that consist of a 3D periodic lattice geometry surrounding a bulk cube [2]. These lattice-resonator materials have shown to support a variety of stop bands in the range of structural vibrations (kHz). Since the wavelength of the stop bands scales inversely with a, we simply scale down the geometry of this initial unit cell to shift the stop band to the MHz range. This produced a unit cell with a 1 MHz stop band shown in Fig. 2. We then simplified the geometry to meet the feature size requirements of direct metal laser sintering (DMLS) additive manufacturing. Specifically, DMLS requires a feature size greater than 0.2 mm and prohibits enclosed voids. This resulted in a phononic material with a very narrow stop band. An analysis of the modes showed the mode at the low frequency side of the stop band to be shear in polarization. To widen the stop band, we decreased the shear stiffness by removing material from the modified matrix in between the solid resonator cubes, as shown in Fig. 3. This manipulation resulted in a stop band centered at 1.98 MHz with a bandwidth of 11%, as shown in the dispersion relation in Fig. 4.

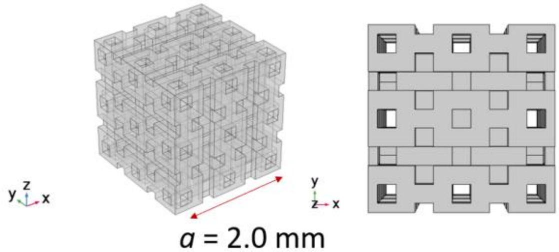

FIGURE 2. UNIT CELL OF IDEALIZED FOAM WITH AN IMBEDDED RESONATOR. LEFT: ISOMETRIC VIEW. RIGHT: VIEW IN THE z DIRECTION.

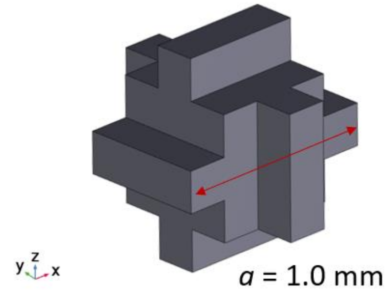

FIGURE 3. PHONONIC MATERIAL'S FINAL DESIGN UNIT CELL.

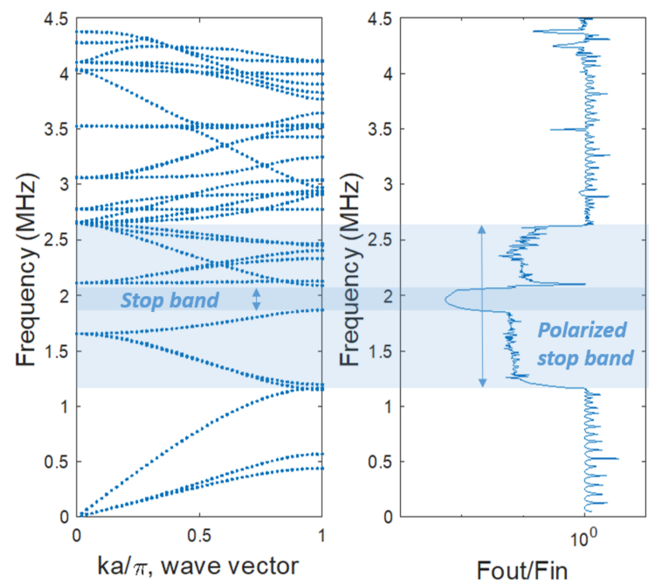

FIGURE 4. LEFT: DISPERSION CURVES CALCULATED WITH FEM SIMULATIONS SHOWING PROPAGATING MODES, THE COMPLETE STOP BAND, AND THE POLARIZED STOP BAND. RIGHT: SIMULATED TRANSMISSION OF LONGITUDINAL WAVES THROUGH A 22-UNIT CELL THICK PHONONIC MATERIAL MODEL.

A frequency sweep FEM study on a material with finite thickness was conducted to validate the 3D periodicity assumed in the eigenfrequency study. Periodic conditions were applied in the cross-sectional directions, y and z, while the displacement was applied in the longitudinal, x, direction to simulate longitudinal excitations, as shown in Fig. 5. To simulate the actual thickness of the fabricated phononic material, we model 22 unit cells in the x direction. The results of this study are shown in Fig. 4.

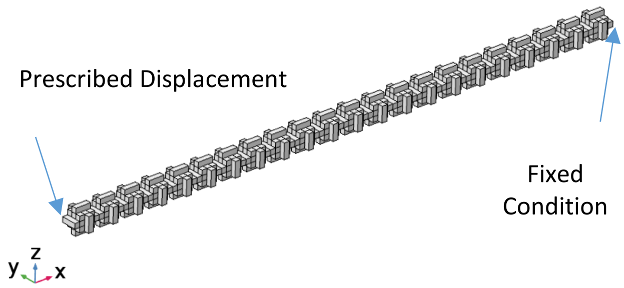

FIGURE 5. A 22 UNIT CELL THICK MODEL WITH PERIODIC CONDITIONS IN THE CROSS-SECTIONAL (*y* AND *z*) DIRECTIONS.

3. EXPERIMENTAL METHOD

The phononic material is additively manufactured using Direct Metal Laser Sintering in titanium (Ti64 ASTM B348). The material is characterized experimentally using the pulse frequency response method, and then its frequency-dependent transmission is compared to that of a solid titanium block of the same overall dimensions. A DPR pulse generator is used with piezoelectric transducers in through-transmission mode, and we calculate the fast Fourier transforms to obtain the frequency response. To find the transmission ratio, we take the ratio of the phononic material response to that of the solid material. In order to find the transmission ratio across a broad range of ultrasonic frequencies, three separate broadband ultrasonic transducers with different center frequencies are used: 1 MHz, 2.25 MHz, and 5 MHz.

4. RESULTS AND DISCUSSION

The frequency sweep study (Fig. 4) shows a transmission of 10 orders of magnitude reduction in the stop band region for longitudinal waves. However, there is also 4-5 orders of magnitude transmission reduction in a larger region of about 1.2-2.6 MHz where modes are present in the dispersion relation. This occurs because in the transmission simulation, the excitation displacement in the *x* direction does not excite shear modes in the *x-y* plane. These unexcited modes create a region called a polarized stop band, where transmission of longitudinal waves is greatly reduced. In the polarized stop band, all propagating modes are shear waves, which will not be excited with a longitudinal excitation. This effectively expands the stop band region. Experimental results on the additively manufactured phononic material that confirm this behavior will be presented.

4. CONCLUSION

The FEM simulation results show this phononic material transmits waves at and below 1 MHz as expected, and has a directional stop band centered around 2 MHz. This stop band manifests as a deep drop in transmission by about 10 orders of magnitude. Results also show a longitudinally-polarized stop band in the range of 1.2-2.6 MHz, where transmission is mitigated by about 5 orders of magnitude. A material with these properties could be used to improve NLU techniques. If this phononic material were applied to NLU measurements, it could potentially transmit fundamental frequencies of 0.6-1.1 MHz and mitigate second harmonic frequencies of 1.2-2.2 MHz, isolating second harmonics generated in the sample material. This design approach for phononic materials with stop bands could be applied to a range of operational frequencies and other types of propagating ultrasonic waves such as shear, Rayleigh, or Lamb waves.

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