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Acoustic properties of additive manufactured narrow tube periodic structures

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ABSTRACT

Quarter tube periodic resonators are used to attenuate the acoustic energy of discrete frequencies wherein their sizes can vary from narrow to large. This paper reports acoustical properties of additive manufactured, narrow tube, single and multi-periodic structures, both, theoretically and experimentally. Herein, multi-periodic structures are defined as periodically arranged unit sections of tubes, where each section is composed of periodically repeated unit cells of different sizes and shapes. Structures with hexagonal narrow tubes and octagonal narrow tubes with interfacial gaps are considered for the study, and normal absorption coefficients of these samples are measured by using impedance tube. the theoretical absorption coefficient of these structures is predicted using unit section analysis method and narrow tube theory, where shape dependent viscous and thermal losses are incorporated. Estimated theoretical absorption coefficients are in good agreement with measured results. The result shows that the frequency and amplitude of maximum absorption can be varied by altering the aperture ratio and/or the length of periodic structure. The proposed theoretical method gives an alternative approach for designing and manufacturing periodic narrow tubes for different applications such as absorbing panels, acoustic transducers, and engine filter elements.

1. Introduction

Periodic tubes are used as acoustic absorbers in various engineering applications, for example, in ships, aircrafts, automobiles and building structures [1–3]. When tubes in the periodic structure become narrower, visco-thermal effects play a vital role in attenuation of sound. The mechanism of sound attenuation involves thermal conduction and viscosity losses at the boundaries of the tube [4,5]. These narrow tube effects depend on the cross-section shape of the tube and help to determine the peak frequency of absorption [6]. Producing millimeter size narrow tubes with perfect shape is difficult and costly by traditionally available methods such as micro-drilling or corrugation. Recent advances in Additive Manufacturing (AM) process gives an alternative method of producing precise complex configurations [7]. Use of AM to produce sound absorbers was first studied by Liu et al. [8]. Liu et al. [9,10] examined multilayer microperforated (MPP) panel for sound absorption where MPP was produced by AM technology. However, there are limited studies which explore additive manufacturing techniques for acoustic applications. In this work, periodic structures of narrow tubes are fabricated using AM technology and the normal sound absorption coefficients are measured using impedance tube test and an analytical model is developed to predict sound absorption coefficient.

The acoustic properties of the periodic structure depend on geometric parameters of narrow tubes, and its sound absorption coefficient is predictable. Sound propagation in the narrow tube was first studied by Kirchhoff [11] who explained the viscous and thermal effects in a narrow tube. However, the proposed theory was too complex to apply for non-circular cross sections. The first time, Zwikker and Kosten [12] proposed a simplified model for sound propagation in circular tubes where thermal and viscous effects were considered separately. Later, the applicability of these models for various ranges of acoustic frequencies had been discussed by Tijdeman [13] and Stinson [14]. Tijdeman [13] proved that the two main parameters namely, shear wave number, which is the ratio of inner tube radius to the viscous boundary layer, and the reduced frequency governs the propagation of sound in rigid narrow tubes. This theory has been used by many authors to solve the wave propagation in narrow tubes for various applications and is a well-known solution. Meanwhile, Cummings [15] described an alternative high and low frequency variational solution, for the sound propagation in a narrow tube of the arbitrary cross-section, which was acceptably accurate in comparison with available solutions. However, Allard and Atalla [16] have provided the generalized form of narrow tube theory where a shape dependent factor in circular tube model is introduced to generalize it for different cross-sections such as square,

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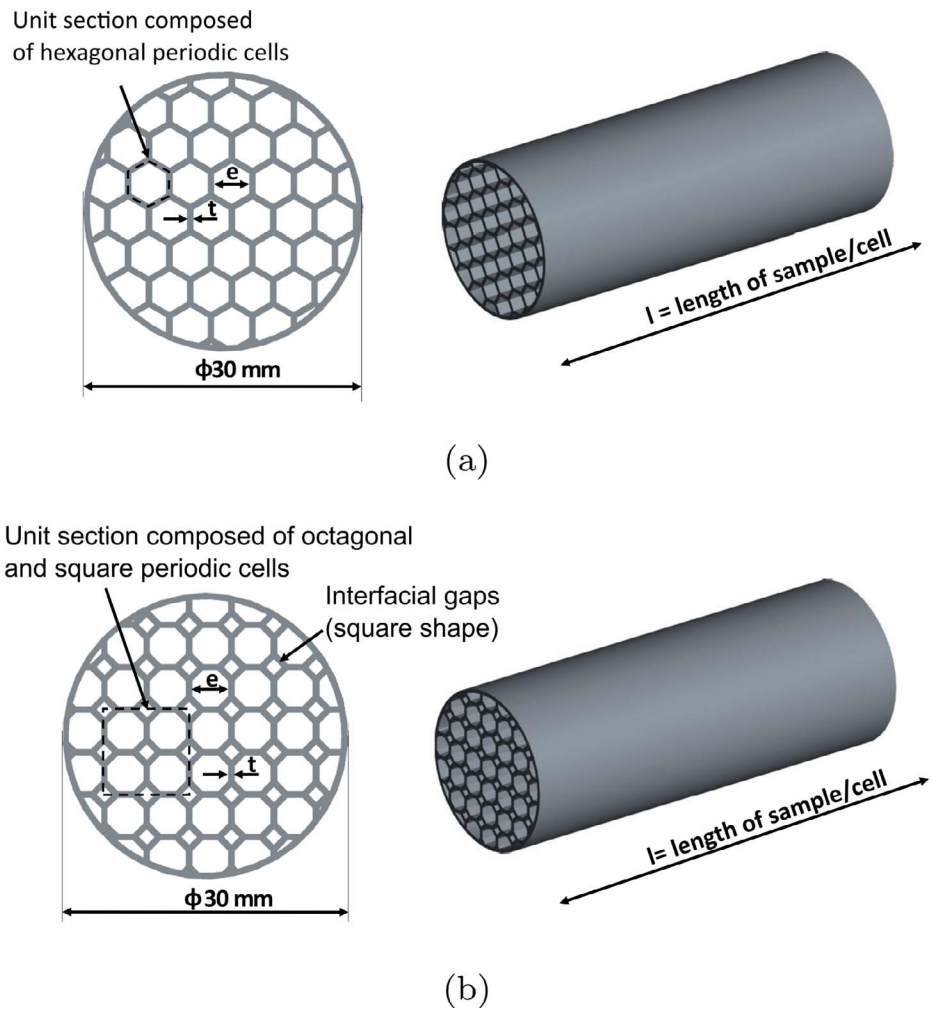

Fig. 1. Terminology and cross-section used in periodic structures (a) Configuration I: Single periodicity (Hexagonal) and (b) Configuration II: Multi-periodicity (Octagonal with interfacial gaps) e: cell size, t: cell wall thickness, l: length of sample/cell.

triangle, rectangle, and slit. Hannink [17] studied-well separated tube resonators for reduction of sound radiation and sound transmission in mid to high frequency range (500–2000 Hz). One dimensional and two-dimensional models including narrow tube effects were presented to predict the sound radiation and transmission through the tube resonator panel. Further, Sakamoto et al. [18] implemented narrow tubes theory proposed by Tijdeman [13] in calculating transmission loss (TL) of louver elements where tonal behavior was observed similar to quarter wave tube resonators. In a later study, Sakamoto [19] calculated the absorption coefficient of periodic interfacial narrow tubes in bundles of cylindrical rods by using transfer matrix method.

Previous researchers mainly focused on modeling of identical shaped periodic narrow tubes i.e. structures with single periodicity, for instance, a periodic structure with hexagonal narrow tubes. However, most structures have the combination of different shaped narrow tubes arranged in a periodical manner. For instance, periodic circular tubes may consist periodic star-shaped interfacial gaps and octagonal periodic tubes will have periodic square-shaped interfacial gaps as shown in Fig. 1. Thus, the complete structure will have multi-periodicity. Here, multi-periodic refers to structures consisting of periodically arranged unit sections, wherein each section is composed of periodically repeating cells of the different narrow tube as shown in Fig. 1. The absorption coefficients of such multi-periodic structures were not yet reported in the literature.

The main objective of this work is to present a generalized methodology for predicting sound absorption coefficient, applicable to both single as well as multi-periodic structures, and also to explore the scope of additive manufacturing for acoustic applications. The current work is organized as follows; Section 2 briefly describes the manufacturing method and material used to fabricate periodic structures. It also elaborates the experimental setup and method used to measure absorption coefficient. Section 3 presents the theoretical modeling of periodic structures based on visco-thermal effects to estimate absorption coefficient. This model was used to estimate the absorption coefficients of complete structure and compared with measured results in Section 4. Further, the effect of geometrical parameters like tube size, shape and length have been studied. Finally, Section 5 concludes the present work based on experimental and analytical results. The methodology presented in this work is generalized and can be used to design single as well as multi-periodic structures having a cluster of narrow channels like engine filter elements or absorbing panels for acoustic performance. This study also demonstrates the potential of additive manufacturing in producing more complex structures, which were earlier difficult using traditional methods, to improve acoustic performance.

2. Samples and experimental setup

2.1. Samples

Fig. 1 shows the basic terminology used for hexagonal and octagonal periodic structures with interfacial gaps. To investigate the effect of different geometrical parameters on acoustic absorption coefficient,

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