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Normal incidence acoustic absorption characteristics of a carbon nanotube forest

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ABSTRACT

The acoustic absorption of carbon nanotube (CNT) absorbers made of vertically aligned CNT forests is investigated experimentally in an impedance tube using the two-microphone method with normal incidence. Results show that a 3 mm thick forest of CNTs can provide up to 10% acoustic absorption within the frequency range 125 Hz–4 kHz. Theoretical predictions of the acoustic absorption properties of CNTs made using classical acoustic theories, including the Biot-Allard and Johnson-Allard models, agree reasonably well with the experimental results in terms of the general trends, although there are significant difference at specific frequencies. This suggests that nanoscopic acoustic absorption mechanisms are important and are not accurately represented within the classical models developed for conventional porous materials. In addition, theoretical studies of the acoustic absorption potential of CNT forest indicate that they may provide better acoustic absorption than conventional porous materials of equivalent thickness and mass, and that the absorption could be enhanced significantly with a lower forest density of CNTs than the samples tested in this study.

1. Introduction

Advances in nanotechnology have provided acoustic researchers with a number of new materials, with features such as nanofibres and nanopores, that can potentially be implemented as porous acoustic absorbers. The molecular behaviour of these new nanoscopic materials may have a significant influence on their sound absorption properties. In addition, their properties could play an important role in reducing the thickness and mass of absorbers compared with currently available materials. In the current era of nanotechnology, a variety of nanotube constituents are available that can be formed into nanoscopic fibres, for instance carbon nanotubes (CNTs) [1,2], boron nitride nanotubes (BNTs) [3] and titania nanotubes (TNAs) [4]. Although carbon nanotubes are the most widely studied materials for nanofibres and composite foams [5], other nanotube types have a similar ability to form nanoscopic fibres and composites [3,6]. Since the discovery of the carbon nanotube (CNT) structure by Iijima [1], numerous potential applications for CNTs have been suggested in the fields of electronics, energy, mechanics, field emission and lighting [5,7]. Although a number of applications of CNTs in noise control engineering have also been suggested [5], they have not been widely used as sound absorbers. In one application, a lightweight CNT foam was fabricated by exploiting the extraordinarily strong inter-tube interaction between the carbon nanotubes, which could be used in shock absorbing and acoustic damping materials [5]. Recent developments in nanotechnology have also made it possible to construct CNT structures with unique alignment of the tubes in a particular direction (i.e. vertical or horizontal), which allows for the creation of structures with various desired fibre orientations [8–10]. In a study by Qian et al. [11], it was shown that super-aligned carbon nanotubes grown on the surface of a micro-perforated panel (MPP) can improve the acoustic absorption performance of MPP absorbers at low frequencies. Investigations were also conducted for nano-integrated polyurethane foam using multi-walled carbon nanotubes [12]. Test results showed that the incorporation of carbon nanotubes improved the acoustic absorption performance by 5–10% in the frequency range 800–4000 Hz. Several other studies on the use of carbon nanotubes for enhancement of the acoustic absorption of conventional porous materials have been reported [13–15]. The use of carbon nanotubes for reducing airplane noise by encapsulating the carbon nanotubes in a polymer nanocomposite to create electrospun fibres has also been proposed [16]. It has been suggested that the nanotubes may improve the sound absorption performance of the polymer nanocomposites as the

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individual nanotubes would oscillate with the sound waves, helping to absorb sound energy [16]. Moreover, vertically aligned CNT arrays was investigated for optical absorption capability. It was observed that low-density vertically aligned CNT arrays can be engineered to make a near-perfect (an ideal black) optical absorption materials that absorbs light at all angles and over all wavelengths [17]. Similarly, an analogues porous lamella structure were fabricated that behaves like a true deaf body [18]. Experimental observations showed that porous lamellas arranged into a low-density crystal backed by a reflecting support can absorb incident sound at all angles for a frequency range exceeding two octaves [18–20]. These developments in nanotechnology offer exciting possibilities for developing acoustic absorption materials using carbon nanotubes.

Carbon nanotubes can be produced with an average diameter in the range of 3–50 nm and typical lengths of 10 µm to hundreds of micrometres [21] and more recently even millimetre lengths [22,23] and thus can be used to produce absorbers with nanopores [5]. In general, for absorber materials, the lower the diameter of the fibre, the greater the acoustic absorption, as a reduction of the fibre diameter entails more fibres to achieve an equal volume density for a given absorber thickness, therefore creating a more tortuous path and higher airflow resistance [24–26]. Moreover, thin fibres can move more easily than thick fibres in the presence of sound waves, inducing vibration in air and increasing airflow resistance by means of friction through the vibration of the air [26]. Hence, absorbers with thin fibres such as CNTs have the potential to provide good acoustic absorption at low frequencies for a given absorber thickness. Moreover, advanced nanostructuring technologies can facilitate the tailoring of open cell structures in CNT arrays [5]. Open pore structures, together with the nanopores of the tubes, can potentially have a significant influence on the enhancement of acoustic absorption of CNT absorbers. Recent improvements [22,23] in the fabrication of CNT absorbers with various CNT forest densities suggests that the investigation of the acoustic absorption of CNT arrays will guide the development of effective acoustic absorbers that make use of various arrangements of carbon nanotubes.

However, a fundamental understanding of the physical mechanisms associated with the use of nanotubes as acoustic absorbers has not been developed, and their potential benefits have not been quantified. Furthermore, measurements of the acoustic absorption properties of nano-materials on their own have not been reported to date. The experimental investigation of the acoustic absorption characteristics of a CNT forest reported in this paper is a first step towards the establishment of a fundamental understanding of acoustic absorption at the nanoscale. Development of this understanding will advance the knowledge base of the discipline, and will also lay the ground work for other novel arrangements of acoustic absorbers to be investigated. This paper presents the acoustic absorption characteristics of a CNT forest based on experimental measurements and theoretical predictions using classical methods. Characterising the acoustic absorption behaviour of the CNT forest will allow researchers to determine the degree to which the acoustic absorption mechanisms of nano-materials are likely to deviate from continuum phenomena and the modelling approaches applicable to conventional porous materials.

This paper examines the absorption coefficient of a forest of CNTs using an impedance tube with a normal incidence sound source. Details of experimental measurement methods and the corrective measures implemented to account for microphone phase mismatch error and tube attenuation are also discussed in this paper. Theoretical predictions of the acoustic absorption behaviour using the Biot-Allard [27,28] and Johnson-Allard [28] models are described and compared with the experimental results. The results highlight the necessity for the existing theoretical models to be adjusted for nanoscale acoustic behaviour. A comparison of the absorption coefficient of a composite absorber made of a CNT absorber component and a conventional porous material is described and the results show the potential acoustic absorption benefits of CNT materials. In addition, a detailed description of the verification procedure of the measured results, including repeatability, reproducibility, and error analysis, is presented. It should also be noted that this article is an extended and a substantially new version of the paper [29] presented at the Inter-noise (2014) conference.

2. Materials and methods

The acoustic absorption coefficient of the CNT forest was measured in an impedance tube using two microphones [30,31] in accordance with the ASTM E1050 standard [32]. It should also be noted that the research presented here forms a foundational study, with experiments performed on a few CNT samples of a limited size that are not intended to be commercial-grade acoustic absorbers.

2.1. Impedance tube method and apparatus

A schematic of the setup for the two-microphone impedance tube method is illustrated in Fig. 1(a). A specimen to be tested is placed in a sample holder at the end of the tube. A sound source generates a plane wave inside the tube, which propagates through the sample and is reflected back from the rigid termination. Thus, a standing wave develops inside the tube. The transfer function between the two microphones located at positions 1 and 2 was measured as $H_{12} = G_{12}/G_{22}$, where G_{12} is the averaged cross-spectrum between the two microphones and G_{22} is the averaged auto-spectrum of the microphone at location 2. The reflection coefficient, R, and absorption coefficient, α, at the face of the sample can be evaluated as [30,31,33]

$$R = e^{2ikl_1} \frac{H_{12} - e^{-ikd}}{e^{+ikd} - H_{12}}, \tag{1}$$

$$\alpha = 1 - |R|^2, \tag{2}$$

where $e^{-ikd} = H_i$ and $e^{+ikd} = H_r$ represent acoustic transfer functions associated with the incident and reflected wave components, respectively [31], l_1 is the distance of the microphone that is further from the surface of the termination, d is the separation distance between the two microphones and k is the wavenumber. The specific surface acoustic impedance Z_s of the sample can also be determined from the measured reflection coefficient using the relation [30,31,33]

$$Z_s/\rho c = \frac{1+R}{1-R}, \tag{3}$$

where ρ is the density of air and c is the sound speed in air.

A custom-made 22.10 mm internal-diameter steel impedance tube was used to measure the normal incidence absorption coefficient of the CNT acoustic absorber. The impedance tube was constructed from a number of pipe lengths, a horn driver, and a pipe section which holds the two microphones that measure the acoustic pressure in the tube. A photograph of the experimental apparatus is shown in Fig. 1(b). Overall, four microphone spacings of 20.43 mm, 29.17 mm, 50.13 mm, and 140 mm were available to conduct the measurements with different operating frequency ranges, as determined by the upper and lower frequency limits [34–36], $f_u < 0.45c/d$ and $f_\ell > 0.05c/d$, respectively. A list of the upper and lower frequency limits for each of the microphone spacings of the impedance tube calculated using these equations is