Acoustic Absorption Behaviour of a Tall Carbon Nanotube Forest

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ABSTRACT

Previous investigations have shown that a 3-mm-high carbon nanotube (CNT) forest has an acoustic absorption coefficient of about 5-10% within the frequency range 125 Hz-4 kHz, which is above that of conventional acoustic materials on a per-mass basis. It was hypothesised that a CNT array of greater height, lower density, and with a non-uniform arrangement of the nanotubes could enhance the amount of acoustic absorption. In order to investigate this hypothesis, an impedance tube test was conducted to measure the acoustic absorption coefficient of a relatively tall 6-mm CNT forest. The results indicate that a greater length and lower density of CNTs may improve the absorption performance of CNT-based acoustic absorbers. Analyses of the results showed anomalies in the measured acoustic absorption coefficient compared with previous investigations. Theoretical analyses were performed based on classical models of acoustic absorption to explain the anomalies. This study describes the factors that may affect the acoustic absorption behaviour of nanomaterials.

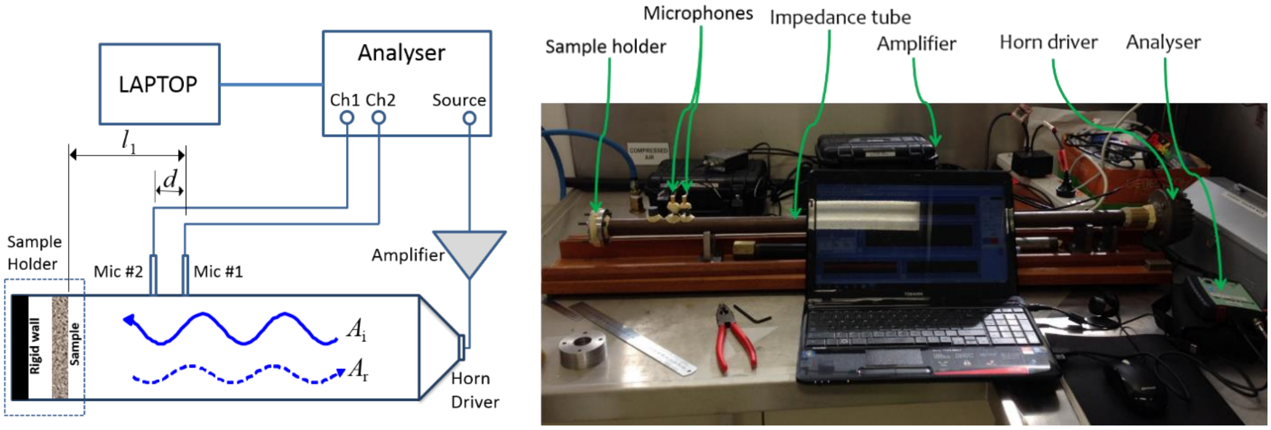
1. INTRODUCTION

Interest in carbon nanotubes (CNTs) for various applications has grown rapidly because of their extraordinary properties and versatility in forming different types of composite nanostructures. Consequently, bulk production of CNTs presently exceeds several thousand tons per year (De Volder *et al.* 2013) and considerable research investment has been made to realise new functionalities such as high damping (Xu *et al.* 2010), near-ideal black-body absorption (Mizuon *et al.* 2009) and thermoacoustic sound emission (Xiao *et al.* 2008). The fabrication of desired physical structures of these materials with modified mechanical and thermal properties show promise as sound-absorption materials for noise control (Ajayan *et al.* 2006; Cho *et al.* 2014a; 2014b). Hence, the potential of using CNTs and composite absorbers for noise-control applications has been investigated in various studies. Qian *et al.* (2014) have shown that super-aligned CNTs grown on the surface of a micro-perforated panel (MPP) surface can improve the acoustic absorption performance of MPP absorbers at low frequencies. Investigations have also been conducted for nano-integrated polyurethane foam using multi-walled CNTs (Cherng 2006). Test results showed that the integration of CNTs improved the acoustic absorption performance by 5-10% in the frequency range 800-4000 Hz. CNTs incorporated into flexible polyurethane (PU) foams have also been reported to enhance the absorption performance of these conventional porous materials (Bandarian *et al.* 2011; Verdejo *et al.* 2009; Basirjafari *et al.* 2012). It was suggested that the nanotubes may improve the sound absorption performance of the polymer nanocomposites as the individual nanotubes oscillate with the sound waves, helping further absorb sound energy (Crawford 2012).

Carbon nanotubes can be produced that have an average diameter in the range of 3 to 50 nm and an average length of 10 µm to hundreds of micrometres (Seetharamappa *et al.* 2006). Having fibres at the nanoscale provides the ability to produce absorbers with nanopores (Ajayan *et al.* 2006) and thin fibres, which creates a more tortuous path and higher airflow resistance of the porous materials compared with conventional absorption materials. In addition, thin fibres can move more easily than thick fibres in the presence of sound waves, which induces structural vibrations of the nanotubes that contribute to dissipation of acoustic energy by means of friction through the vibration of the air. These factors give a potential advantage for absorbers with thin fibres such as CNTs to provide good acoustic absorption at low frequency for a given absorber thickness. In addition, the emergence of advanced manufacturing technologies offers exciting possibilities for creating tailored acoustic absorbers using carbon nanotubes (De Volder *et al.* 2013; Cho *et al.* 2014a; 2014b). However, there have been few attempts to measure the acoustic absorption properties of CNTs on their own. The AVC (Acoustics, Vibration and Control) group in the School of Mechanical Engineering at the University of Adelaide has studied the acoustic absorption behaviour of CNTs and their absorption mechanisms (Ayub *et al.* 2011; 2013; 2014; 2015). Previous investigations (Ayub *et al.* 2014) by the authors showed that a 3-mm-high carbon nanotube (CNT) forest has an acoustic absorption coefficient of about 5-10%, and can produce better absorption performance than conventional acoustic materials for an equivalent mass. In that study, it was anticipated that a CNT array of greater height, lower density, and with a non-uniform arrangement of the nanotubes could enhance the amount of acoustic absorption. In order to explore to what degree the absorption can be enhanced by a taller (compared with previous work) CNT forest, an independent impedance tube test was conducted to measure the acoustic absorption coefficient of a CNT forest of 6 mm. In this paper, the absorption performance of the 6 mm CNT forest and its acoustic bahaviour is compared with a 3 mm CNT forest. The study will contribute to developing understanding of the absorption capabilities of CNTs and various factors that might affect the absorption performance of CNTs.

2. MATERIALS AND METHODS

The acoustic absorption coefficient of the CNT forest was measured in an impedance tube using two microphones in accordance with the ASTM standard (ASTM E 1050; Chung & Blaser 1980a; 1980b). A custom made Ø25.40 mm copper impedance tube was used to measure the normal incidence acoustic absorption coefficient of the carbon nanotube sound absorber. A schematic and photograph of the experimental apparatus is shown in Figure 1. The instrumentation compromised two ¼ inch Brüel & Kjær (B&K) array microphones type 4958, a four channel B&K Photon+^{TM} data acquisition system and LDS Dactron software (LDS Group 2013). The B&K microphones have a free field frequency response (re 250 Hz) of ±2 dB within the frequency range 50 Hz to 10 kHz. A B&K type 4231 acoustic calibrator was used to calibrate the microphones to 94 dB at 1 kHz. Measurement data was acquired to give a 4 Hz frequency resolution, with a sampling interval of 7.60 µs (with 12800 lines and 32768 points) and sample records of finite duration of approximately 106 s for 300 averages using a Hanning window. The standard microphone-switching technique (Chung & Blaser 1980a; Katz 2000) was implemented to calibrate the microphones used in the impedance tube, which ensured that any variation in the magnitude and phase of the measured transfer function due to the differences in the two sensors was eliminated. During the measurement, it was identified that the tube has significant attenuation, which indicated this tube performed as a lossy waveguide. Hence, an additional correction, using a method developed by Han *et al.* (2007), was also applied to account for the tube attenuation due to viscous and thermal losses at the tube walls, as well as damping and leaks. Details of these corrections and the impedance tube method can be found in previous work (Ayub *et al.* 2014; Han *et al.* 2007).

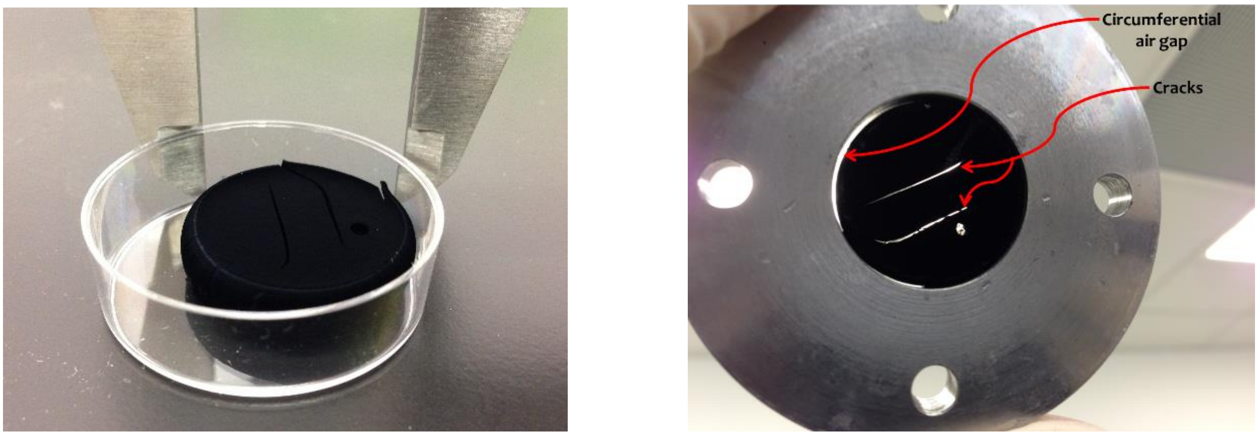


(a) (b)

Figure 1: (a) Schematic and (b) photograph of impedance tube and instrumentation used to measure the absorption coefficient of the fabricated CNT sample.

The carbon nanotube samples were manufactured by a research team in the Nanoworld Laboratories at the University of Cincinnati, USA. A vertically aligned carbon nanotube forest was grown on a substrate (silicon wafer) to produce the absorber sample. However, the CNT arrays in this particular sample were not attached to the substrate during the acoustic testing. Each sample was 6 mm thick and cut to have the same circular diameter of 25.40 mm to match the internal diameter of the impedance tube. The bulk density of this sample was calculated as 20.70 kg m^{-3}, which is lower than that of the previous CNT sample of 3 mm thickness (Ayub *et al.* 2014), for which the density was

$\sigma_{3mm\ CNT} = 43.40\ kg\ m^{-3}$. A photograph of the 6 mm CNT forest detached from the substrate is shown in Figure 2. Details of the manufacturing method and reaction condition during the fabrication of the CNT forest can be found in previously published works (Ayub *et al.* 2014; Cho *et al.* 2014a; 2014b).



(a) (b)

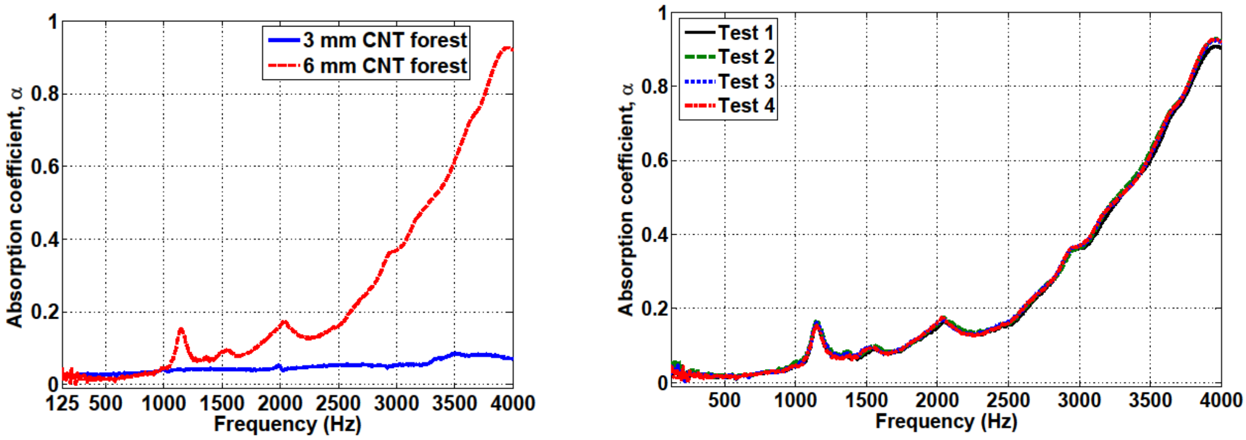
Figure 2: Photographs of (a) test sample of a 6 mm CNT forest and (b) the test sample placed inside an impedance tube sample holder.

3. RESULTS AND DISCUSSIONS

The experimental investigation of the acoustic absorption of a tall CNT forest comprised measurements of the normal incidence absorption coefficient of a 6 mm CNT forest (detached from substrate) and its composite with a conventional material using the impedance tube for a frequency range of 125 Hz to 4 kHz. The tests were repeated to check the repeatability of the results. The acoustic absorption performance results of the 6 mm CNT forest were also compared with the authors' previous work (Ayub *et al.* 2014), in which absorption behaviour was studied for test samples of 3 mm CNT arrays attached to silicon substrates. Figure 3(a) shows the absorption behaviour of a 6 mm-long CNT forest and the comparison of its absorption performance with a 3 mm CNT forest. It can be seen that the 6 mm-long CNT forest shows an acoustic absorption of more than 10% at frequencies lower than 2.50 kHz and a sharp rise in absorption of more than 20% at frequencies greater than 2.50 kHz and reaches a maximum of 90% at the frequency of 4 kHz. It can also be noticed that the absorption behaviour of the 6 mm-long CNTs is significantly different from that of the 3 mm CNTs. The results show a considerable increase in absorption compared with that of the 3 mm CNTs at high frequencies above 2.50 kHz, which is not anticipated for a 6 mm CNT sample considering that the thickness is just twice that of the 3mm CNTs. The repeatability of the result obtained for the 6 mm CNT forest was checked by measuring absorption coefficients for four tests with the same sample, but rotating it to different orientations. The results for the tests are displayed in Figure 3(b), which confirm the repeatability of the measured absorption coefficient. In addition, a consistency (reliability) test was conducted using a composite absorber sample comprising a conventional material of 9.50 mm polyurethane (PU) foam, 11.50 mm air gap, and the 6 mm CNT forest. Figure 4 shows results of the acoustic absorption coefficient of two equivalent configurations of the sample with and without the CNT forest, but replaced with an air gap of equivalent thickness. A similar trend of absorption increase above 2.50 kHz was found for the absorber sample incorporating the 6 mm CNT forest. These results indicate that the absorption performance of the sample could be improved by using longer CNTs and lowering the density of the forests in the sample. However, the acoustic behaviour of this tall CNT forest shows anomalies in the absorption spectra compared with the shorter CNT sample and conventional absorption materials.

Several explanations for the absorption increase of the 6 mm CNT sample were considered and analysed to understand this unusually enhanced absorption above a frequency of 2.50 kHz. An appropriate quantitative analysis of absorption behaviour of the CNT forest is currently very difficult due to the lack of theoretical models for nanomaterials. Hence, theoretical analyses were performed based on classical methods to explain the anomalies in the measured acoustic absorption coefficient. In addition, due to the lack of CNT samples and the limited availability of CNT samples for each test setup, the analyses have not been extensively verified experimentally (specifically by repeating measurements for a given setup using a number of similar CNT samples) at this stage and should be the subject of future investigation. The following factors were considered for the analysis and their effects on the measured absorption coefficient are elaborated in the subsequent sections:

- circumferential air gap,
- sample mesoporosity,
- catalyst layer in the sample,
- nanotube forest density, and
- bending vibrations and frame resonance of the sample



(a) (b)

Figure 3: Acoustic absorption coefficient of (a) a 6 mm and a 3 mm-long CNT forest and (b) a 6 mm-long CNT forest for a number of repeated tests obtained by rotating the sample, measured using the impedance tube of inner diameter 25.40 mm.

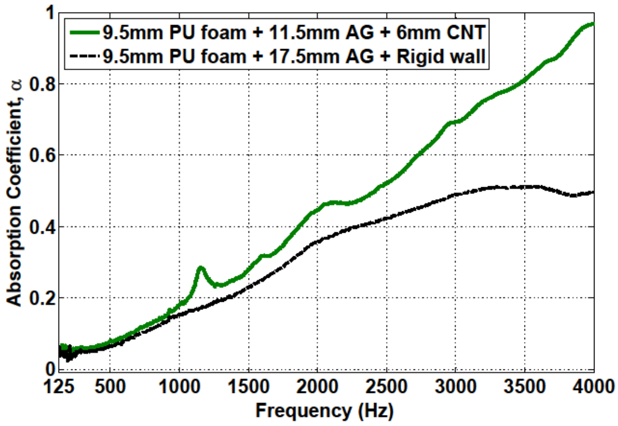


Figure 4: Comparison of the absorption coefficient for a composite absorber sample comprised of 9.50 mm polyurethane foam, 11.50 mm air gap and the 6 mm-long CNT forest.

3.1 Effect of Circumferential Air Gap

The effect of a circumferential air gap on the measured absorption coefficient of the CNT forest was measured. When the sample was inserted into the impedance tube, there was a circumferential air gap between the sample and the inside of the tube about 0.83 mm thick as shown in Figure 2(b). The presence of an air gap usually causes a decrease in the measured absorption (Pilon *et al.* 2004). On the other hand, it may exhibit an absorption increase for a material with an extremely high flow resistivity due to its high permeability contrast, a dimensionless parameter given by the ratio of the static visco-inertial permeability of the micro-and macro-porous network of a representative double porosity material (Pilon *et al.* 2004). However, it was suggested that this phenomenon might not be of significance for a thin sample. Pilon *et al.* (2004) developed a method, in which a criterion (referred to as the acousto-visco-inertial criterion) based on the given material sample and experimental setup was used to identify materials that are affected by the presence of a circumferential air gap. Through the use of this criterion, which relies on estimates of the permeability contrast between the micro- and macro-porous network, an educated guess can be made to identify which absorption is measured: the actual absorption of the material or one affected by the presence of the circumferential air gap. A similar strategy was employed for the 6 mm CNT sample to determine the effect of the circumferential air gap on the measured absorption coefficient. It was identified that the presence of the circumferential air gap leads to a significant increase in the measured absorption coefficient from the actual value. However, the evaluation was based on the estimate of permeability ratio of the CNT sample using the approximate values (calculated using classical models) of the non-acoustical properties of the 6 mm CNT forest, in which the values were out of the prescribed range suitable for making an educated guess on the effect of a circumferential air gap (Pilon *et al.* 2004).

In order to verify how this phenomenon would actually affect a thin sample of high flow resistivity material (which emulates the physical properties of CNTs) and a thick sample of low flow resistivity material, tests were conducted using an impedance tube for a low and a high flow resistivity material, polyurethane (PU) foam and refrasil, respectively. A thin sample of 3.50 mm refrasil (0.224 g and 166.8 kg m^{-3}) and a relatively large thickness of 15.50 mm of PU foam (0.151 g and 19.19 kg m^{-3}) were tested with and without a 1.65 mm circumferential air gap. A comparison of the absorption coefficients for both materials with and without the circumferential air gap is shown in Figure 5.

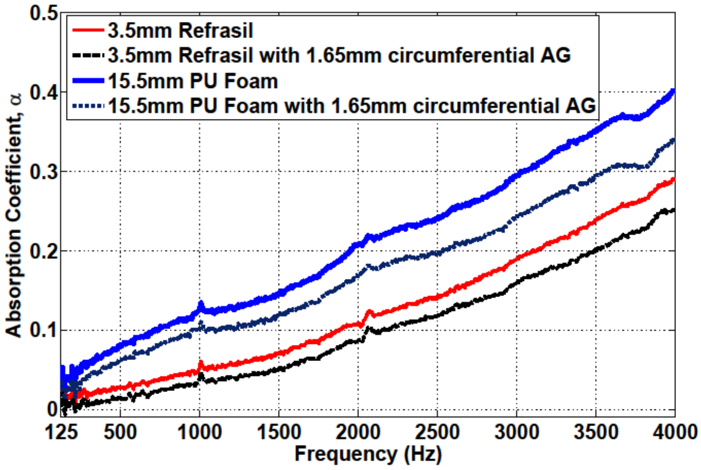


Figure 5: Absorption coefficient as a function of frequency in the 25.40 mm impedance tube for a sample thickness of 3.50 mm refrasil and 15.50 mm PU foam with and without a 1.65 mm circumferential air gap.

It can be seen that the acoustic absorption decreases in both cases in the presence of the circumferential air gap. This indicates that the effect of the circumferential air gap on the measured absorption coefficient of the 6 mm CNT sample could be different from the earlier observation made based on the methodology of Pilon *et al.* (2004). Therefore, an additional experiment was conducted with a loosely-supported sample holder setup (details can be found in previous work by Satoh *et al.* (2014)) by placing the 6 mm CNT sample of diameter 25.40 mm inside an impedance tube of smaller diameter of 22.10 mm. This kind of setup reduces the effect of the circumferential air gap and unwanted flexural vibrations of the sample on the measured absorption coefficient (Satoh *et al.* 2014). The CNT sample in the 22.10 mm impedance tube was backed with an air gap of 2 mm during the test as required to protect the CNTs from being crushed when the sample was placed inside the tube of smaller diameter. A comparison of the absorption results for both impedance tube tests is presented in Figure 6. It can be observed that the sample with the loosely-supported setup (solid line) exhibits a significant increase in the absorption coefficient from the standard test (dotted line) in the mid to high frequency range. Therefore, it may be assumed that the reduced circumferential air gap may have contributed to the increase in the acoustic absorption, which is similar to the observation made for a thin sample of high flow resistivity material of 3.50 mm refrasil. The presence of the air gap of thickness 2 mm with the absorber is unlikely the reason for the higher absorption of the 6 mm CNTs, as an air gap of thickness larger than 25 mm would be required to observe a shift of the resonance peak at a frequency of 3.50 kHz or less as shown in Figure 6. Overall, this implies that the absorption of the 6 mm CNT forest could be greater than that of the measured results obtained in the presence of a circumferential air gap.

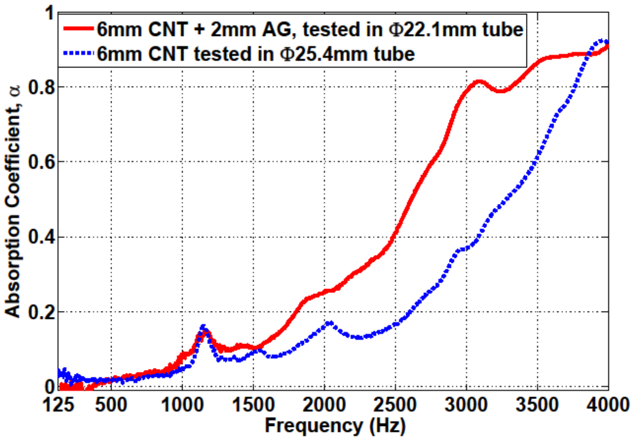


Figure 6: Absorption coefficient of the 6 mm CNT sample tested in two different impedance tubes of diameters 25.40 mm and 22.10 mm with the standard sample holder setup and the loosely-supported sample holder setup (Satoh *et al.* 2014), respectively.

3.2 Effect of Forest Density

It is anticipated that lowering the forest spatial density (number of tubes per unit area) of the nanotubes will increase the acoustic absorption of the CNT arrays. Although during the fabrication process it was not intended to reduce the forest density of the particular sample of the 6 mm-long CNT forest, the measured bulk density (which is nearly half that of the 3 mm CNTs) suggests that the forest density might be lower than that of the 3 mm sample. However, the reality is a bit more complicated. During the growth of the long CNTs, the nanotubes, due to their stickiness, have a tendency to tug on their neighbours as they grow on the nanoparticles (Bourzac 2009; Cho *et al.* 2014a; 2014b). Hence, long CNT arrays tends to have high forest densities at the upper part of the forest and relatively low forest densities at the lower part of the forest near to the catalyst layer and the substrate (Cho *et al.* 2014a). As a result, a long CNT forest may have a lower bulk density compared with a shorter CNT forest. Consequently, having a comparatively low bulk density in the long CNT forest provides a higher porosity and lower flow resistivity than that of a shorter CNT forest, which ideally contributes to increasing the acoustic absorption of a relatively high flow resistivity material such as the CNT forest. Theoretical estimates of the flow resistivity of the 3 mm CNT sample indicate that the values vary from 1.77×10^7 Pa s m^{-2} to 3.59×10^7 Pa s m^{-2}, whereas for the 6 mm CNT sample it varies from 5.37×10^6 Pa s m^{-2} to 1.27×10^7 Pa s m^{-2} . This implies that the low forest density of the 6 mm CNT sample may have contributed to enhancing the absorption performance at high frequencies.

3.3 Effect of Sample Mesoporosity

The presence of additional mesopores in a microporous material usually affects the acoustic absorption behaviour of the porous material (Sgard *et al.* 2005). The mesoporosity (double porosity) of the 6 mm CNT forest was investigated because the test sample of the CNT forest had additional pores in the form of two cracks (each approximately 0.33 mm wide and 1.32 mm long) and a cylindrical hole (of diameter approximately 1.80 mm) in the middle of the structure as shown in Figure 2(b). In order to determine the effect of the meso-perforation and its contribution to increasing the acoustic absorption of the CNT forest, the test sample was modelled as a meso-perforated material and the acoustic behavior was analysed theoretically using the model developed by Sgard *et al.* (2005). The radius and mesoporosity were estimated as R = 1 mm and $\phi_p = 0.0068$ (defined as the ratio of the area of the hole to the total sample area) corresponding to a representative double porosity configuration of one equivalent circular hole for the aforementioned perforations of the CNT sample. Figure 7 shows a comparison of the theoretically predicted acoustic absorption coefficient of the 6 mm CNT forest for a uniform unperforated nanoporous CNT configuration and a representative double porosity CNT configuration.

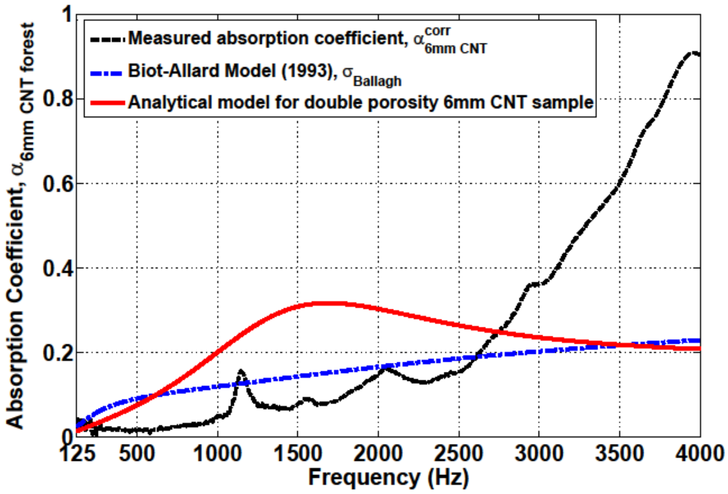


Figure 7: Theoretical prediction of the acoustic absorption coefficient of a 6 mm CNT sample calculated for a uniform unperforated nanoporous CNT sample and a representative double porosity CNT configuration of radius R = 1 mm and mesoporosity ϕ_p = 0.0068. The experimentally measured absorption coefficient of the 6 mm CNT sample is also shown to illustrate the difference between the experimental results and the theoretical estimates based on classical methods. Here, $\propto^{corr}_{6\ mm\ CNT}$ corresponds to the acoustic absorption coefficient estimated with the implementation of the correction for tube attenuation (see Section 2) and $\sigma_{Ballagh}$ indicates the theoretical prediction of absorption coefficient using a flow resistivity value calculated from an empirical model suggested by Ballagh (Ballagh 1996).

It can be seen that the theory predicts that the acoustic absorption for the double porosity CNT sample is enhanced in the frequency range of 1000-3000 Hz due to the presence of mesopores (cracks and hole). Therefore, the effect of meso-perforation can be substantial considering that the overall theoretical absorption performance of the CNT forests is low. However, these results also suggest that the effect is in the wrong frequency range, i.e. the absorption increases in the mid and low frequency range rather than in the relatively high frequency range, where the increase in absorption is observed in the experimental results. The shape of the mesopores may have an effect on the prediction as the calculation was performed with the assumption of an equivalent circular pore.

3.4 Effect of Catalyst Layer in the Sample

The fabrication process of the CNTs (details in Cho *et al.* 2014a; 2014b) comprises the deposition of a thin catalyst layer of Fe/Gd on the substrate structure, on which the vertical arrays of CNTs are grown. As mentioned previously, the CNT arrays in this particular test sample were not attached to the substrate. During the fabrication of the detached CNT forest, there is a possibility that the catalyst layer can be retained on the CNT arrays once they are detached from the substrate. For long CNTs, the catalyst layer could be anywhere between 2 to 5 nm in thickness. This layer could act like an acoustic membrane when excited by sound waves, which might have an effect on the measured acoustic absorption of the detached CNT forest. The resonance created by the membrane might also contribute to the peak observed around a frequency of 1150 Hz, which will be discussed later in Section 3.5. The results suggest that a CNT forest attached to a substrate and a CNT forest detached from the substrate can behave differently for acoustic excitation. In addition, the frame resonance of the CNTs will be affected by the presence of the catalyst layer. Hence, the catalyst layer may have an effect on the acoustic absorption of a CNT forest detached from the substrate and the ways in which it may act in response to acoustic excitation. However, there is no specific evidence for these effects and a means of estimating the membrane effect for the catalyst layer is not available at this stage of the current investigation.

3.5 Effect of Bending Vibrations and Frame Resonance of the Sample

It is hypothesised that the peak observed at a frequency of around 1150 Hz in the absorption curve of Figure 3 for the 6 mm CNT sample could be due to either the bending vibration of the CNT sample or the frame resonance induced by the individual vibrations of the CNTs. Theoretical values of the frequencies corresponding to the bending vibration modes of a similar circular plate made of CNTs for a simply supported condition (as the CNT sample was simply inserted into the holder without any additional constraints around the edge as shown in Figure 2(b)) were predicted using the relation, $\lambda^2 = \omega a^2\sqrt{\rho/D}$ (Leissa 1969), where λ is the eigenvalue of the simply supported circular sample, ω is the natural frequency of bending vibration modes in rad/s, a is the radius of circular plate, ρ is the mass density per unit area of the plate. Here, the term $D\ (= Eh^3/12(1-\upsilon^2))$ corresponds to the flexural rigidity, where E is the Young's modulus, h is the plate thickness and υ is the Poisson's ratio. The theoretical calculation was performed using the Young's modulus of the CNT forest as 1 MPa, which usually varies within the range of 1-10 MPa (Olofsson *et al.* 2009). The forest density of the CNT was not uniform throughout the sample. Hence, the natural frequencies of the bending vibrations of this material were estimated theoretically using the mass densities of 10.85×10^{-2} kg m^{-2} and 26.04×10^{-2} kg m^{-2} for the 6 mm and 3 mm CNT sample, respectively, and an average value of the two mass densities of both CNT samples as 18.50×10^{-2} kg m^{-2}. The corresponding natural frequency values estimated based on the classical theory of plates (Leissa 1969) for these mass densities are approximately 2065 Hz, 1354 Hz and 1608 Hz, respectively. It can be seen that the last two frequencies are close to the experimental value observed in the absorption curve displayed in Figure 3, whereas the value of 2065 Hz does not match with the frequency of the peak observed. This indicates that the dispersion in the approximate value of the surface density of the CNT sample greatly affects the theoretical values of the frequencies corresponding to the bending vibration modes of the CNT sample. Hence it is likely that the peak observed at a frequency around 1150 Hz is due to the bending vibrations of the sample inside the sample holder. The study performed by Swift *et al.* (2000) suggested similar absorption behaviour due to sample bending vibrations.

The possibility of the peak being related to the frame resonance of the CNT sample cannot be excluded. Previous research by Dahl *et al.* (1990) on the acoustic absorption behaviour of fibrous materials (Kevlar fibres) suggests that the frame resonance is substantially affected by the fibre orientation to the sound wave propagation. The excitation of the frame resonance was attributed to the fibre motion induced by the viscous drag and pressure gradient across the length of the fibre (Dahl *et al.* 1990). It was concluded that when the fibres are oriented normal to the direction of the sound propagation the forces are strong enough to laterally displace (vibrate) the materials (or fibres), whilst the forces created along the fibres, in the case of fibres orientated parallel to the direction of sound propagation, are not strong enough to cause the fibres to vibrate (Dahl *et al.* 1990). The current investigation suggests that the frame resonance in the measured absorption coefficient of the 6 mm forest could potentially be neglected due to the orientation of the CNTs, which was parallel to the direction of sound propagation. However, in the case of CNTs, even though the fibres are oriented in the direction parallel to the sound propagation, the forces might be strong enough to vibrate the nanotubes and generate frame resonance in the sample, considering their nanoscale dimension, high length-to-diameter ratio, and light weight. In addition, the strong intermolecular van der Waals forces between the nanotubes may influence the frame resonance. This behaviour could possibly be confirmed with the molecular simulation of the acoustic behaviour of CNTs.

4. CONCLUSIONS

This study presents an independent measurement of the acoustic absorption coefficient of a relatively tall CNT forest of 6 mm compared with the previous study of a 3 mm CNT forest. The results indicate that a larger length and lower forest density of the CNTs may improve the absorption performance of CNT-based acoustic absorbers. The physical reasons for the differences in the absorption between the 3 mm and 6 mm CNTs are still under investigation. However, based on theoretical analyses performed in this study it can be summarised that the low forest density of the nanotubes, presence of mesoporosity, and catalyst layer in the sample may be responsible for the absorption increase in the 6 mm CNT forest compared with the 3 mm forest. Analysis based on the experimental results for conventional materials indicates that the presence of a circumferential air gap may cause a decrease in the measured absorption (from the actual absorption of the material) of a thin sample of high flow resistivity material such as a CNT forest. Hence, the presence of circumferential air gap may not be a contributing factor to the absorption increase in the 6 mm CNT forest. The peak at low frequency in the absorption curve may have been induced by the bending vibration of the sample. This additional peak at low frequency could also be related to the frame resonance of the CNT sample. The analyses presented in this paper are preliminary and further work is necessary to confirm the proposed hypotheses. However, this analysis demonstrates that the acoustic absorption characteristics of CNT forests is complicated and does not adhere to classical material absorption models. Possible factors that might affect the acoustic absorption behaviour of nanomaterials include the physical and geometrical conditions of the fabricated sample, the orientation of the nanotubes inside the impedance tube, how they were prepared for the impedance tube tests, and finally the consistency of mounting conditions of each sample during the tests. These exploratory experiments and theoretical analysis provide insight into the possible conditions required for performing simulations to investigate the nanoscopic absorption mechanisms for nanomaterials.

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