Acoustic absorption behaviour of carbon nanotube arrays

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ABSTRACT

Advances in nanotechnology have provided acoustic researchers with a number of new materials with nano-fibres and nano-pores that can potentially be implemented as an acoustic porous absorber. This paper investigates the acoustic absorption behaviour of carbon nanotube (CNT) arrays, in order to quantify the acoustic characteristics and absorption performance of nanoscopic fibres in comparison with conventional porous materials. Tests were conducted using an impedance tube to measure the normal incidence acoustic absorption coefficient of vertically aligned carbon nanotube (CNT) arrays. Results show that a forest of 3 mm CNT arrays can provide as much as 10% acoustic absorption capability within the frequency range 125 Hz - 4 kHz. It was found that CNT arrays, in some cases, may provide better acoustic absorption than conventional porous materials of equivalent thickness and mass. The outcomes of this investigation highlight the potential of nanoscopic fibres for use as light-weight acoustic absorbers.

Keywords: Carbon nanotube, CNT Forest, Acoustic absorption coefficient, Porous absorption materials
I-INCE Classification of Subjects Number(s): 35.2.1 (01.9)

1. INTRODUCTION

In the current era of nanotechnology, a variety of nanotube constituents are available which can be formed into nanoscopic fibres, for instance: carbon nanotube (CNT) (1, 2), boron nitride nanotube (BNT) (3) and titania nanotube (TNA) (4). Although carbon nanotubes are the most widely studied materials of the nanofibres and composite foams (5), other nanotubes also have similar ability to form nanoscopic fibres and composites (6, 3). Since the invention of the carbon nanotube (CNT) structure by Iijima (1), numerous potential applications for CNTs have been suggested in the fields of electronics, the energy sector, mechanics, field emissions and light applications (7, 5). However, although a number of applications of CNTs in noise control engineering have been suggested (5), they have not been widely used as sound absorbers. In one application, a lightweight CNT foam was fabricated utilising 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 are also providing the opportunity 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 orientations of the fibres (8, 9, 10). In a study conducted by Qian et al. (11), it was shown that super-aligned carbon nanotubes grown on the surface of a micro-perforated panel (MPP) surface 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 integration of carbon nanotubes improved the acoustic absorption performance by 5 - 10% in the frequency range 800 Hz - 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, 14, 15). There is also an anticipated use of carbon nanotubes for reducing airplane noise by encapsulating the carbon nanotubes in a polymer nanocomposite to create electrospun fibres (16). It was suggested that the nanotubes may improve the

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sound absorption performance of the polymer nanocomposites as the individual nanotubes will oscillate with sound waves, helping further absorb sound energy (16). These developments in nanotechnology offer exciting possibilities as the basis for acoustic absorption materials using nanotubes.

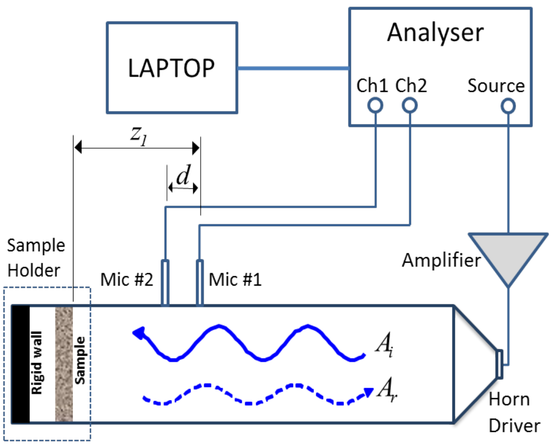
Carbon nanotubes can be produced that have an average diameter in the range of 10 nm to 100 nm and an average length of 10 μm to hundreds of micrometers. Having fibres at the nanoscale will provide the ability to produce absorbers with nanopores (5). In general, for absorber materials, the lower the diameter of the fibre, the greater will be the acoustic absorption, as the reduction of fibre diameter causes the requirement of more fibre to reach an equal volume density for the same thickness, which creates a more tortuous path and higher airflow resistance of the porous materials (17, 18, 19). Moreover, thin fibres can move more easily than thick fibres in the presence of sound waves which induce vibration in air and increase airflow resistance by means of friction through the vibration of the air (19). Hence, absorbers with thin fibres such as CNTs have the potential to provide good acoustic absorption at low frequency for a given absorber thickness. Moreover, advanced technology for nanostructures will facilitate the tailoring of open cell structures in an array of CNTs (5). Open pore structures, together with the individual nanopores of the tubes, can potentially have a significant influence on the enhancement of acoustic absorption of CNT absorbers. However, to date isolated measurements of the acoustic absorption properties of nano materials have not been reported. The current investigation of the acoustic absorption of CNT arrays will guide the development of an effective acoustic absorber that makes use of various arrangements of carbon nanotubes.

This paper examines the absorption coefficient of a forest of CNTs using an impedance tube with a normal incidence sound source. The absorption characteristics of a CNT forest are also compared with that of conventional porous materials to highlight the significance of the absorption performance of nanoscopic fibres, based on separate comparison with samples equivalent thickness and equivalent mass of the sample.

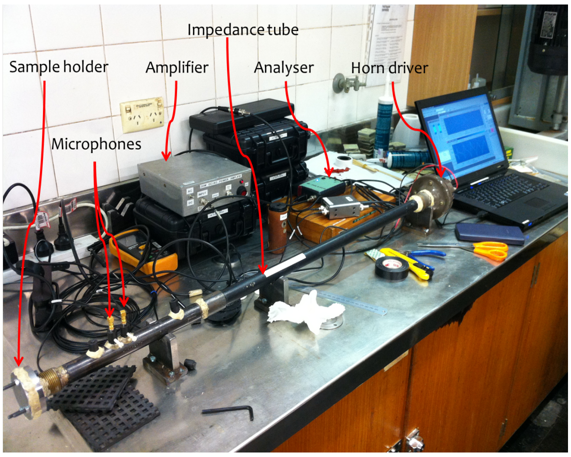
2. MATERIALS AND METHODS

2.1 Impedance Tube Apparatus

The acoustic absorption coefficient of the CNT array was measured in an impedance tube using two microphones in accordance with the ASTM standard (20, 21, 22, 23). A custom made ∅22.10 mm steel impedance tube was used to measure the normal incidence absorption coefficient of the carbon nanotube 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 schematic and photograph of the experimental apparatus is shown in Figure 1.



(a) Schematic of impedance tube set up



(b) Photograph of impedance tube set arrangement in the acoustic lab

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

The instrumentation compromised two $\frac{1}{4}$ inch Brüel & Kjær (B&K) array microphones type 4958, a four channel B&K Photon+^{TM}data acquisition system and LDS Dactron software. 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 pistonphone calibrator (B&K type 4230) was used to calibrate the microphone sensitivity to 94 dB at 1 kHz. Measurement data was acquired with 4 Hz frequency resolution, with a sampling interval of 7.6 μs (with 12800 lines and 32768 points) and sample records of finite duration of approximately 106 s for 300 averages.

2.2 Correction for Microphone Phase Mismatch Error and Tube Attenuation

The acoustic impedance was measured using the two-microphone method(22, 23). When the transfer function between two microphones is measured, the phase error between the microphones is unavoidable and must be corrected. The standard sensor-switching technique (22) was used to calibrate the microphones used in the impedance tube. Each transfer function H_{12} measured between the microphones was corrected (e.g., H_{12}corrected$= H_{12}/H$cal) by a calibration transfer function Hcal$(= \sqrt{H_{12} \times H_{21}})$ (24), which ensured that any variation in the magnitude and phase of the measured transfer function due to the differences in two sensors was eliminated. H_{12} and H_{21} are obtained by switching the locations of microphone 1 and microphone 2 shown in Figure 1a, then measuring the transfer function. An additional correction was applied for the tube attenuation due to viscous and thermal losses at the tube walls, as well as damping and leaks using a method developed by Han et al. (25). The real wave number k in the wave equation is replaced by a complex wave number,

$$k' = k - jk'' \tag{1}$$

where $k = 2\pi f/c$, with f and c being the frequency and sound speed, respectively and k'' is the attenuation constant which can be predicted theoretically using an empirical relationship provided in the standards (25, 20, 21),

$$k'' = A\sqrt{\frac{f}{cD}} \tag{2}$$

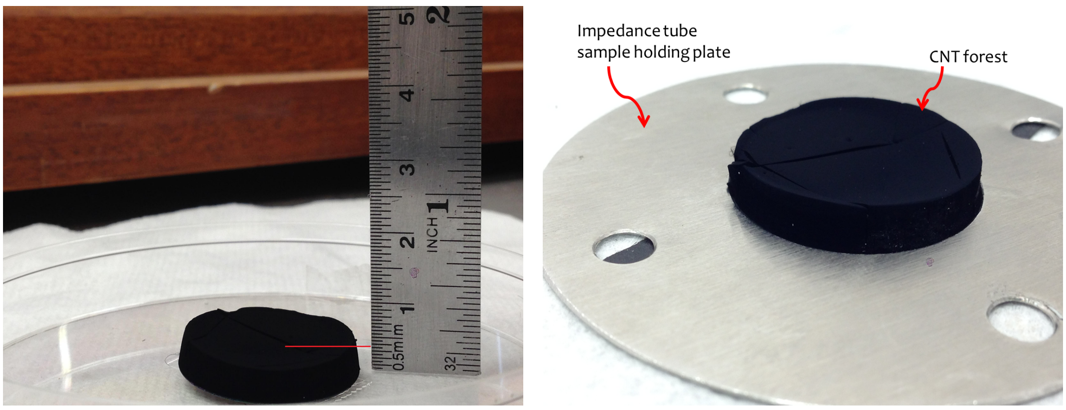
where D is the diameter of the tube and A is a constant. Values of A = 0.02203 (20) and A = 0.0194 (21) have been specified previously. The attenuation constant k'' can also be measured directly as an alternative to Equation 2 from the measured transfer function for an (assumed) rigid termination. The attenuation constant is estimated based on the relationship between reflection coefficient R and transfer function H_{12}, with the assumption of $R = 1$ for the rigid termination (25),

$$H_{12} = \frac{\cos[(k - jk'')(z_1 - d)]}{\cos[(k - jk'')z_1]} \tag{3}$$

where z_1 is the distance of the furthest microphone from the surface of the termination and d is the separation distance between the two microphones. Equation 3 can be solved numerically for k'' using the Newton-Raphson iteration scheme (25, 26).

2.3 Carbon Nanotube Sample Preparation

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 as exhibited in Figure 2. Each sample is 3 mm thick and cut to have the same circular diameter of 22.10 mm to match the internal diameter of the impedance tube.



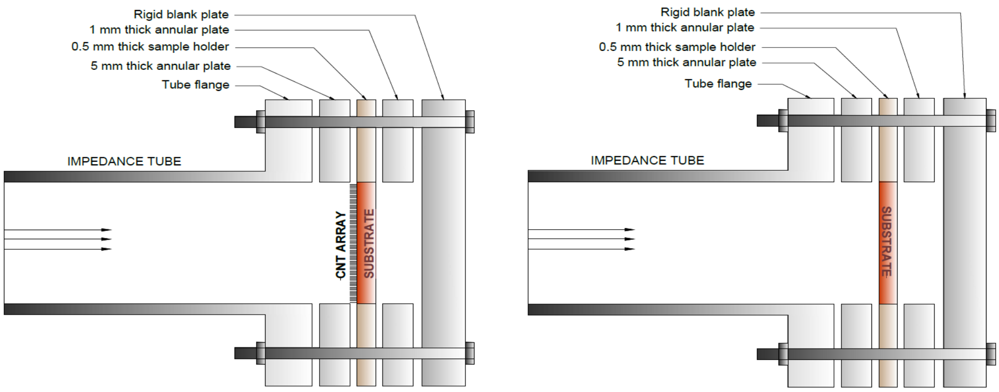
(a) Fabricated CNT sample (b) CNT forest and sample holder

Figure 2 – Fabricated sample of 3 mm forest of CNT arrays. Figure 2a shows the total thickness of the CNT sample with the attached 0.5 mm substrate.

The vertically aligned CNT array was grown in a 50.8 mm (2 inch) quartz tube reactor (ET 1000 by FirstNano) using a water assisted Chemical Vapor Deposition (CVD) process. The substrates were prepared as follows: (1) deposition of 20 nm Al (aluminum) film on a 101.6 mm (4 inch) Si wafer (100) coated with a (500 nm) SiO_2 layer by electron beam evaporation, (2) oxidation of the Al film to form an Al_2O_3 buffer layer, (3) deposition of (1.5 nm) Fe/Gd thin film on the formed $Al_2O_3/SiO_2/Si$ substrate structure by e-beam evaporation. The growth parameters were 400 SCCM Ar, 100 SCCM H_2, 75 SCCM C_2H_4 and 900 ppm H_2O vapor. The deposition temperature was maintained at 780^0C. Details are presented elsewhere (27, 28).

3. EXPERIMENTAL RESULTS AND OBSERVATIONS

The experimental investigation of the test samples using the impedance tube comprised measurements of the normal incidence sound absorption coefficient of the CNT forest for the frequency range between 125 Hz and 4 kHz. The results were compared with those of solely the substrate (Si) material, a blank impedance tube and conventional absorptive materials. Measurements were conducted for several arrangements of the sample to yield the acoustical absorption capability of CNT forest. The mounting configurations shown in Figures 3a and 3b were utilised for the measurement of absorption coefficient of the CNT forest and substrate material.



(a) Carbon nanotube array (b) Substrate only

Figure 3 – Arrangement of the sample configuration for (a) CNT array and (b) substrate.

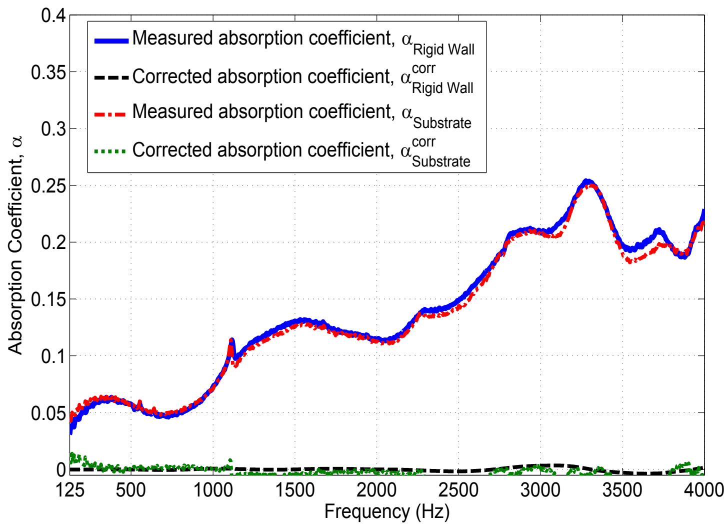


Figure 4 – Measured and corrected normal incidence sound absorption coefficient of substrate material and tube with rigid termination.

The measurement for solely the substrate material was conducted to determine the influence of the substrate material on the CNT forest absorption measurements. The absorption coefficient of the blank impedance tube was also measured to estimate the acoustic absorption by the impedance tube itself. The comparison of the acoustic absorption coefficient by these three configurations is necessary to determine the absorption of the CNT forest alone. The sound absorption coefficients (α) of the CNT forest, the substrate material and the blank impedance tube was estimated from the transfer function (H_{12}) measured between the two microphones placed with a separation distance of 20.175 mm. The assumed rigid termination consisted of a 5 mm mild steel blanking plate. Figure 4 shows the measured absorption coefficient of the blank impedance tube (with the rigid termination) and that of the substrate material for the sample configuration shown in Figure 3b, without and with the implementation of the correction for tube attenuation. It may be observed that both the substrate and the rigid wall termination show almost the same amount of absorption, which indicates that the substrate material can be considered as a rigid wall for the comparison of the absorption behavior with that of the CNTs. As shown in Figure 4, impedance tube exhibits an absorption of less than 25%, which occurs predominantly due to the attenuation associated with the smaller tube diameter (25), as well as sound leakage around the tube end and the background noise. However, the expected result of zero absorption for the rigid wall termination is nearly achieved once the correction for tube attenuation (25) is applied. Figure 5 shows the measured absorption coefficient of the CNT forest for the sample configuration shown in Figure 3a. The absorption coefficient is estimated by applying the correction to the measured results, which is also comparable with the difference of absorption coefficients between that of the CNT forest and the tube with rigid termination. It can be seen that the CNT forest shows a 5% - 10% normal incidence acoustic absorption coefficient over the entire measurement frequency range.

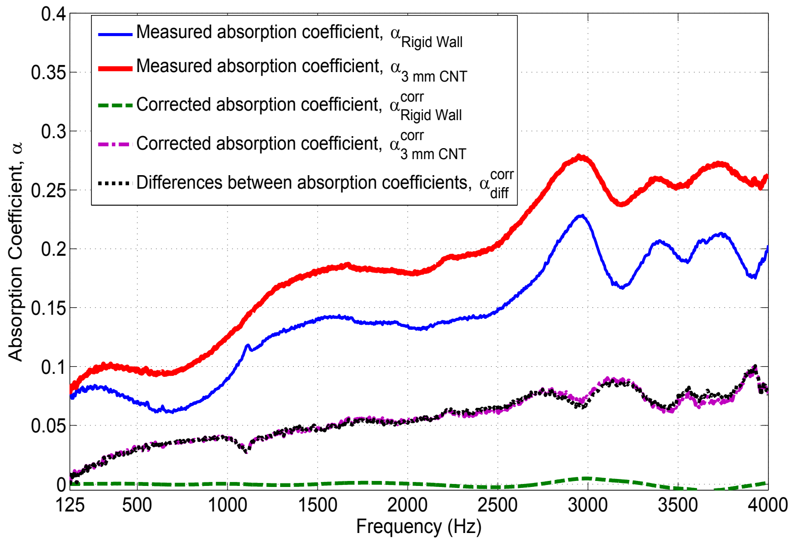
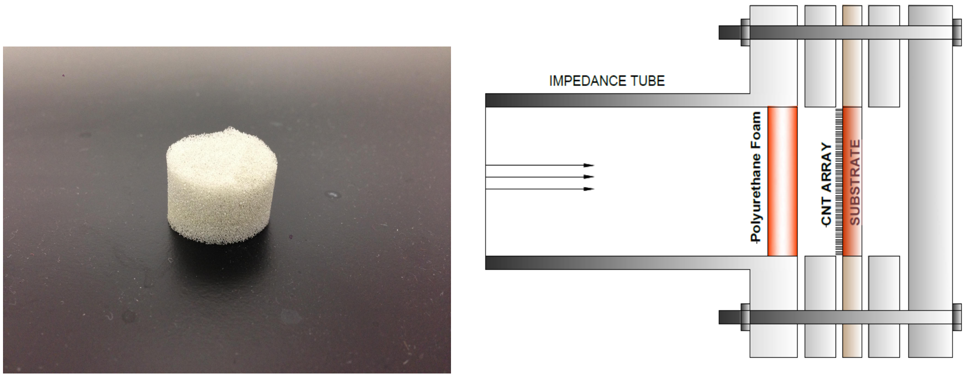


Figure 5 – Measured and corrected normal incidence sound absorption coefficient of CNT forest sample compared with that of tube with rigid termination.

Similar absorption behaviour of the CNT forest as shown in Figure 5 can be observed if the CNT forest is combined with conventional porous materials to make a composite absorber panel. A conventional absorption material, 14.5 mm polyurethane foam, was placed in front of the CNT forest as shown in Figure 6. Previous arrangements of the sample configuration shown in Figure 3 were utilised to carry out the measurements for an equivalent absorber of three different mounting conditions of the CNT forest, substrate material and rigid wall. For the arrangement equivalent to that in 3a, polyurethane foam backed with a 37 mm air gap was placed facing towards the sound source in front of the 3 mm CNT forest. The 3 mm CNT forest was replaced with an additional 3 mm air gap (in total 40 mm cavity depth) in front of the substrate and rigid wall for the measurement of the absorption coefficient of an equivalent absorber without the CNT utilising the arrangement equivalent to that in 3b. The mounting configuration shown in Figure 6b was for the arrangement of a 14.5 mm thick polyurethane foam backed by a 37 mm air gap and the 3 mm CNT forest. The estimated absorption coefficient results from the tests are shown in Figure 7. As expected, the polyurethane foam backed by the CNT forest (solid bold line in the figure) exhibits a higher acoustic absorption coefficient than that of the substrate material and rigid wall. This result endorses the reliability of the earlier assessment of the absorption capability of CNT. The findings also highlight the ability of CNTs to enhance the acoustic absorption coefficient of conventional porous materials.

These aforementioned results reflect previous findings on the acoustic damping provided by CNTs investigated by Bandarian et al. (13), Verdejo et al. (14) and Basirjafari et al. (15). In the previous investigations, CNTs were dispersed within porous polyurethane (PU) foam with the anticipation of improving the thermal, mechanical and acoustic damping ability of the foam. It was found that the inclusion of CNT increased the absorption ability of the foam by 5% to 10%, even though the mechanisms involved for the dispersed CNT



(a) Polyurethane foam sample (b) Sample configuration of the composite absorber panel

Figure 6 – The arrangement of sample configuration for a 14.5 mm polyurethane foam (0.1176 g, 21.1 kgm^{-3}) backed by a 37 mm air gap and the 3 mm CNT forest.

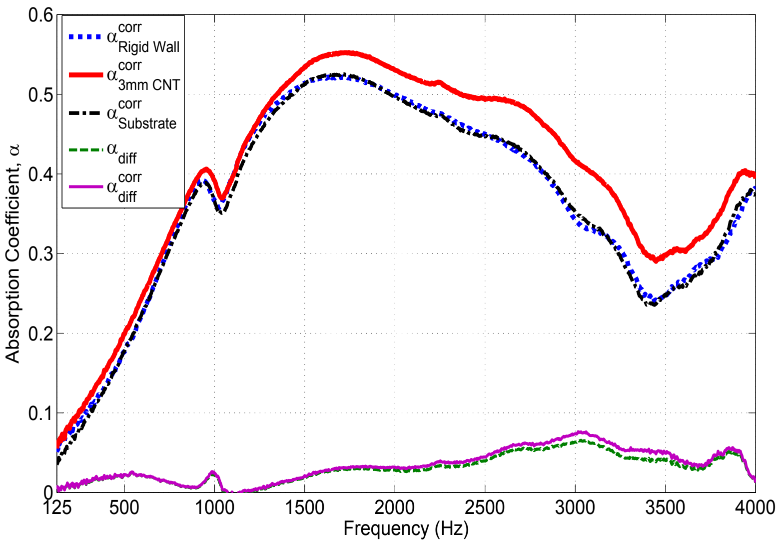


Figure 7 – Comparison of the absorption coefficient for a combination of polyurethane foam and the CNT forest. Here, α^{corr} represents the corrected absorption coefficient, and α_{diff} and α_{diff}^{corr} corresponds to the difference of measured and corrected absorption coefficients between the CNT and rigid wall.

would be very different compared to the current investigation of the pure CNT arrays.

3.1 Comparison with Conventional Materials

The significance of the acoustic absorption performance of the CNT forest can be demonstrated by considering the analogues absorption characteristics of conventional materials such as melamine foam and glass wool for an equivalent thickness or mass of the material. The analytical framework was initially adapted from Kino and Ueno (29) to predict the normal incidence acoustic absorption coefficient of reference thickness of 25.5 mm melamine foam and 25 mm glass wool using the relevant non-acoustical parameters (29). Thereafter, the model was utilised to predict the acoustic absorption coefficient of both materials by reducing the material thickness to 3 mm, equivalent to that of the CNT forest. Comparison of the absorption coefficient of the 3 mm CNT forest and conventional porous materials of equivalent thickness is displayed in Figure 8, which shows that both conventional materials exhibit lower absorption than that of the CNT forest. It indicates that CNTs may provide comparatively better absorption than that of conventional porous materials of equivalent thickness. A similar comparison of the acoustic absorption coefficient of the CNT forest and porous materials is presented in Figure 9 for equivalent mass to the CNT sample (0.0499 g). It can be observed that a 4.09 mm glass wool of equivalent mass (0.0499 g) may provide similar absorption to a 3 mm CNT forest. Whereas, a 12.63 mm melamine foam of equivalent mass may yield a maximum absorption of 50% over the measured frequency range, which is significantly higher than that of the CNT forest. As shown in Figure 9, even though an equivalent mass of melamine foam may produce significantly higher sound absorption than that of a CNT forest, it is four times the thickness of the CNT forest. These results highlight the significance of the absorption ability of CNT and its potential for the implementation of compact CNT acoustic absorbers in noise control engineering.

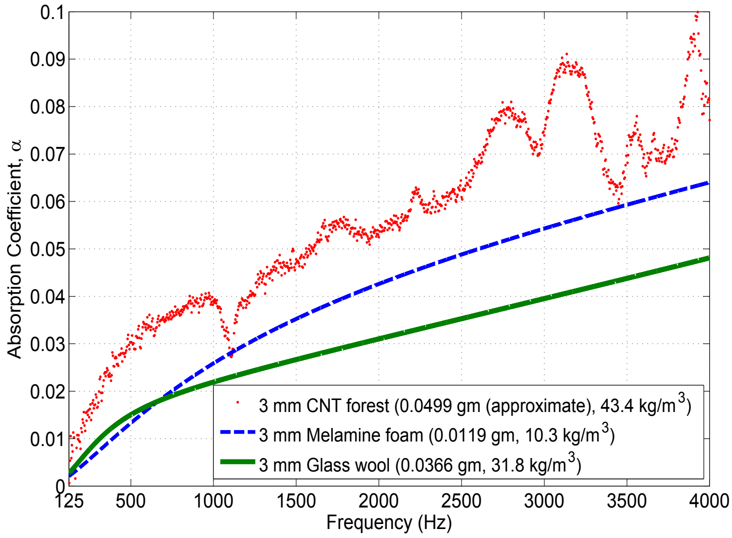


Figure 8 – Comparison of the acoustic absorption coefficient of the CNT forest with two conventional porous materials of equivalent thickness: melamine foam and glass wool. It should be noted that the mass of CNTs (without the substrate) presented here is an approximate estimation from the current sample configuration shown in Figure 2a where the CNTs were attached with the substrate. More accurate estimation of mass, which should be made separately after extracting the CNTs from the substrate, may differ from the approximate value. However, the difference is anticipated to not be significant.

Other acoustic absorption materials may exhibit a similar or even higher absorption than that of a CNT forest. For instance, the sound absorption coefficient of a 3.5 mm Refrasil (0.224 g and 166.8 kgm^{-3}) was measured and the result is presented in Figure 10. As shown in the figure, this conventional porous material with a high flow resistivity shows a better absorption coefficient (almost twice as much absorption) compared to that of the CNT forest. Nonetheless, the objective of this entire investigation was not intended to explore the CNT forest as a better acoustic absorber compared to that of conventional porous materials, rather to explore the potential acoustic absorption ability of nano-materials in particular CNT-based acoustic absorbers considering their molecular structures and advantage in mechanical properties. In that sense, it can be said that the current investigation is successful and results showed that the CNTs can be implemented as an acoustic absorber in noise control engineering. Consequently, it should be clarified that the estimated acoustic absorption coefficient of the CNT forest samples available to this study as shown in Figures 5 and 8 is very small and not sufficient to consider the CNT forest beneficial as a sound absorber in its current form. In addition the arrangement of CNTs has not been optimised in any way for acoustic absorption considerations. Advanced manufacturing methods are allowing researchers to create CNTs of in the range of *cm* length scale (27, 28, 30, 31, 32). It is anticipated that a forest of CNTs of greater length (in the *cm* range), lower density and possibly with a variation in the arrangement of the nanotubes can be used to provide enhanced acoustic absorption. Current advancement in nanotechnology shows that centimetre-long CNT forest can be grown more efficiently using water-assisted thermal CVD (chemical vapour deposition) process with a controlled growth time (27, 28). In addition, it was shown that a wide range of forest densities can be synthesised by controlling the catalyst nano particle formation process (33). Long carbon nanotube arrays with low forest density may permit the CNTs to vibrate with sound waves, which will induce additional absorption. Furthermore, patterned CNT array can currently be fabricated with various densities of CNTs, for example, CNT arrays in which the nanotubes are bunched together in 1 mm diameter post-like structures (27) and for which the density of the forest could be optimised to increase the acoustic absorption. Several other arrangements of carbon nanotube are also possible (27, 28), including super-aligned arrays (11). This experimental study conducted on a CNT forest of a limited size indicates that promise. Further experiments are needed to measure the absorption coefficient of a CNT sample of greater length and possibly lower forest density with the aim of observing an increased absorption coefficient sufficient for practical application and denominating a CNT-based acoustic absorber.

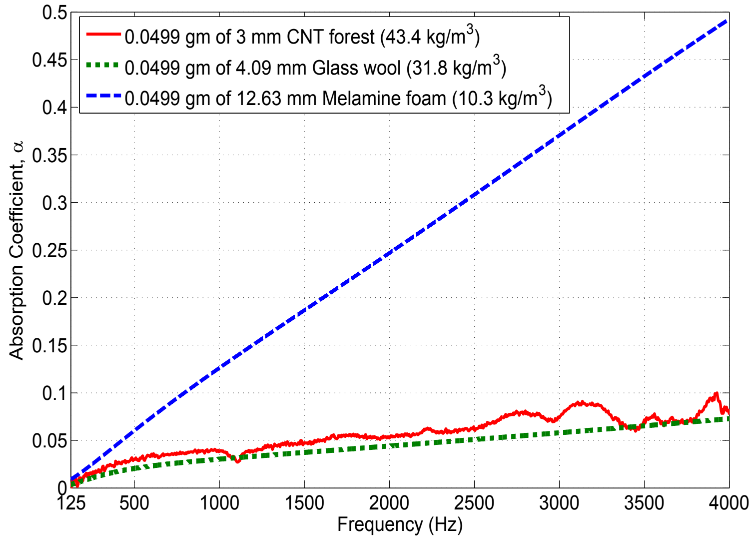
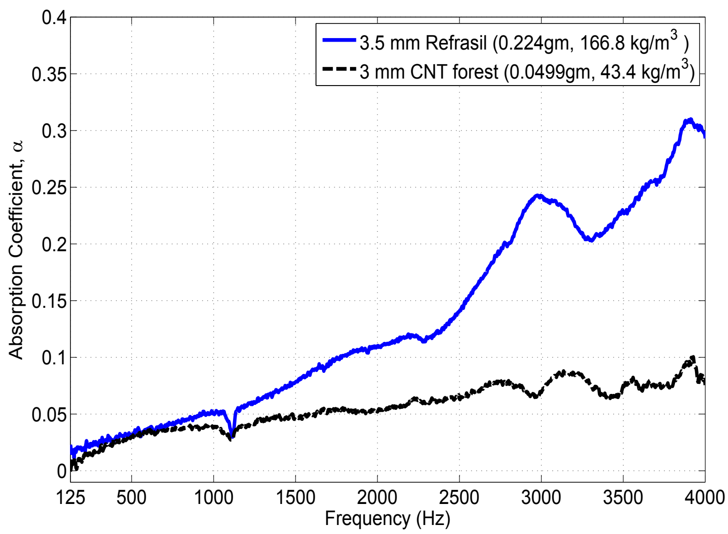


Figure 9 – Comparison of the acoustic absorption coefficient of the CNT forest with two conventional porous materials of equivalent mass: melamine foam and glass wool.

(a) Refrasil sample



(b) Measured absorption coefficients of 3.5 mm Refrasil and the 3 mm CNT forest

Figure 10 – Comparison of the sound absorption coefficient of the CNT forest with a high absorption coefficient specimen Refrasil (3.5 mm), measured in the acoustic lab using impedance tube.

4. CONCLUSIONS

This article presents the results from an experimental investigation of the acoustic absorption coefficient of a carbon nanotube forest using an impedance tube. Results showed that the 3 mm forest of vertically arranged CNTs can provide as much as 5% $\sim$ 10% acoustic absorption and exhibits enhanced acoustic absorption performance as a composite CNT and conventional porous material panel. A comparison of the absorption ability between the CNT forest and conventional porous materials showed that the CNT absorber of lower thickness and mass can achieve the equivalent (or significantly higher) absorption coefficient to a conventional material. However, a similar or lesser absorption ability is observed when compared with a high acoustic absorption specimen (Refrasil). Based on the experimental investigation, it can be concluded that the carbon nanotube (CNT) has favourable acoustic absorption ability which has the potential to replace conventional materials as an acoustic absorber. Finally, it is worth noting that a typical CNT forest available in the nanomaterials lab was used for the investigation without specific optimisation for the acoustic absorption behaviour. Hence, further investigations would be required to choose the types and arrangement of carbon nanotube forest beneficial as a sound absorber.

ACKNOWLEDGEMENTS

This research was supported under Australian Research Council's Discovery Projects funding scheme (project number DP130102832). The authors would like to thank Prof. Vesselin Shanov and Prof. Mark Schulz of Nanoworld Laboratories (University of Cincinnati, USA) for providing the carbon nanotube samples. The authors would also like to acknowledge the financial support for the postgraduate student Md Ayub provided by the University of Adelaide through an International Postgraduate Research Scholarship (IPRS) and an Australian Postgraduate Award (APA). The assistance of Mr Hywel Bennett with the experiments is greatly appreciated.

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