Applied Acoustics 172 (2021) 107604

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Influence of MWCNT fillers on vibroacoustic characteristics of polymer nanocomposite and coated aircraft panels

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ARTICLE INFO

Article history:
Received 14 April 2020
Received in revised form 11 August 2020
Accepted 12 August 2020

Keywords:
Multi-Walled Carbon Nano Tubes (MWCNT)
Vibro-acoustics
Sound transmission loss (STL)
Impedance tube

ABSTRACT

Noise pollution is one of the major concerns around the globe, and it is the driving force behind the development of new sound absorption and insulation materials. In the present work, Multi-Walled Carbon Nano Tubes (MWCNT) is studied for its soundproofing characteristics on the aircraft panels and its effect subsequently on the vibroacoustic performance. The sound transmission loss (STL) property of all the samples was measured using impedance tube instrument. The MWCNT nanoparticles were reinforced in a polymer system with varying weight percentages (0.5%, 0.75%, 1%, 2% and 3%) and its effect on sound transmission loss of nanocomposites was initially evaluated. These coated samples of Aluminium and Fibre Metal Laminate (FML) were then tested to assess the influence of MWCNT on the vibro-acoustic characteristics of the panels. Interesting results are presented in terms of STL on the aircraft fuselage panels, which confirm that MWCNT coating can be considered as a promising passive noise treatment approach without much weight penalty. FML has displayed comparatively a good STL in the frequency band of 63 Hz–500 Hz, compared to aluminium. MWCNT coating thickness and direction of coating appear to play an important role to produce the best STL characters of aircraft panels.

1. Introduction

Noise has become a major environmental issue due to the development of faster, more powerful machineries, which run automobiles, ships, aeroplanes and other industrial appliances. Hence, the environmental bearing of noise is a matter of increasing concern. Legislation on noise regulation has been drafted in the industrialized countries. Significant efforts have been laid to find an effective means of noise abatement in many regions. In recent years, the noise reduction from machineries, automobiles, and appliances has been extensively studied [1–4]. Sound absorption techniques and insulation materials to reduce ambient noise have received much attention in this area of research [5–8]. Application of sound absorption through insulation materials is widely accepted as an efficient method to decrease the noise. The distinguishing nature of materials plays a vital role in noise reduction. While developing the soundproof materials, the main purpose is to search for a material that has high absorption rate, transmission loss and insulation efficiency.

In the contemporary world of nanotechnology, a variety of nanotube ingredients are developed [9], which can be fabricated to nanoscopic fibres; for instance: Carbon Nanotube (CNT), Titania Nanotube (TNA) and Boron Nitride Nanotube (BNT) [10]. Although CNTs are the most extensively studied nanomaterials, other nanotubes also have a similar capability to form nanoscopic fibres and composites [11]. Ever since the invention of the carbon nanotube (CNT) structure by Iijima, several potential applications for CNTs have been proposed in the fields of mechanics, electronics, the energy sector, field emissions and light applications. However, although some uses of CNTs in noise control engineering have been suggested [11], they are not extensively examined as sound absorbers.

Yan et al. [12] investigated the soundproofing properties of nano clay–polypropylene nanocomposites. It was noticed that the sound insulation properties of these nanocomposites had enhanced with an increasing filler content of nano clay up to a certain loading (6.5 wt%). PP/clay (6.5 wt%) sample exhibited the best soundproofing property in comparison with other composites with different clay contents. Ajayan et al., [13] filed a US patent for making and using the carbon nanotube foam. Lee et al., [14] studied the sound insulation effects of carbon nanotube (CNT)-filled Acrylonitrile Butadiene Styrene (ABS) based nanocomposites. It was shown

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https://doi.org/10.1016/j.apacoust.2020.107604
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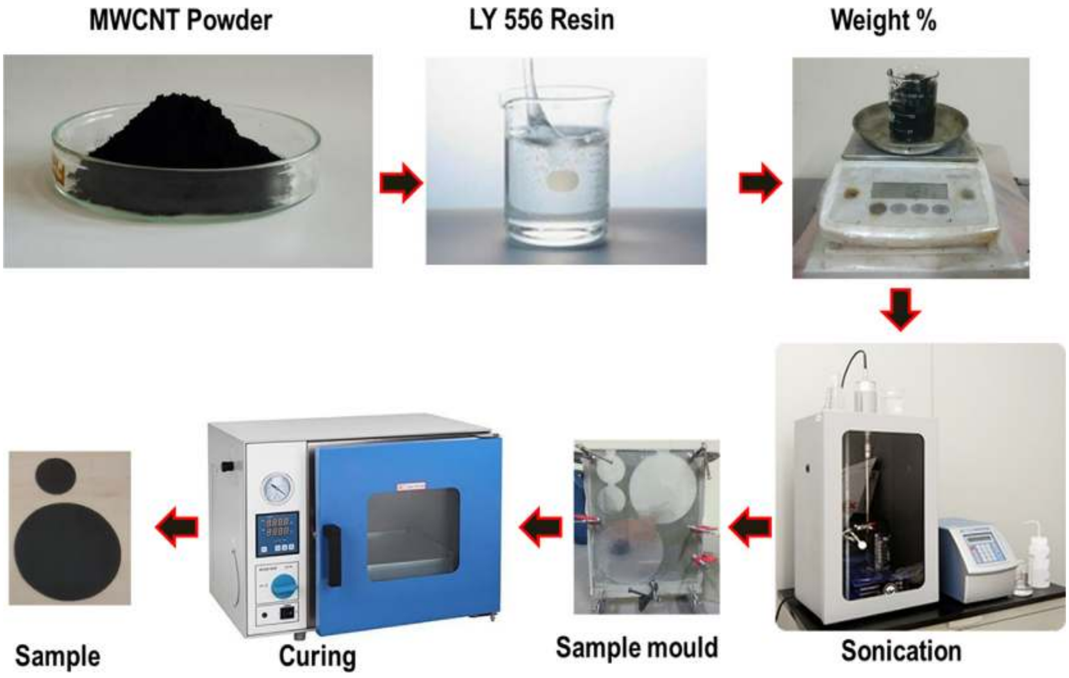


Fig. 1. MWCNT sample preparation Process.

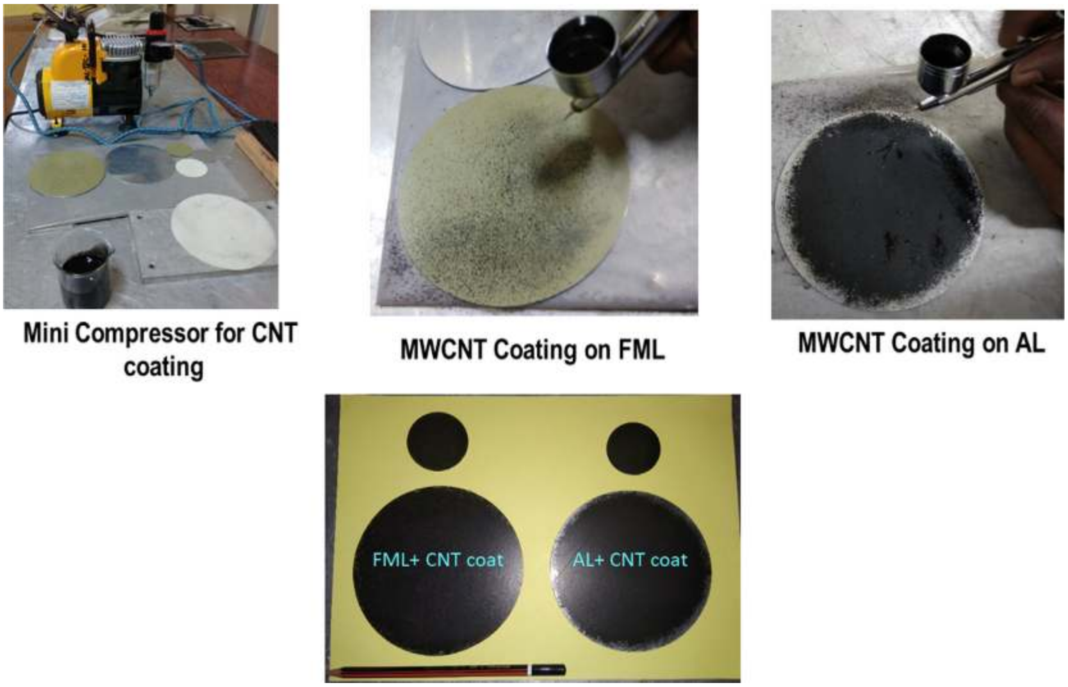


Fig. 2. MWCNT Coated Samples.

that, as the CNT content in ABS composites was increased, the STL values were improved. Md Ayub et al., [15] examined the acoustic absorption behaviour of carbon nanotube (CNT) arrays, in order to quantify the absorption performance and acoustic characteristics of nanoscopic fibres, in comparison with conventional porous materials. Wasim A Orfali [16] demonstrated that the addition of 0.35 wt.% carbon nanotube and silicon oxide nanopowder (S-type, P-Type) to the host material improved the sound transmissions loss (Sound Absorption) up to 80 dB, compared to pure polyurethane foam sample. Bihola et al., [17] emphasised the potential use of nanomaterial in the acoustic application, taking into consideration of the results, available from the various research works, carried out in recent times. Jun and Myung-Sub [18] evaluated the soundproof insulation of polypropylene (PP)/clay and PP/CNT composites by measuring the STL through impedance tube. Naoki and Takayasu [19] investigated the effect of frame resonance, resulting from oversized glass fiber and felt samples by impedance tube measurements.

Damping property of a material is one of the key parameters that is mostly explored and exploited by the designers for develop-

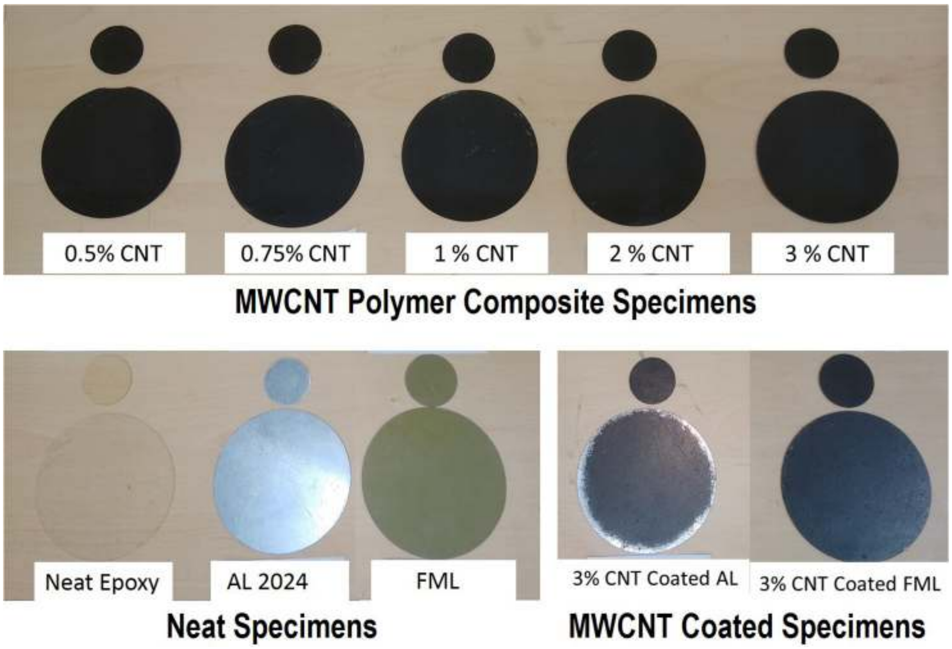


Fig. 3. Samples Prepared for Test.

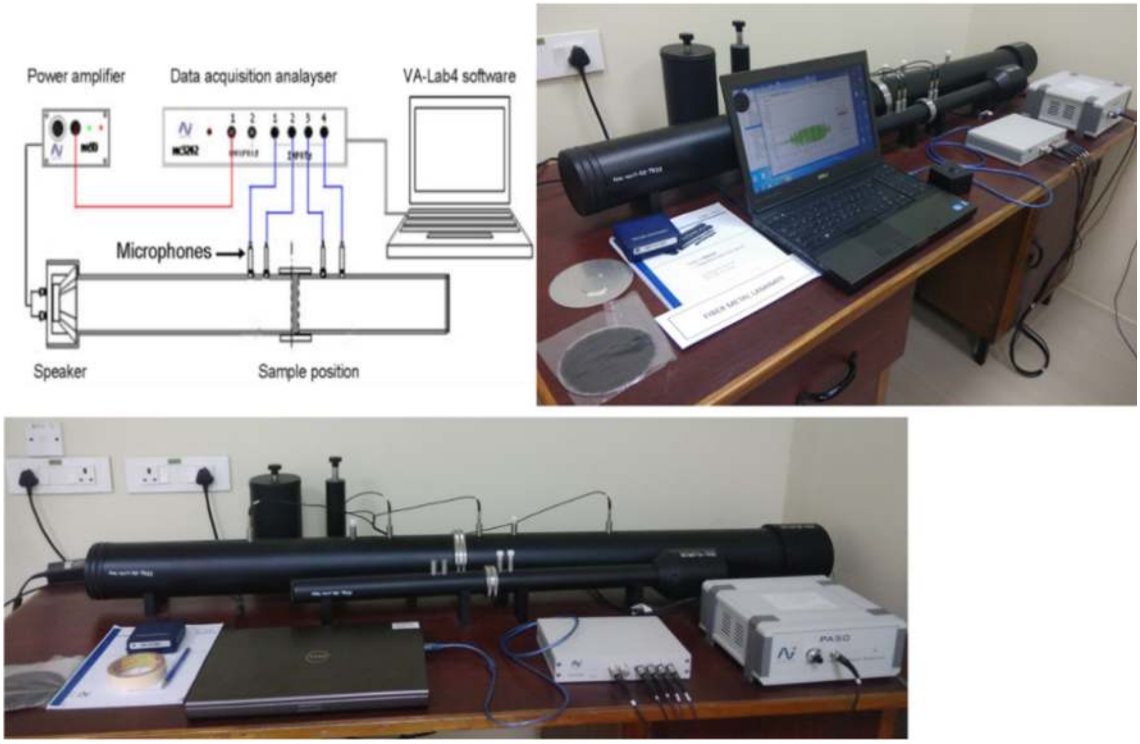


Fig. 4. Schematic diagram and experimental setup of the Impedance tube.

ing passive noise reduction solutions apart from stiffness and mass of the material. In recent years, various studies [20–23] had proved that nanomaterial reinforced polymers could be used for structural damping applications. A novel method of incorporating the nanoparticles in multiscale GFRP composites using the combined techniques of spraying and nanoparticle-resin mixture was adopted by Rafee et al., [24]. In their studies, they had examined experimentally the use of graphene for vibration damping of multiscale composites. It was found that the increase in the CNT wt.% decreased the natural frequency but increased the damping ratio because of their increased ductility. Wang et al., [25] studied the damping properties of multicore based solvent-free nanofluid (GCNF)/epoxy nanocomposites. The excellent dispersion stability of GCNF had enhanced the damping property of epoxy resin, incorporated with nanofillers.

Simoes et al., [26] studied the dispersion technique of carbon nanotubes (CNT) and its influence on the production of aluminum matrix nanocomposites. A 200% increase in the tensile strength was observed that proved the strengthening effect of the CNT. Liew et al., [27] experimentally studied the damping properties of cementitious CNT reinforced composite structure and showed the flexure, and compressive strengths of CNT/cement got improved by 16.3% and 17.3%, respectively. The effects of graphene nanoplatelets (GNPs) on vibration and damping behaviour of two-phase epoxy composites (pristine and functionalized) was characterized and experimentally investigated by Rafee et al., [28]. The study confirmed from the vibration experiments that the increase in the damping ratio (26%) was attributed to the beneficial effect of graphene nanoplatelet inclusions (0.4 wt.%). Mahmoodi and Vakilifard [29] deliberated the elastic and viscoelastic damping behaviors of MWCNT reinforced polymer nanocomposite, with CNT percolation. It was noticed that the effective properties

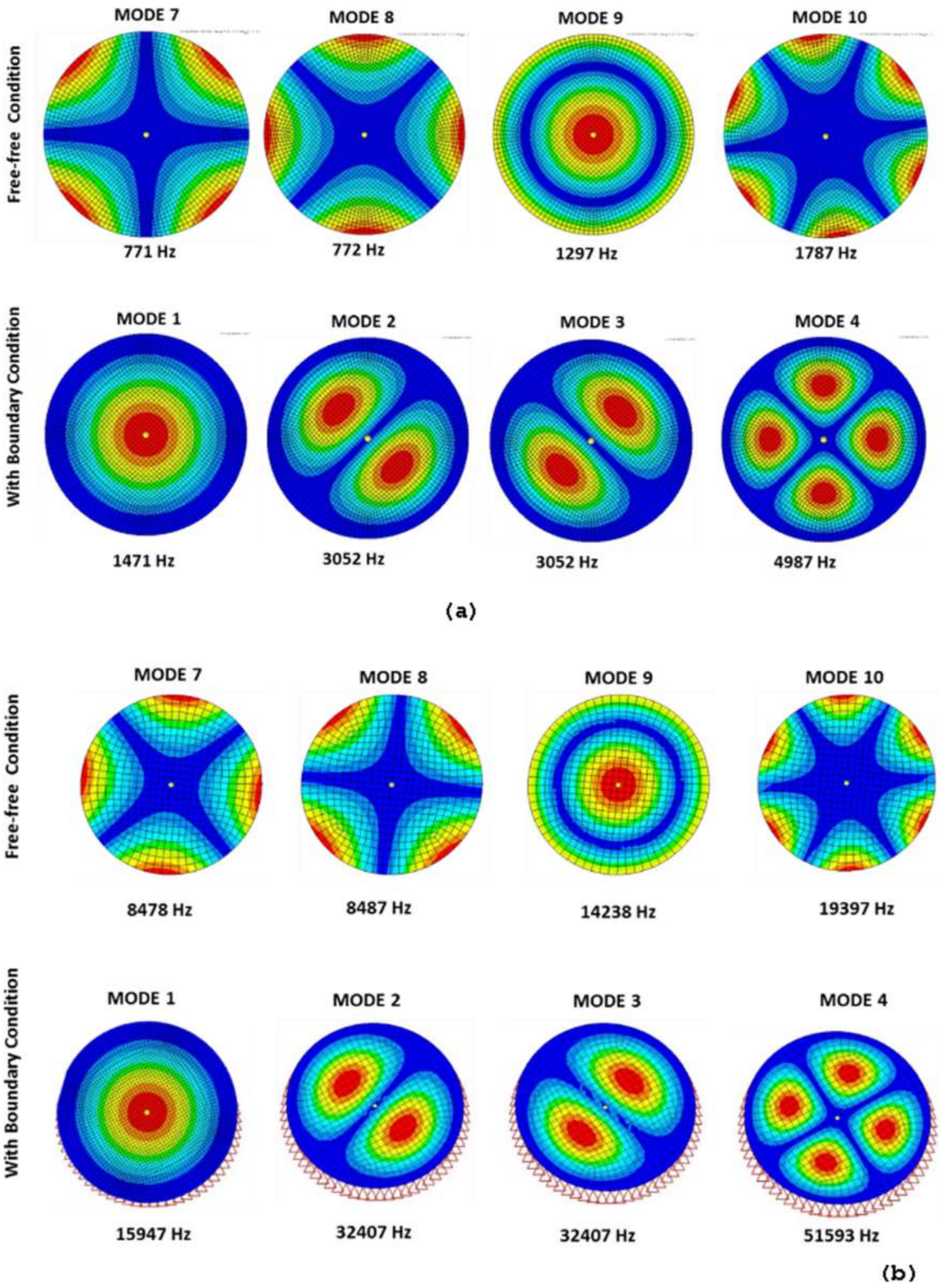
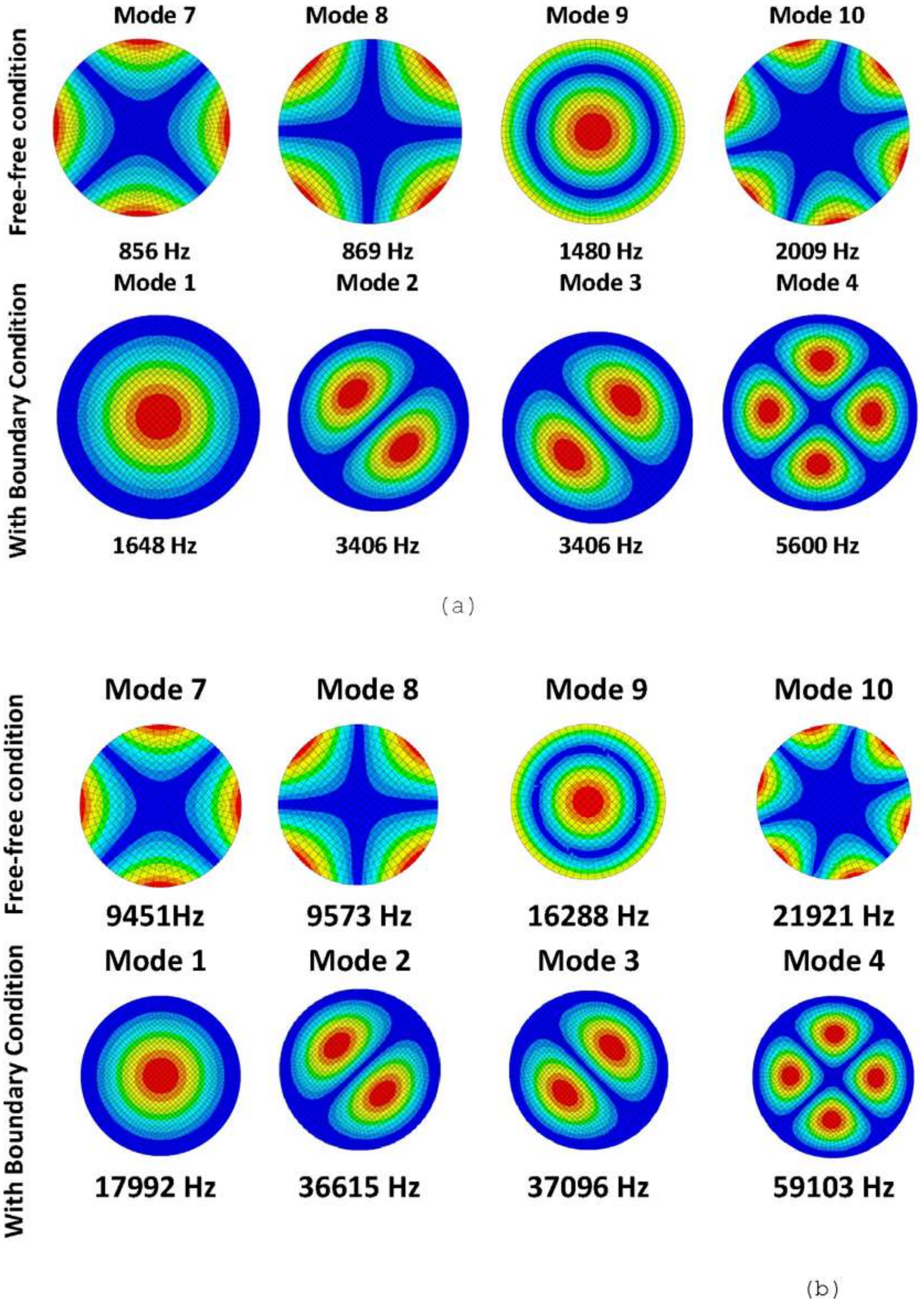


Fig. 5. Vibration modes and frequencies of AL 2024 sample with and without boundary conditions (a) 100 mm (b) 30 mm.

of nanocomposite had improved up to a threshold value of CNT volume fraction.

Rokni et al., [30] introduced a novel concept of distributing the MWCNTs through-thickness to optimize the dynamic behaviour of laminated nanocomposites. It was found that the presence of MWCNTs improved the damping ratio around 27.8% to 38.9%. Mahmoodi et al., [31] reported a micromechanical model for extracting the damping properties of polymer matrix nanocomposites, reinforced with vapor grown carbon fiber. The results confirmed that the effective damping properties of nanocomposites were enhanced due to higher bonding strength, augmented storage and loss modulus. Rafiee et al., [32] examined the epoxy composites, reinforced with pristine and functionalized MWCNTs for structural applications. The damping ratio of nanocomposites was improved by the addition of p-MWCNTs.

The researches so far, have focused on the development of different variants of CNTs as arrays, nanoclays, CNT forest and either applied them for acoustic applications, mostly as acoustic absor-



(a)

(b)

Fig. 6. Vibration modes and frequencies of FML sample with and without boundary conditions (a) 100 mm (b) 30 mm.

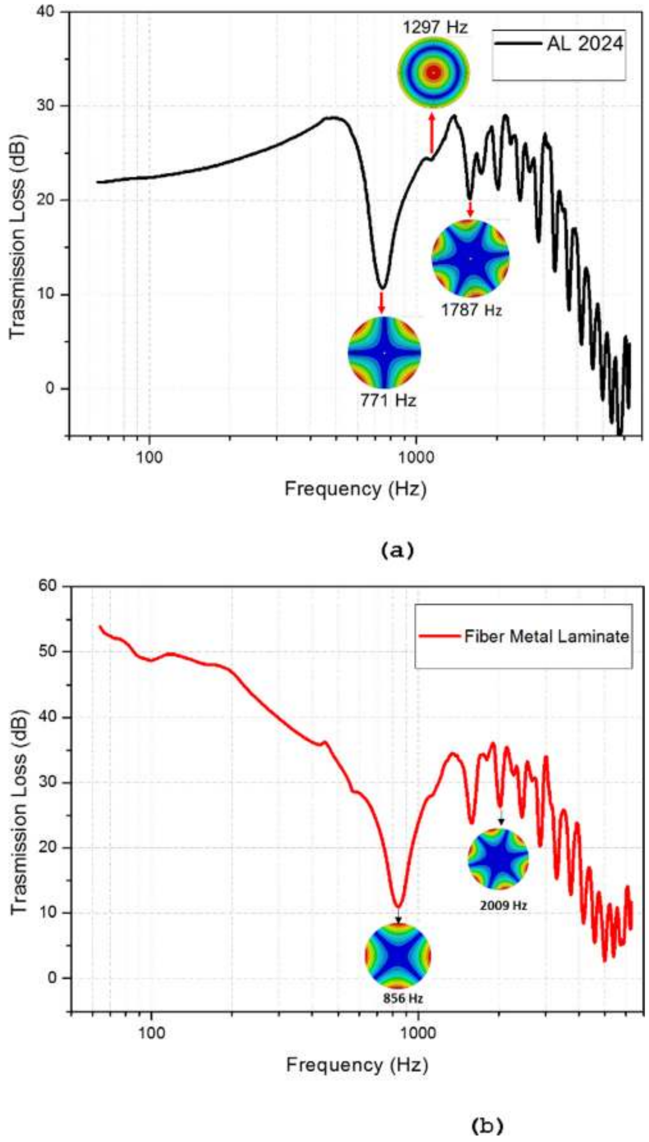


Fig. 7. Vibration modes and frequencies for Free-Free edge condition samples of (a) AL 2024 (b) FML.

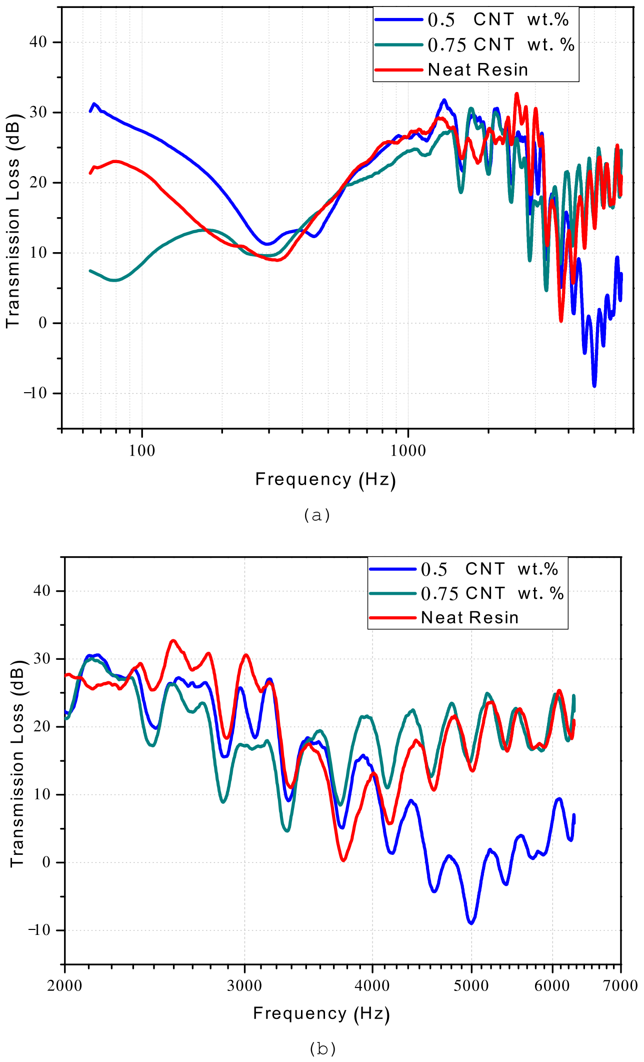


Fig. 8. STL curves comparison of neat resin with 0.5 and 0.75 MWCNT wt.% loadings.

bers or to improve the vibration damping. However, to the best of author's knowledge, the MWCNT has not been studied as a coating material on aircraft structures for noise transmission characterization and noise reduction applications. Nevertheless, the use of these nano-materials as the basic structure, directly for aircraft noise solution has been very challenging with the limitation of available manufacturing techniques. Therefore, to overcome this problem, one can exploit the good properties of CNTs and introduce these very tiny materials as a coating on the conventional aircraft panels.

In the present study, MWCNT fillers were first dispersed into aircraft-grade polymer system, to optimize its wt.% for better VA performance. Subsequently, coupons were made and tested in the impedance tube. Then, the resin reinforced with optimal wt.% fillers was applied as a coating on the considered aircraft panels, namely Aluminium and Fiber Metal Laminates. The influence of MWCNT nano-coating on VA characteristics of panels was evaluated and the results are presented in this article.

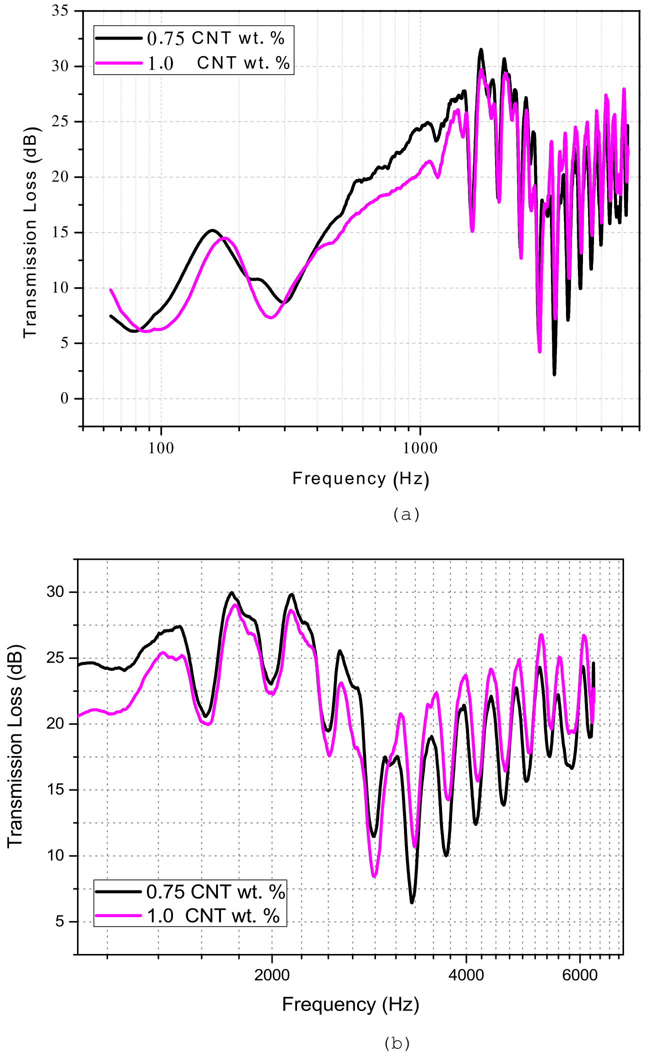
This paper is organized as follows. In Section 2, the description of the impedance tube apparatus and the process of sample preparation are explained. Section 3 explains the edge effect of the samples with simulation results. In Section 4, experimental results of various cases are shown. Finally, in Section 5, some important conclusions are presented.

2. Materials and methods

2.1. Preparation of samples

The MWCNTs (Acid functionalized) with the best mechanical properties were used for preparing the samples. The MWCNTs was obtained from NANOSHELL, India. Each sample was made with different wt.% of CNT filler content in order to study its effects on VA performance. The weight percentages considered were 0.5%, 0.75%, 1%, 2% and 3%, respectively. Aircraft-grade epoxy (LY 556) resin was used, which has the properties like Anhydride-cured, low-viscosity, and long pot life. The reactivity of the polymer system was regulated by varying the accelerator content. This epoxy system meets the MIL specifications R 9300, and therefore, it is suitable for aircraft structural applications.

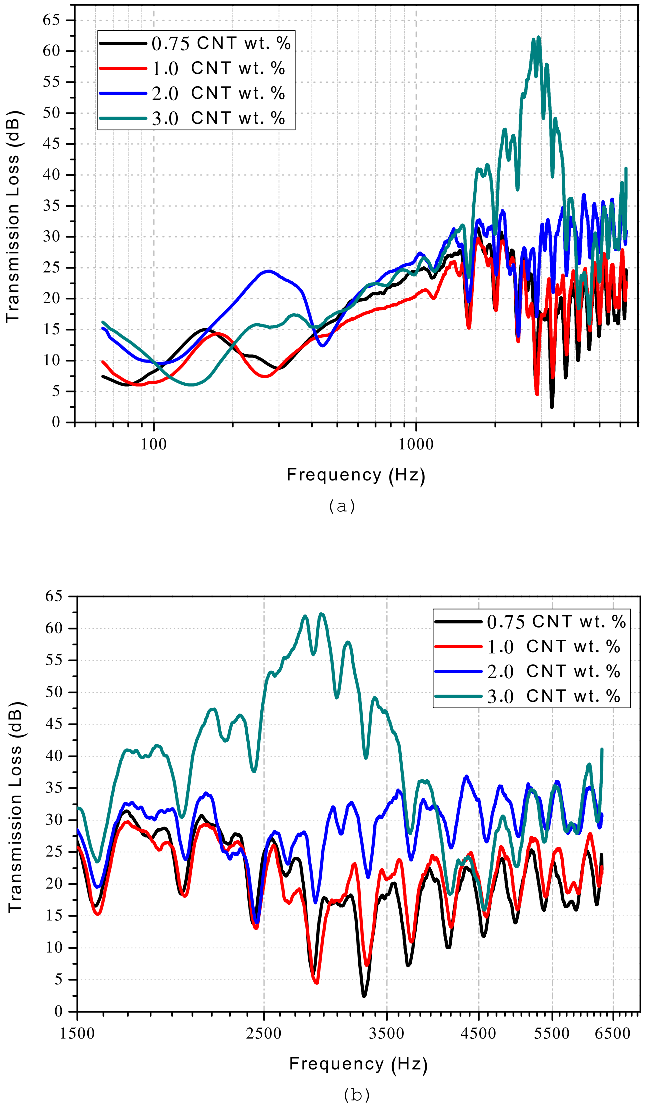
After measuring the weight percentage of the CNT filler content, it was then mixed with the resin. The mixture was placed in the Sonicator, which evenly blended the mixture. The sonication time was maintained as 3 h; however, the effective sonication was done



(a)

(b)

Fig. 9. TL curves 0.5, 0.75 CNT wt.%



(a)

(b)

Fig. 10. STL curves 0.5, 0.75, 1, 2 and 3 CNT wt.% (a) overall (b) High Frequencies.

for 1 h, since the sonicator has an ON time of 20 s and OFF time of 40 s in 1 min. The blended compound was then allowed to cool for a few hours. Before pouring the compound into the mould, the hardener (HY951) was added with a resin to hardener ratio of 100:12, and the mixture was kept aside subsequently for 24 h curing at room temperature. The specimen with the mould was placed in the thermal oven for polymerisation and post curing. The post-curing was done, following temperature and time steps; 50 °C for 30 min; then 70 °C for 1 h; yet again 85 °C for 2 h. Afterwards, the samples were prepared for the required sizes based on the impedance tube measurements. The process involved in preparing the sample is shown in Fig. 1. The low frequency and high-frequency samples were accordingly made with a diameter of 100 mm and 30 mm, respectively (refer to Fig. 3). These samples were used in the impedance tube to evaluate the transmission loss using the four-microphone method (Fig. 2).

2.2. Impedance tube apparatus

Impedance tube is commonly used to measure the sound absorption coefficient (SAC), specific impedance, sound transmission loss (STL) and acoustic properties (characteristic impedances, effective densities propagation wave numbers, bulk moduli) of acoustic materials in normal incidence conditions. Researchers in the field of innovative materials development widely use impedance tube to acoustically evaluate their merits.

The STL property of all the samples is measured by impedance tube from BSWA®, which uses four microphones in accordance with the ASTM standard E2611. The impedance tube works on the principle of transfer function method, employing four microphones, two on the sender tube and the other two on the receiver tube, respectively. A schematic and photograph of the experimental apparatus are shown in Fig. 4.

The instrumentation has a ¼-inch MPA416 microphones, which have excellent phase matches and are ideal for impedance applications. The microphones are directly connected to a 4-channel MC3242 data acquisition hardware using BNC-to-SMB cables. The BSWA VA-Lab software with impedance module is used, which helps to collect the data in all the three frequency ranges (63 Hz–500 Hz, 250 Hz–1600 Hz and 1000 Hz–6300 Hz, respectively) and combines the three transmission curves to generate a full curve for the entire frequency band. The microphones have got a free-field frequency response (20 Hz–20 kHz). A pistonphone calibrator is used to calibrate the microphone sensitivity to 114 dB at 1 kHz.

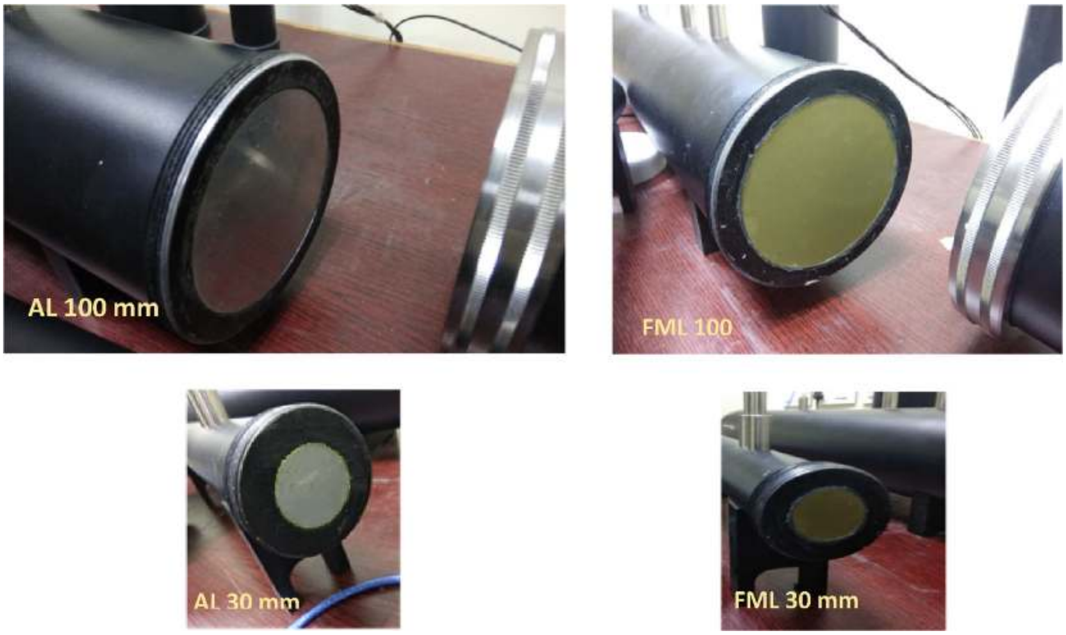
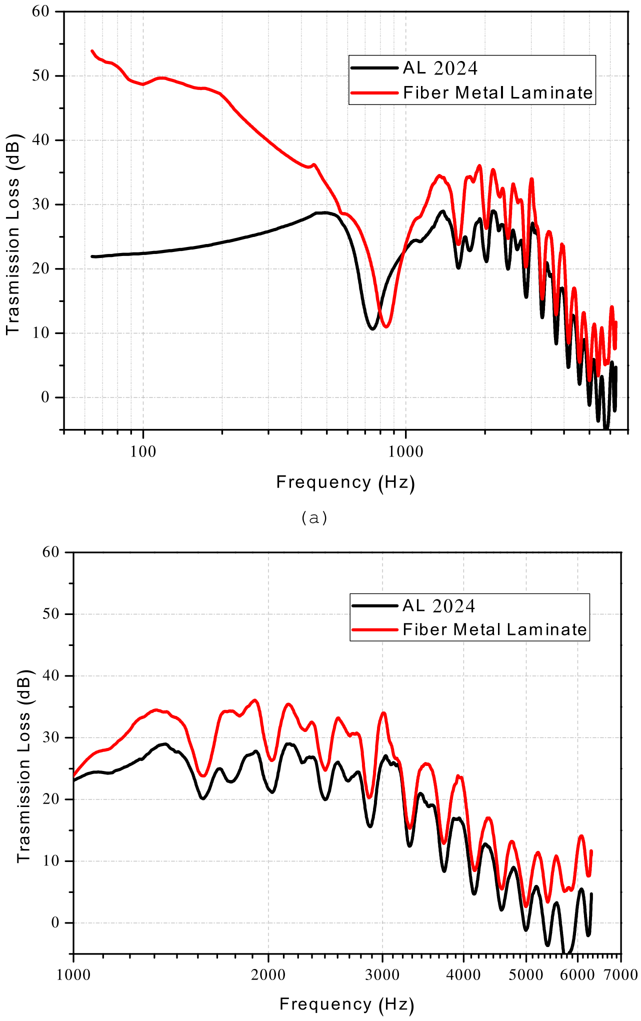


Fig. 11. AL and FML samples in impedance tube.



(a)

(b)

Fig. 12. STL curves FML and AL2024.

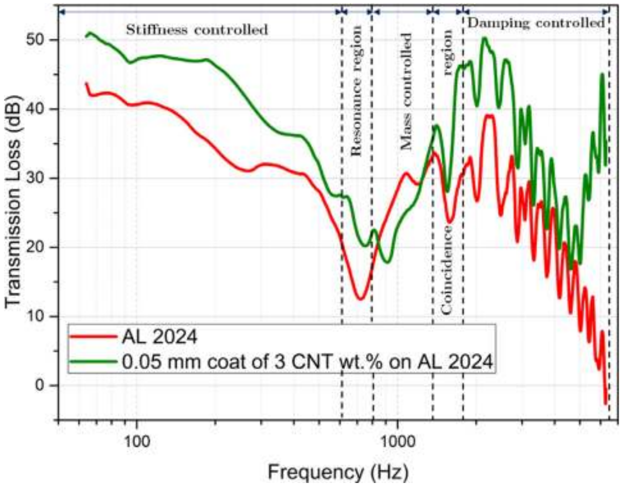
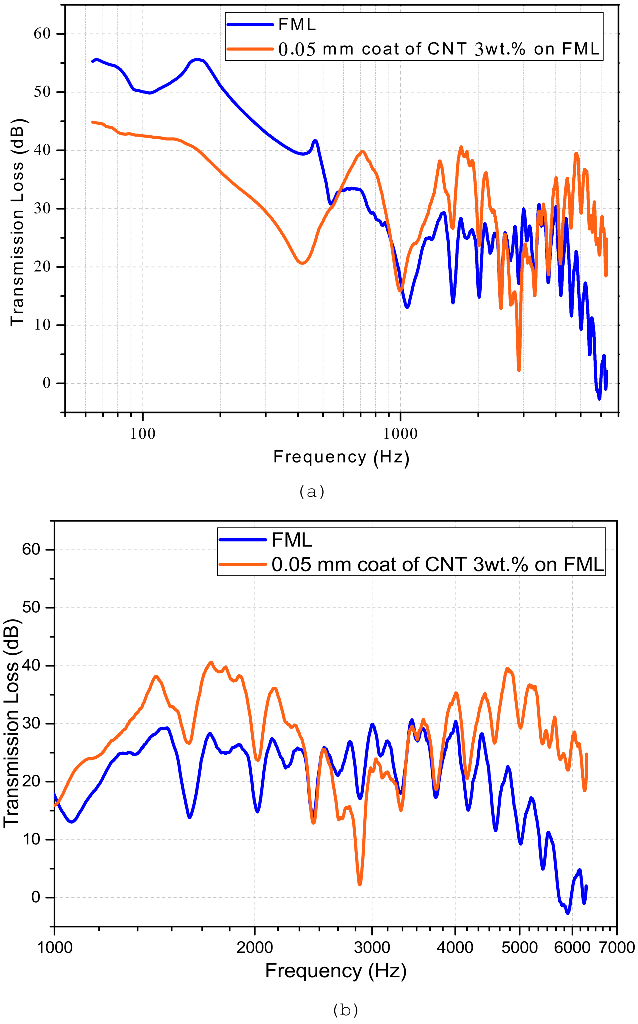


Fig. 13. TL curves for 3 wt.% CNT coating on AL and without Coating.

3. Vibration and edge effects of impedance tube samples

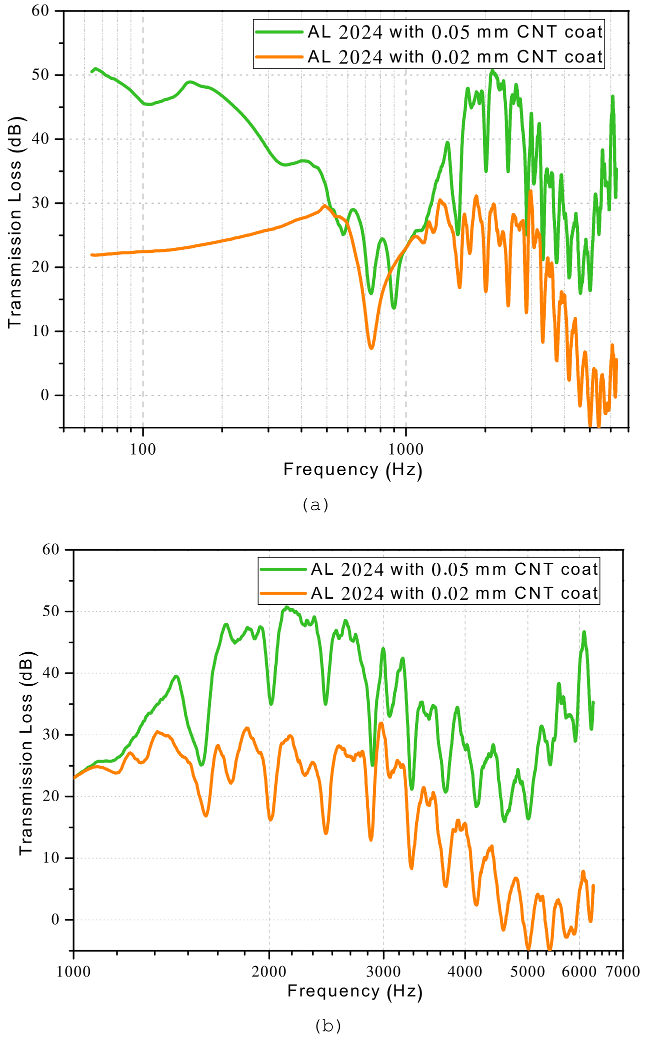
The impedance tube test mandates to check whether the samples placed in the impedance tube are in free-free condition without any edge effects; so that the samples are not constrained radially, which in turn affects the results. To confirm the edge conditions of the samples and to understand the structural vibration characteristics of the 100 mm and 30 mm samples, finite element models of the samples were made in Hypermesh® (pre-processor) and solved in MSC NASTRAN. In the analysis, structural vibration modes were evaluated for the samples with (circumferentially fixed) and without (free-free) boundary conditions. The modal contours and frequencies of the 100 mm and 30 mm samples of AL2024 and FML are presented in Fig. 5 (a) & (b) and Fig. 6 (a) & (b), respectively. For the free-free boundary condition, only the elastic modes are presented. The frequency of the 100 mm samples is higher, i.e., more than 1000 Hz, therefore the effect of vibration and boundary condition of the plates has minimal impact on STL in low frequency. In the case of 30 mm samples, the frequencies are



(a)

(b)

Fig. 14. TL curves for 3 wt.% CNT coat on FML and without Coat.



(a)

(b)

Fig. 15. TL curves AL with 0.02 mm and 0.05 mm MWCNT coat.

found to be above 8000 Hz for free- free condition, and for the sample with boundary condition, it is above 15,000 Hz. It is to be noted that the impedance tube measurement range is only up to 6300 Hz for the high-frequency samples. Therefore, the vibration and edge effects on the STL for high-frequency samples seem to be negligible. The STL plots of the tested samples with the frequencies in Fig. 7 (a) &(b) confirm that the tested samples were placed in a free-free condition.

4. Results and discussions

4.1. Effect of lower MWCNT weight percentage on STL

The Epoxy LY 556 without any inclusions is termed as neat resin. The polymer composite samples with 0.5 and 0.75 wt.% filler contents are compared with neat resin in Fig. 8 (a). At the low and mid-frequency segments, the STL of neat resin is observed to be in between 0.5, and 0.75 CNT wt.% loaded specimens. However, in high frequencies (refer to Fig. 8 (b)), the variation in STL curves of neat resin and 0.75 CNT wt.% is found to be very minimal. It is clearly showing that the lower CNT loadings have less significance in mid and high frequencies.

When comparing the STL curves of 0.75 and 1.0 CNT wt.% (refer to Fig. 9 (a)), it is noticed that a marginal increase in the CNT wt.% has not influenced the STL up to 3000 Hz. However, at higher frequencies, i.e., after 3000 Hz (see Fig. 9b), there is an increase of 5–8 dB in the STL. The minimum wt.% increase from 0.75 to 1 wt.% has created a lower interface bonding.

The STL curves for 0.75, 1.0, 2.0 and 3.0 wt.% are presented in Fig. 10 (a); increase in the CNT wt.% has shown a significant effect on the STL property at higher frequencies, particularly in the frequency band of 1500 Hz–3500 Hz (refer to Fig. 10 (b)). The higher weight percentage of MWCNT has increased the interface bonding [28], thereby helping the STL to perform well in the damping dominant region of the STL plots.

4.2. Transmission loss comparison of AL and FML

Having examined the influence of filler wt.% loadings on STL of polymer nanocomposites, the optimum 3 wt.% was chosen for further study as a coating on the aircraft grade panels (samples). Accordingly, the impedance tube samples were made from aircraft-grade Aluminium 2024 and Fiber metal laminate.

These samples were then tested for the transmission loss characteristics in low to high-frequency band. Fig. 11 shows the samples of AL and FML in the 100 mm and 30 mm section of the impedance tube.

The generated STL curves of AL and FML samples are presented in Fig. 12 (a). It can be noticed that FML, made of aluminium and glass–epoxy layers, has shown good STL properties in low, mid, and high-frequency bands, compared to AL 2024 of the same thickness. The FML has shown more STL advantage over isotropic AL

2024 due to its alternate stacking sequence of AL and S2 glass layers.

4.3. Effect of MWCNT coating on transmission loss

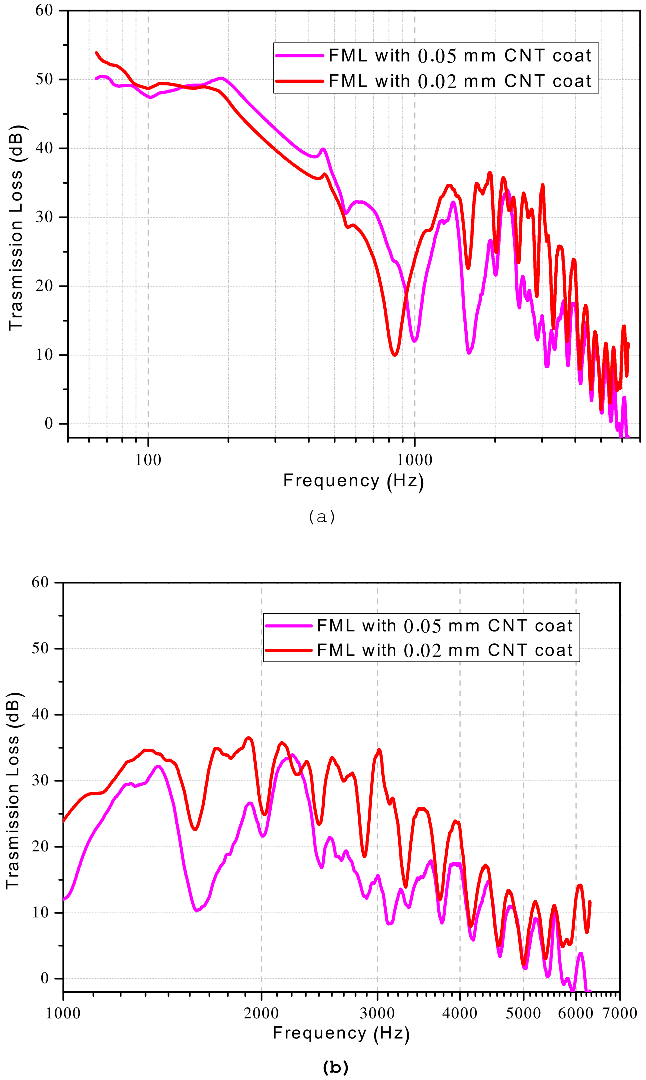
To evaluate the effectiveness of MWCNT coating on AL and FML panels, samples were prepared with and without the nano-coating. Using the spray technique, a coating thickness of 0.05 mm with 3 wt.% MWCNT loading was achieved and accordingly, 100 mm and 30 mm diameter samples were made. Fig. 13 clearly shows that there is an enhancement in the STL, in the case of AL with nano-coating. The dominant parameters that control the frequency regions in STL graph are shown in Fig. 13. It is also evident that the MWCNT coating, according to [24,28] alters the frequency and also has beneficial effects of improved STL in higher frequencies due to its damping property. In contrast, in Fig. 14 (a) & (b), MWCNT coating on FML has shown improved STL characteristics only in higher frequencies; this is due to orthotropic nature of FML, which alters the sound transmission through its layers at different frequencies.

4.4. Effect of MWCNT coating thickness on transmission loss

The MWCNT coating thickness over the AL and FML samples was varied to study the effectiveness of coating thickness on the STL characteristics. The coating thickness of 0.02 mm and 0.05 mm were achieved on the samples and subsequently tested in the impedance tube. From Fig. 15 (a) & (b), it is evident that an increase in the thickness of the coating has enhanced the STL behaviour of AL samples in Low and high-frequency bands. When the coating thickness is increased, the physical bonding between the coating and the substrate material also got improved, thereby indirectly improving its interface bonding. The physical bonding has improved the STL of AL in both low and high frequencies. In contrast, an increase in the coating thickness has shown minimal benefit for FML samples, in low & mid-frequency regions (refer to Fig. 16 (a) & (b)). Since the bought out FML sheet had the treated AL layer surface, the applied MWCNT coating could not produce an effective physical bonding between the substrate and thin nano-layer, which has influenced the effectiveness of coating in the low and mid-frequency regions.

4.5. Effect of MWCNT coating direction on transmission loss in FML

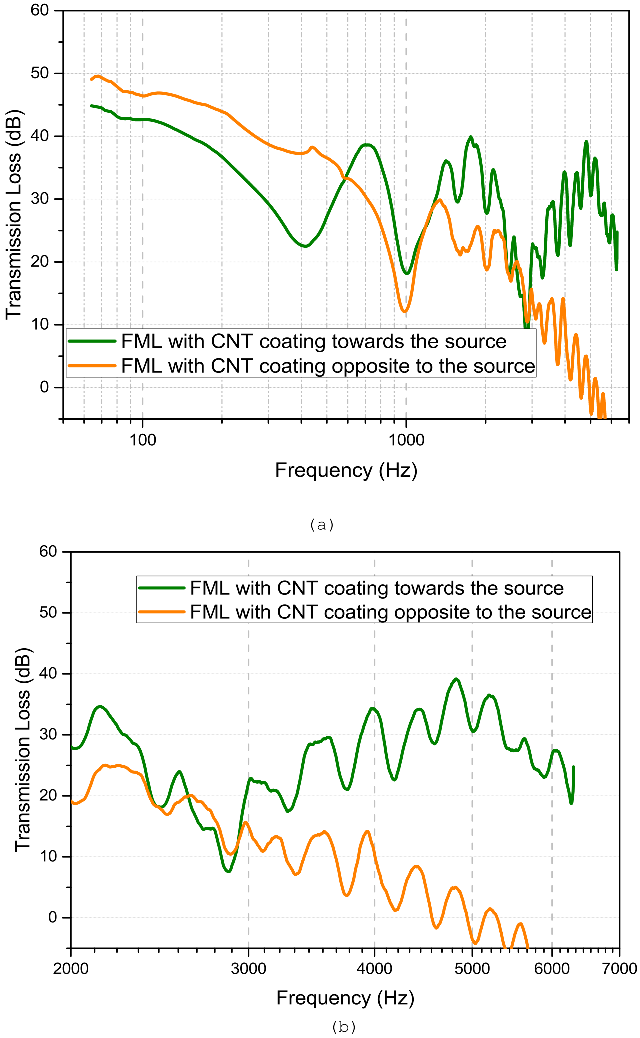
The direction/ side on which the coating applied was considered as an important design parameter to be evaluated. This indeed would help in choosing the correct side of the fuselage panel, in which coating may be applied in order to achieve optimum STL. In this study, first, the coated sample was placed towards the noise source in the impedance tube, and later, the same sample was kept



(a)

(b)

Fig. 16. TL curves FML with 0.02 mm and 0.05 mm CNT coat.



(a)

(b)

Fig. 17. TL curves FML with MWCNT coating in different noise source direction.

Table 1
Comparison of weight with other coatings as per 100 mm diameter sample.

Product Name	Class	Material	Density (Kg/m^3)	Coating Thickness (mm)	weight increase %
Coat of Silence (Spray-On Sound Reducing Coating) [34]	Acrylic emulsion	Butadiene styrene copolymer		0.9 mm	24.8
		Base Coat	1134.756		
		Finish Coat	1182.687		
ACOUSTICRYL (Sound Damping Coatings) [35]	Acrylic copolymer emulsion	ACOUSTICRYL™ SD-380	1066.46	6 mm	268.9
		Titan 200 Calcium Carbonate	2700		
Constraint Layer Dampers [36]	Layered dampers	Constrained layer	2800	0.2 mm	9.6
		Viscoelastic	1200		
Present MWCNT coating	Epoxy Reinforced Nanocomposites	MWCNT	1000	0.02	0.5
		Resin LY556	1150	0.05	1.3
		Hardener HY951	981		

Table 2
Material Properties.

Property	Air	AL	S2 Glass	MWCNT
Refractive Index	1.000277	1.7	1.521 [38]	2.47 [37]
Acoustic Impedance (Ns/m^3)	420.175	1.71e + 7	2.02e + 7	3.12e + 7

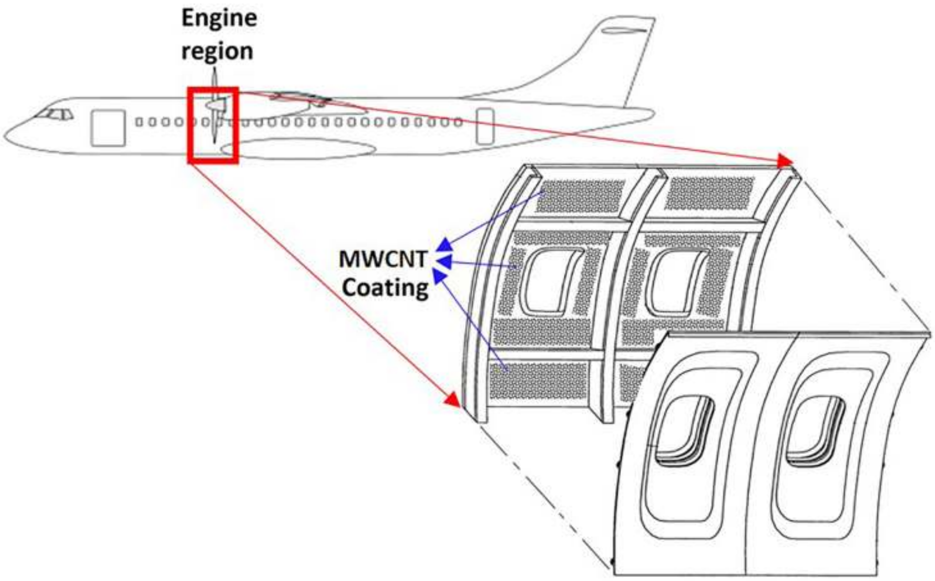


Fig. 18. Typical application of MWCNT coatings in aircrafts panels.

opposite to the source. From the case study, the coating towards the direction of source was found beneficial in mid and high frequencies than, when the coating was done the opposite to the source (refer to Fig. 17). The MWCNT coating has filtered the low-frequency sound transmission, when applied opposite to the source; thus, improving the STL in low frequency region (i.e. stiffness-controlled). However, in case of coating towards the source, the sound in the mid and high-frequency is attenuated before transmission because of the altered coincidence frequency, as well as due to damping effect of MWCNT.

5. Envisaged application of MWCNT coatings in aircraft

The Federal Aviation Administration (FAA) accounts the weight, added to the aircraft in the form of the painting [33]. The weight added to the aircraft requires extra fuel to be burned, which will increase the operating cost. Therefore, its mandatory in aircraft industries to have noise solutions with a minimal weight increase. The 100 mm diameter AL sample(s) with MWCNT coating were taken as the reference surface (See Table 1) and compared with the commercial coatings available for noise reduction.

The percentage weight increase was estimated using the properties of available coating materials and reference surface area of the sample. It can be noticed that MWCNT coating certainly show very promising feature for noise reduction with a minimal weight increase. The acoustic impedance of each material was calculated based on their density and the acoustic velocity, as this property is essential to determine the transmission at the boundary of two materials with different impedance values. The refractive index [37] and the acoustic impedance of MWCNT are higher when compared to Aluminium, and S2 glass (used in FML), refer to Table 2. Besides other properties, these properties of MWCNT makes it a better coating material for fuselage panels for noise abatement.

In general, the transmitted noise to the fuselage cabin panels is high at the engine plane region (propeller plane). Indeed, the panels in this region are more susceptible to noise transmission. As shown in Fig. 18, if the panels near to the engine region are coated with MWCNT, which will improve the sound transmission loss and thereby reducing the noise transmitted into the cabin in a high noise segment of the fuselage.

6. Conclusions

A systematic investigation is carried out to evaluate the influence of nano-coating on the vibro-acoustics of aircraft panels. For this, MWCNTs were used as nanofillers, and impedance tube-based STL measurements were performed. The STL performances in low, mid and high-frequency segments were examined. The following major observations are made.

(1) Low wt.% filler loading, namely 0.5% and 0.75% have shown moderate improvement in STL performance than (1–3%).
(2) However, higher wt.% of MWCNT has demonstrated a dominating effect in higher frequencies, because higher wt.% reduces the pore size in the interface bonding.
(3) FML has displayed comparatively a good STL in the frequency band of 63 Hz–500 Hz, with respect to aluminium.
(4) Nanofiller coating thickness appears to play a vital role in influencing its effect on STL characters of aircraft panels; so, it needs to be optimized as a design parameter, for a target value of STL.
(5) Nanofiller coating has improved STL performance of FML in the frequency band of 500 Hz–6300 Hz.
(6) Coating towards the noise source improves the STL of aircraft fuselage panels in higher frequencies.
(7) Dispersion of CNTs in the polymeric system enhances stiffness and damping while experiencing vibration. Up to 500 Hz, a different trend in the Sound transmission is seen than high-frequency band till 6500 Hz. Multifunctional properties of CNTs make such changes, which are visible from the experimental results.
(8) The current experimental studies conducted have shown the overall effectiveness of MWCNTs usage in aircraft panel for the reduction of noise in the fuselage structure, as shown in Fig. 18. Indeed, the results have suggested that the use of MWCNT coating in aircraft is advantageous as a passive noise reduction strategy with very minimal weight increase, compared to other coating materials.

CRediT authorship contribution statement

B. Balakrishnan: Methodology, Investigation, Formal analysis, Writing - original draft. **S. Raja:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Amirtham Rajagopal:** Writing - review & editing, Data curation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research work is funded by Council of Scientific and Industrial Reserach (CSIR), India, under 12th five year plan project titled "Advanced Structural Technologies for Aircraft (ASTA)" with project no. ESC-02-12-02. The authorswould like to acknowledge Dr. G Jerald Maria Antony of Structural Technological Division (STTD), CSIR-National Aerospace Laboratories, for helping in preparing the samples for Impedance Tube Testing. Experimental support received from Dr. N. Chandra, STTD, CSIR-NAL is greatly appreciated.

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