

Article

Low-Frequency Noise Reduction by Earmuffs with Coir and Coir/Carbon Fibre-Reinforced Polypropylene Ear Cups

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Abstract: Natural fibres have been extensively studied due to their potential in a wide range of applications. This study aims to demonstrate the viability of composite earmuffs for low-frequency noise reduction in continuous and transient noise environments. Pink noise and aircraft take-off exterior noise were considered for the former and the latter, respectively. The assembly components of the composite earmuffs were kept identical to a commercial earmuff, which served as a reference for results comparison. Based on the profile of the ear cups from the commercial earmuff, composite ear cups were fabricated from coir fibre and coir/carbon fibre fabrics reinforced with polypropylene. In contrast to the commercial earmuff, the composite earmuffs showed improvements in insertion loss at specific frequencies in the respective noise environments. In pink noise, up to 12 dB improvement in insertion loss was achieved. In aircraft take-off exterior noise, up to 8.6 dB improvement in insertion loss was achieved at 160–544 Hz particularly by the coir fibre-reinforced polypropylene earmuff. Consequently, the proposed earmuffs may find applications in areas where noise exposure is predominantly low-frequency—in some vehicle cabins, at airports, and at construction sites, for example.

Keywords: low-frequency noise; noise reduction; hearing protection; earmuffs; natural fibre; occupational noise

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1. Introduction

In recent years, the study of natural fibres has been increasing rapidly due to their potential in a wide range of applications. Natural fibres are advantageous in several aspects. Some of the key advantages include affordability, availability, biodegradable, environmentally friendly, lightweight, and good mechanical properties [1–8]. Unsurprisingly, there are also disadvantages of natural fibres concerning issues such as durability and fire resistivity. However, researchers are already exploring means to improve these drawbacks as highlighted by a recent review paper [3]. As the community is becoming more aware of the importance of environmental impact, natural fibres may be a potential

alternative to synthetic fibres in certain applications. One of these applications include low-frequency noise reduction.

Consider a typical airport, noise generated within the environment is dominantly contributed by aircraft engines. Generally, the noise generated by the engines is of a low-frequency (<500 Hz) and transient nature due to the variation in the rotating speed of the compressor blades and fan blades during the take-off or landing of the aircraft. This noise can be excessively loud to the extent of adversely affecting the auditory system of the ground crew. Excessive exposure to aircraft noise has also been reported to contribute partly to psychological and physiological health issues [9]. Some of these health issues are critical such as cardiovascular disease and hypertension. Additionally, the ground crew may experience an increased stress level while performing their routine tasks. Certainly, it is a priority to minimise such health issues that may be experienced by the ground crew.

Clinical studies have been performed to gain better understanding of the underlying biochemical and molecular mechanisms of hair cell death in the cochlea [10,11]. The death of hair cells is an irreversible process, resulting in hearing loss of the human. To date, clinical research is ongoing to understand noise-induced hearing loss. For example, Ralli et al. [12] found that workers—limited to only Italians—were likely to experience noise-induced hearing loss if they were exposed to a noisy working environment over an extended period of employment. The findings were consistent with a recent study by Masterson et al. [13], which instead focused on the Americans. Rosler [14] highlighted that a larger population with hearing loss would be expected in developing countries because of lesser emphasis on hearing protection programs.

In practice, hearing protection devices (HPDs) are provided to the ground crew to reduce noise exposure throughout their working hours. The common types of HPDs are earplugs and earmuffs with each having their unique advantages and disadvantages. Earplugs are advantageous for being disposable, inexpensive, and easy to use. Unfortunately, improper fitting of the earplugs compromises the intended performance in noise attenuation [15]. An obvious solution is to provide workers with proper training, albeit shown to be ineffective by Toivonen et al. [16]. They reported that poorly fitted earplugs may lower the intended performance in noise attenuation by up to 10 dB. Expectedly, if the earplugs are poorly fitted, leakage paths may exist and permit exterior noise to enter the ear canals directly instead of first propagating through the earplugs and then into the ear canals. Nonetheless, Toivonen et al. [16] emphasised that incompatible ear canals may also contribute to the drop in acoustical performance of the earplugs.

Considering the characteristic of aircraft noise, earmuffs are typically recommended over earplugs for better hearing protection [17]. This recommendation is because typical earmuffs can achieve a noise attenuation of about 9 dB per octave between 125 Hz and 1 kHz before reaching a saturation point of around 35 dB noise attenuation above 2 kHz. Earplugs, on the other hand, are typically more effective for noise attenuation above 1 kHz with the assumption that a proper fit is ensured by the user [18].

Earmuffs may be costly and bulky but their acoustical performance is independent of the ear canals and require minimal user knowledge. As compared to the earplugs, the user is less likely to wear the earmuff incorrectly. Hence, the intended acoustical performance of a given earmuff may likely be achieved in contrast to the earplugs. Nonetheless, a drop in acoustical performance of the earmuffs can be expected in the field as compared to that achieved from a laboratory test because the earmuffs are usually worn in an ideal manner without much considerations of comfort [18]. For example, a tight headband may provide a better seal around the pinnae but the forces exerted on the temporal bones may lead to discomfort. Additionally, personal protective equipment, such as eye goggles, face shields and helmets, and facial hair may also adversely influence the acoustical performance of the earmuffs.

An extensive range of earmuffs is available commercially for general use, including proprietary models designed for specific noise environments. Expectedly, the proprietary models come with a hefty price tag and may also be much heavier. Alternatively, the acoustical performance of typical earmuffs can be improved by modifying the assembly components—namely the cushion pads, headband, ear cups, and inner foam lining [19–22].

Augustine [23] recently showed that natural fibre-reinforced polymer composite earmuffs could improve the noise reduction at certain frequencies. The acoustical performances of several synthetic fibre-reinforced polymer earmuffs were measured and compared with various commercial earmuffs. The acoustical performances of the composite ear cups were found to be different depending on the noise environment—continuous and impulse—albeit not discussed in detail. Apart from this study, limited reports with similar interest can be found in the literature.

Earlier studies focused on the viability of natural fibres rather than the understanding of their acoustical properties [7,8]. Recent studies, however, showed a rise in research effort to understand the acoustical properties of natural fibres. For example, coir fibre was considered in place of synthetic fibre as an absorptive layer behind a micro-perforated panel [24,25]. Results showed remarkable sound absorption properties (up to 0.95) of the panel assembly above 1 kHz. Unfortunately, the findings were unable to represent the acoustical properties of coir fibre independently. This gap was later addressed in a separate study by the same research group [26]. The follow-up study investigated several parameters and found that, if properly designed, coir fibre could achieve good sound absorption properties below 1 kHz. At that point in time, the conclusion was made based on numerical simulations without any validation work, until much later [27]. To date, research efforts are still ongoing to understand and improve the acoustical performance of coir fibres [28,29].

Coir fibres have been characterised based on sound absorption properties but their transmission behaviour has yet to be investigated, especially in the context of industrial applications. This research gap motivated the present work to consider coir fibre-reinforced polypropylene (Coir-PP) as an alternative to the material selection for the ear cups of earmuffs. Additionally, a hybrid model—coir/carbon fibre-reinforced polypropylene (Coir/C-PP)—was also considered. This work aims to demonstrate the feasibility of composite earmuffs for low-frequency noise reduction in continuous and transient noise environments. The former and the latter were emulated by pink noise and aircraft take-off exterior noise, respectively. The acoustical performances of the composite earmuffs were evaluated experimentally in a reverberation chamber. Consequently, the proposed earmuffs may find potential applications in noise environments that are predominantly low-frequency—at airports, at construction sites, and in some automobile cabins, for example [30,31]. In Section 2, the specimen details and experimental approach are elaborated. In Section 3, the acoustical performances of the composite and the commercial earmuffs are presented and discussed further in Section 4. Section 5 provides conclusions based on the earlier sections.

2. Materials and Methods

This section first presents the information on the commercial earmuff used for benchmarking and the materials used to fabricate the composite ear cups. Subsequently, the fabrication process of the composite ear cups is provided. The last part of this section presents the experimental method used to evaluate the respective earmuffs and discusses the considerations made to minimise experimental uncertainty.

2.1. Specimen Details and Materials

The composite ear cups were designed with high resemblance to the ear cups of a commercial earmuff (Peltor™ Optime™ I H510F, 3M, Maplewood, MN, USA), which was purchased off-the-shelf. The commercial (or reference) earmuff served as the reference to distinguish the acoustical benefits and drawbacks of the composite earmuffs. Apart from the ear cups, the remaining assembly components—headband, cushion pads, and inner foam lining—were kept identical between the reference and the composite earmuffs for consistency. It should be noted that the Young's modulus of the reference ear cups—made from acrylonitrile butadiene styrene (ABS)—is proprietary. Hence, the Young's modulus of the material was taken as a typical value (2.6 GPa) from a materials handbook [32].

Compression moulding technique was used to manufacture the composite ear cups. First, fibre fabrics and PP films were placed between a two-piece aluminium mould according to a prescribed stacking sequence. The aluminium mould was designed to replicate the profile of the ear cups from the reference earmuff. The set-up was then placed into the Collin hot press for 15 min under a processing temperature and pressure of 190 °C and 20 bar, respectively. Thereafter, the set-up was cooled to room temperature at a rate of -10 °C per minute. Finally, the excess material was removed by cutting to form the composite ear cups. Figure 1 shows the composite ear cups assembled with the inner foam lining and cushion from the reference earmuff.



Figure 1. Closed-up view of the composite ear cups assembled with the inner foam lining and cushion: (a) coir fibre-reinforced polypropylene (Coir-PP); and (b) coir/carbon fibre-reinforced polypropylene (Coir/C-PP).

Coir-PP ear cups were made from nine layers of coir fibre fabric with a fibre volume fraction of 28%. One layer of PP film was added in between each layer of coir fibre fabric and at the outermost (exposed) layers. Coir/C-PP ear cups were made from six layers of coir fibre fabric, which were sandwiched by one layer of carbon fibre fabric. Similarly, PP films were added in between each layer of fibre fabric. In the hybrid model, the volume fractions of carbon fibre and coir fibre were 8% and 19%, respectively. The estimated Young's moduli of the composites were around 2.0–2.3 GPa. Figure 2 shows the schematic representation of the fibre stacking sequence for the respective composite ear cups. Table 1 shows the mass and the estimated cost of the respective ear cups.

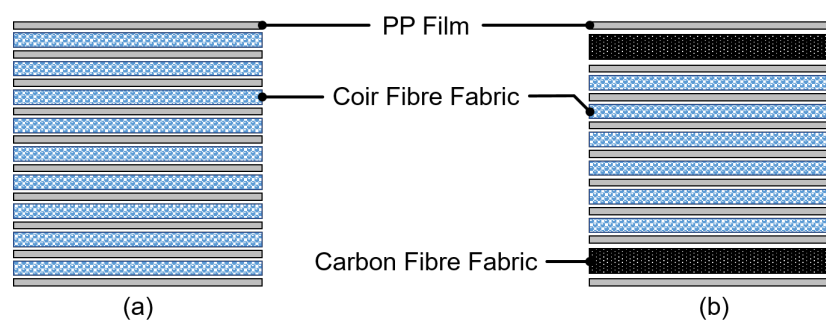


Figure 2. Schematic representation of the fibre stacking sequence for (a) the coir fibre-reinforced polypropylene (Coir-PP) ear cups; and (b) the coir/carbon fibre-reinforced polypropylene (Coir/C-PP) ear cups.

Table 1. Mass and estimated cost of the respective ear cups.

Ear Cup	Mass (g)	Estimated Cost (\$/kg) *
Reference	39.0	5.00
Coir Fibre-Reinforced Polypropylene	27.6	3.00
Coir/Carbon Fibre-Reinforced Polypropylene	28.1	8.00

* Note: Amount is in Singapore dollar.

The raw materials were provided by different sources, which are as listed in Table 2. Due to manufacturing limitations, only three samples were fabricated for each type of composite ear cups as opposed to five samples as specified in ANSI S12.42 [33]. Nonetheless, such requirement is not specifically indicated in BS EN ISO 4869-3 [34].

Table 2. Details of the materials used.

Material	Type	Density (g/m ²)	Source
Coir Fibre Fabric	Non-Woven	120	Can Tho University, Can Tho, Vietnam
Carbon Fibre Fabric (282 3K)	Plain Woven	197	Hexcel, Stamford, CT, USA
PP Film (Cosmoplene Y101E)	Unmodified	90	The Polyolefin Company, Singapore

2.2. Experimental Details

The experiment was performed in a reverberation chamber of 226.9 m³ with reference to ANSI S12.42 [33] and BS EN ISO 4869-3 [34]. A sound quality head and torso simulator (Type 4100, Brüel & Kjær, Nærum, Denmark) and a data acquisition unit (Type 3663, Brüel & Kjær, Nærum, Denmark) were placed on a table, which was positioned at the centre of the chamber. Pink noise (50–12,800 Hz) was generated and amplified by a noise generator (Type 1405, Brüel & Kjær, Nærum, Denmark) and a signal amplifier (BAS002, Larson Davis, Depew, NY, USA), respectively. The signal was then transmitted by an omnidirectional loudspeaker (BAS001, Larson Davis, Depew, NY, USA) situated at one corner of the chamber. An additional microphone was placed at 1 m away from each side of the simulator's moulded pinna. These additional sensors served to ensure consistency in the sound field with reference to the sound pressure level (SPL) recorded by the simulator without any earmuff (open ear). Figure 3a shows the experimental set-up in the reverberation chamber.

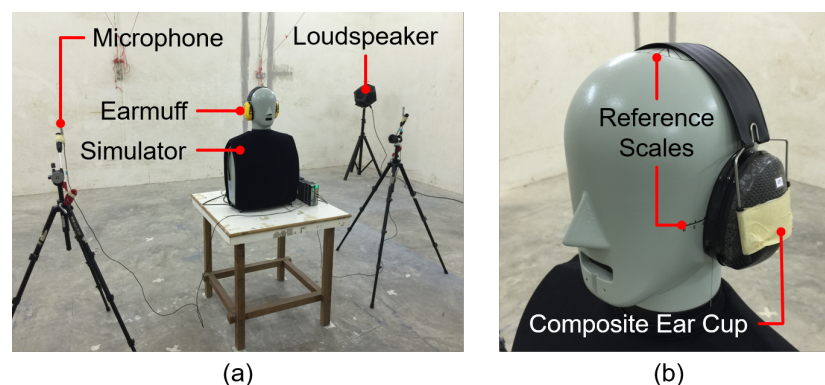


Figure 3. (a) Overview of the experimental set-up in the reverberation chamber with a reference earmuff worn on the simulator; and (b) closed-up view of the simulator with the composite earmuff worn based on the reference scales.

It should be noted that the simulator was designed for evaluating sound quality in vehicle cabins and other optimisation studies [35]. As such, the results obtained from the simulator were only valid

as relative measurements for benchmarking of the composite earmuffs with the commercial earmuff. Ang et al. [36] highlighted the same limitation in a recent study. Therefore, the presented results must not be misunderstood as a direct indication of real-ear attenuation values, which is one of the most accurate evaluation methods for HPDs [18].

The subsequent stage of the study involved the consideration of aircraft take-off exterior noise to emulate the noise field exposed by the ground crew at the airport. It should be noted that the use of a reverberation chamber to emulate the aircraft take-off exterior noise environment is a limitation of the present study. An anechoic chamber would better emulate the scenario albeit such a facility was not available. The recorded soundtrack—downloaded from the Internet—was played via an audio system (ZS-RS70BT, Sony, Minato, Tokyo, Japan). Due to technical limitations, the omnidirectional loudspeaker was substituted with a pair of self-powered loudspeakers (DXR15, Yamaha, Hamamatsu, Shizuoka, Japan), which were placed at different corners of the chamber.

Comparing the simulator and a real human head, it may be understandable that leakage paths exist differently in both cases. In view of this concern, efforts were made to minimise possible leakage paths that may exist in the simulator and reduce experimental uncertainty. For instance, prior to each set of measurements, the simulator was inspected to ensure that the moulded pinnae remained well-fitted in the respective recesses of the simulator. This inspection was essential because the fitting of the pinnae in the respective recesses could be affected during the process of changing the tested earmuffs. Experimental uncertainty was further minimised by ensuring consistency in the fitting and the positioning of each earmuff worn on the simulator. This consistency was achieved by taking note of the reference scales around the moulded pinnae of the simulator and at the top of its head. The reference scales are partly shown and labelled in Figure 3b. Interested readers may refer to the manufacturer's manual for a detailed projection view of the simulator [35]. The extended length of the headband for each earmuff was also kept constant throughout the experiment to minimise the possibility of inconsistent sealing. Additionally, the consistency in the position of the earmuff based on the reference scales and the extended length of the headband helped to minimise discrepancy in the headband force for each earmuff. However, the headband force could not be measured because it would require a specially designed test rig as demonstrated by Hsu et al. [37], for example.

Six measurements were recorded for each earmuff in the respective noise fields. This number of measurements exceeded the minimal number as specified in both test standards (at least two and three measurements for ANSI S12.42 and BS EN ISO 4869-3, respectively). The reason for this approach was to reduce experimental uncertainty by obtaining the results from the average of more datasets, even though the noise level at any field point in the reverberation chamber should ideally be the same. All earmuffs were first measured in pink noise to obtain a complete dataset before moving on to aircraft exterior take-off noise. The measurement durations were 30 and 15 s for pink noise and aircraft exterior take-off noise, respectively. The SPL of each noise source was ensured to be at least 15 dB higher than the background noise within the chamber. All measurements were recorded in the time domain at a sampling rate of 32,768 Hz and saved as wave files.

The saved data were then post-processed and presented in terms of insertion loss (IL) as defined by the SPL difference between without and with an earmuff worn on the simulator as given by

$$IL_f = L_{w0,f} - L_{w,f} \quad (1)$$

where the subscript f denotes a frequency-dependent term; L_{w0} and L_w denote the time-averaged SPL without and with an earmuff worn on the simulator, respectively (dB). The time-averaged SPL was computed by the arithmetic average between the left and the right ears of the simulator based on the assumption of a reverberant sound field. As specified in ANSI S12.42, the use of arithmetic average to calculate IL is permitted if the SPL at each ear is within a difference of 5 dB. Else, the IL curves must be presented and discussed based on each ear. It should be noted that the characterisation of the earmuffs using sound transmission loss values or sound absorption coefficients would not be representative due to the requirements of the respective test standards [38,39].

3. Results

This section presents and discusses the acoustical performance, in terms of IL, of the earmuffs in pink noise and in aircraft take-off exterior noise. To better show the overall characteristics of the earmuffs, the IL curves are plotted in narrowband frequency range instead of octave band frequency range. The IL curves in pink noise and in aircraft take-off exterior noise are plotted with a frequency resolution of 8 and 16 Hz, respectively. Instead of presenting the mean IL values, each IL curve is represented by a shaded area, which is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95% (i.e., coverage factor = 2) [40]. Systematic error was taken to be 0.5 dB.

3.1. Acoustical Performance of the Earmuffs in Pink Noise

The acoustical performance of each earmuff was first evaluated based on the IL in a continuous noise environment. Figure 4 shows the IL curves of the earmuffs in pink noise. It should be noted that the results were truncated at 6 kHz, as no significant differences were observed above this frequency.

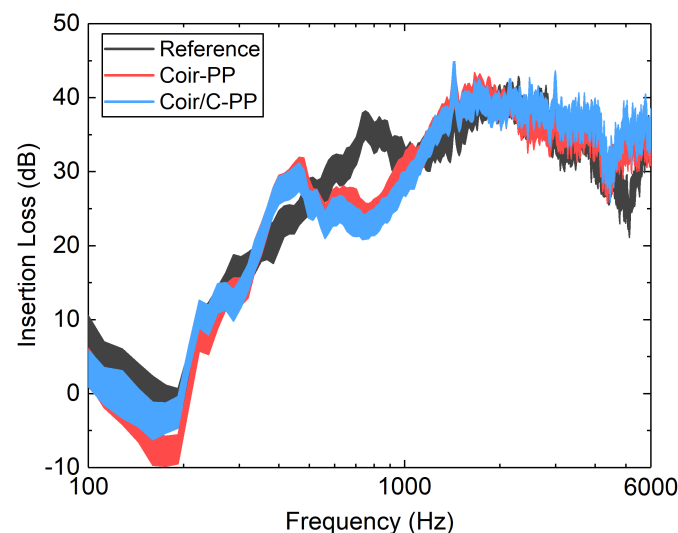


Figure 4. Insertion loss curves of the reference earmuff (dark grey), the Coir-PP earmuff (red), and the Coir/C-PP earmuff (blue) in pink noise. Shaded area is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95%. Note that the frequency interval is 16 Hz.

Based on the mean values, Coir-PP earmuff showed better IL within a narrow bandwidth (320–512 Hz) in contrast to the reference earmuff. Although this improvement came with a compromise in IL below 192 Hz, the inclusion of carbon fibre brought the IL closer to that of the reference earmuff. At higher frequencies (>1120 Hz), the acoustical performance of Coir-PP earmuff showed improvements in IL by up to 8.2 dB. This value increased by 3.8 dB at the same frequency (4928 Hz) with Coir/C-PP earmuff. Having a total noise reduction of 12 dB, more than half the perceived loudness could be reduced.

In general, the overall trend of the IL curves was similar with a distinct IL dip at around 170 Hz. Since the physical design of the composite ear cups was kept identical to that of the reference earmuff, this observation suggested that the phenomenon was not influenced by the assembly components of the earmuff. In this case, the IL dip was due to the resonance (pumping motion) of the ear cups, which is dependent on the design parameters and the leakages around the cushion pads. In another work, Paurobally and Pan [41] demonstrated that the presence of leakages could deteriorate the intended performance of an earmuff in the low-frequency range (<500 Hz). To improve the IL at this frequency range, a perfect seal could be a feasible solution. Unfortunately, it would be challenging to achieve zero leakage as the compliance of the cushion pad with the morphology of the temporal bone

(around the pinna) may not be perfect. The pressure exerted by the headband could also be tuned to minimise leakages around the cushion pads of the earmuff. For example, Boyer et al. [42] showed that a higher headband force would provide a better sealing of the cushion pads, improving low-frequency performance of the earmuffs. However, the higher headband force would lead to a higher equivalent stiffness of the cushion pads, which could compromise comfort, discouraging the user from wearing the earmuff over a prolonged period of time as suggested by Zannin and Gerges [22].

The second IL dip occurred at different frequency for the reference and the composite earmuffs. Similarity was only observed between the composite earmuffs. The IL dip occurred at around 1088 Hz and 736 Hz for the reference and the composite earmuffs, respectively. This observation could be attributed to the structural resonance of the ear cups. Elaborating further, the ear cups of the reference earmuff were made from ABS, which had a higher structural stiffness as opposed to the composite ear cups. Hence, a higher structural resonance would be expected for the ABS ear cups.

Up to this point, the presented results suggested that the composite earmuffs would be ineffective for low-frequency noise reduction, which is the dominant source of noise exposed by the ground crew at an airport. However, it should be noted that the acoustical performance of the composite earmuffs were determined based on only the continuous noise environment (pink noise). In the study by Augustine [23], he showed that the acoustical performance of composite earmuffs may differ in transient noise environments. As such, the proposed composite earmuffs were further evaluated based on aircraft take-off exterior noise.

3.2. Acoustical Performance of the Earmuffs in Aircraft Take-Off Exterior Noise

The ground crew at an airport is exposed to the noise mainly generated from an aircraft take-off at specific time intervals. This transient noise event generally lasts for 15–20 s before the aircraft eventually leaves the runway. In this study, the scenario was emulated in the reverberation chamber by an audio playback. Figure 5 shows the open ear SPL of the aircraft take-off exterior noise alongside the background noise measured by the simulator in the reverberation chamber. It should be noted that transient noise is different from impulse noise where the main characteristic of the former and the latter is time-dependent and instantaneous, respectively. An example of impulse noise is the firing noise generated by a gunshot, which was considered by Augustine [23]. In this case, an aircraft take-off exterior noise would be more appropriate to be categorised as a transient noise due to the speed variation of the engines.

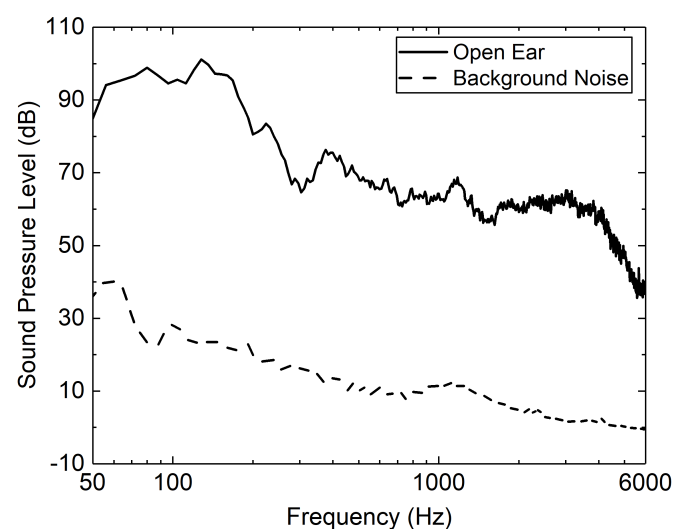


Figure 5. Time-averaged open ear sound pressure level of the aircraft take-off exterior noise and the background noise measured by the simulator in the reverberation chamber. Note that the frequency resolution is 8 Hz.

Figure 6 presents the IL of the earmuffs. In overall, similar trend was observed as that achieved in pink noise where the first and the second IL dips occurred at approximately the same frequency range. Interestingly, the acoustical performance of the composite earmuffs in the lower frequencies (160–544 Hz) showed an improvement in IL by up to 8.6 dB at 256 Hz in contrast to the reference earmuff. At the higher frequencies, an improvement in IL was also observed for Coir-PP earmuff (1280–1952 Hz) albeit not extending beyond 1952 Hz, which was the case in pink noise. In general, Coir/C-PP earmuff was observed to perform poorer than Coir-PP earmuff.

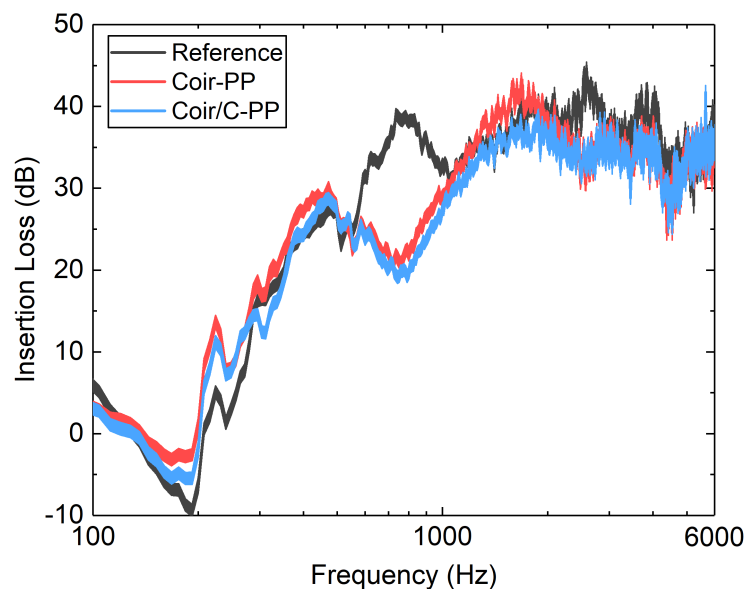


Figure 6. Insertion loss curves of the reference earmuff (dark grey), the Coir-PP earmuff (red), and the Coir/C-PP earmuff (blue) in aircraft take-off exterior noise. Shaded area is bounded by the upper and the lower limits of the expanded uncertainty at a confidence level of 95%. Note that the frequency interval is 8 Hz.

The results suggested that Coir/C-PP earmuff may not be beneficial if the intended use is in a transient noise environment. However, both composite earmuffs—Coir-PP in particular—showed improvements in IL at the lower frequencies (160–544 Hz) as compared to the reference earmuff. As such, Coir-PP earmuff may potentially help to reduce low-frequency noise exposed by the ground crew at the airport because the acoustical energy of the noise environment falls between 100 Hz and 300 Hz as shown in Figure 5.

4. Discussion

Coir-PP and Coir/C-PP were considered as potential alternatives to the material selection of the ear cups of typical earmuffs. To reiterate, this work aims to explore the viability of composite earmuffs in low-frequency noise reduction in contrast to a reference earmuff. Results indicated a difference in IL of both composite earmuffs in continuous noise environment (pink noise) and transient noise environment (aircraft take-off exterior noise).

In continuous noise source, Coir-PP earmuffs showed improvements in IL in contrast to the reference earmuff at 320–512 Hz. This improvement, however, resulted in a compromise in IL below 192 Hz albeit this compromise was found to reduce with the inclusion of carbon fibre into the Coir-PP ear cups. In the higher frequencies (>1120 Hz), Coir-PP earmuff achieved up to 8.2 dB improvement in IL. This improvement increased further by 3.8 dB when the hybrid ear cups (Coir/C-PP) were considered, suggesting that the loudness perception could be reduced by more than half.

Interestingly, otherwise was observed in transient noise environment where a higher IL was observed in the lower frequencies (160–544 Hz) for both composite earmuffs. In contrast to the reference earmuff, the improvement in IL went up to 8.6 dB at 256 Hz. Although both composite earmuffs showed marginal drop in IL in the higher frequencies (>1952 Hz), it was not crucial because low-frequency noise reduction is the key interest. The improvements in IL achieved by the composite earmuffs could be attributed to the high damping property of the natural fibres. Such property is usually low in thermoplastics—ABS, for example.

As highlighted in Section 2.1, the assembly components—headband, inner foam lining, and cushion pads—of the earmuffs and the physical profile of the ear cups were kept identical. As such, it would be interesting to discuss the cost to produce the respective ear cups. Based on Table 1, the estimated cost to produce a pair of the reference, the Coir-PP, and the Coir/Carbon-PP ear cups would be \$0.39, \$0.17, and \$0.45, respectively (Singapore dollar). The estimated cost suggests that the composite earmuffs may provide a cheaper and greener alternative in reducing low-frequency noise as opposed to the proprietary earmuffs. It should be noted that the cost of the reference ear cups was calculated based on only the material cost without taking into consideration of the manufacturer's branding, which could further increase the cost. Moreover, the reduced weight (up to 29%) of the composite earmuffs in relative to the reference earmuff suggests that the user may be more likely to wear the earmuff over an extended duration of time.

Future work may include the numerical simulations to gain better understanding of the acoustical performance of the respective ear cups and optimise their designs, resulting in enhanced acoustical performance. Additionally, a modal analysis may also be considered to understand the acoustic-structure interaction between the ear cups and the surrounding components, such as the cushion pad, inner foam lining, pinna, and the enclosed fluid cavity. Different manufacturing parameters may also be considered to understand their influence on the acoustical performance of the composite ear cups—processing temperature and pressure, for example. Various types of transient noise sources may also be considered to evaluate the composite earmuffs and understand their potential in such noise environments. Additionally, the present study may also be extended for clinical studies with the possibility to analyse temporary threshold shift and distortion product otoacoustic emissions on human subjects.

5. Conclusions

In conclusion, this study shed light to the potential of composite earmuffs for low-frequency noise control applications. Although the study was limited to the evaluation of the composite earmuffs in a laboratory rather than an actual site, the results could still suggest that the consideration of composite ear cups—combining natural and synthetic fibres—may be beneficial in reducing noise exposure for the ground crew at an airport. Such consideration could reduce the need for expensive and heavy customised commercial earmuffs. Consequently, the proposed composite ear cups may find potential applications to areas where the noise field is predominantly low-frequency such as in certain vehicle cabins, at construction sites, and at airports.

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Author Contributions: Yong Khiang Koh and Heow Pueh Lee conceived the idea; Steve Phillips and Le Quan Ngoc Tran fabricated the specimens; Linus Yinn Leng Ang performed the experiments, analysed the data, wrote and revised the paper; and Heow Pueh Lee edited and approved the paper for submission.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this paper:

ABS	Acrylonitrile Butadiene Styrene
Coir-PP	Coir Fibre-Reinforced Polypropylene
Coir/C-PP	Coir/Carbon Fibre-Reinforced Polypropylene
HPDs	Hearing Protection Devices
IL	Insertion Loss
SPL	Sound Pressure Level

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