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The performance of active noise-canceling headphones in different noise environments

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ABSTRACT

The performance of active noise-canceling (ANC) headphones is typically determined in pink noise and expressed in terms of insertion loss (IL) curves. However, these curves may not be consistent with the actual noise environments. The aim of this study is to assess the performance of several commercial ANC headphones by comparing performance curves under different noise conditions with the respective IL curves obtained in pink noise. The results indicated that the passive performance remained consistent under different noise conditions. In contrast, the active performance diminished based on the noise environment, brand, and active noise controller. The decrease in performance was especially significant in highly transient events and resulted in a noise amplification extending to 20.4 dB. Therefore, the deviation between results of headphones tested in actual noise environments and those tested in pink noise strongly suggests that it is necessary to consider actual noise environments in future studies to obtain a more accurate evaluation of ANC headphones.

1. Introduction

Headphones or earphones are an essential piece of equipment of daily commuters, and they allow commuters to select a listening experience based on their individual choice. In certain environments, such as construction sites or airports, this experience can be hampered owing to the ineffectiveness of passive devices to attenuate low-frequency and mid-frequency noise (<500 Hz) [1,2]. It may be necessary to alter certain design parameters to improve the attenuation capability of these headphones in this frequency range [3]. Unfortunately, this can eventually lead to a bulky and aesthetically unpleasing product that may not satisfy end-users. Thus, a few manufacturers incorporated active noise reduction technology in their products to overcome the limited noise attenuation capability of passive headphones. This feature is commonly known as active noise-canceling (ANC). The fundamental concept of ANC involves the design of an active noise controller to sense undesirable ambient noise and to generate an anti-phase signal to counter the same [4,5]. Consequently, the attenuation of low-frequency noise is achieved without requiring bulky passive headphones.

Although ANC technology is novel, it has a few disadvantages. Recently, Rudzyn and Fisher [5] investigated a wide range of commercial ANC headphones including both supra-aural and circum-aural types to determine their effectiveness in an overloaded and impulse noise environment. The results did not indicate any significant improvement in noise attenuation when the ANC feature was turned on, and this was consistent across all the studied headphones. This suggested that an individual could instead perceive higher ambient noise and increase the volume of their music to aid in improving audibility, and thereby inadvertently subject their auditory systems to potentially damaging volumes. The risk of occurrence of the fore-mentioned phenomenon is further heightened by the fact that it is often difficult to be conscious of exposure to loud music in a noisy environment [6].

In an effort to consider actual noise environments, a group of researchers evaluated ANC headphones in an aircraft cabin. Nevertheless, they focused on investigating the intelligibility of announcements as opposed to the acoustical performance of the headphones [7,8]. Other studies that considered actual noise environments focused on passive hearing protection devices with respect to the interests of industrial workers [9–12].

Although previous studies provide useful information on the evaluation of ANC headphones, there are evidently a limited number of extant studies that focus on evaluating the performance of ANC headphones in actual noise environments. Thus, in this study,

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several commercial ANC headphones were investigated to evaluate their performance in actual noise environments relative to those obtained in pink noise. The noise environments that were considered in the study include ambient noise at a construction site, an airport departure hall, an aircraft cabin during takeoff, and a bus cabin while commuting. The details of the commercial ANC headphones that were examined are presented in Section 2. Additionally, Section 3 discusses the results under each noise condition. In Section 4, the observations are discussed, and a conclusion based on earlier sections is presented in Section 5.

2. Materials and methods

2.1. Headphones

In this study, three commercial ANC headphones, hereinafter referred to as headphones, were investigated (Table 1). Bose QC25 and Sony MDR-10RNC are circumaural headphones that are designed to encompass pinnae with a large circular or ellipsoidal ear cushion. In contrast, the Sennheiser Momentum 2.0 is a supra-aural headphone that is designed to press against the pinnae with a circular ear cushion. Only a unit per model was assessed.

2.2. Experimental methodology

The experiment was performed in a reverberation chamber with a volume of 226.9 m^3. The average room temperature and relative humidity corresponded to 26 °C and 68%, respectively.

Fig. 1 provides a schematic representation of the experimental set-up for the respective noise fields. A sound quality head and torso simulator (B&K Type 4100) was used. As opposed to a cylindrical acoustic test fixture, the simulator allowed for a better representation of a human subject as it was designed to consider the anthropometry and acoustical characteristics of an average adult. The molded pinnae on the simulator provided directivity patterns that were similar to those of human ears. Two microphones were positioned considering the spatial separation between the human ears in which interference patterns caused by the head and torso were captured. Finally, a proprietary-designed cover (Fig. 2) was included to consider the change in reflections from the torso to increase the accuracy of directivity and body absorption [13,14]. However, it is important to note that B&K Type 4100 was designed for sound quality evaluation in automobile cabins and other sound optimization studies [14]. Thus, the results obtained from the simulator were only valid as relative measurements to aid comparisons between the different types of headphones.

The simulator and a data acquisition unit (B&K Type 3663) were placed on a standard test table positioned at the center of the chamber. Two active loudspeaker units (Yamaha DXR15) were each placed at a trihedral corner of the chamber to transmit the noise signal. Pink noise (50–12,800 Hz) was generated by a signal generator (B&K Type 1405) while other noise signals, such as construction noise, bus/aircraft cabin noise, and airport departure hall noise, were generated from audio tracks played on an audio system (Sony ZS-RS70BT). The audio tracks were either recorded from actual sites in Singapore or downloaded from the Internet. Additionally, a condenser microphone was placed at a distance of 1 m from each pinna of the simulator to record the sound pressure level (SPL) during each measurement. The heights of these microphones were aligned with the Frankfurt plane of the simulator. This adjustment was performed to ensure good agreement and consistency in the reverberant noise field during each measurement that was performed in the respective noise environments. Fig. 2 shows the actual experimental set-up in the reverberation chamber.

Table 1
List of headphones considered in the study.

Headphone type	Brand and model
Circumaural	Bose QC25
	Sony MDR-10RNC
Supra-aural	Sennheiser Momentum 2.0

Prior to placing a headphone on the simulator, a battery check was performed to ensure sufficient power was present to activate the ANC module. The headphone was carefully aligned with the scales around the pinnae and the top of the simulator to ensure consistent positioning. Additionally, the extended length of the headband was kept constant throughout the experiment to minimize inconsistent sealing. The passive and active performances of the headphones in each noise environment were measured six times for a duration of 30 s at a sampling rate of 32,768 Hz to ensure that the SPL of each noise source in the chamber for each measurement was considerably higher ($\geqslant$15 dB) than that of the background noise.

2.3. Calculation of passive and active performance

The recorded data was subsequently post-processed and computed in terms of insertion loss (IL), which is a parameter that is commonly used to evaluate the acoustical performance of hearing protection devices [5]. Specifically, IL is defined by Eqs. (1)–(3) in which the subscript f indicates a frequency-dependent term; L_O denotes time-averaged open ear SPL (without headphones); L_{C-OFF} denotes time-averaged SPL with headphones (ANC deactivated); and L_{C-ON} denotes time-averaged SPL with headphones (ANC activated). Additionally, IL_P, IL_T, and IL_A denote the passive, total, and active performance of the headphones, respectively.

$$IL_{P,f}(dB) = L_{O,f} - L_{C-OFF,f} \tag{1}$$

$$IL_{T,f}(dB) = L_{O,f} - L_{C-ON,f} \tag{2}$$

$$IL_{A,f}(dB) = L_{C-OFF,f} - L_{C-ON,f} \tag{3}$$

The arithmetic average between the SPL measurements at both the ears of the simulator were calculated based on the assumption of a diffuse field. An arithmetic average is acceptable and valid if the SPL difference between both ears falls below 5 dB.

Although the active performance of the headphones could be observed based on a comparison between IL_P and IL_T, the computation of IL_A allowed for an easier visualization of the effect of the frequency range on the noise level as a result of the active module. These IL curves were presented in a frequency spectrum as opposed to octave bands as it was probably not possible for the latter to illustrate the overall characteristic as clearly as the former.

3. Results

3.1. Performance curves of the headphones

The performances (passive, active, and total performances) of the headphones were determined by the IL of pink noise (50–10,000 Hz). The results were truncated at 10 kHz since energy levels beyond this frequency in the considered noise environments is too low to make meaningful observations. The background noise is important to demonstrate minimal electromagnetic interference (EMI) from the equipment and is presented in Fig. 3(a) along with the time-averaged open ear SPL of pink noise measured by the simulator. Fig. 3(b)–(d) present the performance curves of the headphones in terms of IL.

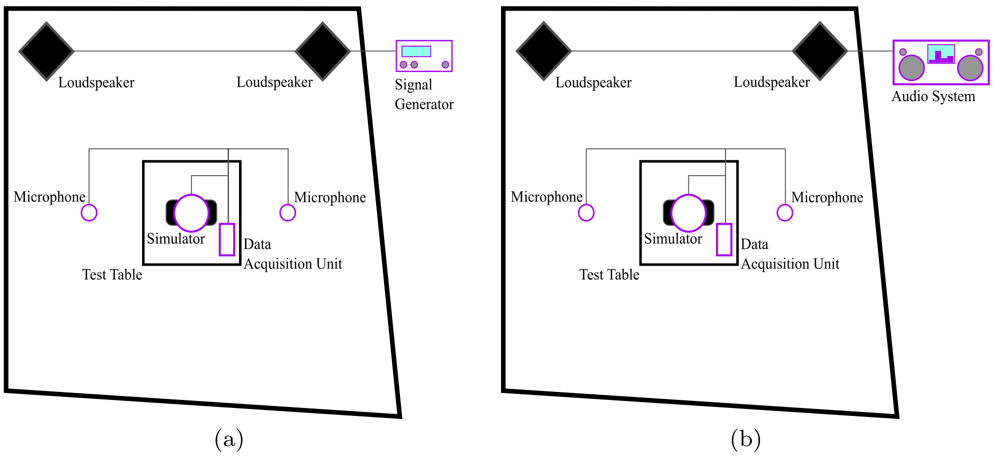

Fig. 1. A schematic representation of the experimental set-up for (a) pink noise and (b) other noise sources such as construction noise, bus/aircraft cabin noise, and airport departure hall noise.

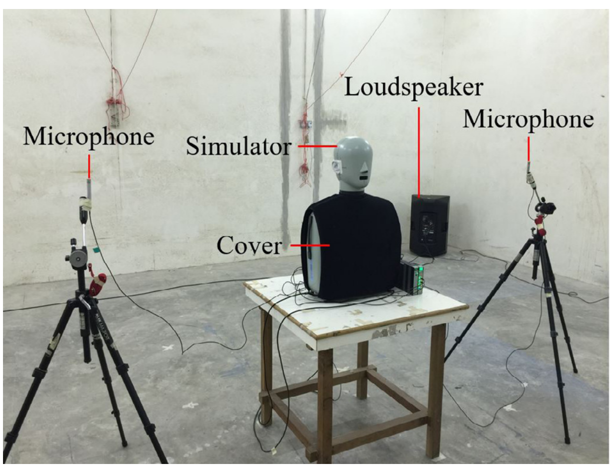

Fig. 2. Actual experimental set-up in the reverberation chamber.

An IL dip was consistently observed for both circumaural headphones at 184 Hz, and this resulted in noise amplification to a maximum of 7.2 dB. In the Sennheiser Momentum 2.0, the IL dip appeared at a higher frequency (320 Hz) with lower noise amplification (5.2 dB). This observation could be attributed to the cavity resonance of the air enclosed by the headphones on each side of the ears [5,15]. Additionally, the supra-aural headphone exhibited a wider bandwidth of poorer acoustical performance in a low-frequency range (50–480 Hz) relative to that of the circumaural headphones. This decrease in performance was due to the relatively poorer compliance of the cushion pad on the pinna, which is geometrically complex, and resulted in a poorer seal. Conversely, the circumaural headphones could achieve a better seal since the compliance of the cushion pad with the morphology of the temporal bone (around the pinna) was better.

However, the improvement in acoustical performance at the lower frequency range was observed for the headphones when the active module was activated. Specifically, Bose QC25 presented a significantly higher maximum IL of 31.5 dB at 128 Hz. Nevertheless, this performance was accompanied by a compromise in terms of performance in the higher frequency range (1.4–2.5 kHz). In frequencies beyond 2.5 kHz, prominent contributions of the active module in which the headphones effectively functioned as a passive device were not observed. A similar trade-off pattern was observed in frequencies exceeding 900 Hz for Sony MDR-10RNC. In contrast, the Sennheiser Momentum 2.0 did not exhibit this phenomenon despite the fact that the improved IL reached a maximum of only 11.2 dB at 224 Hz.

3.2. Airport departure hall

The recording as shown in Fig. 4(a) mainly consisted of footsteps and flight announcements within an airport departure hall. The IL curves of the headphones are presented in Fig. 4(b)–(d).

The observations indicated that all the headphones performed as expected, that is, passively, with the exception of performances at frequencies exceeding 6 kHz. This could be explained by Fig. 4(a) in which the noise energy is mainly confined in the lower frequency range. Conversely, the results indicated that the active performance was only consistent for both circumaural headphones. With respect to the Sennheiser Momentum 2.0, a better IL was achieved at frequencies below 240 Hz. This observation could be attributed to the difference in contact between the cushion pads and pinnae of the simulator.

3.3. Bus cabin during commute

This recording was performed to emulate a typical noise environment within a passenger cabin when a bus is in motion. In this case, the main contribution of the noise emanates from the engine as shown in Fig. 5(a).

The passive performances of all the headphones were again consistent with those corresponding to pink noise (Fig. 5(b)–(d)). Similarly, a lower noise energy above 3 kHz resulted in a drop in IL. With respect to the active performance, both the circumaural headphones functioned as expected, and the results were consistent with the earlier results. Conversely, the Sennheiser Momentum 2.0 maintained an IL below 240 Hz that was comparable to that observed in an airport departure hall although a slight deterioration was observed in the range corresponding to 240–3,500 Hz.

3.4. Aircraft cabin during takeoff

In contrast to the previously discussed noise environments, this recording was performed to emulate a transient noise environment. Generally, the noise in the passenger cabin of an aircraft involves a tonal nature (engine excitation) during flight. Nevertheless, this is not applicable during takeoff. The noise energy during a flight is dominantly concentrated in the lower frequency range (<200 Hz) as shown in Fig. 6(a).

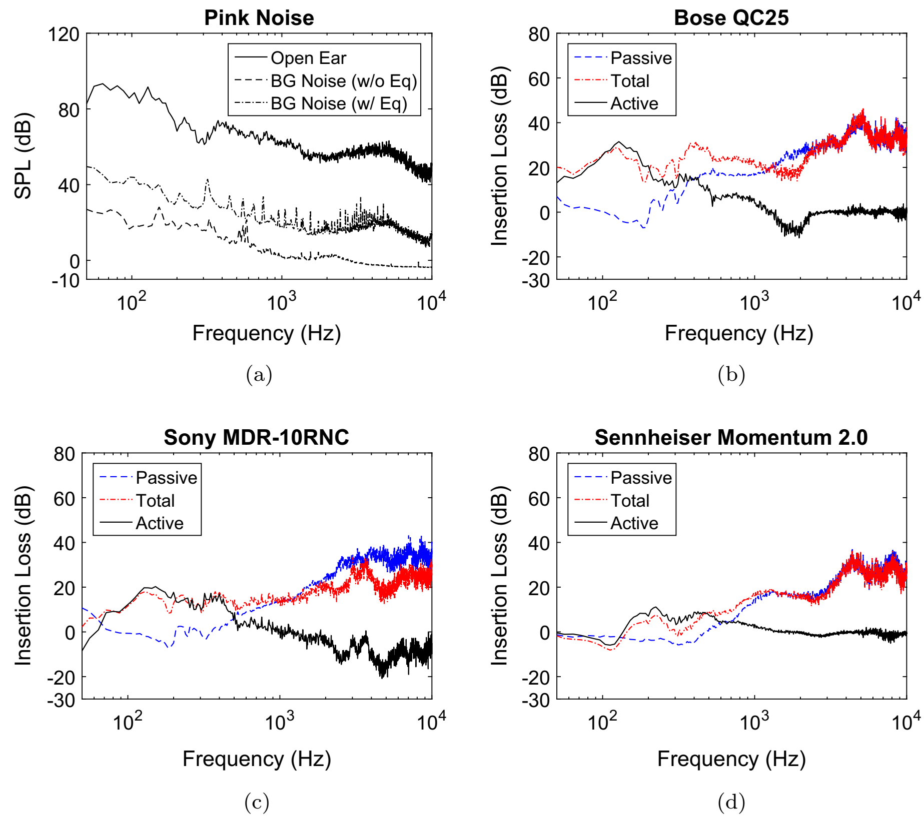

Fig. 3. Plots illustrating (a) the background noise (with and without test equipment turned on) and time-averaged open ear SPL due to pink noise and the passive, total, and active IL for (b) Bose QC25; (c) Sony MDR-10RNC; and (d) Sennheiser Momentum 2.0.

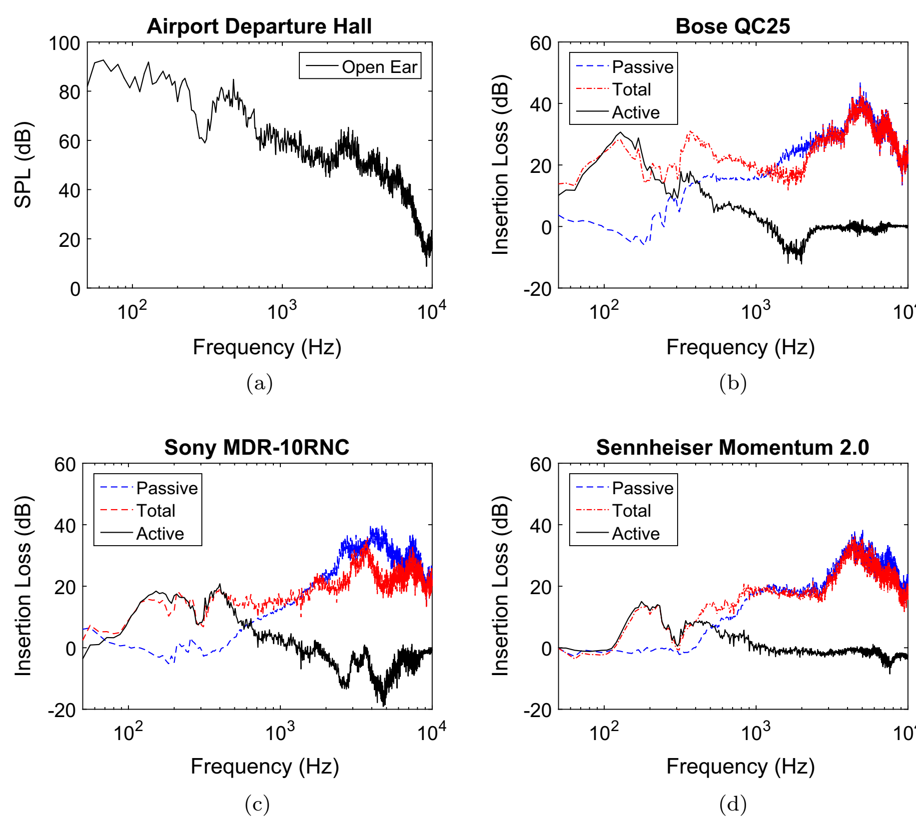

Fig. 4. Plots illustrating (a) the time-averaged open ear SPL due to the ambient noise in an airport departure hall and the passive, total, and active IL for (b) Bose QC25; (c) Sony MDR-10RNC; and (d) Sennheiser Momentum 2.0.

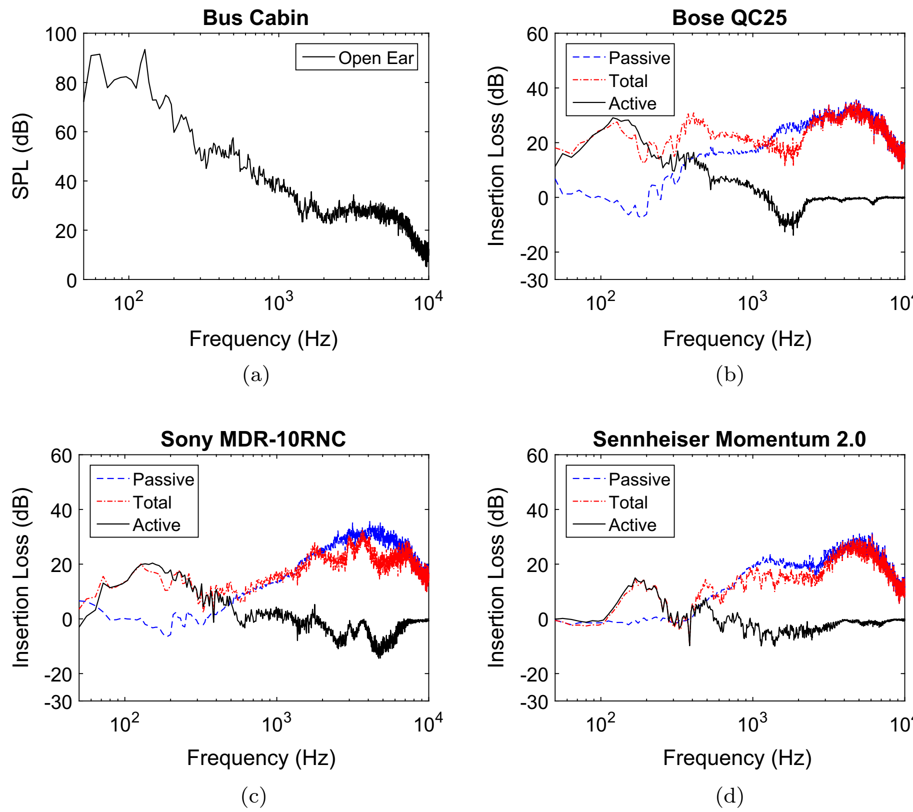

Fig. 5. Plots illustrating (a) the time-averaged open ear SPL due to the ambient noise in a bus cabin while commuting and the passive, total, and active IL for (b) Bose QC25; (c) Sony MDR-10RNC; and (d) Sennheiser Momentum 2.0.

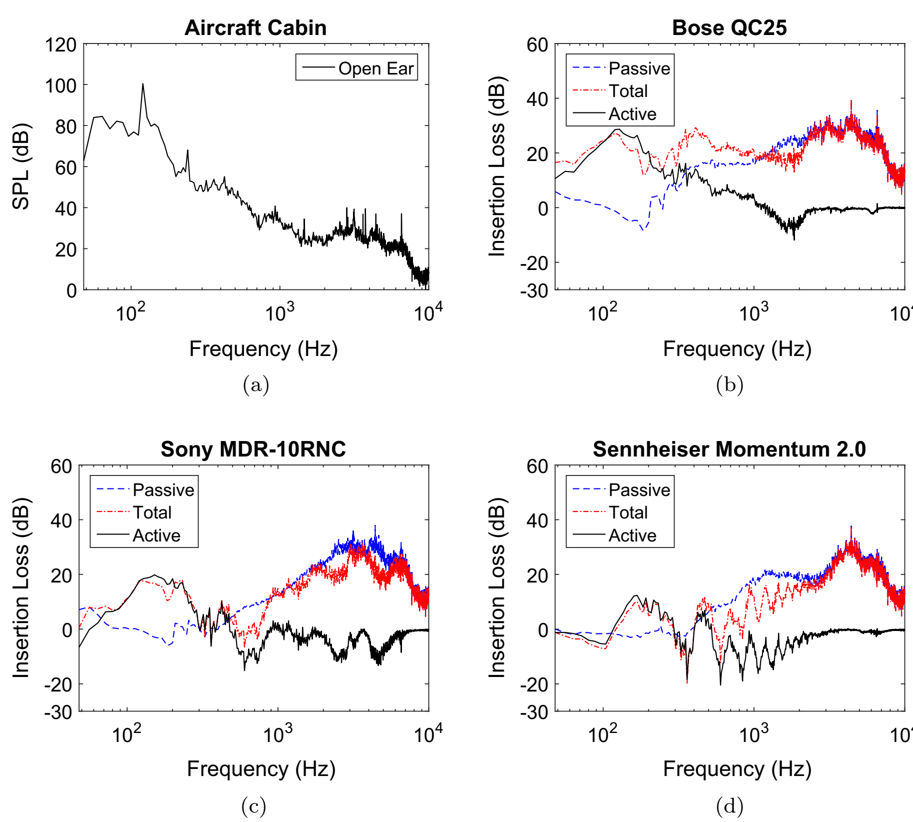

Fig. 6. Plots illustrating (a) the time-averaged open ear SPL due to the ambient noise in an aircraft cabin during takeoff and the passive, total, and active IL for (b) Bose QC25; (c) Sony MDR-10RNC; and (d) Sennheiser Momentum 2.0.

In a manner similar to the previously obtained results, the passive performances of all headphones did not significantly differ from those in Fig. 6(b)–(d). With respect to the active performance, the performance of the Bose QC25 was consistent with that achieved in pink noise. The performance of the Sony MDR-10RNC exhibited fluctuations in the range corresponding to 270–930 Hz albeit less prominently than that of the Sennheiser Momentum 2.0 (Fig. 6(d)). These fluctuations caused an increase in noise amplitude (especially at 600 Hz) up to 20.4 dB.

3.5. Construction site

Similarly, this recording was performed to assess the performance of the headphones in a transient noise environment. It mainly consisted of impact noises from work tools and engine noise from specialty vehicles. The noise energy from these sources typically falls in the lower frequency range (<200 Hz) as shown in Fig. 7(a).

With respect to the passive performance, the performances of the headphones were again consistent with earlier findings and did not indicate any significant differences (Fig. 7(b)–(d)). Interestingly, Sennheiser Momentum 2.0 exhibited a similar phenomenon of instability that was more prominent than that observed in an aircraft cabin during takeoff. As a result, the ambient noise was amplified by up to 18.3 dB, and this was particularly observed at 384 Hz.

4. Discussion

Generally, the passive performance of the ANC headphones was consistent and significant abnormalities were not observed irrespective of the noise environments. However, a visible peak was observed at approximately 120 Hz irrespective of the noise environments. The consistency of this peak suggested that it could be an EMI of the equipment that was potentially more visible if the gain increased. This claim is supported by Fig. 3(a) in which the peak is less visible at zero gain. However, when the active module was activated, it was observed that the active performance of the ANC headphones differed from the performance curves obtained in pink noise when evaluated in different noise environments. Nevertheless, the difference in the active performance between the different noise environments is dependent on the brand and model of the ANC headphones.

For example, Bose QC25 exhibited consistency in its performance irrespective of the noise conditions, and this may be observed by comparing the IL curve of each considered noise condition relative to that of the performance curve obtained in pink noise. Conversely, the Sony MDR-10RNC exhibited a deviation from its performance curve in transient noise environments including an aircraft cabin during takeoff and a construction site. This deviation was again observed when compared to the IL curve obtained in pink noise. Similarly, the Sennheiser Momentum 2.0 exhibited differences albeit more prominent in its performance in the same transient noise environments as indicated by the presence of fluctuations in IL between 200 Hz and 2,000 Hz. This resulted in a noise amplification of up to 20.4 dB, which corresponded to a significant level and was potentially rather alarming. In contrast, the overall A-weighted noise attenuation of each headphone based on the same transient noise environment can be considered. Due to these fluctuations, Sennheiser Momentum 2.0 resulted in an overall noise amplification corresponding to 2.8 dB (A). The performances of Bose QC25 and Sony MDR-10RNC were acceptable relative to the noise attenuation with 23.3 dB(A) and 13.6 dB(A), respectively. Although the overall noise amplification

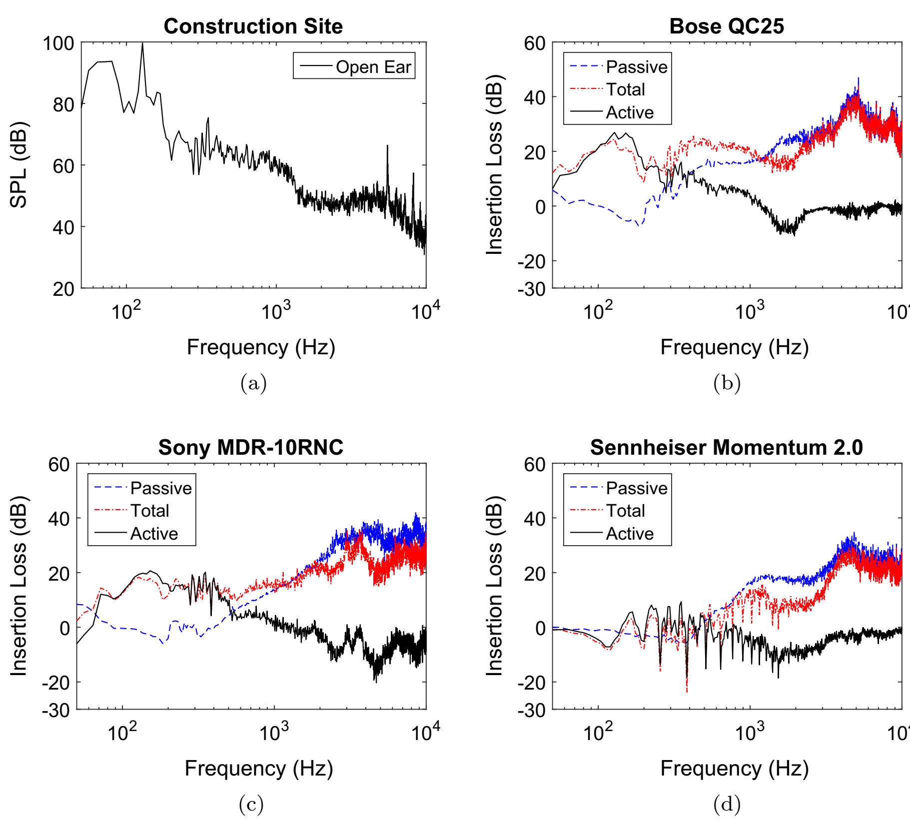

Fig. 7. Plots illustrating (a) the time-averaged open ear SPL due to the ambient noise at a construction site and the passive, total, and active IL for (b) Bose QC25; (c) Sony MDR-10RNC; and (d) Sennheiser Momentum 2.0.

of 2.8 dB(A) is relatively less alarming when compared to 20.4 dB, it is definitely noteworthy.

These fluctuations could indicate an overloaded active module. Overloading occurs when the limiting threshold of the active module is exceeded and an anti-noise signal of the highly-varying noise excitation cannot be reliably generated. This implies that the active module of this particular system reduced robustness in transient noise environments. Conversely, Rudzyn and Fisher [5] did not observe any fluctuations in IL even when the active module of the ANC headphone was overloaded. In contrast, it was demonstrated that the active performance was relatively poorer with a lower IL to the extent that the performance was similar to that of a passive headphone. However, the fore-mentioned study was limited to only a specific circumaural ANC headphone despite their wide range of considered ANC headphones. Hence, there is a possibility that a similar phenomenon could be observed if the remaining ANC headphones were evaluated. Additionally, the active noise controller used in the design of the active module can also contribute to the eventual performance of the ANC headphones under transient noise conditions [16,17].

Therefore, as shown in this study, while evaluating ANC headphones, it is also necessary to consider their performance in actual noise environments due to the vulnerability of active modules to instability in certain scenarios that results in unnecessary noise amplification.

5. Conclusion

In this study, a general approach to evaluate the performance of ANC headphones is examined to obtain IL in pink noise. Test standards are commercially available for this type of an evaluation. However, to date, extant research has not determined as to whether or not these results can be extended to actual noise environments. Hence, this study aims to investigate the differences in the performances of three commercial ANC headphones in various noise environments as opposed to their performance curves obtained in pink noise.

When the active module was deactivated, the performances were observed to be consistent between the IL curves obtained from actual noise environments and pink noise. When the active module was activated, differences in performances were observed especially for transient events such as those in an aircraft cabin during takeoff and at a construction site. However, this was dependent on the noise environment, active noise controller, and brand/-model of the ANC headphones. Specifically, the Sennheiser Momentum 2.0 exhibited fluctuations in IL over a wide frequency range, and this implied the instability of the active module. This led to a noise amplification of up to 20.4 dB. Thus, it was shown that the ANC headphones may deviate from their intended performance in certain noise environments. At a broader level, this could adversely affect the auditory system of an individual.

Conversely, the results indicated that the ANC headphones were reliable in stationary noise environments as opposed to those in environments that are highly transient. However, it should be noted that such observations do not necessary prove the ineffectiveness of ANC headphones in all transient noise environments. The headphones may still be effective if the transient event occurs for only a short period of time relative to the total duration of noise exposure. For example, a typical commercial aircraft takeoff typically lasts only for a few minutes when compared to the entire flight duration (which takes hours). In this case, the majority of the noise is contributed by tonal excitation from the engines.

In conclusion, it is necessary to ensure that the performance of ANC headphones is not limited to pink noise as the results of this study demonstrated that the performances of ANC headphones differed in certain noise environments and especially in a noise environment of a highly transient nature. Thus, surrounding noise can be amplified excessively, and this is undesirable. Hence, the performances of ANC headphones will only be truly representative if actual noise environments are considered and evaluated beyond those of IL curves obtained in pink noise. Specifically, it is necessary to consider highly transient noise events in the evaluation process to better characterize the feasibility and robustness of ANC headphones for specific uses.

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