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1pNSa7. An active hearing protection device for musicians

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Professional musicians have to deal with two main problems when wearing hearing protection devices (HPDs): the occlusion effect and the isolation effect. The occlusion effect is an unnatural and annoying perception of one's own voice when wearing HPDs. It will affect all musicians whose instrument induces vibrations to the skull, including singers and musicians whose instrument is pressed against any part of the head. The isolation effect is the unnatural sensation of being isolated from a given sound environment. It is caused by a non-uniform attenuation of the HPD over the audio spectrum and the absence of compensation for equal loudness contours. These two effects are highly unfavorable to the musicians' auditory perception and compromise their capacity to perform to the best of their abilities for their audience. This paper presents an active HPD for musicians, providing occlusion effect reduction and isolation effect compensation. Preliminary performance of the occlusion effect reduction system is presented and discussed.

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AN ACTIVE HEARING PROTECTION DEVICE FOR MUSICIANS

Introduction

Discomfort caused by wearing hearing protection devices (HPDs) can discourage musicians from wearing HPDs to protect their hearing from potentially dangerous noise levels. According to GMMQ (Guilde des musiciens et musiciennes du Québec), representing over 3000 professional musicians, 40% of musicians develop hearing loss during their career [1]. While physical discomfort has already been addressed by solutions such as custom fit hearing protection devices, acoustical and psychoacoustical discomfort remain a problem. Two main causes are responsible for this perceptual discomfort: the occlusion effect and the isolation effect.

The occlusion effect is an unnatural and annoying perception of one's own voice when wearing HPDs. It will affect all musicians whose instrument induces vibrations to the skull, including signers and musicians whose instrument is pressed against any part of the head, such as a trumpet or violin. The vibrations will travel to the ear canal walls by bone conduction, causing those walls to vibrate and causing pressure changes in the air contained in the ear canal, producing an acoustical wave that will be picked up by the auditory system. When the ear canal is unoccluded, most of the energy propagated through the ear canal by bone conduction exits by the ear canal's orifice, and what is heard is predominantly the sound wave arriving from the air conduction path between the source (e.g. vocal tract) and the ear. However, when the ear canal is occluded, the energy wave travelling by bone conduction is trapped within the ear canal and is picked up by the auditory system while the air conduction path is blocked, so what is heard is predominantly the sound wave travelling by bone conduction. Since bone conduction is efficient in conducting low frequencies, the result will be an augmented and unnaturally "boomy" perception of one's own voice. Fig. 1 illustrates how the occlusion effect occurs and indicates pertinent sound pressure level (SPL) measurement points, L_{OP} (SPL in the open ear canal), L_{OC} (SPL in the occluded ear canal) and L_{REF}(SPL from the air conduction path). The transfer function between L_{OC} and L_{REF} shown in Fig. 2 displays an approximation of the SPL increase in the ear canal caused by occlusion effect. Since the air conduction path prevails when the ear canal is unoccluded, L_{REF} can be used to approximate L_{OP}, and is more convenient to measure. L_{OC} and L_{REF} were measured respectively by an internal and external microphone on a prototype earpiece worn by the first author as he was humming. It is apparent from Fig. 2 that the SPL increase caused by occlusion effect occurs in the lower frequencies of the speech bandwidth. This transfer function is only an approximation of the SPL increase caused by occlusion effect, but it is generally consistent with other similar measurements made by [2] or [3].

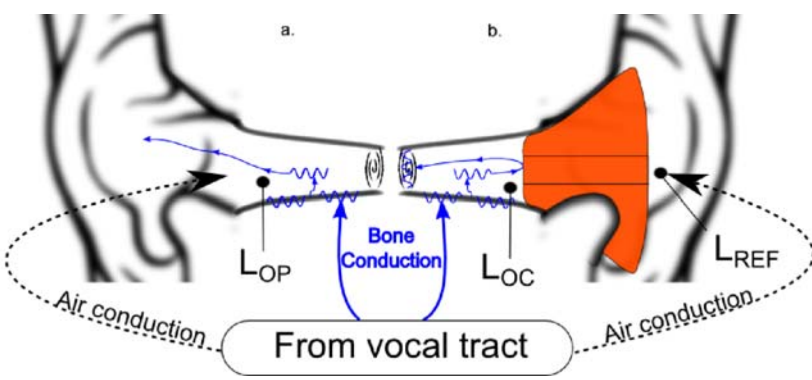

FIGURE 1: Occlusion effect: a) the sound wave induced by the vibration of the ear canal walls mostly escapes the ear canal and the sound wave travelling along the air conduction path is predominantly heard b) the trapped sound wave propagating from the bone conduction path will cause the eardrum to vibrate, while the air conduction path is blocked, causing an unnatural and augmented perception of one's own voice.

The isolation effect is the unnatural sensation of being isolated from a given sound environment and can be caused by wearing HPDs. Passive HPDs do not necessarily attenuate the entire audio spectrum evenly and do not take equal loudness contours into consideration. Most passive HPDs will attenuate high frequencies much more than low frequencies and, in a musical context, will considerably alter the wearer's perception of timbre. Occluding the ear canal also shifts its main resonance from quarter wavelength to half wavelength [4], further altering the wearer's perception. While passive and active solutions to these problems exist, they involve a fixed attenuation. Although this may be suitable in some situations, in others, a predetermined attenuation will provide either insufficient or excessive protection.

Furthermore, the equal loudness perception curves differ as the stimuli gets louder. Therefore, simply attenuating evenly over the whole audio spectrum does not accurately convey the spectral balance that would be perceived without wearing perfectly uniform-attenuation HPDs. Instead, some high, low midrange and low frequencies will be perceived as more attenuated than the rest of the spectrum, while some mid frequencies may seem less attenuated. Fig. 3 shows a few equal loudness curves at different loudness levels, and the perception shift that would occur if one was to wear uniform-attenuation HPDs.

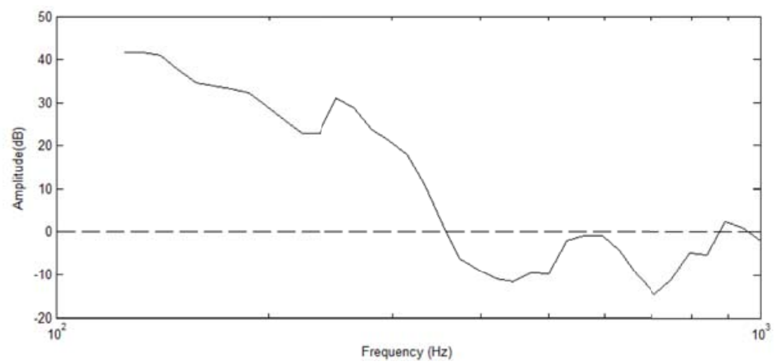

FIGURE 2: Occlusion effect: transfer function between an internal microphone, inside the occluded ear canal, and an external microphone, at the orifice of the ear canal, as the author is humming. The figure shows an estimation of the sound pressure increase caused by the occlusion effect. The sound pressure is seen to increase as high as 40 dB in the lower frequencies.

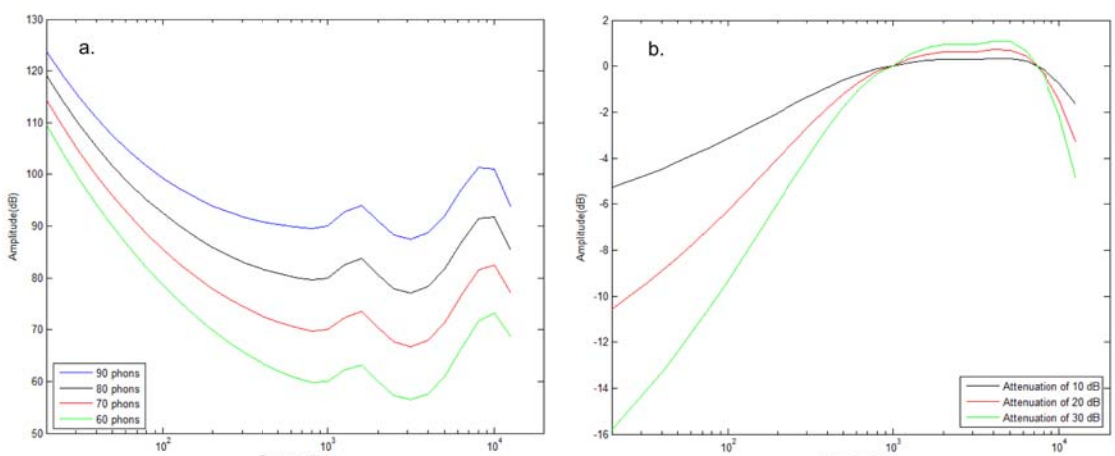

FIGURE 3: Equal loudness contours according to ISO226 [5]: a) The curves represent the required sound pressure level for a given pure tone at one frequency to be perceived as loudly as another pure tone at another frequency on the same curve. Each curve is valid at a specific loudness level, in phons, where 1 phon is set to 1 dB (SPL) at 1 kHz. b) Theoretical resulting perception shift when wearing uniform attenuation hearing protection devices in a 90 dB (SPL) sound environment for different uniform attenuation values.

The isolation and occlusion effects are highly unfavorable to the musicians' auditory perception and compromise their capacity to perform to the best of their abilities for their audience. The isolation effect can make it difficult for musicians to judge the sound quality that is being presented to their audience. When, as a consequence of the occlusion effect, an augmented and unnatural perception of one's own voice or instrument is predominantly what is heard, musicians cannot hear the subtle cues that they depend on to adjust their playing. Cues such as knowing how their timbre blends with their colleague's or how loudly their instruments sounds and resonates in a given space can make a big difference in one's performance. These adverse effects may cause some musicians to decide not to wear HPDs.

Proposed Solution

The proposed solution, addressing previously outlined issues, is a system to provide occlusion effect reduction and isolation effect compensation. The next section presents the occlusion effect reduction system.

Addressing the Occlusion Effect

The occlusion effect reduction system is based on active noise control (ANC) of the low frequency sound wave which becomes predominant in an occluded ear canal. A carefully selected miniature loudspeaker and microphone assembly (referred to as *plant*) is placed in the ear canal, within the HPD. A feedback controller uses the error signal picked up by the internal microphone to generate a corresponding anti-noise with the loudspeaker. The anti-noise adds up to the noise, in the acoustic domain, and reduces the occlusion effect, as shown in Fig. 4. Fig. 5 shows the architecture of the ANC system.

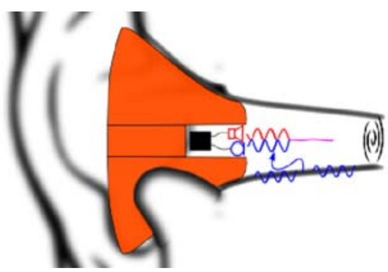

FIGURE 4: Active noise control of occlusion effect: noise in the ear canal is picked up by an internal microphone, and a cancellation signal is generated with the loudspeaker.

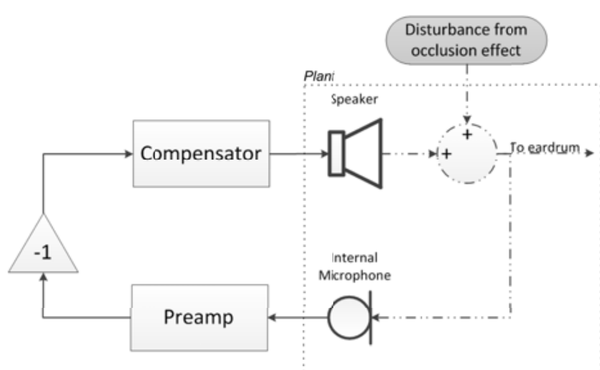

FIGURE 5: Architecture of the occlusion effect ANC system and the *plant* (miniature loudspeaker and microphone assembly in the occluded ear canal).

An analog feedback controller design was selected for its simplicity and stability. The compensated plant response was obtained from the initial plant response, in this case the loudspeaker to microphone transfer function when inserted in the ear canal, as shown in Fig. 6. The theoretical occlusion effect attenuation is shown in Fig. 7, predicting over 10 dB of attenuation from 100 Hz to 400 Hz, where the occlusion effect has been shown to be most significant. Slight regeneration in mid to high frequencies is also observed as a side effect of the feedback control. Regeneration occurs at the frequencies where the plant response's projection on the real axis is negative. Since the acoustical wave resulting from the occlusion effect does not contain much of these frequency components, this regeneration should not prove to be problematic.

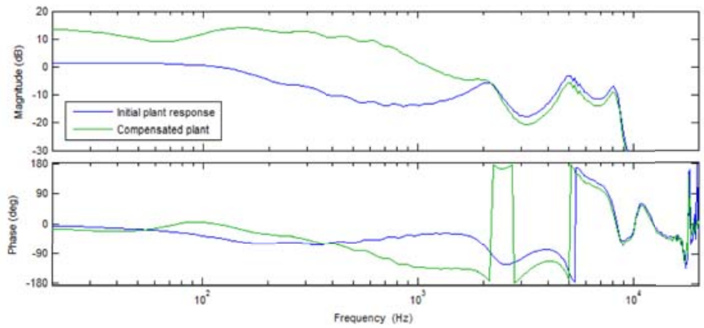

FIGURE 6: Transfer functions of the plant and compensated plant

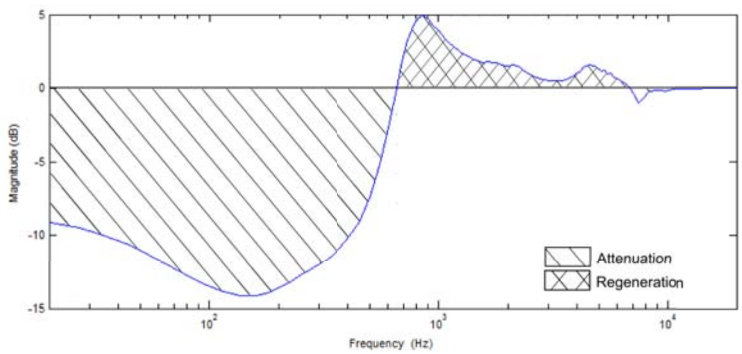

FIGURE 7: Projected occlusion effect attenuation: Attenuation is achieved over the bandwidth of interest, but unavoidable regeneration also occurs.

Addressing the Isolation Effect

This section describes the methodology addressing the isolation effect. An external microphone placed on the outside of the HPD could be used to capture the useful signal, transform and reproduce it at variable volume through the internal miniature loudspeaker. A passive HPD will usually attenuate sound unevenly, letting through more low frequencies than high frequencies. To flatten the attenuation, it is possible to reduce low frequencies by active noise control and amplify high frequencies to match the attenuation level of mid frequencies, as shown in Fig. 8. This procedure is very similar to the one described in [6].

Since ANC of the occlusion effect already cancels some of the low frequencies inside the ear canal, a simple filter can be used to flatten the attenuation and achieve maximum attenuation within the constraints imposed by the performances of the ANC and the passive attenuation of the HPD. This filter includes ear resonance correction for a uniform perceived attenuation. To further tweak the uniform attenuation and compensate for equal loudness contours, a set of filters can be chosen from. Using the outside noise level and the desired attenuation as input parameters, it is possible to account for the shift of perception from one equal loudness curve to another, previously shown in Fig. 3. By doing so, the perceived spectral balance is the same with or without the hearing protection.

The digital signal processor (DSP) housing the filters can measure the sound pressure level outside the HPD. It can then either calculate and apply the required attenuation to follow a certain standard, or apply a user-defined attenuation level. The internal microphone is used to verify that the attenuation is indeed correct. The complete system architecture required to implement both the occlusion effect reduction and isolation effect compensation system is shown in Fig. 9.

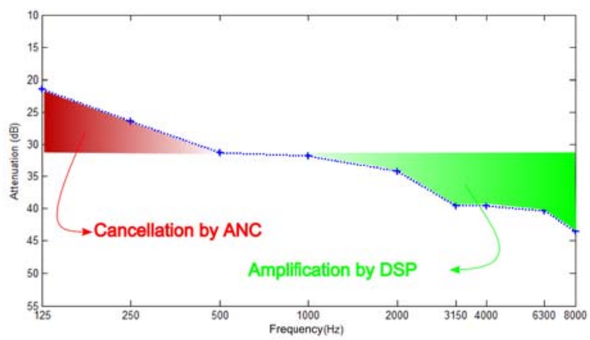

FIGURE 8: Example of achieving uniform attenuation: Since passive attenuation is usually the lowest in the low frequency region, using active noise control in that region will flatten the attenuation. A DSP could then be used to amplify high frequencies and achieve uniform attenuation in that region as well.

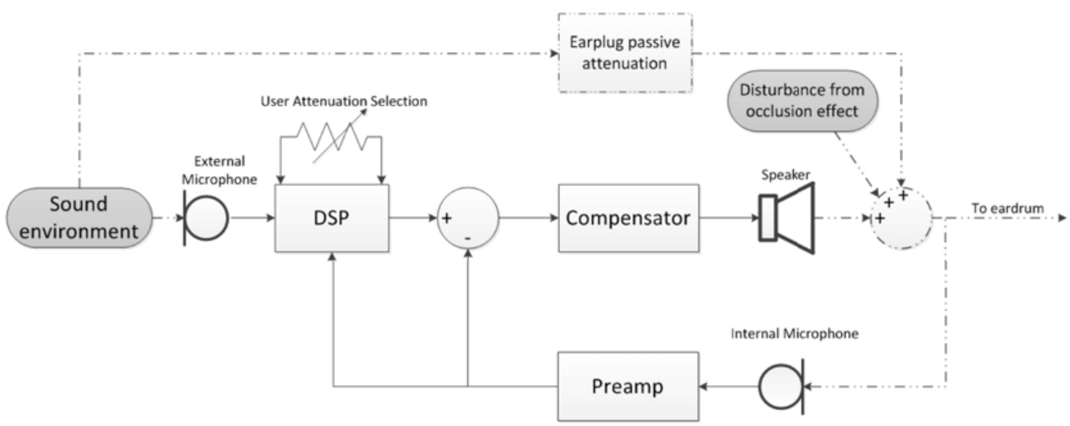

FIGURE 9: Complete system architecture

Preliminary Performance Assessment

At the time of writing, only preliminary performance for occlusion effect reduction had been quantified. First, a correction curve was obtained by characterizing the differences in occlusion effect level when humming, between the first author's left and right ears, occluded by identical earpieces. Then, the occlusion effect ANC system was activated in the first author's right ear, and a transfer function between the reference earpiece (left) and the active earpiece (right) was calculated and corrected using the previously obtained correction curve. Fig. 10 shows the performance of the implemented occlusion effect ANC system in reducing the author's occlusion effect as he hums. A decrease of over 10 dB can be observed from about 100 Hz to about 500 Hz. While this might seem to be a small difference, the perceptual difference is substantial. To better assess the perceptual reduction of the occlusion effect, psychoacoustic tests need to be conducted on a larger number of human subjects.

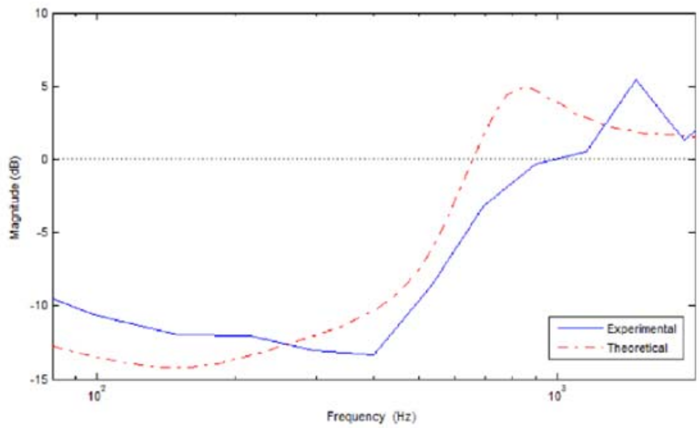

FIGURE 10: Occlusion effect cancellation: the dashed line shows the expected occlusion effect reduction from theory and design. The solid line shows the achieved occlusion effect cancellation for the first author.

A second test was conducted to assess the performance of the ANC system on the attenuation of the plug. First, white noise was played using over-the-ear headphones on a Bruel & Kjær head and torso simulator (HATS) model 4157 as the mannequin was wearing the earplug in passive mode. Second, the procedure was repeated with the earpiece in active mode. The transfer function between the two signals recorded using the microphone located at the eardrum of the HATS is shown in Fig. 11. Although they may seem similar, the measured curve using this method differs from the other experimental attenuation curve from Fig. 10. It is possible that a better fit was achieved on the mannequin than in the author's ears, thus shifting the response of the plant. Soft silicone does not guarantee the same fit with every use, and since it was used to couple the prototype earpiece to the ear canal, the resulting performance can vary. Scheduled test performed on more subjects will provide more information. Nevertheless, the preliminary experimental performance of the active occlusion effect reduction system are comparable to the results presented in [7].

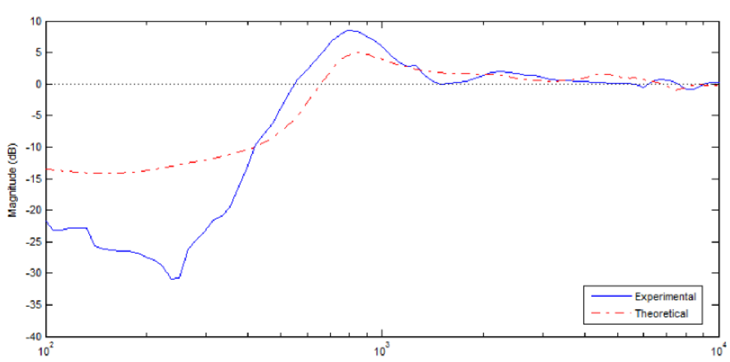

FIGURE 11: Active attenuation: the dashed line shows the expected active attenuation from theory and design. The solid line shows the measured active attenuation. Differences between the curves could be attributable to the variability of the acoustic seal which could in fact influence the *plant* response and therefore the performance of the system.

Having characterized active attenuation, it is possible to present a more realistic overall attenuation scenario. The measured passive attenuation curve of an earplug that would be a good candidate to host the prototype earpiece presented in this paper is shown in Fig. 12 . Projecting the previously presented experimental active attenuation curve on the passive attenuation curve shows the increase in effectiveness of the earplug in the areas where it is the least effective. Given the resulting curve, it is possible to amplify the over-attenuated frequencies to match the attenuation of the least attenuated frequencies, using a DSP. By doing so, higher maximum uniform attenuation can be achieved than what was possible without the active system. Another advantage is the adjustability of the attenuation: using the DSP, the level of uniform attenuation can be adjusted by the user depending on his or her needs. Thus, in the case presented in Fig. 12, uniform attenuation values could range from about 19 dB to any defined lower attenuation bound, such as 6 dB, or even complete bypass of the HPD.

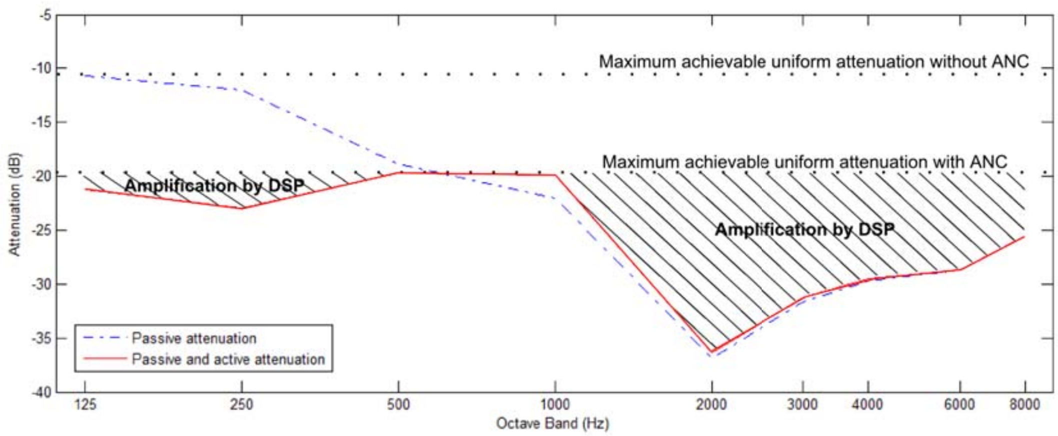

FIGURE 12: Example of achieving uniform attenuation: the dotted line shows the passive attenuation, measured on a human subject, of a potential candidate earplug that could host the prototype. The solid line shows that the experimental active attenuation from Fig. 11 added to the passive attenuation would enable the increase of the maximum achievable uniform attenuation of the hearing protector. Starting from the solid line curve, frequencies lacking intensity could be amplified at the user's ear, using the external microphone, the DSP, and the internal speaker. The maximum uniform attenuation curves achievable by using this method are shown in dotted lines. The figure shows how the active solution would help increase the maximum achievable uniform attenuation.

Conclusions

Musicians still face drawbacks when trying to protect themselves from overexposure to sound. The occlusion effect and isolation effect can discourage musicians from wearing HPDs. Both effects could jeopardize musicians' performance, by altering the auditory perception on which they rely. In this paper, solutions to both effects have been presented, as well as a complete system architecture capable of accounting for these effects. An occlusion effect reduction system was designed, implemented, and preliminary characterization of the performance has been achieved. Preliminary performances are promising, and further validation on a greater number of human subjects is to be done.

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