Measurements on active earplugs and effect of ear canal resonances on spectral balance

Tapio Lokki
Department of Computer Science, Aalto University School of Science, Espoo, Finland

Ilkka Huhtakallio
Department of Signal Processing and Acoustics, Aalto University School of Electrical Engineering, Espoo, Finland

Summary
Modern earplugs have active components, which enable frequency dependent and non-linear signal processing for different purposes. One recent development is the introduction of active earplugs that limit high level signals, but convey reasonable level sound as such to the eardrum. Such earplugs are marketed in particular for musicians, as active earplugs would allow to hear quiet music naturally and hearing protection is active only in loud passages. In this paper, we present the measurements of one such active earplug with a pinnae and ear canal simulator. The simulator has a miniature microphone replacing the eardrum and the ear canal and pinnae are made from plastic. The measurements consisted of open ear canal, blocked ear canal with active earplug, and the same earplug with the active circuit switched off. The presented results indicate that although the active earplugs work well by limiting high level sound, they color the sound significantly. The main coloration comes for the fact that the measured active earplug does not compensate the differences between open and blocked ear canals. Therefore, this active earplug does not sound natural at any sound pressure level.

PACS no. 43.66.Vt, 43.50.Hg

1. Introduction

The hearing losses of the symphony orchestra musicians have been studied more and more in the recent years. The studies show that in particular the musicians sitting close to the loudest instrument groups (brass and percussion instruments) suffer more often hearing problems and they should use hearing protection in their occupation [1, 2, 3]. However, passive earplugs are not convenient for non-amplified music. Although, with careful design and individual fitting such earplugs could reduce the level of all frequencies about the same amount, the problem of hearing low levels remain. That makes ensemble playing difficult.

Recently, some earplug manufacturers have released adaptive noise reduction earplugs for musicians. Such an earplug has a microphone, an electronic circuit and a small earphone to enable automatic adjustment of the sound levels. In other words, the adaptive earplugs let the low level sound to be heard, but when the sound level raises the plug limits the levels to a certain level. This sounds really promising technology for musicians who want to hear naturally and need protection when hearing is at risk. Moreover, adaptive earplugs make it unnecessary to remove earplugs at silent passages.

The adaptive noise reduction earplugs should sound as natural as possible because musicians want to hear other instruments without coloration. As such devices are quite new, we found only one recent study [4] that reports some measurements and usability tests. In that study 26 musicians tested such earplugs for at least four weeks. Musicians generally preferred the devices to previous earplugs, but they also identified issues including difficulty with orchestral balance, perception of dynamics and quality of sound provided by the devices. To understand better, why the quality of sound was criticized, we measured one novel active earplugs in an anechoic room. The measurements were performed with an ear simulator—consisting of plastic models of a pinnae and an ear canal— to understand how the sound spectral balance is changed with adaptive earplugs. Note that the measurements were more like "hi-fi" type of ad-hoc measurements. We also want to emphasize that the measurements are purely experimental and do not follow to any standards. However, we hope that the presented results give information to developers of such active earplugs.

Figure 1. The measurement setup in an anechoic chamber, the distance between the loudspeaker and the ear simulator is 2m.

2. Resonances of the open and closed ear canals

Sound enters the ear canal and propagates as a plane wave towards the tympanic membrane. Most sound reflects back from the membrane and returns back towards the open end to be reflected again from the open end. Thus, the traveling waves constitute resonances at frequencies, which depend on the length of the ear canal. An open ear canal is a tube closed in one end and open in another end, and the resonances of such a tube occur at frequencies

$$f_n = \frac{nc}{4L}, \tag{1}$$

where $n = 1, 3, 5, \ldots$ is an odd number, L is the length of the tube, and c is the speed of sound. Note that the L is the actual length of the tube. At ear canal the effective length increases due to a tapering termination of the ear canal at concha. In other words, at ear canal the concha makes the tube typically a bit longer effectively.

When the ear canal is closed with the ear plug the tube is closed at both ends, thus the resonances occur at frequencies

$$f_n = \frac{nc}{2L}, \tag{2}$$

where $n = 1, 2, 3, \ldots$, and L is the length of the tube.

To summarize, when an ear canal is closed with the earplug the resonant frequencies are changed compared to the normal situation (an open ear canal).

3. Measurement equipment

The measurements were done in the large anechoic chamber of the Aalto University, Finland. The measurement setup consisted of a Genelec 8030 active

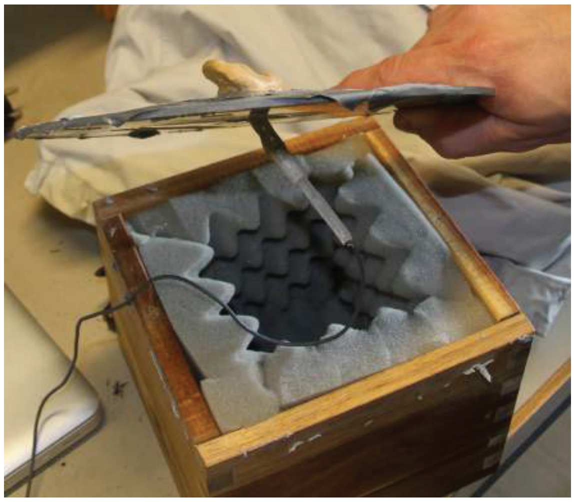

Figure 2. The used ear simulator. The ear canal is made of a plastic tube and the microphone is in the end of this tube at the position of the tympanic membrane.

loudspeaker and an ear simulator at the distance of two meters, see Fig. 1. The custom made ear simulator is a wooden box that has on one side both a pinnae and an ear canal, see Fig. 2. The microphone (Knowles FG 23329) is mounted in the end of the ear canal at the position of the tympanic membrane. Thus, the ear simulator mimics well the structure of the human outer ear and enables to study acoustics of both open and blocked ear canals.

The measurements were performed by measuring impulse responses with FuzzMeasure Pro 3 software [1] using a logarithmic sweep as an excitation. The measurement setup was kept constant at all measured cases, i.e., different earplugs, as illustrated in Fig. 3. Moreover, the adaptive earplug was measured with three different options, *OFF, -9 dB* or *-15 dB* settings.

4. Responses of the open and plugged ear canal

In each case (open or plugged ear) the impulse responses were measured with 5 different levels. The A-weighted sound pressure levels of the measurement signal were at 6dB steps: L_{AS} = 63, 69, 75, 81, and 87 dB. The reading of the slow A-weighted sound pressure (L_{AS}) level was monitored during the 4 second long full range sweep. The values given here corresponds the maximum readings that occurred during the excitation of mid band frequencies. The sound pressure level was measured at the location, but without the presence, of the artificial ear. In the following analysis the responses are compared both in the time and frequency domains.

[1] http://www.fuzzmeasure.com/

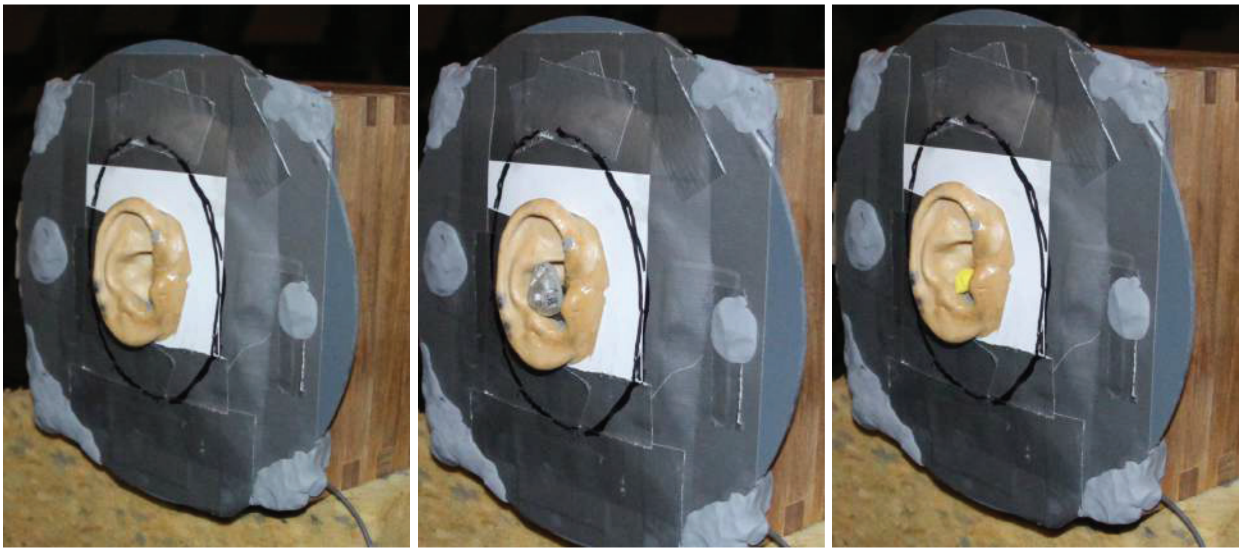

Figure 3. The measured earplugs. From left: open ear canal, active earplug, and standard EAR.

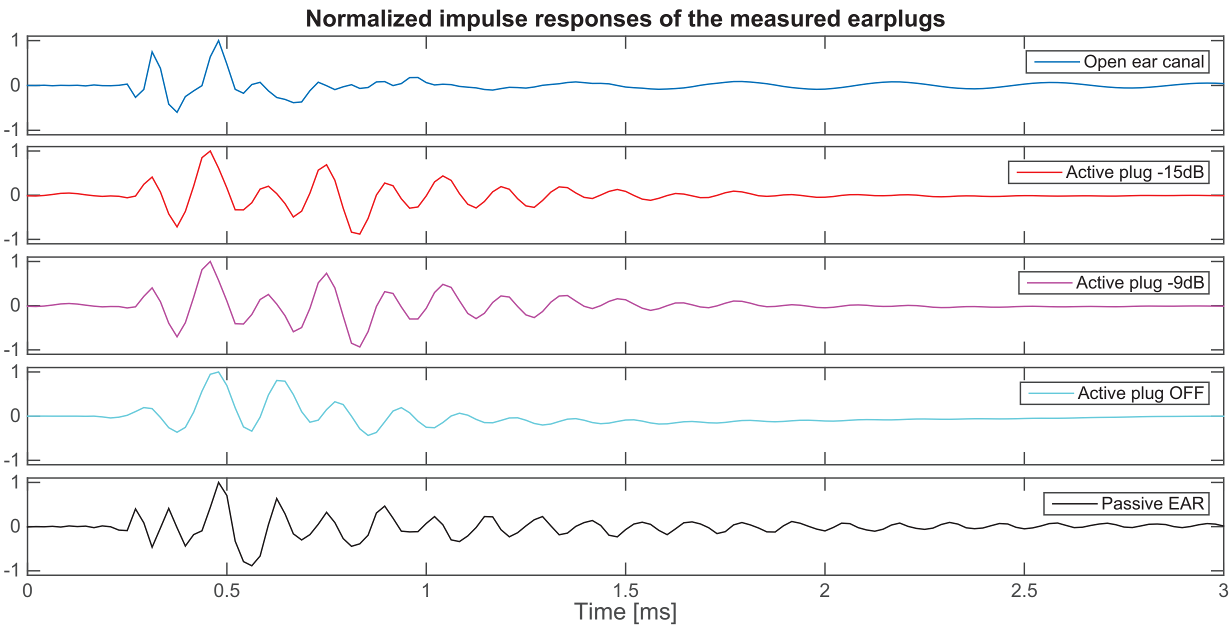

Figure 4. Early part of the measured impulse responses at $L_{AS} = 87$ dB.

4.1. Impulse responses

The beginning of the measured impulse responses are plotted in Fig. 4. The *open ear canal* response shows two clear peaks: the direct sound and a reflection from the open end. When the ear canal is blocked *Active earplug (all three cases)* more reflections can be seen as the direct sound is attenuated and earplug reflects sound more effectively than an open ear. In addition, it can be seen that the first reflection is a bit earlier than in the open ear case. It seems also that when the active circuit is switched OFF, there are less reflections, i.e., the active system increase the reflected energy.

4.2. Frequency responses at the loudest level

The frequency responses of different cases at the level of $L_{AS} = 87$ dB. are plotted in Fig. 5. The *open ear canal* response has resonances at 2512, 7527, and 12298 Hz, which correspond to $1/4\lambda$, $3/4\lambda$, and $5/4\lambda$ resonances of a tube open at one end (λ is wavelenght). According to Eq. 1, these corresponds 31.9, 31.9, and 32.6 mm long ear canal, respectively. The *Active earplug* (both -9 and -15 dB) has the main res-

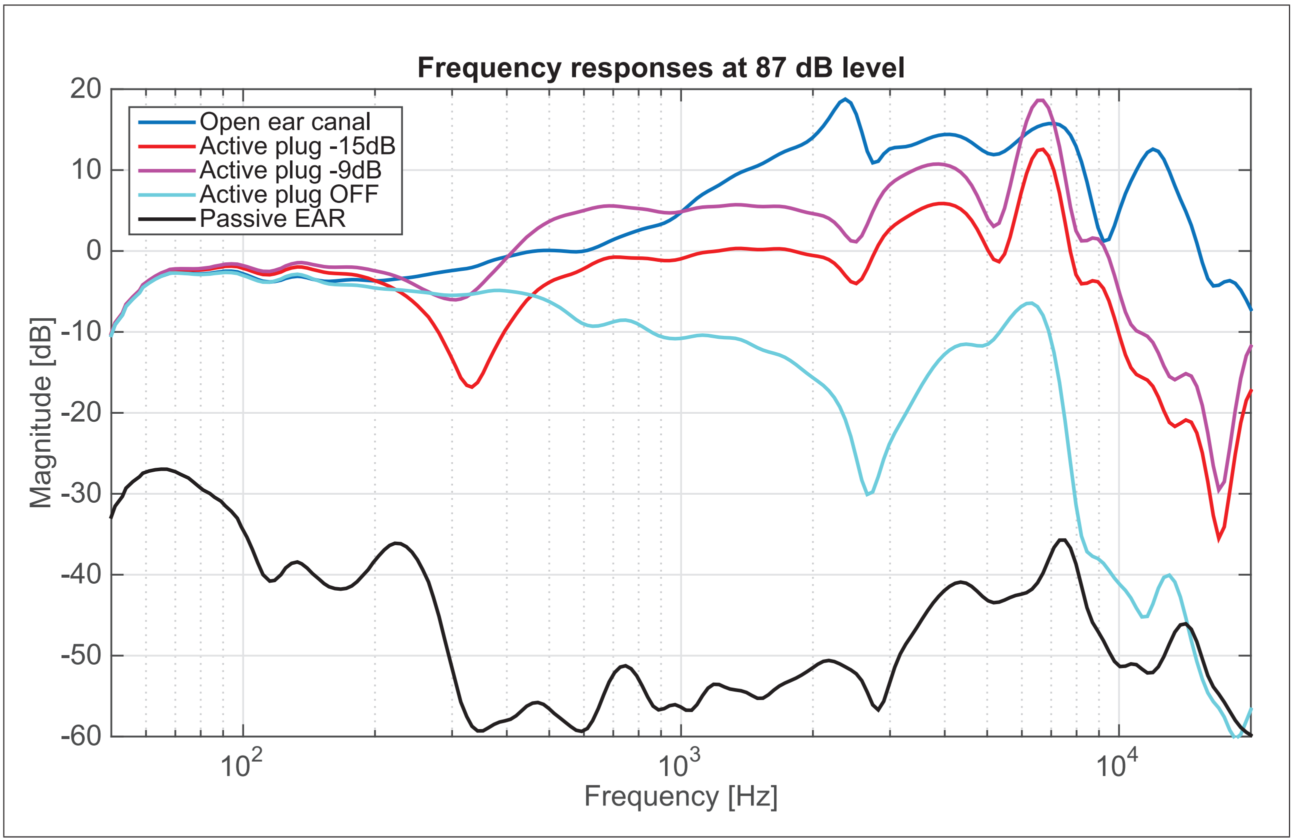

Figure 5. Frequency responses (1/3 octave smoothed) at the highest measurement level at L_{AS} = 87 dB.

onance at 6706 Hz, which corresponds to $1/2\lambda$, resonances of a tube of 25.6 mm (tube with both ends closed). The $1/1\lambda$ resonance is at 14210 Hz (equivalent to a tube of 24.1 mm). Moreover there is a strong dip at 2512 Hz, which is at the same region as the $1/4\lambda$ resonance of the open ear canal. When the active circuit is switched off, the $1/2\lambda$ and $1/1\lambda$ resonances are clearly visible, although slightly at different frequencies: 6515 and 13029 Hz resulting in 26.3 and 26.3 mm ear canal, respectively. Finally, the resonances with the *Passive EAR* are at 7747 and 14625 Hz resulting in 22.1 and 23.5 mm ear canal lengths.

The above analysis shows that the measurements are well in line with the theory. The ear canal length seems to be about 30 mm and the different earplugs shorten the ear canal depending on the depth they are positioned. In our measurements, the *Passive EAR* was easy to put quite deep to the ear canal, deeper than the *Active earplug*. Moreover, when switching the active circuit off the plug had to be removed and put back in the ear, and it seems that the positioning has 1 mm difference between measurements.

5. Differences of open ear canal and plugged ear canal with different earplugs

Based on the frequency responses, it is evident that the *Active earplug* completely ignores the changes in acoustical resonances of the ear canal. Moreover, the active earplug seems to amplify some frequency regions. In the optimal case the frequency response with the earplug should not modify much the shape of the open ear canal response. Therefore, it is interesting to look at the differences in the frequency response to understand how much the spectral balance is changed due to the earplugs.

First, we illustrate the effect of passive plugs. Figure 6 shows the differences of open ear canal and passive earplug responses. The active plug (option OFF) obviously leak the low frequencies as they are not touched at all. This might be due to bad fitting of the earplug to the simulator, however similar results are also presented by other researchers [4]. At above 400 Hz the earplug starts attenuating sound regardless of the measurement level, as expected. However, due to the changed ear canal resonances the attenuation curves have some peaks and valleys and the blocked ear canal resonance around 6 kHz is pronounced. The *passive EAR* attenuates almost 50 dB at mid and high frequencies. With the ear simulator

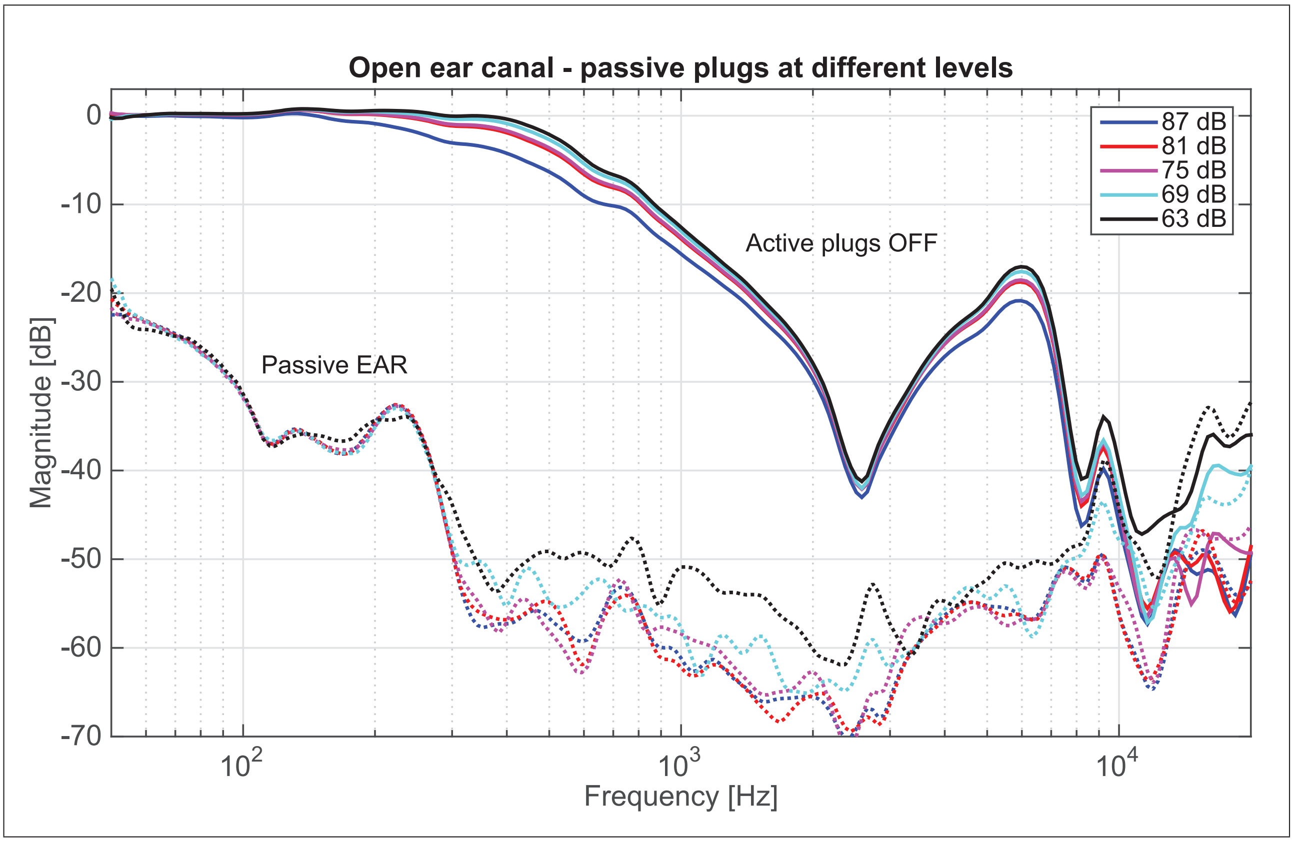

Figure 6. Frequency responses (1/3 octave smoothed) of the difference between open ear canal and passive earplugs.

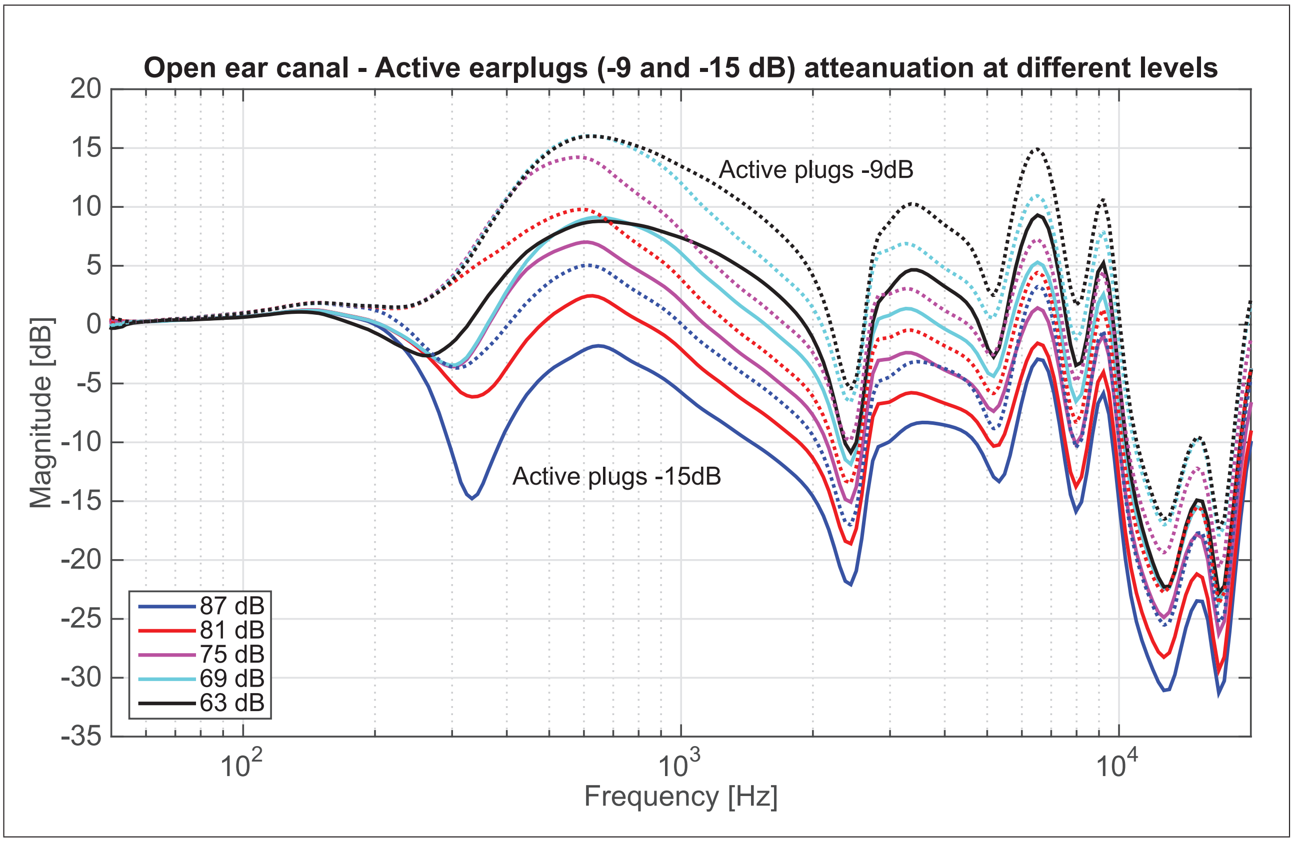

Figure 7. Frequency responses (1/3 octave smoothed) of the difference between open ear canal and active earplugs.

it was relative easy to put the EAR deep to the ear canal simulator, thus the very high attenuation. At the lowest measurement level the background noise limit was reached and therefore the curve of 63 dB differs from others.

The most interesting comparison is between the open ear canal and the active earplug responses, plotted in Fig. 7. Again the low frequencies are not changed, but between 300 and 2000 Hz the plugs clearly amplify sound. Between 400-1000 Hz only -15dB setting at the highest measurement levels do not amplify sound. In addition, the active circuit introduces peaks and dips to the responses, mainly at resonant frequencies of the ear canal.

5.1. Discussion

Based on the objective measurements the active earplug acts as a dynamic compressor by limiting at higher levels, but is change radically the spectral balance of the sound. Our informal listening confirms the measurements. When plugs are used the sound is unnaturally bright, maybe due to pronounced frequency regions 3-5 kHz and around 7 kHz. In addition, the low frequencies sound weak as the spectral balance is not low-passing as usual with passive earplugs (see Fig. 6). Finally, we noticed some distortion with very high level, i.e., when playing drums and hitting the symbals.

6. Conclusions

The idea of dynamic compression of active earplugs is good, but the current implementation totally ignore the acoustics of the ear canal. With an ad-hoc measurements, we show here that normal open ear canal resonance is killed when the ear canal is blocked with the earplug. Moreover, the blocked ear canal introduced strong resonance at 6-7 kHz, which is not attenuated with the active circuit. Therefore, we confirm the earlier study, which found that active earplugs color the sound unnaturally. Our subjective impressions, when testing the earplugs support the measurement findings and the too bright sound of active plugs might not be liked by musicians. Finally, we hope that our results help the developers of such active earplugs to make more natural sounding devices in the future.

References

[1] E. Toppila, H. Koskinen, and I. Pyykkö. Hearing loss among classical-orchestra musicians. *Noise & Health*, 13(50):45–50, 2011.

[2] F. A. Russo, A. Behara, M. Chasinc, and S. Mosherd. Noise exposure and hearing loss in classical orchestra musicians. *International Journal of Industrial Ergonomics*, 43(6):474–478, 2013.

[3] I. O'Brien, W Wilson, and A. Bradley. Nature of orchestral noise. *Journal of the Acoustical Society of America*, 124(2):926–939, 2008.

[4] I. O'Brien, T. Driscoll, W Williams, and B. Ackermann. A clinical trial of active hearing protection for orchestral musicians. *Journal of Occupational and Environmental Hygiene*, 11(7):450–459, 2014.