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Experimental evaluation of earplug behavior in front of high-level impulse noises.

Cyril Blondé-Weinmann[1,2,*], Thomas Joubaud[2], Pascal Hamery[2], Sébastien De Mezzo[2], Véronique Zimpfer[2], Sébastien Roth[1].

[1]Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS/Univ. Bourgogne Franche-Comté, France.

[2]Acoustics and Soldier Protection, French-German Research Institut of Saint-Louis, 68300 Saint-Louis, France.

[*]cyril.blonde-weinmann@isl.eu

Abstract

High-level impulse noises such as weapon noises or mine charges can cause irreversible damage to the hearing system. Hearing protectors are used to reduce airborne sound propagation. However, the resulting attenuation of protectors worn singly or in combination is limited and may be insufficient in some extreme situations. One reason for these limitations is the behavior of the protectors under high stresses. For example, high-level impulse noises could induce a slight earplug movement in the ear canal. In order to quantify this effect, a new experimental set-up with an artificial simplified ear canal is developed. Thus the earplug movements are measured with a laser Doppler vibrometer and a high-speed camera under various configurations (high-impulse stimulation levels, ear canal lengths, earplug adjustments, and positions). These investigations highlight relative displacements that can exceed one millimeter and modify the final earplug position in the ear canal. The observed effects could be responsible for an alteration of the protection efficiency. New hypotheses are formulated to limit these phenomena and improve hearing protectors.

Keywords: high-level impulse noise, hearing protection, earplug.

1 Introduction

Prolonged exposure to high-level noises can irreversibly damage the sensory cilia of the organ of Corti and result in varying degrees of hearing loss. Alone or in combination with continuous high-level noise, impulses can cause more injuries to the auditory system [1]. There are many sources of impulse noises, such as gunfires, explosions, and landmines. These are defined by their maximum peak pressure and A-duration (positive phase duration), two characteristics that reflect their danger. Indeed, the greater the amplitude, the more harmful the consequences on the hearing system. In addition, the impulse duration is also decisive since it can reach the inner ear by supplanting the stapedius reflex [2]. It is conventional to use hearing protectors to occlude the ear canal external meatus to attenuate the direct air propagations. However, this protection is partial since it provides only a limited attenuation depending on the type of occlusion and the stimulation characteristics [3]. The addition of a second protector does not always improve the protection [4] which gradually erodes the idea that waves propagate only through air paths. Therefore, imperfect ear canal occlusion is not the only source of hearing protection limitation. The tissue conduction by the skin [5], the bones [6], or the cartilages [7] are, for example, as many paths taken by the waves. It then activates mechanisms of hearing at the origin of an auditory perception [8] by loading the hearing protection environment. In addition, some of the hearing protectors' limitations could result directly from the protection behavior itself. Indeed, depending on the impulse characteristics, passive protectors can adopt structural non-linearities, which make their behaviors difficult to apprehend [9]. For instance, in the case of high-level impulses, it has been demonstrated that earmuffs act as acoustic antennas by capturing the waves and retransmitting them to the external ear tissues [10]. This could partly explain the insufficiency of the earmuffs worn alone for the protection against impulse noises [11]. Similarly, earplugs could also carry consequences, perhaps even more critical because of their positioning close to the eardrum. Indeed, the induced ear canal walls displacement resulting from earplugs [12] are in favor of waves transmissions through the secondary acoustic paths. This paper will study the earplug behavior using a simplified Artificial Ear Canal (AEC) and a laser Doppler vibrometer (LDV). Although this measuring device can provide accurate results, the context of impulse noise makes the operations difficult because of the diverse signal alterations. The protocol presented in this study lists these alterations and proposes an adapted methodology. A comparison with a high-speed camera (HSC) is performed to compare the results. Besides, the various situations considered allowed to evaluate the influence of the plug's initial position, its adjustment, the length of the ear canal, and the incident impulse level.

2 Materials and methods

2.1. High-level impulse noise generation

Impulse generation using loudspeakers does not achieve the levels encountered by military personnel, which may reach a 190 dB peak. In this study, the impulse waves were generated using explosive charges. Indeed, the use of explosive detonation has the advantage of generating impulses whose characteristics (peak level and A-duration) will depend on the weight of the charge and the distance. It allows an adjustment to obtain the required amplitude. The earplug's behavior has been studied in the case of impulses of 172 and 176 dB peaks. In Table 1, the different explosive charges (mass and type), as well as the distances for the impulse waves generation, are described for these two levels. The resulting temporal pressure evolution after the impulse is shown for both loads in Figure 1.

Table 1: Required type and mass of explosive charge and distance between the explosive charge and the measurement point.

Peak pressure level [dB]	Charge masse [g]	Charge type [-]	Charge distance [m]
172	70	$C4$	7.0
176	220	$C4$	7.0

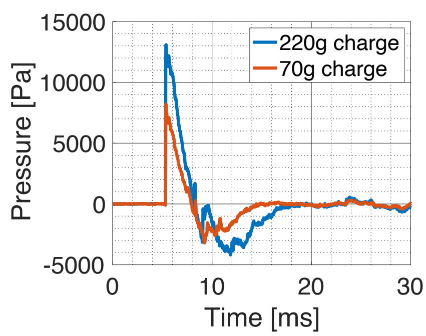
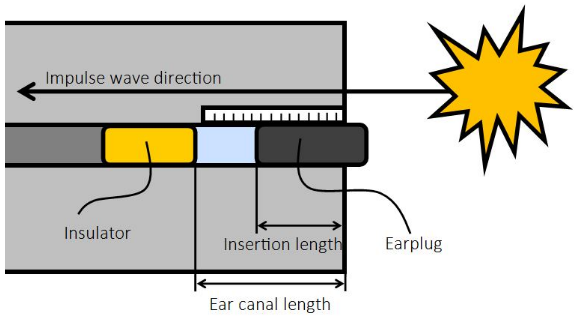


Figure 1: Pressure variations at 7.0m for a 70g and 220g C4 charges.

2.2. Earplug displacement visualization in simplified ear canal

It would be difficult to visualize the longitudinal earplug movement in the ear canal of an artificial head (acoustic test fixture). For this reason, an experimental device was built to make the plug movement visible. A transparent artificial ear canal of 24.7 cm in length and 8.05 mm in diameter is used to allow measurements under various conditions of lengths. In particular, it was desired to evaluate the displacement of the plug without pressure constraints resulting from a closed air volume while limiting the propagation of the wave on the opposite side of the occlusion. The device is presented in Figure 2a. The simplified cylindrical geometry of this artificial ear canal cannot be held as an exact representation of reality. However, numerical simulations in the frequency domain have shown a limited impact for the 1.5-4 kHz frequency range. Outside this range, the consequences are negligible [13]. As the frequency spectrums of the impulses used in this study are mostly low frequencies (under 1 kHz), this simplification can bring first relevant elements compared to a human ear canal. This geometry also respects the intention to recreate an axisymmetric numerical model of the experiment. The material used to manufacture the canal is plexiglas®. Its thickness is 2.2 mm. The use of rigid material is justified by the will to limit secondary acoustic conductions, in particular, the canal deformations following the shock wave, although they are inevitable for very high-level impulses. The canal is inserted in polyethylene support to limit lateral stresses from the impulse side. The insulation with the vibrations propagated by the ground is made with a layer of polystyrene. A part of the artificial ear canal is exposed to measure the earplug displacements visually. The differences with an artificial head are related to the coupling between the plug and the canal due to the materials and possible effects of the pinna, not transcribed here. A 3M E-A-R Classic acoustic foam plug is used as an insulator to limit the ear canal length. The displacement is measured in the direction of the propagating impulse wave. These designations are presented schematically in Figure 2b.

(a) AEC photography.



(b) AEC schematic representation.

Figure 2: AEC and corresponding study lengths designations.

2.3. Earplug displacement measurement

Two measuring devices capture the longitudinal earplug's motions. A high-speed camera PHOTRON SAZ with a 50 kHz sampling frequency is positioned face to the uncovered lateral side of the artificial ear canal. An OPTOMET SWIR laser Doppler vibrometer with a 51.2 kHz sampling frequency points at the base of an Acrylonitrile Butadiene Styrene (ABS) earplug made in our laboratory and records the motion velocity of the earplug in the AEC axis with a dynamic range of 245 mm/s. The measurement of the impulse noise with the LDV requires to take into account the superposition of various signals:

- the perturbation of the impulse wavefront entering the laser measuring field with the duration of the initial impulse;
- the useful signal, i.e., the actual displacement of the plug measured by the vibrometer, also approximatively of the initial impulse duration;
- the disturbance of the LDV body by the impulse that can last longer because of the induced mechanical vibrations and the duration of the dispersion;
- The involuntary reflections of the environment (as ground reflection for instance) that have a limited impact on the measurement of the plug displacement due to energy dissipation.

To avoid a superposition of these signals, it is essential to distribute sensors, source, and target so that each perturbation intervenes separately in time. Therefore, the propagation time and duration of each perturbation must be taken into account. A measurement of the perturbations resulting from the disposition shown in Figure 3 is given in Figure 4. For example, the beginning of perturbation 1 corresponds to the propagation of distance d_1, which value is given in Table 2.

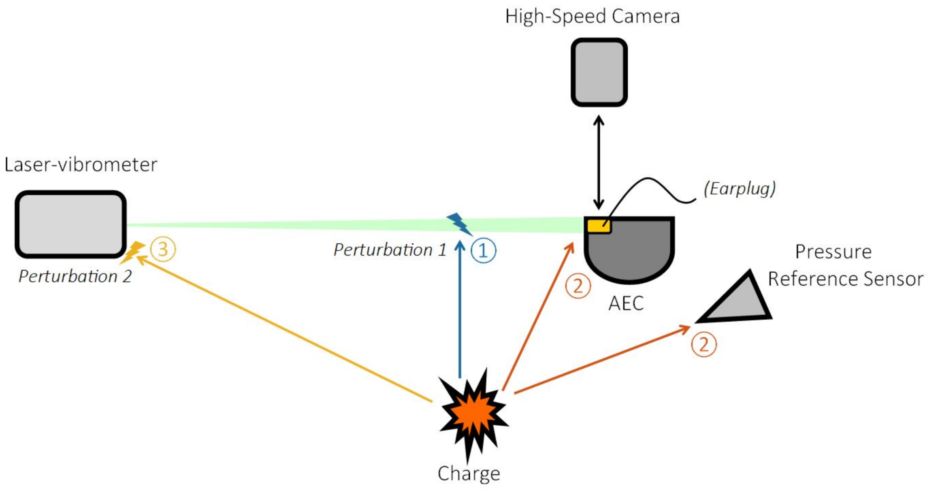


Figure 3: Positioning of the source, ear canal and sensors. The pressure reference sensor was manufactured in our laboratory from a KISTLER-6031 quartz sensor.

The distances between the sensors considered and the signal obtained with the laser vibrometer are explained respectively on the Figure 4 and the Table 2.

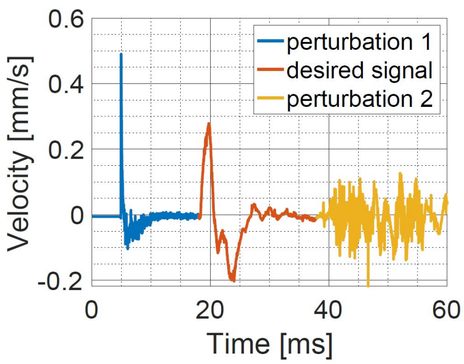


Figure 4: Velocity measured with the LDV with the distances between the sensors considered in the Table 2 allowing for a disambiguation of the perturbations and desired signals.

Table 2: Distance and approximate time from which the perturbation would be visible on the measurement signal of the laser vibrometer.

Distance name [-]	Distance value [m]	Approx. prop. duration [ms]
d_1	2.0	6
d_2	7.0	20
d_3	14.1	41
d_4	20.7	–

2.4. Configurations studied

(a) Comparative study between the laser Doppler vibrometer and the high-speed camera tracking

First, a comparative study between the displacement of an 8.05 mm diameter ABS plastic earplug measured with the LDV and with the HSC was carried out in order to compare the obtained results. The LDV allows a temporal evaluation of the earplug's position. In contrast, the HSC snapshots evaluation aims to evaluate the plug's extreme positions (initial position, maximum insertion, maximum extraction, and final position). This is due to the displacement measurement accuracy, which is much coarser with the HSC than with the LDV. To do this, four iterations of the shooting protocol for an open ear canal and four iterations for a 22.5 cm length ear canal were performed. It was assumed that the longer canal involved higher pressure variations and would less damped plug displacements. Thus, it would allow better visualization of the displacements on the HSC whose accuracy is lower than the LDV and about 0.2 mm.

b) Behavior of the plug under different conditions

To visualize the effects of various mechanical and physical conditions on the earplug's movement, three sets of measurements were performed:

- the initial position influence of an adjusted plug protector in the case of an open artificial ear canal was studied. Two measurements were performed: a measurement with a plug totally inserted (inserted condition) and a measurement mostly extracted from the canal (partially inserted condition).
- Another series of measurements were realized with a 3 cm length artificial ear canal with two different earplug diameters. One measurement was performed with an adjusted earplug of 8.05 mm diameter and a second with a non-adjusted plug of 8.00 mm diameter.
- Last but not least, the incidence of the impulse peak level on the earplug behavior was also evaluated. For an 8.05 mm diameter earplug and a 3 cm length artificial ear canal, 172 dB-peak, and 176 dB-peak levels were studied.

3 Results

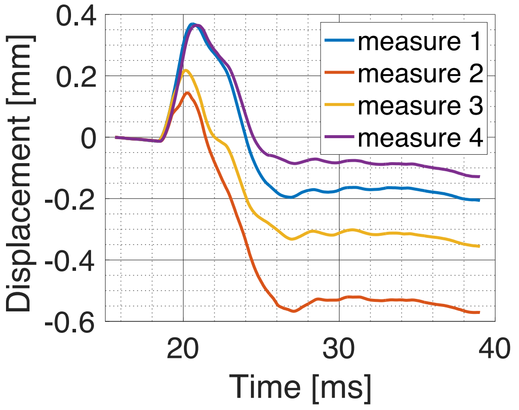
3.1. Comparative study between the laser vibrometer and the fast camera tracking

a) Open artificial ear canal

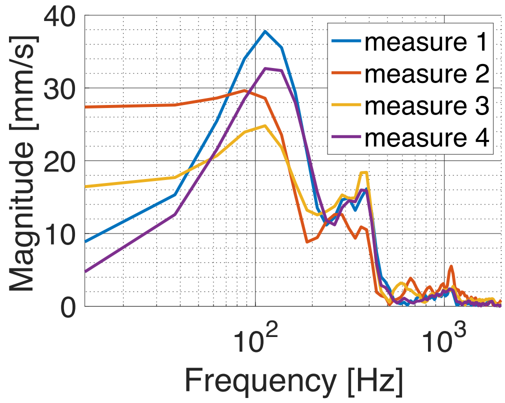
The time displacement and spectral velocity of an 8.05 mm diameter ABS earplug for four 172dB-peak charge iterations with an artificial open ear canal are presented in Figure 5. The earplug's positions (maximal insertions and extractions as well as final positions) determined with the HSC for each iteration and its comparison with the LDV measurement are listed in Table 3. As the initial positions of the earplug were different for each iteration, they were also reported in the same table. It can be observed that the behavior of the earplug respects a similar evolution for the four measurements. However, significant variations of the maximum insertion (extreme values measured 0.14 mm and 0.37 mm) and the final relative position (extreme values measured -0.09 mm and -0.53 mm) appear. Nevertheless, the variations between the maximum insertion and maximum extraction displacement (extremum distance) remain globally constant for all measurements. The spectral representations in Figure 5b highlight a displacement velocity concentrated mainly at low frequencies with two remarkable spectral densities at about 0.1 kHz and between 0.3 and 0.4 kHz corresponding to the resonant frequency of the open canal that appears theoretically at 345 Hz.

Table 3: Comparison between the HSC relative displacements and LDV measured relative displacements for the open ear canal configuration. Positive values correspond to a displacement in the propagation direction of the impulse wave.

Measurement	Measurement 1		Measurement 2		Measurement 3		Measurement 4	
Initial insertion [mm]	17.4		17.2		19.5		17.0	
Sensor	HSC	LV	HSC	LV	HSC	LV	HSC	LV
Relative maximal insertion [mm]	0.4	0.37	0.1	0.14	0.2	0.22	0.4	0.36
Relative maximal extraction [mm]	−0.2	−0.20	−0.5	−0.57	−0.3	−0.33	−0.1	−0.09
Relative final position [mm]	−0.2	−0.16	−0.5	−0.53	−0.3	−0.32	−0.1	−0.09
Extremum distance [mm]	0.6	0.57	0.6	0.71	0.5	0.55	0.5	0.45



(a) Time displacement



(b) Spectral velocity

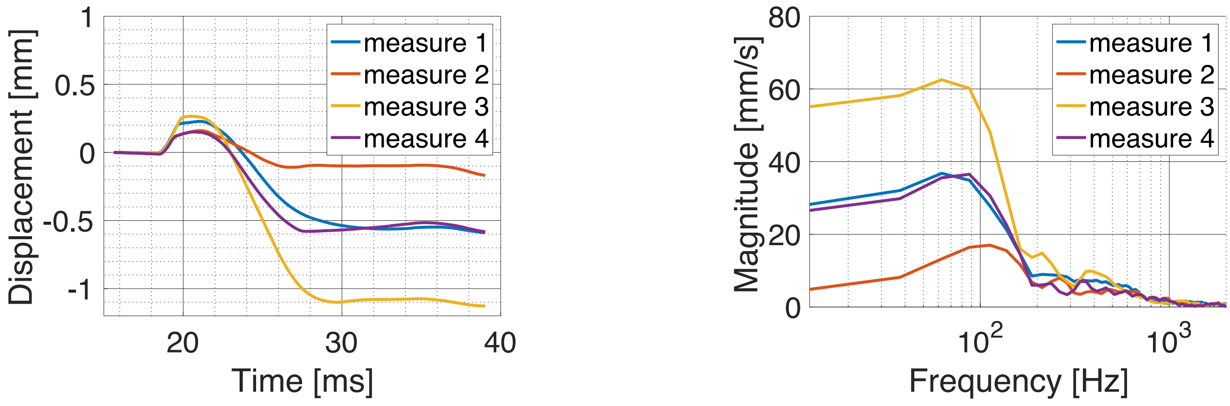
Figure 5: LDV measurement for an artificial open ear canal, 8.05 mm diameter ABS earplug, and 172 dB-peak pressure impulse level stimulation. Positive values correspond to a displacement in the propagation direction of the impulse wave. HSC values are listed in Table 3.

b) 22.5 cm length closed artificial ear canal

The time displacement and spectral velocity of an 8.05 mm diameter ABS earplug for four 172dB-peak charge iterations with an artificial 22.5 cm length closed ear canal are presented in Figure 6. The ear canal is closed with a foam earplug on the lateral side in this configuration. The positions of the earplug determined with the HSC for each iteration and its comparison with the LDV measurement are listed in Table 4. Again, the earplug movement evolution remains the same for all measurements, but very significant variations appear for the same configuration. Suppose the relative insertion has a certain reproducibility from one measurement to another (extreme values measured of 0.27 and 0.15 mm). In that case, especially the final position differs significantly (extreme values measured of -0.10 and 1.08 mm). These final position variations corroborate the spectral behavior of the displacement velocity at low frequencies, as presented in Figure 6b. Then, the extreme distances in this configuration are not reproducible. Besides, no correlation between the earplug's initial position and the earplug's final position seems to be sketched. It is also remarkable that occlusion on the opposite side of the artificial canal leads to suppressing the spectral components above 0.2 kHz. Comparisons between the values measured with the LDV and the HSC allow finding consistent results between the two methods. The differences between the two sensors are contained within the measurement uncertainties of the HSC (± 0.2 mm).

Table 4: Comparison between the HSC relative displacements and LDV measured relative displacements for the 22.5 cm length closed ear canal configuration. Positive values correspond to a displacement in the propagation direction of the impulse wave.

Measurement	Measurement 1		Measurement 2		Measurement 3		Measurement 4	
Initial insertion [mm]	15.7		16.1		15.1		17.2	
Sensor	HSC	LV	HSC	LV	HSC	LV	HSC	LV
Relative maximal insertion [mm]	0.3	0.23	0.2	0.16	0.3	0.27	0.2	0.15
Relative maximal extraction [mm]	−0.5	−0.56	−0.1	−0.11	−0.9	−1.10	−0.6	−0.58
Relative final position [mm]	−0.5	−0.55	−0.1	−0.10	−0.9	−1.08	−0.5	−0.52
Extremum distance [mm]	0.8	0.79	0.3	0.27	1.2	1.37	0.8	0.73



(a) Time displacement

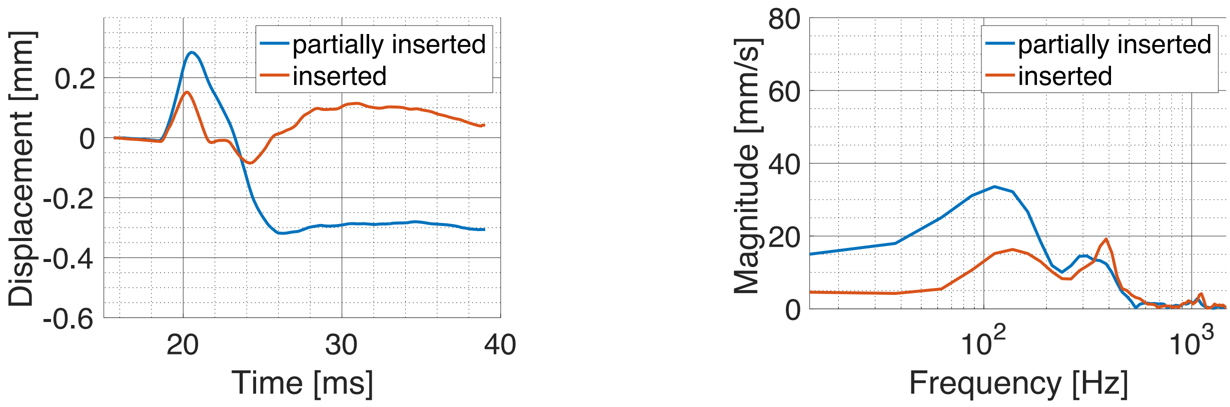
(b) Spectral velocity

Figure 6: LDV measurement for an artificial 22.5 cm length closed ear canal, 8.05 mm diameter ABS plug, and 172 dB-peak pressure impulse level stimulation. Positive values correspond to a displacement in the propagation direction of the impulse wave. HSC values are listed in Table 4.

3.2. Behavior of the earplug under different conditions

a) Influence of earplug initial position

The time displacement and spectral velocity of an 8.05 mm diameter ABS earplug for four 172dB-peak charge iterations with an artificial open ear canal are presented in Figures 7. The "inserted" condition corresponds to a total insertion of the earplug, i.e., 2 cm: only the lateral flat face of the earplug is exposed to the impulse wave. The "partially inserted" position refers to the insertion of two-thirds, i.e., 1.2 cm. The behavior is very different for the two initial positions. The "partially inserted" condition leads to an almost two-times higher insertion. Above all, the final position of the plug is approximately -0.3 mm extracted from the initial position. The "inserted" condition performs an in-out-in oscillation before reaching a final position slightly more inserted than the initial one (less than +0.1 mm). The spectral velocity represented in Figure 7b is also very different, with much lower low-frequency components for the "inserted" condition and a remarkable spectral peak at 0.4 kHz more accentuated than for the "partially inserted" condition.



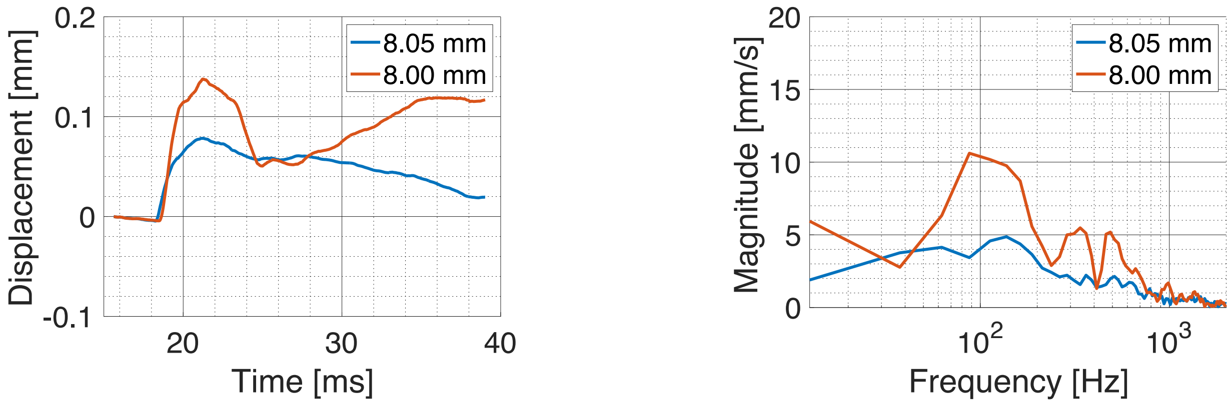
(a) Time displacement

(b) Spectral velocity

Figure 7: LDV measurement for an open ear canal, 8.05 mm diameter ABS earplug, and 172 dB-peak pressure impulse level stimulation for the two initial plug position conditions. Positive values correspond to a displacement in the propagation direction of the impulse wave.

b) Influence of earplug diameter

The time displacement and spectral velocity for two ABS earplug diameters (8.00 and 8.05 mm) on 172dB-peak charge stress with an artificial 3 cm length closed ear canal are presented in Figure 8. The 8.00 mm diameter plug that can move without constraint (except the gravity forces) in the artificial canal has a first insertion amplitude following the attack of the wavefront that is nearly 60% greater than that of the adjusted plug. Nevertheless, it is mainly the final position of the two earplugs that distinguishes them: the 8.05 mm diameter earplug tends to find a final position close to the initial position with insertion of 0.02 mm. In contrast, the 8.00 mm diameter earplug oscillates and tends towards an inserted position of 0.12 mm. The 8.00 mm diameter earplug has a higher spectral peak between 0.1 and 0.2 kHz than the 8.05 mm diameter plug, as well as additional peaks at 0.3 kHz and 0.5 kHz, as visible in Figure 8b.



(a) Time displacement

(b) Spectrale velocity

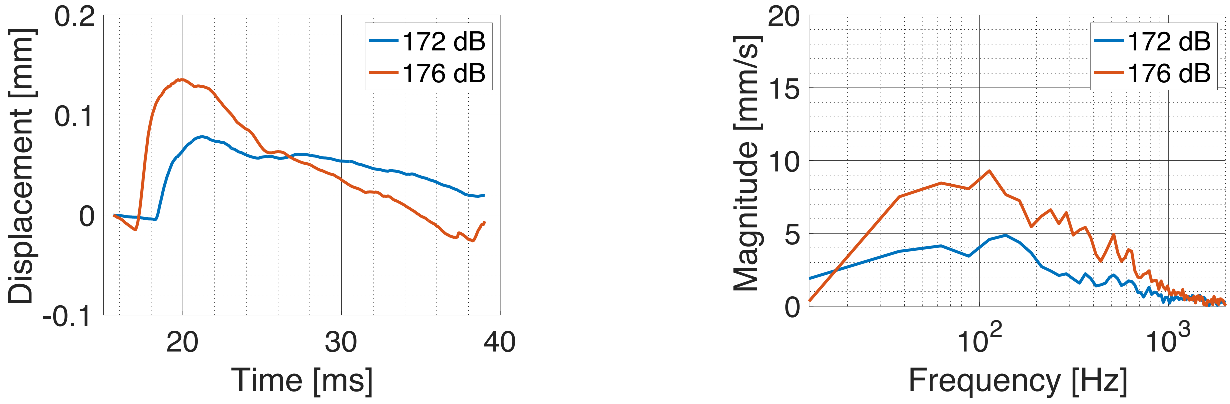
Figure 8: LDV measurement for a 3-cm length closed ear canal, two diameters ABS earplugs and 172 dB-peak pressure impulse level stimulation. Positive values correspond to a displacement in the propagation direction of the impulse wave.

c) Influence of the impulse peak level

The time displacement and spectral velocity for an 8.05 mm diameter ABS earplug under two different charge stresses (172 dB-peak and 176 dB-peak) with an artificial 3 cm length closed ear canal are presented in Figure 9. A 4 dB higher charge leads to 1.75 times larger insertion displacement. This displacement seems to constrain the earplug more. It tends to return to its initial position quicker, leading to a consequent extraction displacement for the 176 dB than the 172 dB charge (0.02 mm extraction displacement for 176 dB and 0.02 mm insertion displacement for 172 dB). The spectral velocity represented in Figure 9b does not show the appearance of significant peaks between the two charges. In general, the magnitudes between the two conditions appear only amplified.

4 Discussion

A new measurement protocol was used to evaluate the behavior of an earplug activated by a high-level impulse under different configurations. The results obtained with an HSC were compared to those acquired with an LDV. This comparison highlighted a good correspondence between the two methods. The advantage of LDV measurement is that it enables a more precise and accurate measurement than an HSC. This significant result makes it possible to consider measurements with the LDV when visibility required for the use of the HSC is not possible. However, it is necessary to judiciously place the sensors, target, and source on the experiment scheme



(a) Time displacement

(b) Spectrale velocity

Figure 9: LDV measurement for a 3 cm length closed ear canal, 8.05 mm diameter ABS earplug and two dB-peak stimulation condition. Positive values correspond to a displacement in the propagation direction of the impulse wave.

to avoid the superposition of undesired disturbances on the desired signal. Besides, these comparisons have also highlighted a significant disparity between the measurements under the same configuration. If the extreme position displacements are small in an open canal, this situation is not encountered in the case of a 22.5 cm occluded canal. The initial position of the plug could have explained these variations. However, no correlation could be found for minor variations of this position. From a spectral point of view, these differences are also illustrated by low-frequency spectral components of different magnitudes for the displacement speed. These differences must be considered in the interpretation of the subsequent tests. For initial positions of the plug fully inserted and two-thirds inserted, the plug behaves significantly differently. A fully inserted plug appears to possess a more inserted final position, while a two-thirds partially inserted plug possesses a more extracted final position. This could be due to two combined reasons. The first could be the result of the mechanical impact of the wavefront. This part depends only on the depression degree of the plug. The second could result from the plug and ear canal surface conditions. Thus, the coupling between the plug and the ear canal appears to depend on the mechanical properties of the materials involved in the interaction. Further studies on the materials and the impact of mechanical properties on the coupling would quantify these effects and limit the harmful consequences. In addition, it might be possible to design a geometry that limits the movement of the plug, in particular the insertion movement, which could result in an increase in pressure at the eardrum and a depression that would decrease the insertion of the plug. Incorporating fixation at the scaphoid fossa or tragus might be a practical option. The final position of the plug seems to be an important consideration: the outward displacement of the plug that occurs with a single impulse could be repeated with each impulse. It could be dangerous because of the effectiveness loss of the protector with a shallower insertion. This seems even more true when the plug is poorly adjusted, and the impulse is higher. Indeed, the earplug fitting is naturally a sensitive issue. A tight plug leads to less plug movement. However, this is multifactorial data with implications on both comfort and wave retransmission to the ear canal walls by solid conduction. Thus, a single consideration of the displacement is insufficient, and a global approach must be taken. These characteristics should be studied in more detail using a real geometry of an artificial canal (for example, with an acoustic test fixture, with a more realistic ear canal). Then a measurement of the pressure alterations behind the protection would quantify the dangers for the auditory system and highlight the main weakness of the protections.

5 Conclusion

A new measurement protocol using an LDV has made it possible to assess the displacement of a plug in an AEC during high-level impulses up to a 176 dB peak. After being validated by comparisons with an HSC, the experimental evaluation highlighted significant variations from one measurement to another and seemed to designate the plug-canal coupling as essential data in the protector movement. The impulse level, the plug adjustment, and the plug's initial position are all parameters that can negatively influence these movements. Further research is needed to quantify these earplug movements' impact on eardrum pressure. In parallel, modeling works are carried out to transcribe the observable phenomena and explain their origins and mechanical interactions.

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