TIME-DOMAIN NUMERICAL INVESTIGATION TO ASSESS NOISE REDUCTION ALLOWED BY A NON-LINEAR PASSIVE EARPLUG FACING IMPULSE NOISES.

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1 Introduction

On the battlefield, soldiers are regularly exposed to high-level impulse noises. These noises are characterized by a rapid and spontaneous acoustic pressure evolution. In order to allow communication between military personnel and situational awareness, Non-Linear Passive Earplugs (NLPE) were developed [1]. These devices provide an attenuation that increases with the impulse level. In this work, a NLPE integrating a filter composed of two perforates patented by the ISL in the 90s will be studied. This filter is present in protectors now widely used by several armed forces. To better integrate these filters in new earplugs' configurations (e.g., molded plug), the consequences on the protection's effectiveness of modifying the plug and filter geometry (length and diameters), material as well as the filter position in the protector are needed. In this context, numerical modeling appears to be a valuable tool. In this work, a time-domain finite-elements model of the acoustic phenomena resulting from high-level impulses on NLPE will be carried out with the software COMSOL Multiphysics 6.1 (© COMSOL Inc).

2 Finite Element Model

The model aims to simulate the non-linear effects arising from a high-level impulse noise propagating through the perforates of a NLPE inserted into an ear canal and the resulting acoustic pressure attenuation. Given the system's geometry, an axisymmetric approach was considered as a first approximation. The wave equation in the time domain was solved at each point of the discretized air domain. Thermo-viscous acoustic equations were also considered in the earplug and the ear canal, where viscous losses and dissipation due to thermal conduction become important. It allows to compute the transient evolution of acoustic pressure variations, velocity, and temperature, as well as non-linear effects as a function of time. To consider the reflection and absorption of acoustic waves at the interface of solid material parts (plug body, non-linear filter, deformable silicone plug, ear canal, and eardrum), impedance conditions were applied. The values were deduced from the considered material's sound velocity and density. The material properties used are summarized in Table 1.

An artificial air volume of 2 cm3 was added behind the plug to induce a compliance equivalent to the eardrum [2]. As an input for the model, the acoustic pressure measured during previous experimental campaigns at the ear canal entrance [3] was applied as an incident plane wave of 110 dB-peak and 150 dB-peak at the inlet. These levels were chosen to compare a situation where non-linear effects are negligible with one where they are significant. The resulting 2D axisymmetric model composed of 6 components is represented in Figure 1.

Table 1: Properties of the solid materials used in the model.

	Density (kg/m^3)	Sound velocity (m/s)
Silicone	1250	1485
Acrylic plastic	1030	2230
Skin	1100	1400
Eardrum	1200	1400

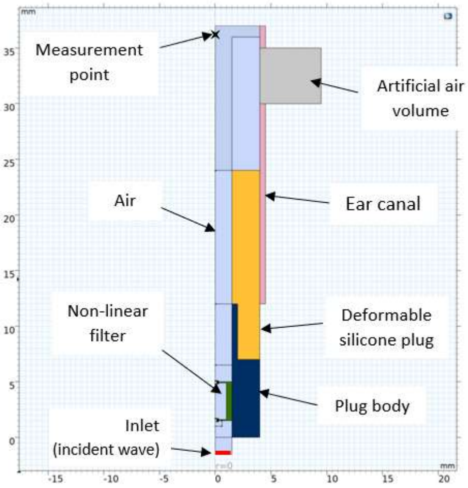

Figure 1: Geometry of the NLPE model.

The maximal resolution frequency was set to 15 kHz. Then, the mesh was built to have sufficient spacial discretization according to the minimum wavelength considered (at least five elements each). Local mesh refinements were made in areas where strong pressure gradients appear. To take into account boundary layers, a dedicated mesh refinement was applied on the orifice's surfaces. Thus, for each pressure level, a dedicated mesh was built. Finally, for 110 dB-peak and 150 dB-peak, the model has 50977 and 157753 degrees of freedom, respectively. The solver used was the generalized-α method with a maximal time step of 1.1 µs to respect the Courant–Friedrichs–Lewy condition. This method was chosen for its good accuracy and low numerical damping.

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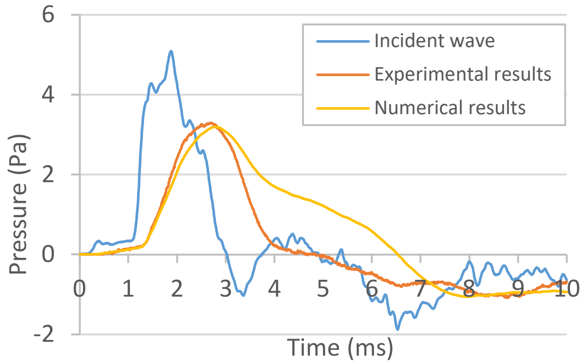
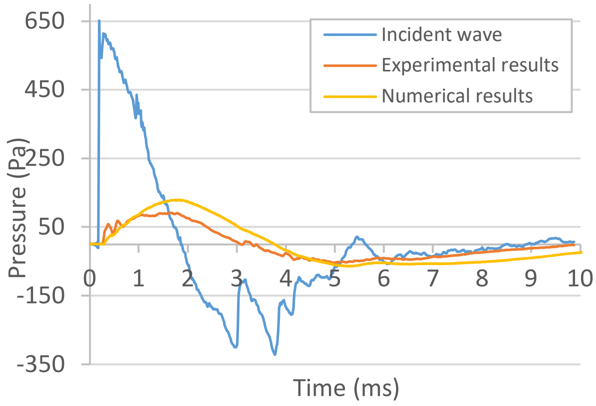
3 Results

The acoustic pressure history close to the eardrum (0.5 mm upstream) for a 110 and 150 dB-peak are shown in Figure 2. A comparison with results obtained with an Acoustic Test Fixture (ATF) from previous experimental campaigns is performed [1].



(a) 110 dB-peak



(b) 150 dB-peak

Figure 2: Comparison of numerical and experimental acoustic pressure measured at the eardrum when the NLPE faces high-level impulse wave of 110 and 150 dB-peak.

For an excitation of 110dB-peak, a good correlation of the peak pressure level can be observed. The pressure decay estimated numerically between 3.5 and 6.5ms is slower than by the experiment. For an excitation of 150 dB-peak, the duration of the positive phase and rising times are similar numerically and experimentally. The resulting Peak Noise Reductions (PNR), estimated from the difference between the stimulation peak pressure and the resulting peak pressure close to the eardrum, are listed in Table 2.

Table 2: Noise reduction estimated numerically and experimentally.

Impulse level	Exp. PNR	Numerical PNR
110 dB-peak	3.8 dB	4.0 dB
150 dB-peak	16.5 dB	13.5 dB

The perforates-induced vortex rings induced by the non-linear effects are illustrated in Figure 3 for a 150 dB-peak impulse wave.

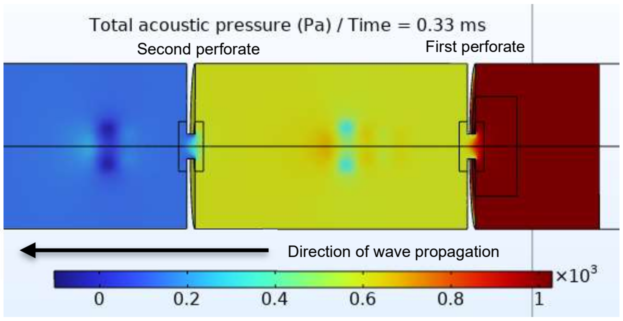


Figure 3: Illustration of the vortex rings induced by the perforates for a 150 dB-peak impulse.

4 Discussion

The numerical acoustic pressure at the eardrum is overall in good agreement with experimental measurements. The differences observed might result from the model simplifications. First, although the added equivalent compliance corresponds to an effective first approximation of the eardrum, it may underestimate its effects. Second, as the mechanical properties of ATFs are still unknown, it was decided to use the actual acoustic properties of the ear canal skin lining, which may therefore differ. Lastly, the plug inertial effects and ear canal compression arising from high-level impulse noises were not modeled. These phenomena could explain the acoustic pressure oscillations during the positive phase of the 150 dB-peak experimental measurements.

5 Conclusion

In this work, a simplified model of a non-linear filter earplug inserted in the ear canal was built in COMSOL Multiphysics 6.1 (© COMSOL Inc). It enabled us to evaluate the noise reduction behind the earplug for two excitation levels and observe the non-linear effects arising from the perforates. The numerical solutions obtained for 110 dB-peak and 150 dB-peak have shown a good correlation with experimental results obtained with an ATF. More excitation levels should be considered in future studies to extend these results. Finally, this work provides new perspectives to integrate non-linear filters in new configurations of earplugs while enhancing their performances.

References

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