

# Design, optimization and validation of a small cabin for standardized objective measurements of earmuffs and earplugs on artificial head (ATF) according to ISO4869-3.

François Fohr<sup>1</sup>  
ALMACOUSTIC  
20 rue Thalès de Milet, 72000 Le Mans, France

Maryna Sanalatii<sup>2</sup>  
ALMACOUSTIC  
20 rue Thalès de Milet, 72000 Le Mans, France

Kevin Renckly<sup>3</sup>  
DELTAPLUS  
BP140 – ZAC La Peyrolière, 84405 APT CEDEX, France

## ABSTRACT

*The attenuation of hearing protection devices is currently mainly measured using the REAT (ISO 4869-1) standardized subjective method. However, during the development step, manufacturers need to carry out numerous tests quickly making the REAT method unsuitable due to its need of a large number of subjects with associated training time and represents a significant cost. As an alternative, the standardized objective method (ISO 4869-3) uses an artificial head (ATF) in a controlled acoustic environment. Delta Plus called on Almacoustic to provide a test facility compliant with the 4869-3 standard, and designed with reduced dimensions to fit easily into its test laboratory. The presented work describes the steps of design, development and validation of a measuring cabin meeting these requirements. The search for a suitable geometry for the cabin volume is based on numerical modeling using boundary elements. The cabin, built using this initial approach, is then empirically optimized using different types of diffusers to meet sound field homogeneity criteria. Comparisons of measurements made using both subjective (ISO 4869-1) and objective (ISO 4869-3) methods are presented at the end.*

## 1. INTRODUCTION

The measurement of the attenuation of hearing protections, such as earplugs or earmuffs is today mainly carried out following the standardized subjective method REAT (ANSI S12.6; ISO 4869-1) [1, 2], based on real-ear attenuation at threshold by a panel of human subjects. The REAT method is considered as the gold standard in the world because it takes into account human factors such as the morphological differences of individuals in the external ear and bone conduction which represents a secondary transmission way of the noise [3, 4]. The measurement method involves mobilizing a set of subjects (16 people for ISO4869-1), training and selecting them for their ability to correctly carry out the tests. Consequently, the measurement is time consuming and requires expensive cost.

Hearing protection manufacturers generally need to characterize the acoustic performances of their products during the development phases and must also be able to control the stability or continuity of these performances over time. For this, objective methods have

---

<sup>1</sup> ffohr@almacoustic.com

<sup>2</sup> msanalatii@almacoustic.com

<sup>3</sup> kevin.renckly@deltaplus.eu

been developed and evaluated for many years. Two types of objective methods are proposed, depending on whether they are implemented on a human subject or an artificial head:

- the MIRE method [5, 6] on a human subject, uses miniature microphones located on either side of the hearing protection to measure the attenuation of the protection (Noise Reduction).
- Objective methods on artificial head such as ATFs (Acoustical Test Fixtures) allow less restrictive implementations since they provide quick measurement of the difference in sound level with and without protection (Insertion Loss IL) on a fixed support. The artificial heads are developed to be more or less representative of the human head with materials approximating the texture of the skin and the presence of a pinna or even an ear canal. In some cases, the design of the artificial head attempts to reproduce the effect of bone conduction.

Numerous studies have compared objective and subjective methods [4, 5, 6, 7] and have highlighted the different factors of discrepancy between the two methodologies, which we will discuss at the end of this paper.

Delta Plus, for the development of its hearing protection products, wanted to equip itself with an objective test bench, complementary to the certification measurements carried out using the standardized REAT method (ISO 4869-1).

Delta Plus wanted to be able to conduct tests with good metrological quality in terms of repeatability of measurements and reproducibility of the acoustic field according to the conditions required by the ISO 4869-1 standard. Furthermore, Delta Plus required a compact test bench (around 1 m<sup>3</sup>).

To meet this need, Almacoustic proposed to design a test bench based on the requirements of the ISO 4869-3 standard [8], which defines an artificial head type support (ATF) and an acoustic field exactly conforming to the same requirements than those of the REAT method. To date, there are only two acoustic rooms in France meeting the criteria of this standard (at INRS in Paris and CRITT S&L in Châtelleraut). Therefore, carrying out such a compact test cabin represented an interesting challenge.

The work presented in this communication describes the steps of numerical design, production and validation of the "Delta cabin". At the end of this paper, first measurements of standard earmuffs carried out with the Delta cabin are compared to certification measurements with the REAT method.

## **2. NUMERICAL DESIGN**

ISO 4869-1 defines the characteristics of the sound pressure field in a reference volume where the ATFs (Acoustical Test Fixtures) will be placed. The main characteristics are homogeneity, absence of measurable directivity and very short reverberation time.

The main constraint is the homogeneity of the sound pressure field, since this implies the absence of acoustic resonance modes in the cabin volume. With a reduced volume of around 1 m<sup>3</sup>, these resonance modes are located in the mid-frequency range, in contrast to larger rooms where it is possible to shift these modes to low frequencies, outside the measurement frequency range.

For this reason, the design of the cabin cannot be based on a regular parallelepiped geometry, and it was necessary to implement a numerical approach to define a suitable volume shape.

The simulation stage enables us to achieve a pre-dimensioning of the cabin whose characteristics approach the homogeneity criteria.

### **2.1. Acoustic pressure computation**

Acoustic wave propagation can be described by the linear wave Equation 1:

$$\frac{d^2 p(r,t)}{dr^2} - \frac{1}{c^2} \frac{d^2 p(r,t)}{dt^2} = 0, \quad (1)$$

where  $p(r,t)$  is sound pressure,  $c$  is celerity,  $r$  is position in space and  $t$  is time.

After a few mathematical transformations, the propagation of sound in the frequency domain radiated from the surface  $S$  of a vibrating object can be expressed in terms of a Kirchhoff-Helmholtz integral Equation 2:

$$p(r) = \int_{V_1+V_2} G(r, r_s) q(r_s) dV_1 + \int_S \left( \frac{dG}{dn}(r, r_s) p(r_s) - G(r, r_s) \frac{dp(r_s)}{dn} \right) dS, \quad (2)$$

where  $G(r, r_s)$  is Green's function, which is a fundamental solution of the Helmholtz equation between a point on the object surface  $r_s$  and a point in space  $r$ ;  $n$  is the normal to the object surface  $S$ ;  $q$  is the volume contribution in volume  $V_1$  inside the surface  $S$  and  $V_2$  outside the surface  $S$ .

To solve this integral for an object of arbitrary geometry, the surface of the object must be divided into segments (known as boundary elements) of sufficiently small size relative to the wavelength, such that it is possible to assume an approximately constant pressure on their surface.

Thus, assuming linearity and isotropic properties of the medium, the boundary element method allows the acoustic field to be calculated simply by considering the given boundaries, which include reflection and diffraction.

Sound pressure propagation is calculated using the AKABAK program, which combines the boundary element method with a lumped element solver [9]. Lumped elements allow electrodynamic transducers to be represented by their electroacoustic models.

In this way, it is possible to calculate the field radiated by loudspeakers inside a closed volume.

## 2.2. Delta Cabin modelling

The acoustic field in a closed rigid volume is highly perturbed by the acoustic modal resonances at lower frequencies. To reduce this effect, it was decided to place the walls nonparallel to each other. The interior volume of the Delta cabin is 1.3 m<sup>3</sup>.

To meet the acoustic pressure field homogeneity requirements around the ATF, it is necessary to consider the use of a sufficient number of acoustic sources to generate the broadband noise. After some preliminary tests, it appeared that the use of eight sources is sufficient to achieve homogeneity.

Given the reduced volume of the cabin, the choice was made to use a single type of source rather than dedicated models for different frequency ranges. The SB Acoustics SB15MFC30-8 speakers providing an acoustic response over a wide frequency band with significant dynamics were chosen. For the simulations, the loudspeaker is associated with a closed rear enclosure volume of 17 liters.

To reduce the effect of the first eigen-modes of the cabin, linked to its geometry, the acoustic sources are distributed quasi-randomly: no symmetrical positions, no sources at the corners, orientation of the sources towards the walls, the membranes of the sources are not parallel to the walls, as presented in Figure 1a. Finally, all the cabin walls are considered perfectly rigid.

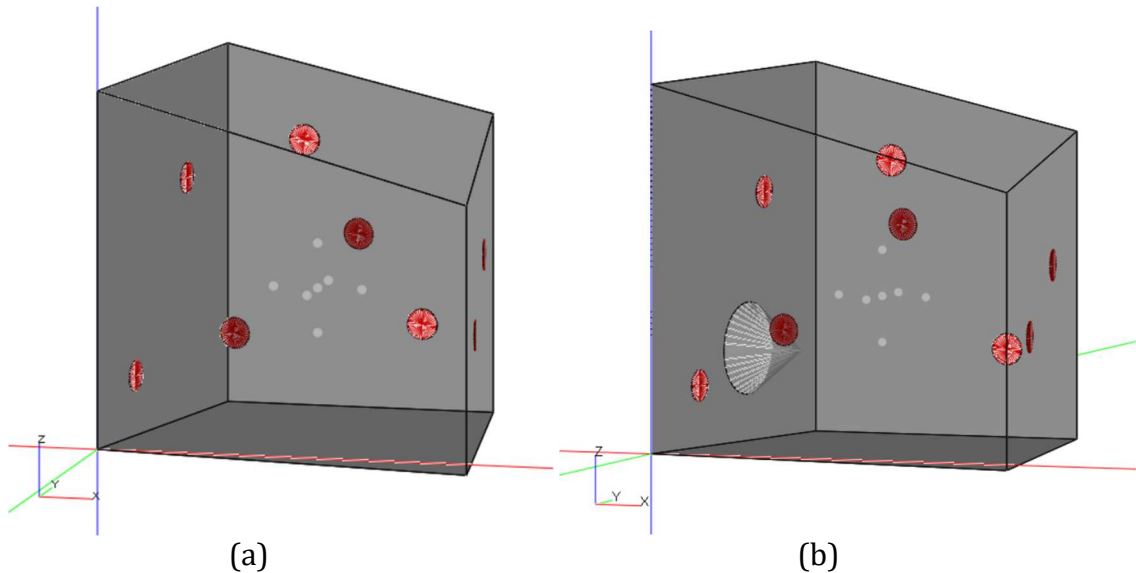


Figure 1: Numerical model of the Delta cabin without a diffuser (a) and with (b).

## 2.2. Numerical modelling results

To evaluate the acoustic performance of the cabin, the pressure is calculated at the approximate center of the cabin and at 6 points 15 cm from the center, located along the orthogonal axes X, Y and Z (7 gray points in Figure 1a). The pressure levels are calculated for a uniform command of 1 V for the third octave bands with center frequencies in accordance with the standard.

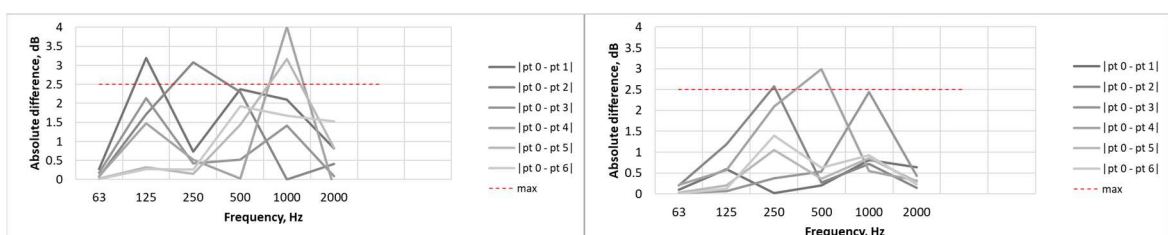
The pressure level differences between the reference (central) point (pt 0) and the other 6 locations (pt 1, pt 2, pt 3, pt 4, pt 5 and pt 6) are given in Figure 2a. As expected, the acoustic field is more perturbed by the eigen modes of the volume at mid frequencies (from 125 Hz to 1 kHz) that correspond to the inner dimensions of the Delta cabin. The pressure difference between locations exceeds the 2.5 dB limit (red dashed line in Figure 2a), prescribed by the standard.

To improve the field homogeneity, a rigid conic shell was added to the wall inside the cabin, as shown in Figure 1b, that breaks the volume modes of the cabin by adding a diffracting surface. The pressure differences between the observation points locations and the center, for this configuration, are presented in Figure 2b. It can be noticed that the diffuser has, indeed, improved the field homogeneity.

The calculations were carried out in the 63 Hz to 2000 Hz bands, because above this frequency, sound pressure field homogeneity is easier to achieve.

For the practical realization of the Delta cabin, it is obvious that a number of deviations from the theoretical model need to be considered: the sources cannot be positioned precisely as in the model, notably because of the constraint of the rear volume, the rigidity of the walls will not be perfect: the presence of an access hatch is not taken into account in the calculations (vibrations, acoustic leakage), etc.

For these reasons, the practical realization of the cabin was initiated without further optimization of the numerical model. This design methodology was successfully used in the past for the Alpha cabin, whose characteristics are not so far removed from those of the Delta cabin.



(a)

(b)

Figure 2: Pressure level difference between reference point in the Delta cabin and 6 points along X, Y and Z axes at 15 cm from the reference point, for the cabin with no diffuser (a) and with a diffuser (b)

### 3. DELTA CABIN PRACTICAL REALIZATION

#### 3.1 Description

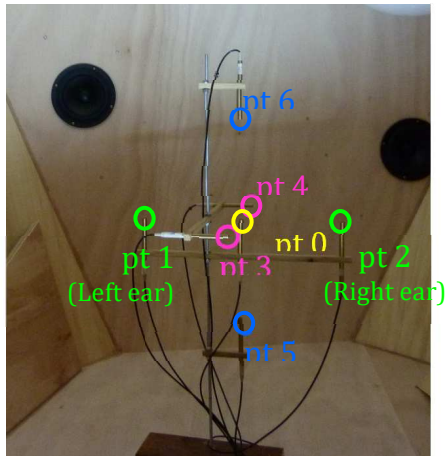
The Delta cabin is made of 22 mm thick plywood with non-parallel walls. The interior volume is 1.3 m<sup>3</sup>. One side of the cabin has an opening of 62x80 cm<sup>2</sup>, which closes with a door. Three sides and the ceiling of the cabin are equipped with eight SB Acoustics SB15MFC30-8 loudspeakers, positioned in a quasi-random manner. Each speaker is mounted with a closed rear enclosure of approximately 17 liters.

The sources are powered by a Focusrite Scarlett 18i20 3<sup>rd</sup> Gen sound card, HPA-D604 amplifiers and INTAC software, that generates and equalizes no correlated pink noise signals.

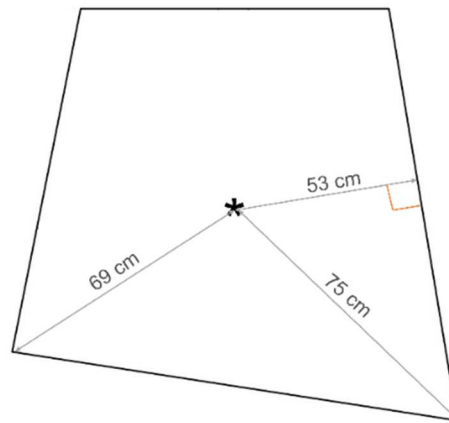
Acoustic pressure acquisition and processing is realized by seven 1/4" free-field Almacoustic microphones MK90, their conditioning amplifier, an acquisition module NI-9250 with a NI CompactDAQ frame cDAQ-9171 and the in-house developed software INTAC. This acquisition chain is used to evaluate the acoustic field in the Delta cabin and will be used after with a single 1/4" MK90 microphone, as a cabin control system.

#### 3.2 Characterization of homogeneity of acoustic pressure field

In accordance with ISO 4869-3, the sound pressure field homogeneity of the Delta cabin is measured at seven points (in the middle of the cabin (pt 0) and at six points 15 cm from it along three axes) using seven microphones mounted on a stand, as shown in Figure 3a. The height of the ears plane from the central reference point is 42 cm.



(a)



(b)

Figure 3: Measurement of the pressure level difference between central reference point and six points at 15 cm along axes X, Y and Z; microphone support (a) and position of the reference points on the plan XY.

Figure 4 shows the measured difference in pressure levels between the reference point and the 6 other positions. As predicted during the simulation phase, the field homogeneity criterion is not fully met for the entire frequency range. In particular, at 125 Hz and 250 Hz, one or two microphones recorded levels slightly in excess of the limits set by the standard.

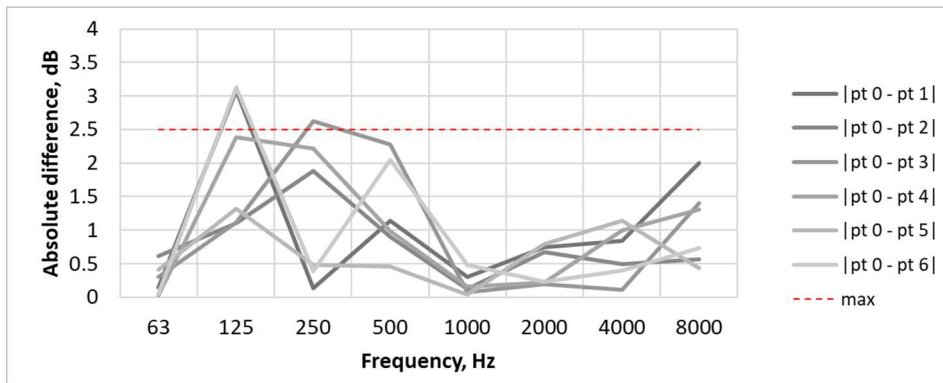


Figure 4: Pressure level differences measured inside bare Delta cabin.

### 3.3 Delta cabin tuning

In order to homogenize the acoustic pressure field in the cabin and reduce the effect of its first natural modes, a set of diffusers has been installed inside the cabin (Figure 5). The set consists in two hemisphere shells, three wooden triangular plates, covering the angles of the cabin and three wooden trapeze shapes plates, placed at some distances from walls. Their shapes and positions have been optimized through trial and error to meet the requirements of the standard concerning the homogeneity and directivity of the acoustic field.

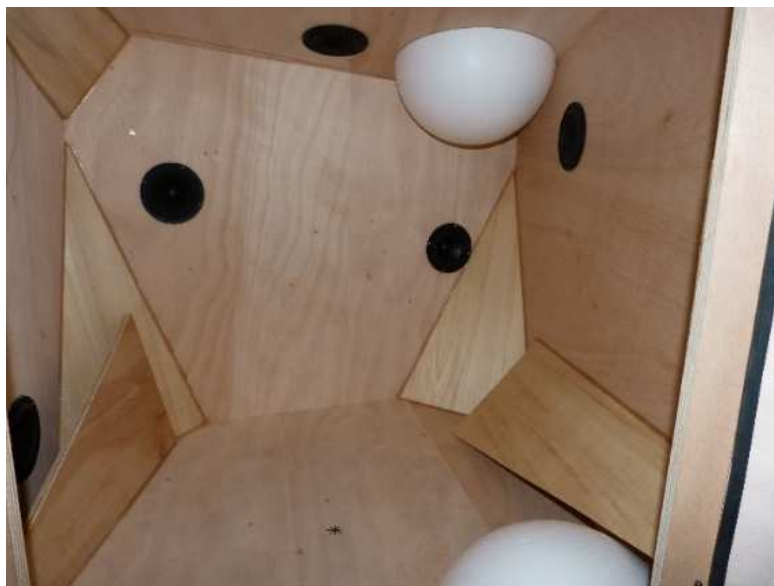


Figure 5: Delta cabin interior volume with acoustic diffusers.

Figure 6 presents the pressure level difference between the reference point and other 6 positions of the cabin with the diffusers inside. At this stage, the standardized field homogeneity criterion is well met.

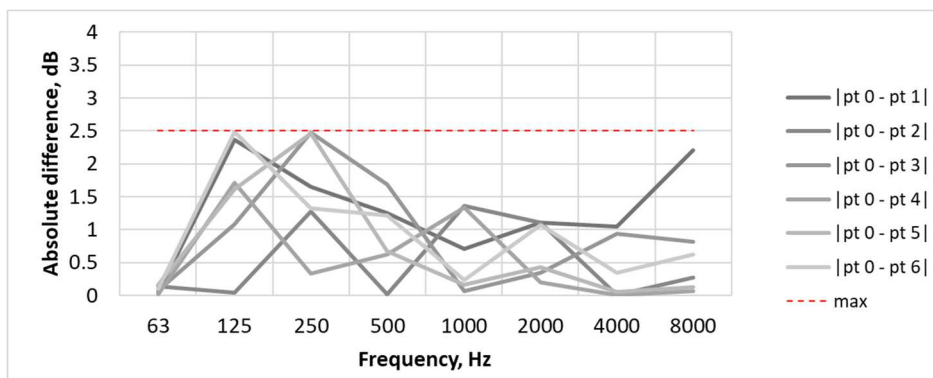


Figure 6: Pressure level differences measured inside Delta cabin with acoustic diffusers.

### 3.4 Delta cabin validation according the norm ISO 4869-1

The standard ISO 4869-1 prescribes the acoustic field to meet following conditions:

- (1) The sound pressure level measured at all test frequencies using an omnidirectional microphone at positions 15 cm from the reference (center) point on the three axes front-back, left-right and up-down, must not differ by more than  $\pm 2.5$  dB from the sound pressure level at the reference point. The difference between measurements taken on the right and left positions must not exceed 3 dB.
- (2) The reverberation time in the test chamber must not exceed 1.6 s.
- (3) The directivity of the sound field shall be evaluated at the reference point for test signals with center frequencies greater than or equal to 500 Hz. Measurements shall be made with a directional microphone with a free-field polar response typical of acoustic field signals. Third-octave test, with at least 10 dB front/side rejection for a bi-directional microphone, or at least 10 dB front/back rejection for a cardioid microphone. The microphone positioned at the reference point must rotate  $360^\circ$  in a horizontal plane. The variation between the sound pressure levels observed for each test signal must remain within the range of deviations permitted by Table 1. It is also possible to obtain the sound pressure levels by taking measurements at fixed points, the microphone rotating in 15-degree increments.

Table 1: Admissible variations in sound field sound pressure levels for corresponding free-field directional microphone rejection values.

| Free-field microphone rejection (FFR), dB | Allowed field variation, dB |
|---|-----------------------------|
| $25 \leq \text{FFR}$                      | 20                          |
| $20 \leq \text{FFR} < 25$                 | 15                          |
| $15 \leq \text{FFR} < 20$                 | 10                          |
| $10 \leq \text{FFR} < 15$                 | 5                           |
| $\text{FFR} < 10$                         | 12                          |

The first criterion of field homogeneity, corresponding to the level difference between the reference point and other 6 positions at 15 cm has been validated in §3.4 (Figure 6). The criterion concerning the left and right ears is validated too as shown in Figure 7.

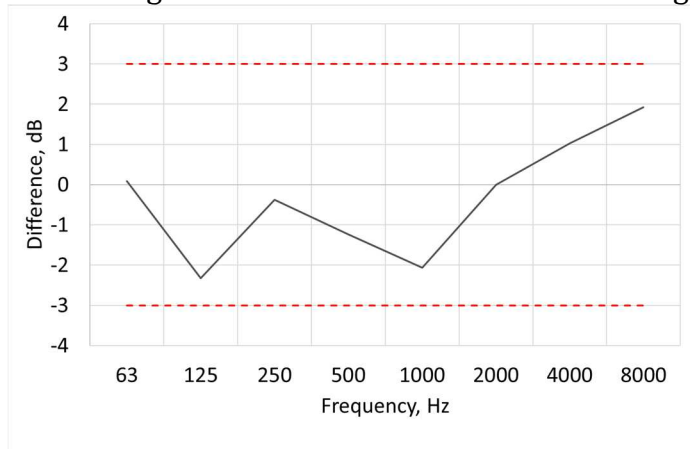


Figure 7: Pressure level difference between two extremes measured inside Delta cabin.

Regarding the reverberation time, Figure 8 shows that it is significantly lower than 1.6 s for the entire frequency range.

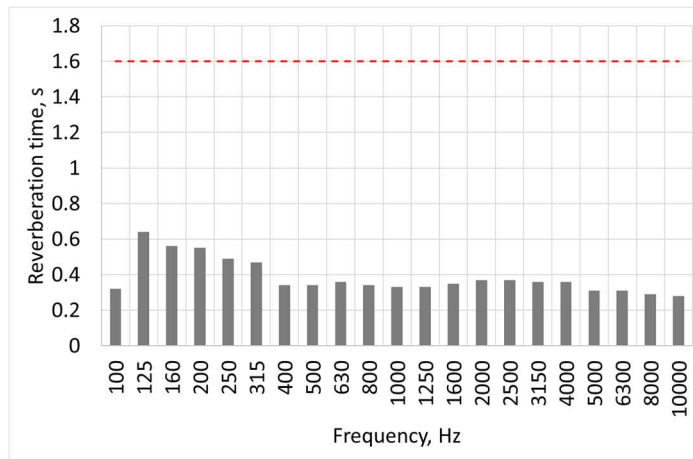


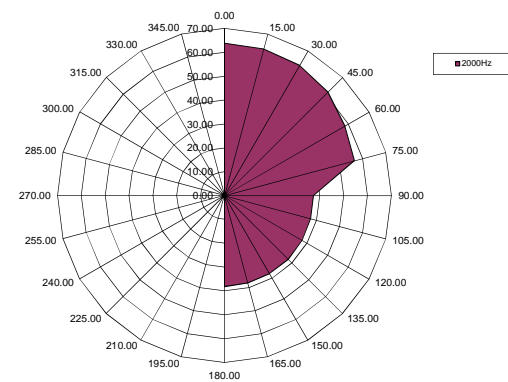
Figure 8: Reverberation time of the Delta cabin.

To measure the directivity (or lack of thereof) of the acoustic field in the cabin, the standard recommends the use of directional microphones. The directivity of these microphones is directly linked to their sensitivity to acoustic velocity. For this reason, we chose to carry out this measurement with an intensity probe, whose first function is characterization of the acoustic intensity vector.

The measurement was made with a miniaturized intensity probe (Almacoustic production) whose free-field rejection is between 20 and 30 dB above 500 Hz (Figure 9).



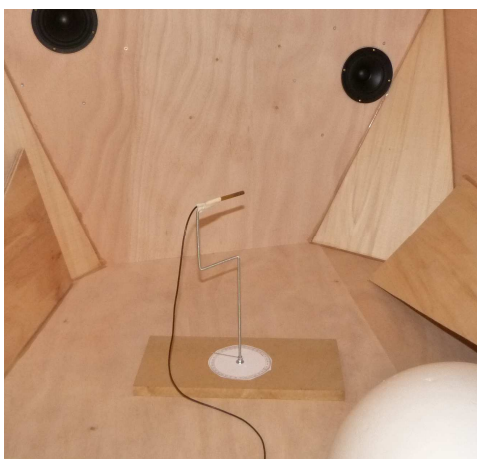
(a)



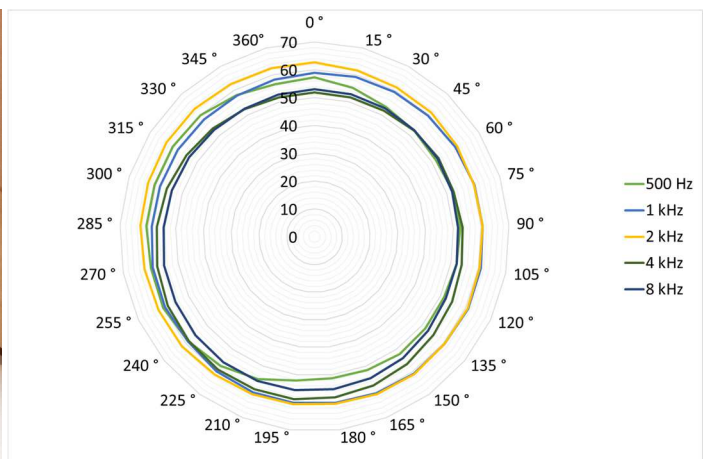
(b)

Figure 9: Miniaturized intensity probe (a) and its directivity pattern at 2000 Hz (b).

According to the standard, the probe is located at the reference point, in the horizontal plan and measurements are made each 15° (Figure 10a). The directivity diagram obtained for each octave band is presented in Figure 10b.



(a)



(b)

Figure 10: (a) Field directivity measurement with an intensity probe; (b) diagram of the field directivity of the Delta cabin.

The maximum sound intensity deviation in the rotation plane for each octave band is presented in Table 2. The requirements of the standard are therefore well respected for all frequency bands (differences < 15 dB).

Table 2: Maximum pressure difference on rotation plan of the mini-intensimetric probe.

| Frequency, Hz | Maximal difference, dB |
|---------------|------------------------|
| 500           | 9.3                    |
| 1000          | 3.1                    |
| 2000          | 2.7                    |
| 4000          | 7.2                    |
| 8000          | 4.0                    |

#### 4. FIRST MEASUREMENTS AND COMPARISON WITH SUBJECTIVE METHOD

A first series of standard earmuff measurements was carried out with the Delta cabin. These measurements were compared to the results of certification measurements with the subjective REAT method.

Three models of earmuffs were tested with the Delta cabin on ATF support. For each model, three samples were tested. Three measurements per sample were carried out.

The mean attenuation for each sample is compared in Figures 11 to 13 with the certification measurement according to ISO 4869-1 (REAT). The uncertainties are calculated as twice the standard deviation (for a 95% confidence interval).

It should be noted that the comparison measurements are not carried out on the same product but on different samples. Consequently, a part of the dispersion of the measurements can be attributed to the dispersion of production. In the case of the Magnycours 2 earmuff, this dispersion appears clearly in the differences in mean attenuations observed between the 3 samples. In the case of Interlagos earmuffs, the production dispersion is significantly lower. The comparison between objective and subjective measurements for these products shows that:

- at 125 Hz, the attenuation measured in the Delta cabin is lower than that measured with REAT,
- at 250 Hz, the values are of the same order,
- from 500 Hz, the attenuations measured in the Delta cabin are 5 to 10 dB higher than those obtained with REAT.

These differences observed between objective and subjective methods are consistent with the results of numerous studies that have notably characterized the occlusion effect [6, 10, 11]. In the case of subjective measurements on human subjects, the threshold detection principle includes a bias linked to physiological noises potentially amplified by the occlusion effect produced by headphones or earplugs. The occlusion phenomenon is also influenced by bone conduction, which represents an influential secondary transmission pathway when the ear canal is protected by earplugs or earmuff. The occlusion effect depends on the type of protection used and in particular the volume between the eardrum and the hearing protection. The low frequencies are mainly affected by notable overestimations of the subjective method.

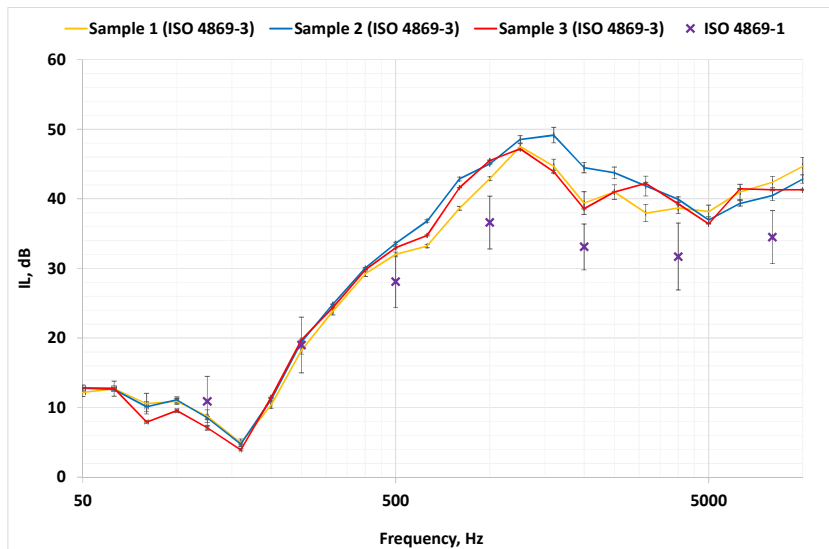


Figure 11: Interlagos Light

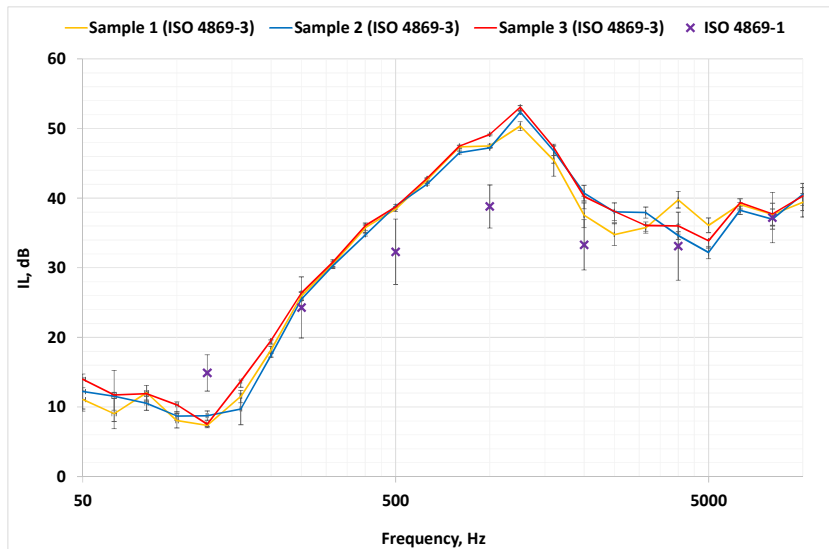


Figure 12: Interlagos 2

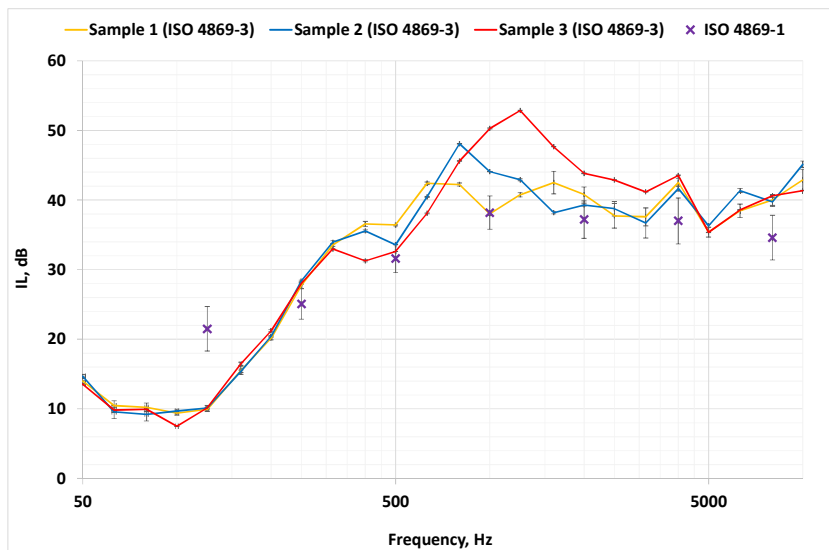


Figure 13: Magnycours 2

## 5. FINAL COMMENTS AND CONCLUSIONS

The purpose of this paper was to present a design approach for a test cabin compliant with the ISO 4869-3 standard. The particularity of this cabin is its small volume which allows good integration into a testing laboratory but complicates its implementation with regard to the criteria of the standard.

The produced Delta cabin meets the requirements of the standard thanks to pre-sizing by digital modeling, the use of 8 uncorrelated acoustic sources and the installation of a set of diffusers positioned empirically.

By complying with the normative requirements regarding the acoustic field around the artificial head, this test bench makes it possible to guarantee reproducibility conditions which are rarely taken into account when comparing measurement methods. The history of the REAT standards has shown [4] how the criteria for defining this measurement environment have evolved over time. It is likely that the characteristics of this acoustic field are among the many causes of the differences between the different methods of the hearing protections qualification.

In future work, it could be interesting to carry out comparison measurements between Delta cabin test bench and the REAT qualifications on the same sample of hearing protection. This would permit to have a more precise estimate of the differences to be considered, depending on the type of protection.

## ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Nicolas Trompette (INRS), for his participation in Delta cabin development.

## REFERENCES

1. ISO 4869-1: 2018, *Acoustique — Protecteurs individuels contre le bruit — Partie 1 : Méthode subjective de mesurage de l'affaiblissement acoustique*.
2. ASA - ANSI/ASA *Methods for Measuring the Real-Ear Attenuation of Hearing Protectors*, Standard S12.6, American National Standard.
3. E. H. Berger. Preferred methods for measuring hearing protector attenuation. In *Proceedings of INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Institute of Noise Control Engineering, pp. 4432–4441, 2005.
4. E. H. Berger. Review of the 2016 Edition of ANSI S12.6 and its place in the panoply of standards on the measurement of real-ear attenuation at threshold since 1957. In *Proceedings of NHCA Conference*, San Antonio TX, February 24, 2017.
5. J. Voix and F. Laville. The objective measurement of individual earplug field performance. *The Journal of the Acoustical Society of America*, **125(6)**, 3722–3732, 2009.
6. D. de Almeida-Agurto, S. N. Gerges, and J. P. Arenas. MIRE-IL methodology applied to measuring the noise attenuation of earmuff hearing protectors. *Applied Acoustics*, **72(7)**, 451–457, 2011
7. H. Nelisse, C. Le Cocq, J. Boutin, J. Voix, and F. Laville. Comparison of subjective and objective methods for the measurements of hearing protector devices attenuation and occlusion effect. In *Proceedings of Meetings on Acoustics*, AIP Publishing, 2013.
8. ISO 4869-3: 2007, *Acoustique — Protecteurs individuels contre le bruit — Partie 3: Mesurage de l'affaiblissement acoustique des protecteurs du type serre-tête au moyen d'un dispositif d'essai acoustique*.
9. J.Pazer. Boundary element subdomain modeling for electroacoustic. In *Proceedings of AES Convention*, New York, October, 2020.
10. E. H. Berger and J. E. Kerivan. Influence of physiological noise and the occlusion effect on the measurement of real-ear attenuation at threshold. *The Journal of the Acoustical Society of America*, **74(1)**, 81–94, 1983.

11. S. Stenfelt and S. Reinfeldt. A model of the occlusion effect with bone-conducted stimulation. *International Journal of Audiology*, **46(10)**, 595–608, 2007.