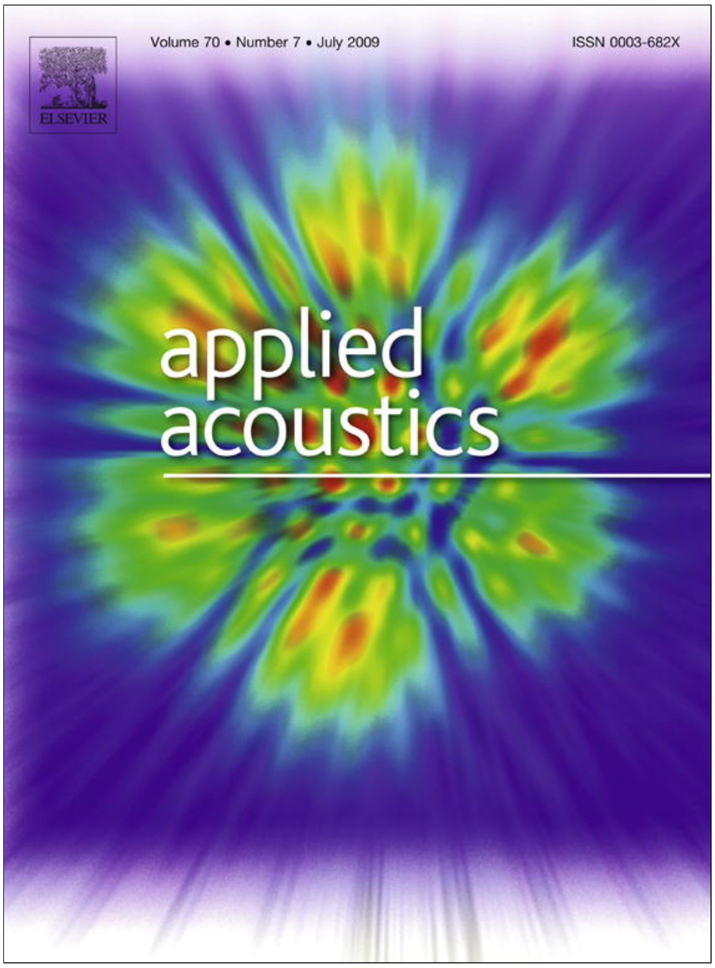
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# Prediction of the attenuation of a filtered custom earplug

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ABSTRACT

A method has been developed to predict the attenuation of an earplug when filtered by passive resistive elements (dampers). The method is based on the assumption that sound transmission paths traveling through the damper element and through the earplug are independent, hence their respective sound energies simply add to each other. This hypothesis was validated with measurements on both an acoustical test fixture and on human subjects, using a commercially available expandable custom earplug. This earplug features a sound-bore that can either be used for an F-MIRE (Field microphone-in-real-ear) attenuation measurement or be fitted with a damper in order to adapt the amount of attenuation to the wearer's needs. The uncertainty associated with the proposed prediction method was formulated and quantified using REAT and F-MIRE attenuation measurements on human subjects. An initial experimental verification of the prediction method, on a limited number of subjects, has been successfully completed.


## 1. Introduction

For hearing protection to be made effective, the research needs established by the National Institute for Occupational Safety and Health (NIOSH) [1] are "*to find a way for workers to be individually fitted and to offer them increased comfort and the ability to hear speech and warning signals*". To address these individual fit and comfort issues (from both a physical and auditory point of view), some manufacturers have recently begun to offer new hearing protection devices (HPD) that are based on a custom earplug for increased physical comfort and that includes a passive acoustical filter for increased auditory comfort: the filter will let some sound energy through, which helps to overcome the problem of *overprotection* that prevents the wearer to perceive speech and warning signals. A recent review of these devices has been conducted by Casali et al. [2,3] under the "adjustable attenuation HPD" category. Unfortunately, the exact attenuation of such devices is not precisely known on an individual basis. The exact attenuation could be determined by two approaches: modeling or measurement. First, in the case of the modeling approach, the only attempt found in the literature [4] is based on modeling of the filter without taking into account sound transmission through the rest of the earplug and fails at properly predicting the filtered earplug attenuation. Second, in the case of the measurement approach, a quick field evaluation of the filtered earplug attenuation could be very useful to adjust the filter to the user's attenuation needs. Unfortunately, the existing laboratory attenuation measurement methods, such as the real-ear attenuation at threshold (REAT) or the microphone-in-real-ear (MIRE) or other methods reviewed by Berger in [5,6], are too long or too delicate to be performed for individual filter adjustments.

The proposed approach combines the use of a field measurement method that assesses the attenuation of the blocked earplug (before installing the filter) and the use of an empirical model that predicts the attenuation of the filtered earplug. Although this approach could be used for any HPD featuring interchangeable filters, it has been specifically developed and validated for a new concept of instrumented expandable custom earplug, presented in Section 2. The filtered earplug attenuation prediction method is defined and implemented in Section 3. The uncertainty associated with the filtered earplug attenuation prediction is evaluated in Section 4 together with an experimental check. Conclusions are given in Section 5.

## 2. Characteristics of the instrumented expandable filtered custom earplug

The goal of this section is to present both the custom earplug concept and the associated F-MIRE method that is an integral part of the proposed filtered earplug attenuation prediction method.

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The earplug used in this study is an expandable custom earplug developed by Sonomax Hearing Healthcare Inc. (Montreal, Canada). It is instantly fitted to the user's ear, by injecting a soft medical-grade silicon rubber between a rigid core and a soft expendable envelope. It was designed specifically to include an inner bore of constant length and diameter that permits the temporary insertion of a miniature microphone probe and the permanent insertion of an acoustical filter.

The expandable custom earplug concept is illustrated in Fig. 1. The internal microphone, inserted inside the generic rigid core, measures the sound pressure level in the residual ear canal at the HPD's tip. Attached to the back of this internal pressure microphone is an external pressure microphone. These two microphones are used to measure the sound pressure level difference across the earplug (noise reduction) while a loud pink noise is generated from an outside reference sound source (frontal angle of incidence, median plan).

The ability to hear speech and warning signals is partially addressed by adapting the earplug attenuation to the actual noise exposure of the wearer [7]. This adaptation is based on a set of acoustic dampers (acoustic resistance resulting from a mesh of plastic fibers) that can be placed into the earplug's sound-bore (see Fig. 2) to result in an effective protected level, denoted $L'_{Ax}$, between 75 and 80 dB(A), following the current EN458 recommendation [8] and CSA standard [9] for proper HPD selection maximizing the ability to hear speech and warning signals. These recommendations for HPD attenuation are defined in Table 1 and suggest that the overprotection is as undesirable as an insufficient protection.

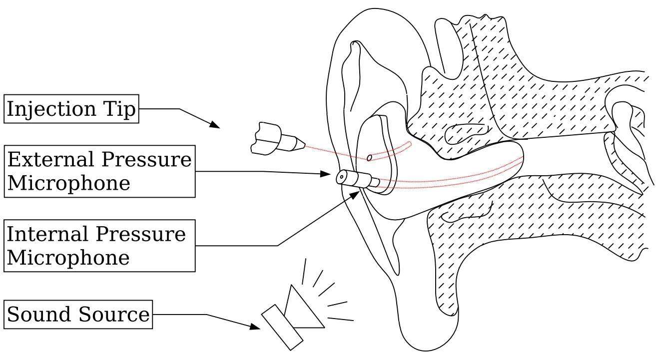


**Fig. 1.** The expandable custom earplug into the wearer's ear showing the injection tip used for the inflation of the earplug, the sound source and instrumented with the dual microphone probe for noise reduction measurement.

The attenuation of the not yet filtered earplug is determined using a prediction method, denoted "F-MIRE". The microphone-in-the-ear (MIRE) technique is based on the measurement of the sound pressure levels at the same location, close to the eardrum, with and without the HPD in place and corresponds to the determination of an insertion loss (IL). The F-MIRE method is the MIRE method that is modified so that two microphones are used to measure simultaneously the sound pressure outside and inside the HPD. From this sound pressure level difference, called the noise reduction (NR), the IL is computed. The most common way to measure the IL on human subjects is to measure the hearing thresholds with and without the HPD in place, per the REAT method. This subjective method is currently considered as "gold standard" [9,11–13] for HPDs' attenuation measurements. To link the objectively measured NR to the REAT attenuation, the following equation has been proposed by the authors [10]:

$$ATT = NR + COMP \tag{1}$$

where *COMP* is a compensation term that averages, for a large group of subjects, the difference between the attenuation measured using the REAT method and the NR measured for the exact same earplug fit, on the same subjects, in the same conditions.

The F-MIRE method is based on an NR measurement that is performed after the wearer removes and refits the custom earplug on

**Table 1**
Protection outcome as defined by EN458 recommendation [8] and CSA standard [9].

| | Protection outcome |
|---|---|
| $L'_{Ax} \geqslant 85$ | Insufficient |
| $85 > L'_{Ax} \geqslant 80$ | Acceptable |
| $80 > L'_{Ax} \geqslant 75$ | Ideal |
| $75 > L'_{Ax} \geqslant 70$ | Acceptable |
| $70 > L'_{Ax}$ | Overprotection |

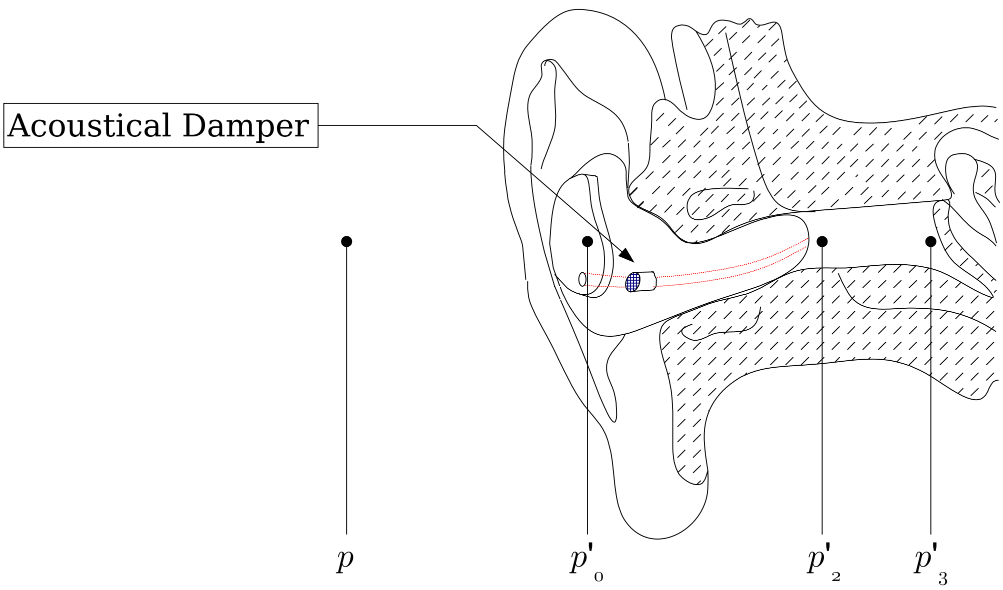


**Fig. 2.** The expandable custom earplug filtered with an acoustical damper and the location of the sound pressure level measurement points.

his own. Such practise, referred to as "subject-fit", is a standard practice to obtain more realistic attenuation values [14].

Based on the presented earplug concept and associated F-MIRE method, the need for a prediction of the filtered earplug attenuation can be derived. The damper that is to be placed in the sound-bore to obtain the desired protected exposure level has to be selected among a set of several available dampers. Even when using a NR measurement that is faster than the REAT, the actual attenuation measurement of the earplug is too long a process to be repeated for each damper. Furthermore, space and acoustical constraints in the design of the expandable custom earplug led to a unique sound-bore rather than one for the damper element and another for the probe microphone. Hence, the sound-bore can either be used by the microphone probe-tube or by the acoustical damper, but not by both at the same time. This makes it impossible to actually measure the attenuation of the filtered earplug with each of the available dampers. It is therefore essential to be able to predict the attenuation of the filtered earplug for each of the available dampers.

## 3. The filtered earplug attenuation prediction method

### 3.1. Justifications, concepts and hypothesis of the proposed model

Transmission matrices (also known as transformation matrices, *T*-matrices and ABCD matrices) are traditionally employed in electro-acoustical analysis of acoustical systems, since they constitute a fast, accurate and elegant way to model each acoustic element and to take into account the coupling that occurs between them [15]. One could have thought of successfully using them for the prediction of the filtered earplug attenuation by separately modelling the solid earplug (with the eventual leak and bone conduction) and the damper, and by associating the two elements in parallel. Unfortunately, in this particular case, this type of transmission matrice approach has its limitations. The overall accuracy of the transmission matrice model depends on the accuracy of the parameters of its constituents. The exact parameters of the earplug element are hard to determine individually; no simple method currently exists (although the authors gave it a try) to extract the pertinent acoustical model parameters from the F-MIRE measurement and the only known alternative method would be to determine for each user the acoustical properties of the earplug using an "impedance tube" test fixture like the one developed by Hiselius [16]. Such an alternative, not yet successfully tested, would require enormous efforts because it would have to be performed on each and every earplug (since the use of typical or average earplug parameters instead of individual parameters would offset all benefits of the accuracy of the transmission matrice approach). Furthermore, even if the aforementioned limitations were to be overcome, the obtained transmission matrix model may not lead to a significant improvement in accuracy or precision, compared to the simple transmission path model described in the next paragraph. This is because the filtered earplug attenuation will be mostly brought about by the damper element itself, which constitutes the dominant path, as demonstrated in Section 3.5.1.

Consequently, the proposed model is based on a representation of the sound transmission paths through a filtered earplug as energy summation. It is illustrated in Fig. 3, in which the symbol $p$ denotes the r.m.s. acoustical pressure and $p^2$ its quadratic value (the exact locations of these pressure points are defined in Fig. 2). The sound energy is first transmitted through the "Pinna" transmission path that essentially contains the diffraction from the head and torso and the "horn effect" of the pinna (also referred to as head related transfer function, HRTF). The path of the sound energy then splits into two paths the "Earplug" (index $P$) and "Damper" (index $D$) sound transmission paths. The "Earplug" transmission path typically includes air leaks, HPD vibrations, transmission through the HPD material, and bone conduction through the human skull. These effects have been widely presented and illustrated in the literature (see for example a detailed explanation by Berger [17]). Parallel to these earplug transmission paths, the acoustical damper and its connecting ducts act as a "Damper" sound transmission path and can be viewed as a controlled air leak that actually lets more sound energy reach the wearer's protected tympanic membrane (TM) through the residual ear canal. Finally, the "*Ear canal*" transmission path leads to the Tympanic Membrane.

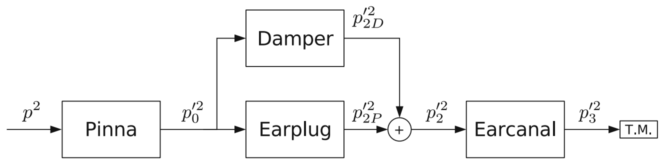


**Fig. 3.** Block diagram of the filtered earplug inside the ear canal: the "Damper" block represents the sound path created by the acoustic resistance; the "Earplug" block represents the combination of all the sound paths to the protected ear; the "TM" block represents the tympanic membrane.

The hypothesis behind this model is that the earplug and damper are two independent paths (i.e. $p'_{2D}$ and $p'_{2P}$ are non coherent pressures) and that no interference (resonance/anti-resonance) should occur between them, hence that the sound pressure $p'_2$ can be expressed as:

$$p'^2_2 = p'^2_{2D} + p'^2_{2P} \tag{2}$$

The use of a damper, by creating an extra sound path through the solid earplug, should always diminish the attenuation of the earplug. In other words, the filtered earplug attenuation ($ATT_{Combo}$) should always be less than the unfiltered earplug attenuation ($ATT_{Earplug}$). This last statement will be verified in Section 3.5.1 to experimentally validate the independent path hypothesis.

### 3.2. Formulation of the filtered earplug attenuation prediction

The prediction of the filtered earplug attenuation ($\widehat{ATT}_{Combo}$) requires that both the blocked earplug attenuation ($ATT_{Earplug}$) of the specific earplug while being worn by the user and the average damper attenuation ($\overline{ATT}_{Damper}$) be known. It is derived from the energy summation relation (Eq. (2)) as follows:

$$\widehat{ATT}_{Combo} = -10\log_{10}\left(10^{-\frac{ATT_{Earplug}}{10}} + 10^{-\frac{\overline{ATT}_{Damper}}{10}}\right) \tag{3}$$

where $ATT_{Earplug}$ is the attenuation determined for the earplug based either on the REAT method (used in Section 4.1) or, as used in Section 4.2, on the F-MIRE method previously presented in Section 2. The term $\overline{ATT}_{Damper}$ is the arithmetic mean of the damper attenuation values obtained from the blocked earplug attenuation and the filtered earplug attenuation of various dampers when worn by various users.

For consistency reasons, these attenuation values should be obtained using the same measurement method. Unfortunately, for practical reasons explained previously in Section 2, it is not possible to use the F-MIRE method to measure $ATT_{Combo}$, since it is not possible to insert the microphone probe while the filter is in place. The REAT method is hence used to measure both $ATT_{Combo}$ (a damper is placed inside the soundbore, as illustrated in Fig. 2) and $ATT_{Earplug}$ (a plastic cap, dubbed *fullblock*, is inserted in the soundbore). Being a subjective assessment of IL, the REAT can be expressed as the difference at the same TM location of two different sound pressure levels, one with an open ear, the other with an occluded ear. The sound pressure level at the TM is denoted $p_3$ for the open ear and $p'_3$ for the occluded situation. The transfer function of the outer ear (TFOE) corresponds to $10\log_{10}\left(\frac{p^2}{p_3^2}\right)$, or in other words, the difference between the free field and the open ear sound pressure levels. The other acoustical pressure variable names used through Eqs. (5) and (6) are directly defined on the diagram of Fig. 3.

The attenuation of the filtered earplug is the attenuation of the summed "Earplug" and "Damper" sound paths (denoted "Combo"). It is mathematically expressed as the difference between the transfer function of the open ear (TFOE) and the transfer function of the occluded ear. Such formulation is adopted to be representative of both the REAT method that is used to measured the attenuation and the insertion loss value that a MIRE measurement system would determine, because it computes the sound pressure level at the tympanic membrane with and without the HPD. The filtered earplug attenuation is hence given by:

$$ATT_{Combo} = 10\log_{10}\left(\frac{p^2}{p_3^2}\right) - 10\log_{10}\left(\frac{p^2}{p_0'^2}\cdot\frac{p_0'^2}{p_2'^2}\cdot\frac{p_2'^2}{p_3'^2}\right) \quad (4)$$

A similar formulation is used for the blocked earplug attenuation, denoted "Earplug". The term $\left(\frac{p^2}{p_0'^2}\right)$ is kept identical to Eq. (4), because the earplug input impedance is practically unchanged given that the filter sound-bore has a very small diameter. Although $p_2'^2$ is different, the term $\left(\frac{p_2'^2}{p_3'^2}\right)$ is kept as in previous equation since the earcanal and terminal tympanic membrane impedance are unchanged.

$$ATT_{Earplug} = 10\log_{10}\left(\frac{p^2}{p_3^2}\right) - 10\log_{10}\left(\frac{p^2}{p_0'^2}\cdot\frac{p_0'^2}{p_{2P}'^2}\cdot\frac{p_2'^2}{p_3'^2}\right) \quad (5)$$

Although the damper attenuation on its own is not something that can be practically measured (since a damper requires a hosting earpiece to be measured using the REAT method), the attenuation of the "Damper" sound path is defined with an expression similar to the previous ones as:

$$ATT_{Damper} = 10\log_{10}\left(\frac{p^2}{p_3^2}\right) - 10\log_{10}\left(\frac{p^2}{p_0'^2}\cdot\frac{p_0'^2}{p_{2D}'^2}\cdot\frac{p_2'^2}{p_3'^2}\right) \quad (6)$$

Here again the terms $\left(\frac{p^2}{p_0'^2}\right)$ and $\left(\frac{p_2'^2}{p_3'^2}\right)$ are kept identical to the ones in Eq. (4) for the reasons previously exposed.

This last expression is used to expressed $ATT_{Damper}$ from the measured value of the quantities defined in Eqs. (5) and (6), and the energy summation relation defined in Eq. (2):

$$ATT_{Damper} = -10\log_{10}\left(10^{-\frac{ATT_{Combo}}{10}} - 10^{-\frac{ATT_{Earplug}}{10}}\right) \quad (7)$$

### 3.3. Measurement methodology for the averaged damper attenuation $\overline{ATT}_{Damper}$

The averaged damper attenuation measurement was conducted on the actual dampers used to filter the earplug. The dampers evaluated are manufactured for the hearing-aid industry by Knowles Electronics (Itasca, IL) and are available in seven acoustical resistances ranging from 330 to 4700 Ω c.g.s.. The effect on attenuation of these seven dampers was evaluated with an IL measurement on an acoustical test fixture (ATF) (similar to the one presented in Section 3.5.1) and it was demonstrated that a subset of only four dampers (with nominal values of 4700, 2200, 1000 and 330 Ω) would be sufficient to theoretically ensure an *ideal* or *acceptable* "Protection Outcome", as defined in Table 1 for up to 95% of the noise exposure cases in the Canadian workforce (see [7] for details). This subset of four dampers, currently used in the field by Sonomax Hearing Healthcare Inc., are evaluated in the current section.

The various configurations of earplug tested are the blocked earplug (for which the sound-bore has been blocked by the fullblock), its attenuation is denoted $ATT_{Earplug}$ and the earplug filtered with respective acoustical damper values of 4700 Ω, 2200 Ω, 1000 Ω and 330 Ω.

The attenuation of these multiple earplug configurations is measured using the REAT method (based on the ANSI S3.19 standard [12]) in an independent third-party laboratory, on 10 human subjects, with 3 trials each (i.e. 3 sets of occluded ear and open ear thresholds), following these steps:

(1) the REAT attenuation is first measured for the blocked earplug: the three trials per subject are later averaged in the "per subject average" approach to an individual arithmetic mean value denoted $ATT_{Earplug}$,
(2) the fullblock plastic cap is removed and a NR measurement is conducted, as described in Section 2 while the earplug remains in the wearer's ear. Great care is taken not to alter the initial earplug position in the wearer's ear,
(3) a given damper is inserted in the earplug's soundbore while the earplug remains in the wearer's ear. Again great care is taken not to alter the initial earplug position in the wearer's ear,
(4) the REAT attenuation of the resulting filtered earplug is measured: again, the three trials per subject that will be later averaged in the "per subject average" approach leads to the attenuation denoted $ATT_{Combo}$,
(5) the damper is removed an objective measurement of the NR is taken after the testing of each damper and compared to the measurement that is taken immediately after step 1; this is to ensure that the repeated removal and re-insertion of the dampers did not affect the initial earplug position in the wearer's ear. If a discrepancy of more than 3 dB between two consecutive NR measurements is found, all of the subject's subsequent REAT results are discarded. This leads to a decreasing number of "*valid fit*" test values as the dampers test order increases (10 "*valid fit*" tests for 4700 Ω damper test down to 7 "*valid fit*" tests for the 330 Ω damper test, as seen in the second column of Table 2).
(6) another damper of different acoustical resistance value is inserted and steps 4 and 5 are repeated to test the three other dampers.

The order in which the dampers are tested is by decreasing value of resistance. Thus, the most critical REAT evaluations (which correspond to the filtered earplug that is closest to the blocked earplug) are performed on human subjects with less auditory fatigue, and with a plug position less susceptible to being altered.

### 3.4. Data screening for "valid threshold"

In some cases, the hearing threshold measured leads to an unexpected situation where the filtered attenuation exceeds the blocked attenuation. In these cases, Eq. (7) is no longer usable since it requires taking the logarithmic value of a negative number. Consequently such cases must be considered as "invalid threshold" resulting from the hearing threshold variability and these *outlier* should be discarded (screened out) accordingly for the computation of the average damper attenuation. Outliers have been

**Table 2**
Amount of "valid fit" tests and "valid threshold" tests for the "per subject average" analysis.

| Damper (Ω) | "valid fit" | "valid threshold" |
|---|---|---|
| 4700 | 10 | 5 |
| 2200 | 8 | 8 |
| 1000 | 7 | 7 |
| 330 | 7 | 6 |

screened out on a "per subject average" basis: if, at one or more frequencies in an individual arithmetic mean, the averaged filtered attenuation exceeds the averaged blocked attenuation, the complete subject data (i.e. the 3 trials) will be discarded. A "per test trial" approach was also tested, in which the complete test data was discarded in a given trial if, at one or more frequencies in a test trial, the filtered attenuation exceeded the blocked attenuation. After careful analysis, it was felt that the "per subject average" approach would increase the dataset size and hence would improve the evaluation of the damper attenuation. The number of "valid threshold" is reported in the third column of Table 2; since it is a screening that occurs after the "valid fit" one, the number of "valid threshold" will be smaller than the number of "valid fit". It is also important to note that these outliers were discarded *only* for the building of the damper attenuation model and that they will all be reincorporated during the evaluation of the prediction error in Section 4.1. This implies that if the model assumptions were wrong (i.e. if the independent path hypothesis was rarely met), huge values of prediction error would be obtained and therefore, unacceptably high values of uncertainty would be obtained for the proposed model.

### *3.5. Analysis of the data collected*

The measured attenuation is reported per subject for every octave-band (all details are available in [18]). It sometimes happens that the attenuation obtained from measured hearing thresholds on human test subjects is greater with the filtered earplug than with the blocked earplug. This type of situation does not meet the independent path hypothesis, which states that the damper always creates an additional independent sound path and that consequently, it always reduces the attenuation of the earplug. This situation can arise from two possible cases:

(1) A destructive interference occurs between the two sound paths.
(2) The uncertainty associated with the hearing threshold assessment (obtained by the REAT method) is significant compared to the difference between the filtered and blocked earplug attenuation.

The first case would imply that the proposed model is inappropriate for the proposed usage. This is not the case as it has been found that the second reason explains the observed abnormality. This is demonstrated in the next two sections in which the validity of the independent path hypothesis is evaluated. The independent path hypothesis validity is first evaluated (in Section 3.5.1) using an ATF.This ATF has the advantage of providing a fast and repeatable IL measurement, and the disadvantage of being less representative of the physical and acoustical properties of the protected ear system of an actual human subject. Secondly, the hypothesis is validated (in Section 3.5.2) on human subjects, who can only be tested with a subjective REAT measurement. This type of measurement has a greater uncertainty but accounts for all the variations of the physical and acoustical properties of the protected ear system between human subjects and is therefore, complementary to the first objective validation.

#### *3.5.1. Evaluation of the independent path hypothesis validity on an acoustical test fixture*

The experimental setup for the measurement of the IL on an ATF of various damper elements is shown in Fig. 4: the Insertion Loss measurement was performed in an anechoic room using the B&K 4128 Head&Torso Simulator, by measuring with a spectrum analyzer the sound pressure level at the eardrum microphone with and without the HPD in place.

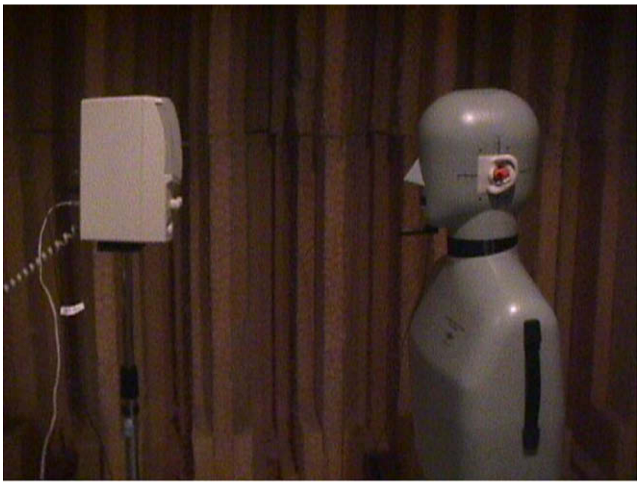

**Fig. 4.** Overview of the B&K 4128 Head&Torso simulator with the ear simulator occluded with a filtered earplug.

The complete set of seven dampers (with nominal acoustical resistance values of 4700, 3300, 2200, 1500, 1000, 680, 330 Ω c.g.s.) were used in this order to increase the number of data points that would later be used to establish the relation between attenuation and acoustical resistance. The earplug with a fullblock and an "open sound-bore" state were also measured, for comparison purposes with the filtered data.

Careful analysis of the acoustical test fixture (ATF) insertion loss data plotted in Fig. 5 does not reveal any significant interference between the damper and the earplug: the attenuation values of the filtered earplug follow almost exactly the progression of the damper resistance values and the unfiltered (blocked) earplug attenuation always appears to be higher than the filtered one. The fact that the filtered earplug has less attenuation than the blocked earplug implies that any coupling effect – if any – is small and that, in practice, the two sound paths can be considered as independent: this is the first validation of the independent path hypothesis.

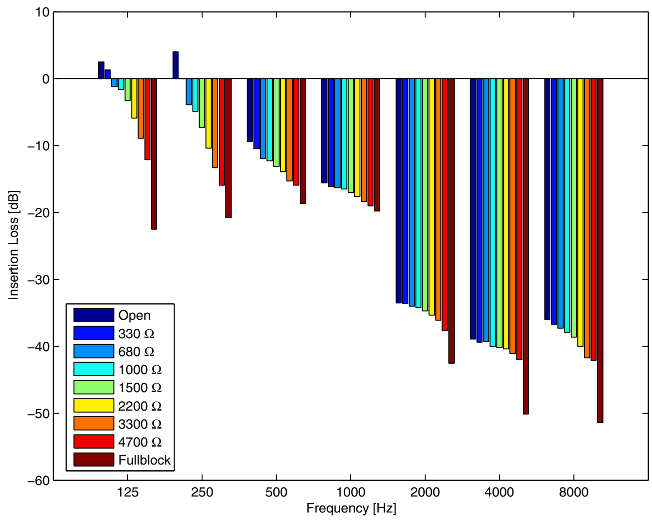


**Fig. 5.** Insertion loss of the earplug with the fullblock, with the seven available damper elements values and with an open sound-bore.

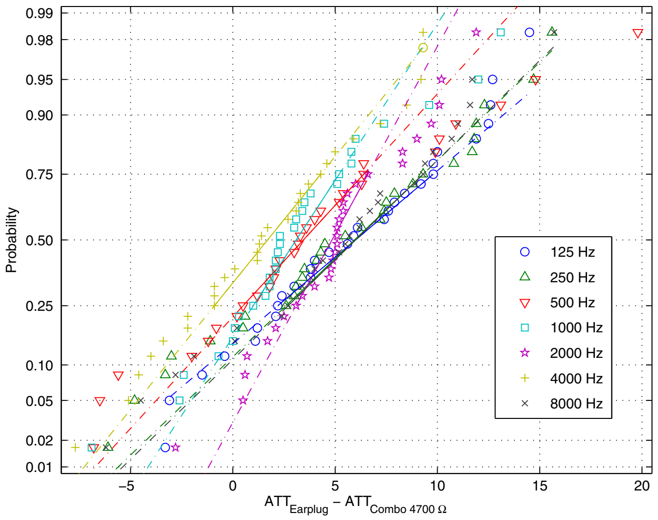


**Fig. 6.** Normal probability plot of $ATT_{Earplug} - ATT_{Combo}$ for the 4700 Ω damper element.

### 3.5.2. Evaluation of the hypothesis' validity on human subjects

The normal probability plot of the difference between the blocked earplug attenuation ($ATT_{Earplug}$) and the filtered earplug ($ATT_{Combo}$) is presented in Fig. 6 for thirty REAT measurements. The purpose of a normal probability plot of a physical quantity is to graphically assess whether this quantity could come from a normal distribution. If the data is normal the plot is linear. Other distribution types will introduce curvature in the plot. These plots provide a visual indication that the difference between the blocked earplug attenuation ($ATT_{Earplug}$) and the filtered earplug ($ATT_{Combo}$) is a normal distribution although some outliers can be observed. It also clearly demonstrates that certain human subjects will actually report more attenuation with the filtered earplug than with the blocked earplug. This is especially true for the 4 kHz octave-band, for which the filtered and blocked earplug have average values that are very close (as seen in Fig. 6 where the 4 kHz normality line is further to the left so that its median value is the closest one to zero). Nevertheless, the normal probability plot shows that the difference follows a normal distribution closely and that the average values of blocked earplug attenuation are greater than filtered earplug attenuation for every octave-band. However, there are some individual values for which the blocked earplug attenuation is lesser than the filtered one. These *outliers* can be seen as the normal spread in attenuation assessment using the REAT method, mainly due to the variability in hearing thresholds (such uncertainty is estimated to be ranking from 2.9 dB in AS1270 [19] to 6.7 dB in the most recent draft of ISO4869 [20]). This second approach with measurements on human subjects leads to the same observations as the first approach on an ATF: the filtered earplug produces – on average – less attenuation than the blocked earplug. This is a second validation of the independent path hypothesis.

### 3.6. Averaged damper attenuation $\overline{ATT}_{Damper}$ data

Using Eq. (7) and the measured attenuation data (averaged on an individual basis, i.e. on the 3 trials), the damper attenuation, $ATT_{Damper}$, is computed for each of the four available dampers, using the "per subject average" analysis. The arithmetic mean and the standard deviation of the selected 1/3 octave-band $ATT_{Damper}$ values are presented in Table 3 (the complete dataset is available in [18]).

The upper part of Table 3 presents the tabulated values of $\overline{ATT}_{Damper}$ to be used for the prediction of the filtered attenuation, as per Eq. (3). The lower part of Table 3 presents the tabulated values of the standard deviation of the damper attenuation $ATT_{Damper}$. This standard deviation will be later referred to as the damper attenuation uncertainty $u_{ATT_{Damper}}$. The high values of $u_{ATT_{Damper}}$ in the 4 kHz octave-band can be explained by the fact that damper attenuation $ATT_{Damper}$ was set at this frequency by comparing the difference between two REAT measurements (one on a blocked earplug, the other on a filtered earplug) which were very close to each other in value, as already discussed in Section 3.5.2.

**Table 3**
Mean and standard deviation of the selected 1/3 octave-band attenuation $ATT_{Damper}$ for the remaining "valid threshold" tests with the "per subject average" analysis.

| Frequency (Ω) | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| *Mean* | | | | | | | |
| 4700 | 16.9 | 16.4 | 17.8 | 20.8 | 30.2 | 42.4 | 37.7 |
| 2200 | 10.6 | 12.9 | 14.3 | 17.2 | 28.3 | 40.2 | 32.8 |
| 1000 | 7.6 | 9.2 | 11.8 | 18.7 | 28.6 | 41.8 | 30.5 |
| 330 | 6.3 | 6.5 | 11.8 | 18.5 | 28.8 | 38.4 | 28.7 |
| *Std.* | | | | | | | |
| 4700 | 3.3 | 2.8 | 3.2 | 2.5 | 3.6 | 8.1 | 4.7 |
| 2200 | 3.0 | 3.5 | 3.1 | 2.6 | 3.2 | 7.6 | 4.7 |
| 1000 | 2.7 | 3.0 | 3.2 | 3.8 | 2.9 | 6.2 | 4.1 |
| 330 | 2.8 | 3.9 | 3.4 | 2.5 | 2.2 | 5.2 | 5.0 |

## 4. Uncertainty associated with the filtered earplug attenuation prediction

No physical measurement is complete without a clear expression of the uncertainty associated with its measurement value. The combined uncertainty associated with the proposed filtered earplug attenuation prediction method will therefore be formulated when using the REAT measurement method (in Section 4.1 ) and when using the F-MIRE measurement method (in Section 4.2). The uncertainty associated with damper acoustical resistance variability will be presented in Section 4.3, while the evaluation of the prediction error with be detailed in Section 4.4. The prediction uncertainty will be experimentally verified in Section 4.5.

### 4.1. Formulation of the uncertainty associated with the proposed filtered earplug attenuation prediction method, REAT method

The uncertainty associated with the proposed model will be estimated by comparing the predicted attenuation $\widehat{ATT}_{Combo}$ of the earplug equipped with a filter (see Eq. obtained from Eq. (3)) with the attenuation $ATT_{Combo}$ actually measured by the REAT method. The total prediction error, denoted $ERR_{Prediction}$ can be defined as:

$$ERR_{Prediction} = \widehat{ATT}_{Combo} - ATT_{Combo} \tag{8}$$

The prediction uncertainty $u_{Prediction}$ is the standard deviation of the prediction error; from Eq. (8), it is also the composition of the uncertainty associated with $ATT_{Combo}$ and $\widehat{ATT}_{Combo}$. The first component of Eq. (8), $\widehat{ATT}_{Combo}$, contains the uncertainty component $\Delta_{\widehat{ATT}_{Combo}}$ that is obtained by using a partial derivative approach on Eq. (3) and can be expressed, after simplification, as:

$$\Delta_{\widehat{ATT}_{Combo}} = \frac{1}{\frac{10^{\frac{ATT_{Earplug}}{10}}}{10^{\frac{\overline{ATT}_{Damper}}{10}}} + 1} \left( \frac{10^{\frac{ATT_{Earplug}}{10}}}{10^{\frac{\overline{ATT}_{Damper}}{10}}} \cdot \Delta_{ATT_{Earplug}} + \Delta_{\overline{ATT}_{Damper}} \right) \tag{9}$$

When $ATT_{Earplug}$ is much larger that $\overline{ATT}_{Damper}$ (and it is the case most of the time, per the independent path hypothesis, as demonstrated in paragraph 3.5.2), the uncertainty component $\Delta_{\widehat{ATT}_{Combo}}$ reduces to $u_{\overline{ATT}_{Damper}}$. This is the uncertainty associated with the arithmetic average of REAT attenuation data for a given damper. It can be expressed as $\frac{u_{ATT_{Damper}}}{\sqrt{n}}$ (where $n$ is the number of independent tests used, as presented in Table 2) and will decrease as the number of REAT measurements increases. Since the damper attenuation calculation (per Eq. (6)) uses two REAT measurements (one for the blocked, one for the filtered earplug), on a damper with an actual acoustical resistance value that may slightly differ from its nominal value, on a complex human acoustical system that has been averaged in the proposed model, the components of $u_{ATT_{Damper}}$ are:

(1) twice the uncertainty component $u_{REAT}$ that is associated with the REAT measurements of the blocked earplug attenuation $ATT_{Earplug}$ and of the filtered earplug attenuation $ATT_{Combo}$: such uncertainty in the measurement of the sound attenuation of a hearing protector using REAT, denoted $u_{REAT}$, may arise from various sources, such as the uncertainty in the measurement of the threshold of the test subjects' hearing, the uncertainty of the sound pressure level measurements, the uncertainty in the controlling attenuators, etc. From AS1270 [19], the standard uncertainty is calculated to be 2.9 dB (whatever HPD is tested), as already mentioned. In the most recent draft of ISO 4869 [20], it is calculated at 5.4 and 6.7 dB for earmuffs and earplugs, respectively. These latter uncertainty figures supplied for earmuffs and earplugs are said to be estimates from measurements at the National Acoustic Laboratories (Australia) and from measurements at NIOSH and are "*considered being representative of the measurements and equipment that would normally be used in hearing protector testing*".

(2) $u_{Resistance}$ is the resistance uncertainty: the dampers come from a regular production lot that has inherent variability; this uncertainty component will be later quantified in Section 4.3.3.

(3) $u_{Method}$ is the method uncertainty. It accounts for the fact that the damper attenuation was obtained from a group average value and therefore eliminates individual characteristics (such as the acoustical load viewed by the damper element or the shifted earcanal resonance, etc.). It also accounts for the fact that the method requires that 2 consecutive insertion of the earplug be performed (to measure both the blocked earplug attenuation and the filtered earplug attenuation per the REAT method). These insertions may lead to a slightly different fit of the earplug in the subject's earcanal and such intra-subject fit variability can be a large contribution to the $u_{Method}$ term. In the current experiment, such intra-subject fit variability was controlled, since the earplug attenuation was checked before each damper insertion to be within 3 dB from previous one.

The damper attenuation uncertainty $u_{ATT_{Damper}}$ can then, be expressed as:

$$u_{ATT_{Damper}} = \sqrt{(2 \times u^2_{REAT} + u^2_{Resistance} + u^2_{Method})} \qquad (10)$$

The second component of Eq. (8), $ATT_{Combo}$, contains one time the uncertainty $u_{REAT}$.

The prediction uncertainty $u_{Prediction}$ can be expressed as the quadratic summation of the two uncertainty components previously described, which gives, using Eq. (10) for the second component:

$$u_{Prediction} = \sqrt{\left(u^2_{REAT} + \frac{2 \times u^2_{REAT} + u^2_{Resistance} + u^2_{Method}}{n}\right)} \qquad (11)$$

### 4.2. Formulation of the uncertainty associated with the proposed filtered earplug attenuation prediction method, F-MIRE method

In the practical implementation of the proposed method, as dispensed for example by Sonomax certified technicians in the workplace, the blocked earplug attenuation $ATT_{Earplug}$ is no longer measured using REAT but is based on the F-MIRE measurement of $ATT_{Earplug}$ presented in Section 2. Consequently, Eq. (11) has been slightly modified to now include the uncertainty associated with the F-MIRE measurement, denoted $u_{FMIRE}$, which replaces one $u_{REAT}$ component. The prediction uncertainty, now denoted $u'_{Prediction}$, is expressed as:

$$u'_{Prediction} = \sqrt{\left(u^2_{REAT} + \frac{u^2_{FMIRE} + u^2_{REAT} + u^2_{Resistance} + u^2_{Method}}{n}\right)} \qquad (12)$$

At this stage, one assumption is that the F-MIRE attenuation uncertainty is less than or equal to the REAT attenuation uncertainty and hence, that the estimation of $u_{Prediction}$ obtained in Section 4.1 with the REAT method will be a safe estimator of the real-life prediction uncertainty $u'_{Prediction}$. In order to validate such a hypothesis, an experimental verification will be conducted in Section 4.5 on a limited number of subjects.

### 4.3. Formulation and evaluation of the uncertainty component associated with the damper acoustical resistance variability, $u_{Resistance}$

The prediction of the filtered attenuation $\widehat{ATT}_{Combo}$ is based on the assumption that damper attenuation $ATT_{Damper}$ remains the same for all the dampers having a nominal acoustical resistance value. As in all manufacturing processes, these dampers will show some variability in their acoustical resistance properties and the manufacturer is only able to ensure a given relative tolerance on the acoustical resistance of the damper elements. The variability in damper attenuation, caused by the variability of its acoustical resistance will be investigated in the current section.

Given the precision or accuracy needed to assess the variability in damper attenuation due to its acoustical resistance variability, the use of the REAT measurement method is no longer an option, because of its large uncertainty. The use of the IL on an ATF, as described in Section 3.5.1, is appropriate: it has a smaller uncertainty than the REAT and, furthermore, the evaluation that is presently conducted is a *relative* assessment of the attenuation variability and does not need an absolute attenuation reference.

#### 4.3.1. IL measurement on several earplug configurations

Using Eq. (7), it is possible to compute the damper attenuation for each of the seven dampers.

#### 4.3.2. Relationship between acoustical resistance and attenuation

Damper attenuation can be plotted as a function of the damper nominal acoustical resistance value. The linear relation between both quantities is clearly visible in Fig. 7.

Thus, it is possible to compute the increase (i.e. the slope of the linear regression lines) of $ATT_{Damper}$ as a function of the nominal acoustical resistance of the seven dampers used.

The slopes, in dB/kΩ, of the linear regression curves between the attenuation versus the nominal acoustical resistance are presented in Table 4. They will be useful in determining the uncertainty associated with the damper nominal resistance variability in Section 4.3.3. It can be observed that the incline of the slopes are generally greater for lower frequencies than for higher frequencies.

#### 4.3.3. Variability of damper attenuation

The damper manufacturer specifies[1] the relative tolerances for the acoustical resistance shown on line three of Table 5. The variabilities in attenuation, $u_{Resistance}$ caused by the variability of acoustical

[1] From: "Outline and Performance Specification Index", Knowles Electronics Inc., Itasca, USA, June 30th, 1994".

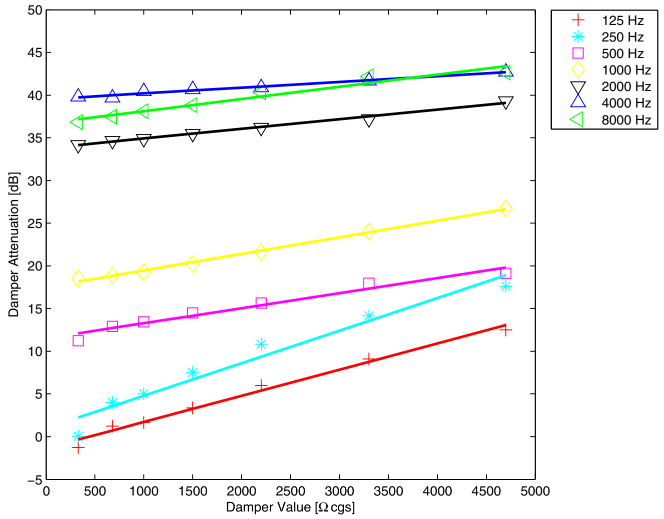


**Fig. 7.** Linear regression curves between the damper attenuation and the nominal acoustical resistance, for the seven dampers used for the selected 1/3 octave-bands from 125 Hz to 8 kHz.

**Table 4**
Slopes of the linear regression curves between the attenuation (insertion loss) and the acoustical resistance of the seven dampers per selected 1/3 octave-bands.

| Frequency (Hz) | Slope (dB/$k\Omega$) |
|---|---|
| 125 | 3.55 |
| 250 | 4.91 |
| 500 | 2.76 |
| 1000 | 3.49 |
| 2000 | 1.64 |
| 4000 | 0.90 |
| 8000 | 1.79 |

**Table 5**
Tolerance on the acoustical dampers nominal resistance values and uncertainty in attenuation caused by the variability of acoustical resistance, $u_{Resistance}$, for the four dampers used (in dB), for the 7 selected 1/3 octave-band frequencies.

| Model | BF-1999 | BF-1860 | BF-1921 | BF-1923 |
|---|---|---|---|---|
| Acoustic resistance (Ω c.g.s.) | 330 Ω | 1000 Ω | 2200 Ω | 4700 Ω |
| Tolerance (%) | 15 | 15 | 20 | 20 |
| 125 Hz | 0.2 | 0.5 | 1.6 | 3.3 |
| 250 Hz | 0.2 | 0.7 | 2.2 | 4.6 |
| 500 Hz | 0.1 | 0.4 | 1.2 | 2.6 |
| 1000 Hz | 0.2 | 0.5 | 1.5 | 3.3 |
| 2000 Hz | 0.1 | 0.2 | 0.7 | 1.5 |
| 4000 Hz | 0.0 | 0.1 | 0.4 | 0.8 |
| 8000 Hz | 0.1 | 0.3 | 0.8 | 1.7 |

resistance are presented in Table 5. They are obtained by multiplying the tolerance values (product of second and third lines of Table 5) by the slopes in Table 4 of the linear relation between the attenuation and the acoustical resistance.

The values presented in Table 5 appear to be quite large considering that, in practice, the prediction uncertainty ($u_{Prediction}$ presented in Table 6) that already includes this resistance variability shows values that are often smaller. This is particularly true for the 2200 and 4700 Ω dampers. A reasonable explanation for this could be that the manufacturer of these dampers is playing it safe by overstating the variability of its dampers' acoustical resistance. Consequently, special attention was paid to eliminate the damper variability during the experimental verification of the prediction uncertainty, in Section 4.5.

**Table 6**
Mean and standard deviation of the prediction error of the selected 1/3 octave-band and overall attenuation of the filtered earplug using the available dampers.

| Frequency (Ω) | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 | Overall |
|---|---|---|---|---|---|---|---|---|
| *Mean* | | | | | | | | |
| 4700 | −0.9 | −2.0 | −1.3 | −1.0 | 0.1 | 0. 3 | −1.6 | −0.9 |
| 2200 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.8 | 0.0 | 0.3 |
| 1000 | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.5 | −0.0 | 0.3 |
| 330 | 0.2 | −0.2 | −0.6 | −0.3 | −1.1 | −0. 3 | 0.2 | 0.0 |
| *Std.* | | | | | | | | |
| 4700 | 2.3 | 3.1 | 2.4 | 1.6 | 2.6 | 2.0 | 3.5 | 1.6 |
| 2200 | 2.7 | 3.0 | 2.6 | 1.9 | 2.5 | 3.0 | 4.3 | 2.0 |
| 1000 | 2.6 | 2.8 | 2.8 | 2.4 | 2.1 | 1.2 | 3.9 | 2.3 |
| 330 | 2.5 | 3.5 | 3.3 | 2.0 | 3.2 | 2.6 | 4.4 | 2.3 |

### *4.4. Evaluation of the prediction error*

The prediction error is computed with Eq. (11) on the original REAT dataset *with no outline removed*. The validity of the error calculation is not altered by using the same $ATT_{Combo}$ dataset, since it is firstly, used as an averaged damper attenuation (screened data) and secondly, as an individual attenuation for the prediction error calculation (unscreened data). The average and standard deviation of such prediction error, per selected 1/3 octave-band and per overall value, are presented in Table 6 (all details are available in [18]). The overall attenuation value $ATT_{Overall}$ is computed with the following equation:

$$ATT_{Overall} = 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{100+C^i}{10}}\right) - 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{100+A^i-ATT^i}{10}}\right) \quad (13)$$

where $A^i$ and $C^i$ are, respectively the A and C weighting coefficient values per octave-bands and $ATT^i$ are the octave-band attenuation data at center frequencies indexed $i$.

The upper part of Table 6 represents the average value of this prediction error $ERR_{Prediction}$: it is not greater than 2 dB (in absolute value) for all the four dampers, at all the selected 1/3 octave-band frequencies and is less than 1 dB in overall value. The lower part of Table 6 represents the standard deviation of the prediction error (referred to as the prediction uncertainty $u_{Prediction}$), it reaches maximum values at high frequencies (8 kHz octave-band), but does not exceed 3 dB in overall value. The relatively small values of the prediction error further support the independent path hypothesis as a reasonable assumption and legitimize the data screening (in Section 3.4). It is of interest to note that except for 2 values (the 4700 Ω damper at 250 Hz and the 330 Ω damper at 2 kHz), the prediction error is less than the damper attenuation variability values (presented in Table 3). Indeed, as Eq. (11) suggests, this damper attenuation variability is a contributing factor to the prediction error, but is divided by $n$. Thus, it has but a marginal effect. The prediction error should then be closer to the REAT uncertainty ($u_{REAT}$), as $n$ increases.

### *4.5. Experimental verification of the prediction uncertainty*

For this initial experimental verification, an F-MIRE attenuation measurement is performed on the custom earplugs of a very limited number of subjects (5 subjects) and the attenuation of the filtered earplug is then predicted using the proposed method. This predicted attenuation value is then compared to the attenuation of the filtered earplug, using the REAT method, for each of the 5 subjects. Since the resistance variability $u_{Resistance}$ previously investigated in Section 4 appears to be very low (but overstated by the manufacturer) compared to other uncertainty components, it has now been discarded from the current verification: the effect has been made negligible by choosing 4 pairs of damper (one pair for each nominal resistance value) with individual precise measured resistance values that will be used and re-used for the 5 subjects.

Three different statistical checks were performed on the predicted and reported data collected during the experimental verification:

(1) a check verifying the normality of the prediction error (the difference between the predicted reported attenuation values),
(2) a check evaluating the statistical significance of differences between the predicted and the reported attenuation values, and
(3) a check observing the confidence intervals of the predicted attenuation values.

*4.5.1. Normality check on the prediction error*

The first statistical check was to verify that the differences between the predicted and reported values are randomly distributed, hence, that the prediction model was not suffering from any bias.

A Lilliefors test (a modification of the Kolmogorov–Smirnov test) was conducted to determine if the null hypothesis of composite normality was a reasonable assumption regarding the population distribution of the prediction error.

The result of the Lilliefors hypothesis test is that, in most cases, the null hypothesis can not be rejected at a significance level of 0.05. The prediction errors follow a normal distribution for all dampers at all octave-band frequencies at the exception of the 4700 Ω damper for the 2 and 8 kHz bands and the 330 Ω damper for the 125 Hz band.

*4.5.2. Check on statistical significance of differences between predicted and reported values*

To check the statistical significance of differences between predicted and reported attenuation values, a *t*-test was performed to determine whether the two sets of attenuation values could have the same mean. To perform such a test, it was necessary to first ensure that both variances could be assumed equal, through an homoscedasticity test.

To assess whether the variances of the predicted and reported attenuation had equal (but unknown) variance, a Levenes test for homogeneity of variances is used. The associated probability for the Levene's test was equal to or greater than 0.05 for all octave-band frequencies, for the 4 dampers, so the assumption of homoscedasticity was met. The experimental data could then be assumed to come from normal distributions with unknown, but equal, variances and the *t*-test could then be conducted.

The *t*-test used is a two-sample *t*-test with pooled variance estimates. For all octave-band frequencies, the *t*-test returns $H = 0$, indicating that the null hypothesis ("means are equal") cannot be rejected at the 5% significance level.

*4.5.3. Check on the confidence interval of the prediction error*

Once the predicted and reported attenuation values had been checked for equal variance and mean values, the individual prediction error could be checked to see that it fell within the expected range defined by the uncertainty values presented in Table 3. Although this table contains the prediction error when using the REAT method to measure the blocked earplug attenuation, it was decided to use it in the case of the Field-MIRE measurements, because the prediction error given by Eq. (12) would not be much smaller than the prediction error given by Eq. (12), since the relative effect of changing $u_{REAT}$ into $u_{FMIRE}$ was diminished by a factor $\sqrt{n}$.

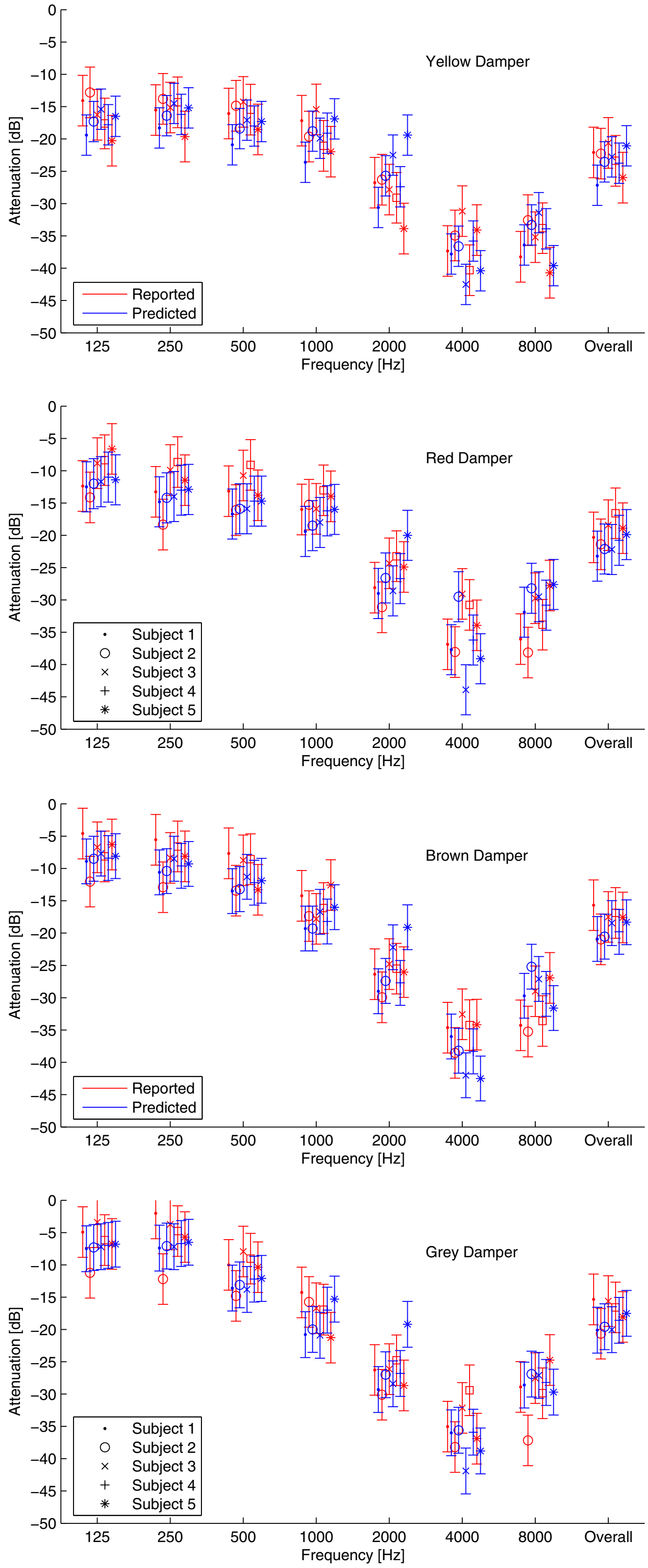


**Fig. 8.** Predicted vs. reported attenuation for the earplug filtered with the 4700 Ω ("Red"), 2200 Ω ("Yellow"), 1100 Ω ("Brown") and 330 Ω ("Grey") dampers.

The results are presented in Fig. 8 with a graph for each damper showing the range of predicted and measured REAT values for each of the five subjects tested at each octave-band and for the overall value. The range of predicted and measured REAT values are generally overlapping, this is true for 131 out of 140 octave-band test cases and 20 out of 20 overall test cases. The validation criteria is therefore met in 93% of the octave-band cases and 100% of the overall cases.

## 5. Conclusions

A model for the prediction of the filtered earplug attenuation was built based on the hypothesis that sound transmission paths through the damper element and through the earplug are independent, hence that their respective sound energies simply add to each other. The damper sound transmission path attenuation is therefore formulated as a subtraction of the filtered earplug attenuation from the blocked earplug attenuation. This damper sound transmission path attenuation is then averaged for a large set of experiments and is later used together with the attenuation of the blocked (not yet filtered) earplug in a formula that predicts the attenuation of the filtered earplug. The independent path hypothesis underlying such an energy summation approach has been validated on both ATF and human subjects.

The uncertainty associated with the proposed prediction method has been formulated in terms of a combination of uncertainty components, for cases in which the blocked earplug attenuation is measured, first, using the REAT method and, second, using a Field-MIRE method (microphone-in-real-ear method adapted for field use).

This quantification of the prediction uncertainty for the proposed Field-MIRE approach has been experimentally checked, on a limited set of subjects: the percentage of measured filtered attenuation values that fall within the predicted range is reasonably close to the expected value.

Further experiments should be conducted in the field to validate, on larger groups of subjects, the underlying assumptions made by the authors and the prediction uncertainty values found. This type of validation should be conducted with earplugs that would be filtered by dampers taken from a regular production lot (rather than sets of repeatedly re-used dampers), even if such damper resistance variability is most probably negligible. Once thoroughly validated, the proposed method could be used in the field to select the damper to be used to match earplug attenuation to the wearer's needs, hence it would help to address the auditory comfort concerns usually associated with earplug use.

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