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JÉRÉMIE VOIX

# MISE AU POINT D'UN BOUCHON D'OREILLE « INTELLIGENT »

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LE 29 JUIN 2006

À L'ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

**MISE AU POINT D'UN BOUCHON D'OREILLE « INTELLIGENT »**

Jérémie Voix

SOMMAIRE

De nombreux travailleurs sont exposés à des niveaux de bruit trop élevés qui les mettent en danger de perdre leur audition. Cependant la réduction du bruit à la source, lorsqu'elle est techniquement possible, est souvent difficile à mettre en œuvre pour des raisons économiques. La protection auditive individuelle reste donc la solution la plus répandue en pratique. Malheureusement, les protecteurs auditifs actuellement disponibles sur le marché sont rarement portés aussi continuellement qu'ils le devraient (car ils sont peu confortables ou doivent être enlevés pour communiquer) et sont généralement mal adaptés aux besoins de protection du travailleur (car leurs atténuation individuelle effective est très généralement inconnue). Ce travail de thèse de doctorat, réalisé en étroite collaboration avec la compagnie SONOMAX SANTÉ AUDITIVE INC. avait pour objectif général le développement d'un bouchon d'oreille intelligent qui remédierait à l'ensemble des problèmes des protecteurs auditifs actuellement sur le marché et permettrait ainsi de prévenir efficacement la perte auditive en milieu industriel. Les problématiques associées à ce développement ont été formulées de façon détaillée sous l'aspect santé-sécurité au travail (port non continu du protecteur et protection inadaptée), l'aspect technique (développement d'un bouchon confortable du point de vue physique et perceptif et dont les performances sont mesurables) et l'aspect scientifique (modélisation de systèmes physiques, traitement du signal, instrumentation et mesure). Les développements techniques ont conduit à la mise au point d'un bouchon d'oreille sur-mesure obtenu par un procédé d'ajustement instantané au sein même de l'oreille du travailleur, dont les performances acoustiques sont mesurables individuellement grâce à l'utilisation d'une sonde microphonique et dont l'atténuation acoustique peut être adaptée au besoin du travailleur par l'insertion de filtres acoustiques passifs au travers du protecteur. Les développements scientifiques ont permis la mise au point d'une méthode de prédiction de l'atténuation acoustique à partir de la mesure d'un affaiblissement acoustique et la mise au point d'une méthode de prédiction de l'atténuation résultante de l'utilisation des filtres acoustiques.

## DEVELOPMENT OF A "SMART" EARPLUG

Jérémie Voix

ABSTRACT

Many workers are exposed to noise levels high enough to put them at risk of loosing their hearing. However, noise reduction at the source, when technically feasible, is often difficult to implement for economical reasons. Therefore, individual hearing protection remains the most widespread solution in practice. Unfortunately, the hearing protectors currently available on the market are seldom worn continuously as they should be (because they are not very comfortable or must be removed to communicate) and do not match the worker's need for protection (because their actual attenuation is generally unknown). This doctorate thesis work, carried out in close collaboration with SONOMAX HEARING HEALTHCARE INC., had the general objective to develop a smart earplug that would solve the problems associated with current hearing protection devices thereby effectively preventing noise induced hearing loss in the industrial environment. The issues associated to this development have been formulated in details under the Health and Safety aspect (non-continuous wearing of the hearing protector and un-adapted protection), technical aspects (development of an earplug that is comfortable both from the physical and sound perception points of view and whose performances are measurable) and scientific aspects (modeling of physical systems, signal processing, instrumentation and measurement techniques). The technical developments have resulted in a custom earplug that is instantly fitted to the wearer's ear by silicone injection. Its acoustical performance can be measured using a microphone probe while the attenuation can be adapted to the user's need by the insertion through the earplug of passive acoustical filters. The scientific developments have resulted in the prediction of the attenuation of the earplug from the Noise Reduction measurement and in the prediction of the filtered earplug attenuation.

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*À Gabriel et Arthur, mes fils adorés...*

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| | |
|---|---|
| $A$ | Pondération A |
| $C$ | Pondération C |
| $L_A$ | Niveau de pression acoustique pondéré A |
| $p_{\mathrm{me(a)s}}$ | Image informationelle de la pression acoustique au microphone de mesure |
| $p_{\mathrm{ref}}$ | Image informationelle de la pression acoustique au microphone de référence |
| $p_0$ | Image informationelle de la pression acoustique en champ libre |
| $p_3$ | Image informationelle de la pression acoustique tympanique |
| $p_2'$ | Image informationelle de la pression acoustique à l'extrémité de la portion canal du bouchon |
| $p_3'$ | Image informationelle de la pression acoustique tympanique (occlus) |
| $p$ | Image informationelle de la pression acoustique en champ libre |
| ANSI | American National Standard Institute |
| ATF | Acoustic Test Fixtures *Montage d'essai acoustique* |
| B | Binaural *Binaural* |
| BC | Bone Conduction *Conduction osseuse* |
| COMP | Valeurs de la fonction de compensation |
| CSA | Canadian Standard Association *Association canadienne de normalisation (ACNOR)* |
| EPA | Environemental Protection Agency |
| ERP | Ear Reference Point |
| ETS | *École de technologie supérieure* |

| | |
|---|---|
| FRF | Frequency Response Function *Fonction de réponse en fréquence* |
| HPD | Hearing Protection Device *Protecteur individuel contre le bruit* |
| IL | Insertion Loss *Perte par insertion* |
| IRSST | *Institut de recherche Robert-Sauvé en santé et sécurité au travail* |
| ISO | International Organization for Standardization *Organisation internationale de normalisation* |
| L | Left *Gauche* |
| MIRE | Microphone In Real Ear *Microphone placé dans une oreille réelle* |
| NIOSH | National Institute for Occupational Safety and Health |
| NR | Noise Reduction *Affaiblissement acoustique* |
| NRR | Noise Reduction Rating |
| OSHA | Occupational Safety and Health Administration |
| PN | Physiological Noise *Bruit physiologique* |
| PPAR | Predicted Personal Attenuation Rating *Indice d'atténuation personnelle prédit* |
| R | Right *Droite* |
| REAT | Real-ear Attenuation at Threshold *Méthode normalisée de déplacement du seuil d'audition* |
| RTA | Real-Time Analyzer *Analyseur de spectre* |
| SNR | Single Number Rating |
| SPL | Sound Pressure Level *Niveau de pression acoustique* |
| STD | Standard Deviation *Écart-type* |
| TF | Transfer Function |
| TFOE | Transfer Function of the Outer Ear *Fonction de transfer de l'oreille externe* |
| TM | Tympanic Membrane *Tympan* |

# INTRODUCTION

## CONTEXTE

### Le problème

Nombreux sont les travailleurs sujets au risque de pertes auditives du fait de leur exposition sonore professionnelle. Or pour des raisons économiques, la réduction du bruit à la source, lorsqu'elle est techniquement possible, est souvent difficile à mettre en œuvre. En pratique, la protection individuelle reste donc la solution la plus répandue. Malheureusement, les protecteurs auditifs actuellement disponibles sur le marché sont rarement portés de façon aussi continue qu'ils le devraient, soit en raison de leur inconfort, soit en raison de la nécessité qu'il y a de les enlever si on veut communiquer. Par ailleurs, ils sont généralement mal adaptés aux besoins individuels de protection des travailleurs, car leur atténuation varie d'un individu à l'autre et n'est pas facilement mesurable sur le terrain.

### Le projet industriel

La mission de la compagnie canadienne SONOMAX SANTÉ AUDITIVE INC., constituée en 1998, est précisément de mettre au point un protecteur auditif qui remédierait à l'ensemble des problèmes que posent les protecteurs actuellement sur le marché et permettrait ainsi de prévenir efficacement la perte auditive en milieu industriel. Bien que très imprécis quant aux moyens à mettre en oeuvre, le plan d'affaires initial comporte déjà le concept de base, à savoir que ce protecteur auditif puisse être fabriqué sur-mesure instantanément (par un mécanisme d'injection restant à finir de mettre au point), que ses performances puissent être certifiées (sans que soit précisée la nature de cette certification) et qu'il incorpore une forme de filtrage « intelligent », capable de protéger le travailleur tout en laissant passer les signaux jugés utiles (parole, alarmes, etc.).

### Le partenariat université-industrie

Une collaboration étroite débute dès 2000 entre l'ÉTS et SONOMAX, au travers du recrutement d'un étudiant au doctorat. Cette collaboration implique notamment la présence de l'étudiant une journée par semaine durant toute la durée de ses études au sein des locaux de SONOMAX, afin de participer au développement de la SONOMAX'S SOLUTION ™, commercialisée au niveau international depuis 2003. L'Institut Robert-Sauvé de Recherche en santé et en sécurité du travail (IRSST) a accordé, en 2000, à l'étudiant une bourse d'étude supérieure pour son projet de doctorat. Le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG) a alloué, en 2002, à l'ÉTS une subvention de recherche et développement coopérative (RDC) pour l'élaboration de solutions avancées de filtrage acoustique du bouchon.

## OBJECTIFS

### Objectif du projet industriel

L'*objectif général* du projet est le développement d'un protecteur auditif « intelligent », qui remédierait aux principales lacunes des protecteurs actuellement disponibles. Celles-ci peuvent être regroupées en deux catégories :

- Premièrement, le manque de confort tant du point de vue physique que perceptif (entrave à la communication et à la perception des signaux d'alarme) conduit à un port non continu des protecteurs, diminuant d'autant leur efficacité;
- Deuxièmement, la difficulté de connaître pour chaque individu l'atténuation du protecteur rend très difficile la sélection adéquate d'un type de protecteur pour un travailleur donné (en fonction de son exposition au bruit, mais également de son éventuelle perte auditive). De plus, les situations de sur-protection sont au moins aussi dangereuses que les situations de sur-exposition, puisque le travailleur se retrouve isolé de son milieu de travail et ne perçoit plus les éventuels signaux avertisseurs l'entourant.

Les *objectifs spécifiques* du projet sont la mise au point d'un protecteur auditif qui remédie aux défauts mentionnés précédement, ce qui suppose que ce protecteur :

- puisse être porté de façon continue, ce qui conduit aux deux sous-objectifs suivants :
  - soit confortable du point de vue physique : adapté à la morphologique individuelle et bien accepté par les tissus de l'oreille externe,
  - soit confortable du point de vue perceptif : intégrant un filtrage adaptatif et sélectif afin de laisser passer les signaux utiles,
- ait des performances adaptées au besoin individuel du travailleur, cet objectif se décomposant en deux sous-objectifs :
  - dont l'atténuation soit mesurée sur chaque travailleur, dans des conditions réalistes d'utilisation,
  - dont l'atténuation soit ajustable en fonction du niveau d'exposition du travailleur et de sa perte auditive. Cet objectif est connexe à celui de confort perceptif et sera donc traité conjointement avec ce dernier.

**Objectif du doctorat**

L'*objectif général* de ce travail de doctorat est identique à celui du projet industriel, soit la mise au point d'un bouchon d'oreille « intelligent ». Cependant, ce travail de doctorat ne concerne qu'une partie des objectifs spécifiques du projet industriel et comporte un objectif supplémentaire par rapport aux objectifs du projet industriel : l'élaboration de la stratégie technique et scientifique à mettre en oeuvre pour le développement d'un bouchon d'oreille « intelligent ».

Les *objectifs spécifiques* du doctorat sont donc :

1. la formulation détaillée de la problématique associée au développement d'un tel bouchon d'oreille « intelligent »,

2. la mise au point d'une méthode de mesure des performances acoustiques du bouchon lorsqu'il est porté par le travailleur,
3. la mise au point d'une première génération de filtrage acoustique du bouchon afin d'adapter l'atténuation au besoin exact du travailleur.

## PROBLÉMATIQUE ET MÉTHODOLOGIE

La problématique associée au premier objectif est de dégager, parmi l'abondance d'informations relatives aux protecteurs auditifs, les principaux axes de recherche du projet industriel. Dans cette perspective, une revue détaillée de la littérature relative aux protecteurs auditifs a été entreprise ainsi que l'analyse et la synthèse de l'ensemble de ces données.

La problématique associée au deuxième objectif est de déterminer une grandeur acoustique qui soit reliée à l'atténuation subjective ressentie par le travailleur. Une méthode de mesure, dite « semi-objective », a été développée afin de relier la mesure de l'affaiblissement acoustique (*Noise Reduction*), c'est-à-dire la différence de niveau de pression acoustique entre des microphones placés à l'extérieur et sous le protecteur, à l'atténuation qui serait rapportée par le travailleur s'il était testé par la Méthode des seuils audiométriques (*Real Ear Attenuation at Threshold*, REAT). Un canal de mesure a donc été rajouté au bouchon précédemment développé afin d'y introduire une sonde microphonique, permettant ainsi la mesure objective de l'atténuation dans l'oreille-même du travailleur.

La problématique associée au troisième objectif est de concevoir un filtre passif capable de laisser passer uniquement les signaux utiles. L'approche proposée consiste à tirer parti des capacités naturelles de l'oreille humaine à discriminer les signaux utiles du bruit ambiant. Dans ce but le niveau de bruit résiduel (sous le bouchon) est ramené à une valeur optimale par l'utilisation d'une série de résistances acoustiques. Une méthode prédictive basée sur la combinaison des chemins de transmission acoustiques permet de déterminer à l'avance lequel des éléments résistifs doit être inséré dans le bouchon. Le canal acoustique du bouchon est donc adapté à l'insertion de filtres acoustiques passifs, créant ainsi une fuite acoustique contrôlée sur le protecteur et laissant simplement passer plus ou moins d'énergie sonore afin d'éviter les cas de surprotection qui empêchent généralement le travailleur de reconnaître la parole dans le bruit.

## STRUCTURE DE LA THÈSE

Le travail de la thèse de doctorat porte sur les principaux développements scientifiques effectués dans le cadre de ce projet et s'articule autour de trois articles de revue (inclus intégralement dans les chapitres 1, 2 et 3) qui répondent aux trois objectifs du doctorat cités précédemment :

1. La formulation détaillée des problèmes actuels que posent les protecteurs auditifs a été publiée sous le titre « *Problématiques associées au développement d'un bouchon d'oreille « intelligent »* » dans la revue PISTES (PERSPECTIVES INTERDISCIPLINAIRES SUR LE TRAVAIL ET LA SANTÉ) en mai 2005. L'introduction comporte une revue de la littérature détaillée sur les dangers des bruits industriel. Elle présente la protection individuelle contre le bruit comme la solution la plus économique et la plus efficace à court terme tout en analysant l'approche à plus long terme de réduction du bruit à la source. L'introduction finit avec une analyse de la situation actuelle des protecteurs auditifs disponibles sur le marché. Dans le corps de l'article, les problématiques associées au développement d'un bouchon d'oreille « intelligent » sont analysées sous leurs aspects de santé-sécurité au travail, leurs aspects techniques et leurs aspects scientifiques. Elles conduisent à un tableau synthétique des développements nécessaires pour la mise au point d'un bouchon d'oreille « intelligent ».
2. Le deuxième article, intitulé « *The objective measurement of individual earplug field performance* » soumis en décembre 2005 au JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, présente la méthode de mesure développée. Dans une

première partie, les différentes méthodes de mesure de l'atténuation des protecteurs auditifs sont passées en revue, il en ressort que seule la méthode MIRE (*Microphone In Real Ear*) pourrait être intéressante pour une utilisation terrain. Cependant, plusieurs adaptations sont nécessaires pour rendre cette méthode simple à mettre en oeuvre et pour qu'elle ne requière pas d'appareillage sophistiqué. Le bouchon instrumentable qui rend possible ces adaptations est présenté en deuxième partie. Les adaptations mises en oeuvre ainsi que la formulation théorique de la méthode de prédiction développée sont détaillées dans la troisième partie de l'article. L'incertitude de cette prédiction et ses différentes composantes sont identifiées et quantifiées dans la quatrième partie à l'aide de mesures expérimentales. En cinquième partie, une validation expérimentale compare les prédictions basées sur la méthode à celles obtenues par une méthode classique de laboratoire. Plusieurs exemples d'utilisation de cette méthode sont proposés dans la sixième et dernière partie de l'article.

3. Le troisième article, soumis en décembre 2005 au journal APPLIED ACOUSTICS et intitulé « *Prediction of the Attenuation of a Filtered Custom Earplug* » traite d'une approche permettant la prédiction de l'atténuation du bouchon lorsqu'il est filtré par un élément de résistance acoustique. L'introduction de cet article illustre le besoin d'une telle méthode en présentant les difficultés rencontrées en pratique pour appliquer les recommandations relatives à la sélection, basée sur leur atténuation, des protecteurs auditifs. La méthode de prédiction, présentée dans la deuxième partie, repose sur une représentation sous forme de fonctions de transfert des différents chemins de transmission d'un bouchon filtré et sur la détermination empirique de l'atténuation propre à l'élément filtrant. La troisième partie détaille l'incertitude associée à la méthode de prédiction de l'atténuation du bouchon filtré, tandis que les résultats d'une validation expérimentale, conduite par un laboratoire indépendant, sont présentés en quatrième partie de l'article.

La conclusion de cette thèse présente séparement les avancements scientifiques, les développements technologiques et les retombées industrielles du travail de doctorat et propose des recommandations relatives aux travaux futurs.

# ARTICLE 1

## PROBLÉMATIQUES ASSOCIÉES AU DÉVELOPPEMENT D'UN BOUCHON D'OREILLE « INTELLIGENT »

Article tel que publié dans la revue PISTES (*Perspectives interdisciplinaires sur le travail et la santé*), Volume 7 N° 2 en mai 2005.

# Problématiques associées au développement d'un bouchon d'oreille « intelligent »

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**Résumé**

*De nombreux travailleurs sont exposés à des niveaux de bruit trop élevés qui risquent de leur faire perdre l'audition. Cependant la réduction du bruit à la source, lorsqu'elle est techniquement possible, est souvent difficile à mettre en œuvre pour des raisons économiques. La protection individuelle reste donc la solution la plus répandue en pratique. Malheureusement, les protecteurs auditifs actuellement disponibles sur le marché sont rarement portés aussi continuellement qu'ils le devraient (parce qu'ils sont peu confortables ou doivent être enlevés pour communiquer) et sont généralement mal adaptés aux besoins de protection du travailleur (car leurs atténuation effective est généralement inconnue). Cet article présente les problématiques rencontrées dans le projet en cours de développement d'un bouchon d'oreille qui résoudrait ces difficultés. Les problématiques touchent des aspects de SST (port non continu du protecteur et protection inadaptée), des aspects techniques (développement d'un bouchon confortable du point de vue physique et perceptif et dont les performances sont mesurables) et des aspects scientifiques (modélisation de systèmes physiques, traitement du signal, instrumentation et mesure)*

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**Abstract**

*Many workers are exposed to noise levels high enough to put them at risk of loosing their hearing. However, noise reduction at the source, when technically feasible, is often difficult to implement for economic reasons. Therefore, individual protection remains the most widespread solution in practice. Unfortunately, the currently available hearing protectors on the market are seldom worn continuously as they should (because they are not very comfortable or must be removed to communicate) and do not match the worker's need for protection (because their actual attenuation is generally unknown). This article presents the issues associated with the ongoing development project of an earplug that would solve these problems. The issues are related to Occupational Health and Safety aspects (non-continuous wearing of the hearing protector and unadapted protection), technical aspects (development of a comfortable earplug both from the physical and sound perception point of view and whose performances are measurable) and scientific aspects (modeling of physical systems, signal processing, instrumentation and measurement techniques).*

## 1.1 Introduction

### 1.1.1 Le bruit industriel : un fléau mondial

Un grand nombre d'individus sont exposés à des niveaux de bruits dangereux pour leur système auditif. Si l'on s'en tient à la limite légale d'exposition au bruit de 90 dB(A) 8 heures par jour, le nombre de travailleurs et travailleuses à risque de perdre l'audition au Québec est estimé à 400 000 (Fédération des travailleurs et travailleuses du Québec 1998), soit environ un travailleur sur cinq, et ce nombre atteint 500 000 (Commission de la santé et de la sécurité au travail 1998) si l'on prend la limite de 85 dB(A) recommandée internationalement. Ce dernier nombre devient 30 millions à l'échelle de l'Amérique du nord (NIOSH 1998) et 120 millions à l'échelle planétaire (Organisation mondiale de la santé (OMS) 2001). En conséquence, la surdité est la maladie professionnelle la plus courante aux USA et au Canada : « La perte de l'ouïe est l'invalidité cachée numéro 1 en Amérique du Nord » traduction libre (World Health Organization 1991).

La surdité est un problème coûteux. Au Québec, selon la CSST, le montant d'une indemnité individuelle pour surdité professionnelle peut varier de 500 à 26 000 $ (Commission de la santé et de la sécurité au travail 1998). Au total, de 1993 à 2002, il en aura coûté près de 95 millions $ pour l'indemnisation de toutes les surdités professionnelles au Québec (CSST DSGI - Service de la statistique 2003), tandis qu'il en coûte 39 millions $US annuellement aux USA (Nykaza and Frank 2003). Aux États-Unis, l'institut OSHA indique qu'en 1992 les coûts (directs, indirects et administratifs inclus) pour les maladies professionnelles s'élevaient à 26 milliards $US (OSHA 1992). Selon Earmarl Otology Network, un réseau médical américain, chaque procès pour réclamation coûte environ 75 000 $US. Les conséquences économiques ont tendance à s'aggraver si on prend comme indicateur le nombre de travailleurs effectuant des réclamations et recevant de l'argent pour la perte d'ouïe en milieu de travail : ce nombre a triplé entre 1991 et 1999 selon l'institut NIOSH

(NIOSH 1998) et a presque doublé entre 1995 et 1999 dans l'état de Washington (Tri City Herald Sept. 16 1999).

### 1.1.2 La protection individuelle, seule solution économique à court terme

Face à ce fléau, il y a bien sûr la législation qui fixe les limites d'exposition à ne pas dépasser et préconise la réduction du bruit à la source comme mesure prioritaire. Dans de nombreux cas, cette réduction du bruit à la source est techniquement possible et il arrive même que cette réduction du bruit (lors de la conception initiale des machines, par exemple) soit moins coûteuse à terme que l'utilisation généralisée des protecteurs auditifs (Fédération des travailleurs et travailleuses du Québec 1998). Cependant, ce constat doit être nuancé par la grande diversité des sources de bruit et la complexité des mécanismes physiques de génération de bruit souvent « contre intuitifs » pour les concepteurs d'équipements industriels. Il n'existe en effet, dans la pratique, aucune solution « toute faite » qui garantisse à tout coup une conception à faible niveau de bruit pour les machines et équipements industriels. Pour présenter ce problème plus en détails, les différentes situations de réduction du bruit ont été regroupées dans ce qui suit en quatre catégories distinctes : celle où les techniques classiques de réduction du bruit sont applicables, celle où la reconception acoustique est nécessaire, celle où un changement fondamental de procédé est indispensable et enfin celle où seule la protection individuelle est envisageable. - Les techniques classiques de réduction du bruit consistent en des encoffrements, des découplages mécaniques, la minimisation des surfaces rayonnantes, etc. Ces techniques sont très bien documentées dans des guides (Commission de la santé et de la sécurité au travail 1998) et rapports techniques (Organisation internationale de normalisation 1995), sont souvent efficaces et permettent rapidement des réductions initiales du bruit assez conséquentes. Elles entraînent généralement un surcoût et amènent parfois des contraintes d'utilisation supplémentaires, mais ces inconvénients peuvent être contrebalancés par la valeur ajoutée que possède un tel équipement « discret » (Tourret and Bockhoff 1995).

- La reconception acoustique intervient lorsque les techniques « classiques » sont insuffisantes. Elle consiste en une réingénierie soignée de l'équipement via une étude des mécanismes fins de génération du bruit et requiert donc de l'ingénieur de solides compétences en conception acoustique de machines, ces compétences demeurent l'apanage de peu de spécialistes à cause du peu de formation dans ce domaine. Quelques exemples où les auteurs de ce texte ont été impliqués sont les projets de réduction du bruit de systèmes surpresseurs fixes (Voix 1997; Beslin 2002), du bruit de rivetage (Dessureault 1995) ou du bruit d'ébarbage de pièces métalliques (Laville 1998). Ces étapes de réingénierie sont généralement onéreuses, mais peuvent parfois conduire à des solutions étonnamment peu coûteuses, malheureusement souvent dédiées à un type particulier d'équipement. Par ailleurs, la commercialisation de telles solutions originales et efficaces restent à ce jour un problème, car ces équipements « discrets » n'ont de valeur que si les manufacturiers et les utilisateurs sont sensibilisés au problème du bruit et de ses conséquences sociétales : par exemple les projets de scies silencieuses (Nicolas 1995) ou de systèmes surpresseurs mobiles à faible bruit (Papineau 2002) restent non commercialisés à ce jour. - Le changement fondamental de procédé est parfois nécessaire lorsque les procédés utilisés sont bruyants dans leur principe même. Ainsi, lorsque les forces mises en jeu au sein d'un équipement sont discontinues dans le temps, l'équipement est susceptible de générer du bruit et il sera en pratique très difficile de limiter ce bruit sans limiter les performances du procédé ou sans changement fondamental du procédé. Par exemple, toutes les opérations faisant appel à l'énergie cinétique pourraient être remplacées par une force continue d'amplitude équivalente : l'emboutissage de pièces métalliques (force transitoire appliquée mettant en jeu l'inertie du poinçon) serait remplacé par une opération de formage à basse vitesse, de même le forage minier pourrait ne plus avoir recours à la percussion de la roche, mais plutôt à l'action de vérins hydrauliques de très hautes puissances, etc. Malheureusement, ces changements fondamentaux du procédé à l'origine du bruit requièrent des technologies qui ne sont généralement pas disponibles ou dont le coût est absolument prohibitif, ce qui fait qu'en pratique cette approche est peu utilisée. - Seule la protection individuelle est envisageable dans certaines situations où l'exposition « professionnelle » au bruit est dangereuse mais où la réduction à la source n'est pas absolument pas souhaitable. Ces situations ne sont pas toujours issues du monde industriel mais plutôt associées à une profession particulière, telle que, par exemple, musicien d'orchestre. Dans ce dernier cas, aucune alternative à la protection individuelle n'est envisageable (sauf à utiliser des instruments en versions électroniques pour les pratiques et les répétitions !) En conclusion, lorsque la réduction du bruit à la source est techniquement possible (par des techniques classiques, reconception ou changement fondamental de procédé), sa mise en oeuvre reste souvent difficile pour des raisons économiques, ce qui fait que ses bénéfices à grande échelle ne sont pas attendus dans un futur proche. La protection individuelle des travailleurs et des travailleuses reste donc la seule solution économique à court terme, c'est la solution la plus répandue.

### 1.1.3 Les problèmes des protections individuelles disponibles sur le marché

Les dispositifs de protection auditive disponibles sur le marché ne sont pas toujours très bien acceptés ou très bien utilisés.

En effet, ils sont peu utilisés pour deux raisons rapportées par de nombreux auteurs. La première raison est qu'ils sont inconfortables, souvent à cause du contact et de la friction sur la peau, de l'excès de chaleur ou de l'entrave aux mouvements, mais aussi parce qu'ils ne sont pas ajustables à une morphologie particulière (Berger 1980; Alberti, Riko et al. 1981; Berger 1981). La deuxième raison est qu'ils constituent une gêne importante dans la communication entre les travailleurs et à la perception des signaux d'alarme, parce que leur atténuation acoustique n'est pas uniforme en fonction de la fréquence et n'est pas modulable en efficacité (Berger 1980; Wilkins 1984; Wilkins and Martin 1987; Suter 1992; Christian 1999). L'entrave à la perception des signaux d'alarme peut par ailleurs être quantifiée au moyen de logiciels, tels que « Détecson » (Laroche, Hétu et al. 1991; Zheng, Giguère et al. 2003; Zheng, Laroche et al. 2003), capables de prédire les capacités de détection des signaux utiles de travailleurs atteints de surdité attribuable au bruit ou à l'âge. Tous ces défauts expliquent que trop fréquemment les travailleurs exposés au bruit ne portent leurs protections que de façon intermittente et ne sont donc pas protégés adéquatement.

Les protecteurs auditifs sont également mal utilisés car il est impossible (Berger 1993; Berger 1996) de connaître l'atténuation effective qu'ils procurent dans des conditions réelles d'utilisation car les mesures normalisées sont basées sur une détermination en laboratoire du seuil d'audition sur un groupe restreint d'individus (ANSI 1974; CSA 2002) et il est en pratique impossible d'offrir au travailleur le niveau d'atténuation que son environnement sonore requiert (Hétu 1994).

La bonne utilisation des protecteurs auditifs pose un problème particulier dans le cas des travailleurs présentant une perte auditive (professionnelle ou non). Ceci est illustré dans un guide pratique sur les bouchons d'oreille moulés (Fortier 2004). En effet, les difficultés rencontrées par ces travailleurs pour reconnaître la parole et les signaux d'alarme noyés dans le bruit sont beaucoup plus complexes que chez les sujets otologiquement normaux. La physiologie et le fonctionnement comparé de la cochlée saine et endommagée sont bien documentés dans plusieurs références dont l'ouvrage de Moore (Moore 1989) et les capacités de reconnaissance de la parole dans le bruit chez ces travailleurs ont été étudiées en détails, une synthèse en est présentée par Berger (Berger 1980). Cependant, la mise en oeuvre pratique de moyens de protéger efficacement ces travailleurs reste difficile. Trois difficultés rencontrées sont présentées. La première difficulté est qu'aucune norme relative à la sélection des protecteurs auditifs « classiques » ne prend en compte une surdité préexistante, voir par exemple les normes CSA Z94.2 (CSA 2002), ANSI S3.19 (ANSI 1974), ANSI S12.6 (ANSI 1997), ISO 4869 (ISO 1990; ISO 1994), AS1270 (AS/NZS1270 2002) , EN458 (EN458 1996). La deuxième difficulté est qu'il n'existe pas de façon simple, en pratique, de protéger adéquatement les travailleurs ayant une perte auditive : autant il est évident que le seuil protégé d'un travailleur ayant une perte auditive rend très difficile la perception de la parole et des signaux d'alarme noyés dans le bruit, même si ce bruit a un niveau modéré, autant il ne semble pas forcément avantageux de diminuer pour autant la protection offerte par le protecteur auditif, car elle deviendrait alors insuffisante lorsque le bruit est plus élevé. La troisième difficulté est que l'utilisation de prothèses auditives pour ces mêmes travailleurs présentant une perte auditive, est délicate : autant la prothèse éteinte constitue généralement un excellent protecteur auditif, autant elle devient, en fonctionnement, une dangereuse source d'exposition sonore (Hétu, Quoc et al. 1994); quant à l'utilisation de prothèse auditive sous un protecteur auditif de type serre-tête, elle reste encore à l'étude (NIOSH 1998).

### 1.1.4 Le besoin d'un protecteur auditif « intelligent »

Le développement d'un protecteur auditif capable de répondre adéquatement à chacun des problèmes évoqués ci-dessus a été la motivation de la recherche entreprise ; un tel produit devrait être confortable et "intelligent" de par le fait qu'il permette : (1) la mesure exacte de ses performances acoustiques, (2) l'adaptation de son efficacité en fonction des besoins du travailleur, à long terme, c'est à dire pour une exposition moyenne donnée ou, à très court terme, pour des niveaux de bruit fluctuants rapidement dans le temps et (3) le filtrage "discriminant" de la parole ou des signaux d'alarme noyés dans le bruit, en tenant compte également de la condition auditive du travailleur (à la façon d'une prothèse auditive). Les trois problématiques (SST, technique et scientifique) associées au développement de ce produit sont présentées dans la section 2.

## 1.2 Problématiques associées au développement d'un bouchon d'oreille « intelligent »

### 1.2.1 Problématique « Santé et sécurité au travail »

La problématique "Santé et sécurité au travail" est la mise au point d'un protecteur auditif pouvant être porté continuellement (car confortable et permettant la perception des signaux utiles) et dont les performances terrains sont mesurables.

#### 1.2.1.1 Importance du port continu d'un protecteur auditif

Il est essentiel qu'un protecteur auditif soit porté continuellement sans quoi son efficacité cumulée est grandement diminuée. Le graphique présenté sur la figure 1 illustre bien la rapidité avec laquelle l'efficacité de protection d'un protecteur diminue lorsque ce dernier est porté de façon intermittente. Ainsi un protecteur dont l'atténuation nominale est de 25 dB (courbe supérieure sur la figure 1) voit celle-ci réduite à une atténuation équivalente de 17 dB environ lorsqu'il a été enlevé seulement 30 minutes durant une journée de 8 heures ! La comparaison de la décroissance de l'atténuation effective entre un protecteur performant (atténuation nominale de 25 dB) et un protecteur peu performant (atténuation nominale de 10 dB) fait également ressortir (ce qui peut paraître paradoxale de prime abord) que plus le protecteur est performant, plus il doit être porté de façon continue pour que le travailleur en retire les bénéfices escomptés.

Les raisons à l'origine du port discontinu des bouchons sont tirées de deux enquêtes et présentées dans les tableaux 1 et 2. Le tableau 1 présente les causes citées par des travailleurs de ligne de production de milieux manufacturiers australiens pour ne pas porter leurs protecteurs auditifs lors de tâches variées, en groupe ou non : les trois principales raisons couramment invoquées pour ne pas porter un protecteur auditif sont l'inconfort des protecteurs existants, le besoin d'entendre et les difficultés éprouvées lorsque le niveau de bruit fluctue de façon importante. Le tableau 2 présente les améliorations souhaitées pour les protecteurs auditifs portés en milieu industriel par des travailleurs danois : un confort accru ainsi qu'une meilleure perception de la parole et du bruit des machines. Elles correspondent bien aux causes recensées dans l'étude australienne et les confirment donc.

Pour remédier au problème du port continu, il est donc nécessaire de développer un protecteur auditif qui ne crée pas d'inconfort physique et qui n'altère pas la perception des signaux acoustiques utiles, tels que le bruit des machines, les signaux d'alarme et la parole. Ces deux aspects sont détaillés successivement dans ce qui suit.

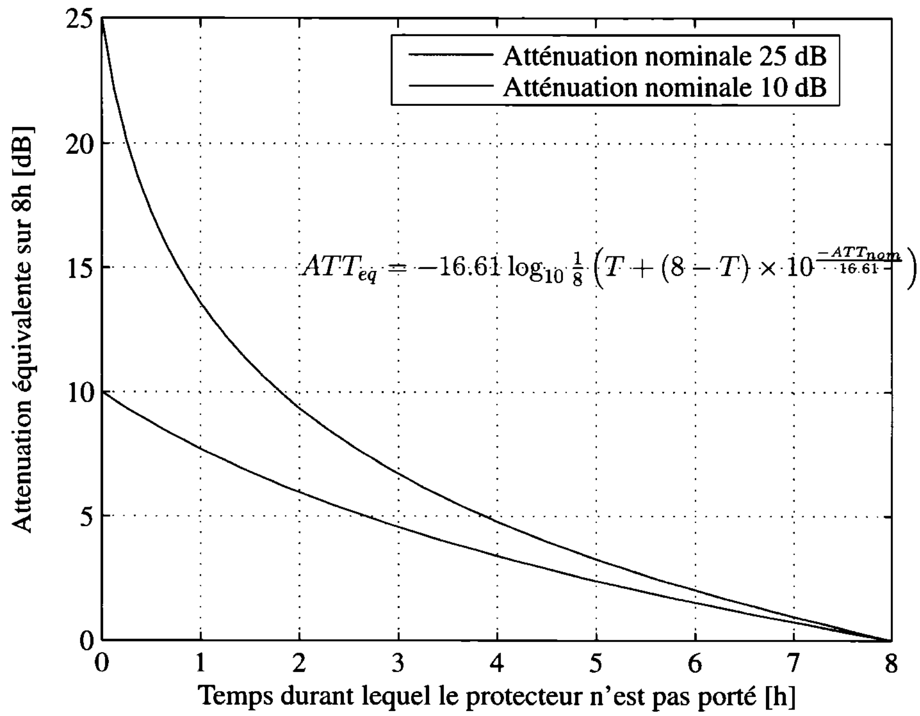


Figure 1 Atténuation équivalente (ATTeq) sur 8h d'un protecteur auditif porté de façon intermittente en fonction du temps (T) durant lequel il n'est pas porté et de son atténuation nominale (ATTnom). L'expression présentée a été obtenue à partir de la formule de calcul du niveau équivalent de bruit utilisée dans la législation sur la protection de l'audition avec un facteur bissecteur de 5 dB en vigueur au Québec (Loi sur la santé et la sécurité du travail 2001) et aux États Unis.

#### 1.2.1.1.1 Premier aspect : confort du protecteur auditif

Pour remédier au problème du confort, une des approches possibles est de façonner un bouchon d'oreille personnalisé (« sur-mesure ») et réutilisable, utilisant des matériaux bien acceptés par l'oreille (biocompatibles) et parfaitement adaptés à un port continu et confortable du protecteur. Les problèmes de faisabilité technique d'un tel bouchon seront exposés dans la première section (2.2.1) de la problématique technique.

Tableau I

Raisons couramment invoquées pour ne pas porter un protecteur auditif chez des travailleurs australiens. (Source : Hickson, Phua et al. 1995)

| Raison invoquée | Fréquence |
|---|---|
| Besoin d'entendre | 21% |
| Inconfort | 8% |
| Autre raison | 7% |
| Bruit fluctuant | 24% |
| Sans raison | 18% |
| Environnement non bruyant | 14% |
| Sans réponse | 8% |
| Total | 100% |

Tableau II

Améliorations souhaitées pour les protecteurs auditifs chez des travailleurs danois. (Source : Poulsen and Möller 1996)

| Amélioration souhaitée | Fréquence |
|---|---|
| Entendre les collègues | 39% |
| Plus de confort | 16% |
| Entendre les machines | 2% |
| Autre amélioration | 5% |
| Sans réponse | 38% |
| Total | 100% |

#### 1.2.1.1.2 Deuxième aspect : nécessité de percevoir les signaux utiles

L'oreille humaine est un instrument d'une extraordinaire sensibilité et l'audition un phénomène d'une grande complexité, aussi la mise au point d'une solution technique au problème de filtrage sélectif apparaît d'ores et déjà comme complexe et longue à mettre en oeuvre. Par ailleurs, les enjeux techniques soulevés par le « bruit fluctuant » empêchent en pratique l'utilisation de simples systèmes passifs. La problématique se situe maintenant à un niveau scientifique qui sera abordé dans la deuxième section (2.3.2) de la problématique scientifique.

Cependant, une approche simple et pragmatique au problème de la perception des signaux utiles a récemment été normalisée par l'Union Européenne (EN458 1993; EN458 1996), c'est la recommandation EN458. Elle consiste simplement à s'assurer que l'oreille protégée est exposée à un niveau sonore dans lequel elle sera au mieux capable d'effectuer naturellement les différentes tâches mentionnées, notamment la reconnaissance de la parole dans le bruit. Cette recommandation (illustrée par le tableau 3) vise en particulier à éviter les situations de « surprotection » (définies comme étant les cas pour lesquels le niveau de bruit résiduel est inférieur à 70 dB(A) ) pour lesquels le travailleur, trop bien protégé du bruit, se trouve complètement isolé de son environnement sonore et encourt alors d'autres risques (accidents). Ces risques associés à la surprotection sont d'ailleurs accrus si le travailleur en question est affecté d'une perte auditive neurosensorielle car la perception de la parole est alors considérablement dégradée (Berger 1980; Michael 2003).

Tableau III

Niveau de protection tels que définis par la recommandation EN458. (Source : CSA 2002)

| Niveau de pression sous le protecteur (dBA) | Niveau de protection |
|---|---|
| 85 + | Insuffisant |
| 80-85 | Acceptable |
| 75-80 | Optimal ou Idéal |
| 70-75 | Acceptable |
| Inférieur à 70 | Sur-protection |

Les problématiques techniques associées à une telle adaptation sont présentées dans la deuxième section (2.2.2) de la problématique technique.

#### 1.2.1.2 Inadéquation entre les valeurs théoriques et les valeurs réelles « terrain » d'atténuation

L'atténuation d'un protecteur auditif est caractérisée en Amérique du nord (EPA 1979) par le NRR (*Noise Reduction Rating*, c'est à dire Indice de réduction du bruit). Bien qu'il existe d'autres façons de caractériser les performances acoustiques des protecteurs auditifs, notamment par l'utilisation des classes et tout récemment des grades au Canada (CSA 2002), c'est, de très loin, l'indicateur le plus couramment utilisé. Le NRR est le résultat d'un calcul (équation 1) basé sur la valeur moyenne (notée REAT pour *Real Ear Attenuation at Threshold*) et l'écart type (noté $\sigma_{REAT}$) de l'atténuation d'un protecteur auditif mesurées par la méthode des seuils auditifs dans un contexte de laboratoire (par opposition au monde réel) sur un groupe restreint d'individus, 10 selon la norme en vigueur (ANSI 1974) :

$$NRR = 10\log_{10}\sum_{i=1}^{7} 10^{\frac{100+C^i}{10}} - 10\log_{10}\sum_{i=1}^{7} 10^{\frac{100+A^i-REAT^i+2\sigma^i_{REAT}}{10}} \tag{1.1}$$

où $A^i$ et $C^i$ sont les valeurs des pondérations A et C pour les bandes d'octave de 125 Hz ($i$=1) à 8000 Hz ($i$=7); les fréquences de 3150 et 6300 Hz utilisées en audiométrie tonale ont été omises, par souci de simplification.

La méthode de calcul et plus particulièrement la méthodologie de mesure ont été l'objet - à juste titre - de nombreuses critiques (Berger 1993) et il ressort aujourd'hui que cet indicateur (pourtant largement utilisé en Amérique du nord) n'est pas représentatif des performances de « terrain » des protecteurs auditifs. Le graphique présenté dans la figure 2 illustre bien la non-représentativité de ces valeurs de NRR : non seulement celles-ci sont-elles très différentes des valeurs obtenues dans la pratique (« terrain »), mais en plus, l'ordre relatif n'est pas conservé ! Ainsi un protecteur théoriquement excellent (NRR de 27 dB pour le « EP-100 ») peut ne procurer que 2 dB d'atténuation en pratique, tandis qu'un protecteur théoriquement inférieur (NRR de 19 dB pour le « Sound-Ban »), protégera beaucoup mieux en pratique avec un NRR de 7 dB !

La conséquence directe de cette inadéquation a été, aux États-Unis, la politique de déclassement (derating) recommandée par l'association OSHA (OSHA 1998); elle consiste à systématiquement diminuer de 50% les valeurs du NRR des bouchons d'oreille afin qu'elles soient plus réalistes. Néanmoins, en pratique, il demeure impossible par la simple utilisation de la valeur du NRR d'un protecteur auditif de s'assurer que la pro-

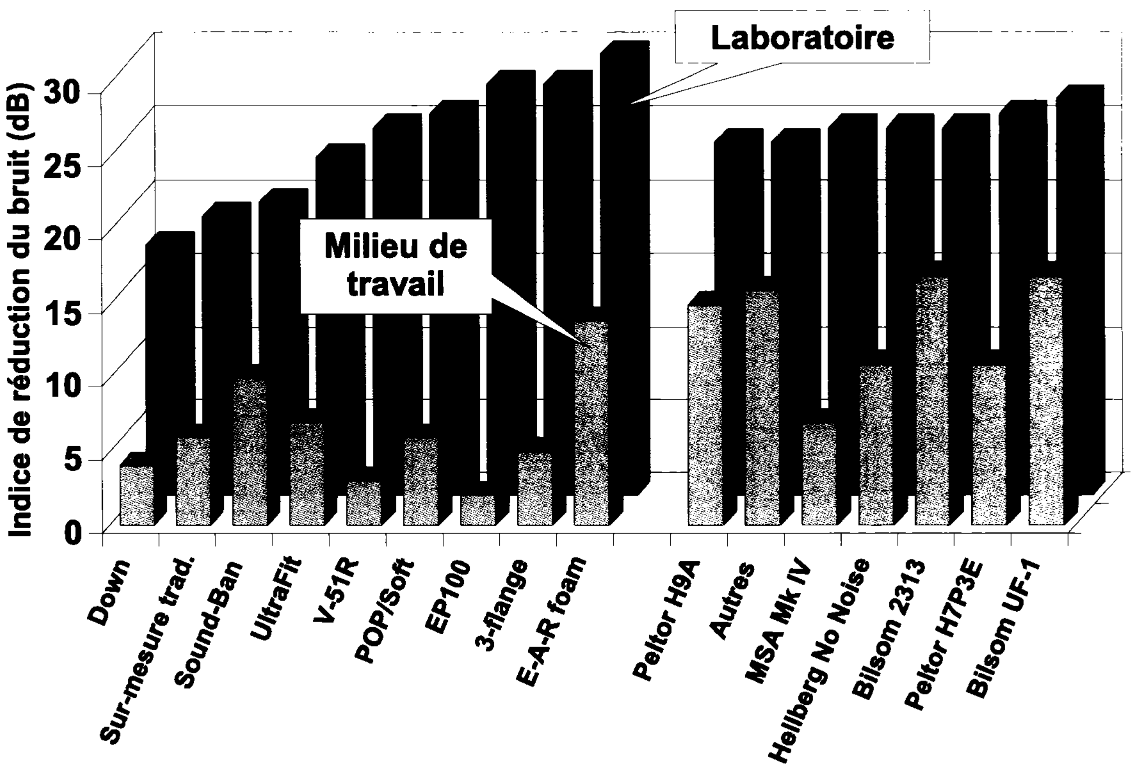


Figure 2 Comparaison entre les NRR publiés en Amérique du nord (valeurs en provenance des tests de laboratoire) et les valeurs réelles obtenues en milieu de travail selon 20 études indépendantes. Les 9 colonnes de gauche sont des produits de type « bouchon d'oreille », tandis que les 7 colonnes de droites sont des produits de type « serre-tête ». (Source : Berger 2000. Adapté avec l'aimable permission de l'auteur)

tection d'un travailleur sera adéquate. Cette incertitude serait levée par l'utilisation d'un protecteur auditif aux performances acoustiques rigoureusement mesurables pour chaque travailleur. La problématique technique associée à un tel système de mesure sera présentée dans la troisième section (2.2.3) de la problématique technique et la problématique scientifique dans la troisième section (2.3.3) de la problématique scientifique.

### 1.2.2 Problématique technique

#### 1.2.2.1 Un bouchon d'oreille adapté à la morphologie individuelle et biocompatible

Les besoins identifiés au paragraphe 2.1 en terme de santé et sécurité au travail poussent au développement d'un protecteur auditif qui soit sur mesure, confortable et biocompatible. Or, la réalité du marché est que les pressions économiques ont jusqu'à présent toujours poussé les manufacturiers à développer des « produits de masse » aux formes génériques (« taille unique »), économiques et jetables (Frost and Sullivan 2002). La compagnie canadienne SONOMAX a mis au point (McIntosh and Saulce 2004) un protecteur auditif de type bouchon d'oreille qui puisse à la fois répondre aux besoins des travailleurs (produit personnalisé) et aux contraintes du marché (produit de masse). Ce bouchon est composé d'un noyau de forme générique recouvert d'une fine membrane de silicone entre lesquels il est possible d'injecter un silicone thermodurcissable afin d'ajuster très précisément le bouchon à la forme du conduit auditif du travailleur (figure 3). Il est ainsi possible, après quelques minutes de durcissement, d'obtenir un bouchon d'oreille parfaitement ajusté à l'oreille et composé d'un matériau souple, résistant et biocompatible (élastomère de silicone de qualité médicale).

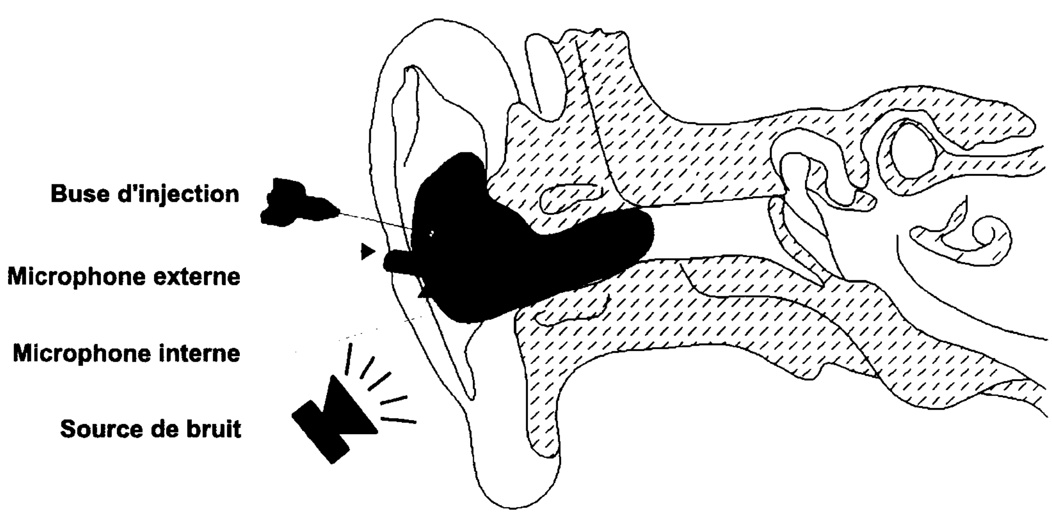


Figure 3 Schéma de principe du bouchon développé par la compagnie SONOMAX et du système de mesure associé. Source : SONOMAX (Voix et Laville 2004a)

### 1.2.2.2 Adaptation du bouchon à l'exposition du travailleur

Appliquer la recommandation EN458 revient à trouver une façon de modifier l'atténuation apportée par chaque protecteur auditif en fonction des besoins exacts du travailleur qui le portera. Le moyen mis en oeuvre est illustré à la figure 4 et consiste en une série de petits filtres acoustiques passifs interchangeables pouvant être placés dans le canal de mesure au sein du bouchon. Ces filtres peuvent être de simples éléments purement résistifs (Damper) dont les valeurs s'échelonne entre 330 et 4700 Ohms (cgs) ou bien un obturateur en plastique. La sélection d'un de ces filtres se fait, à l'aide d'un logiciel ad hoc, en tenant compte de l'exposition du travailleur (par bandes d'octaves ou en valeur globale équivalente, telle que le TWA « Time Weighted Average » ou le niveau équivalent Leq) et de l'efficacité de protection mesurée (à l'aide du système présenté dans la section 2.2.3) sur le bouchon non encore filtré.

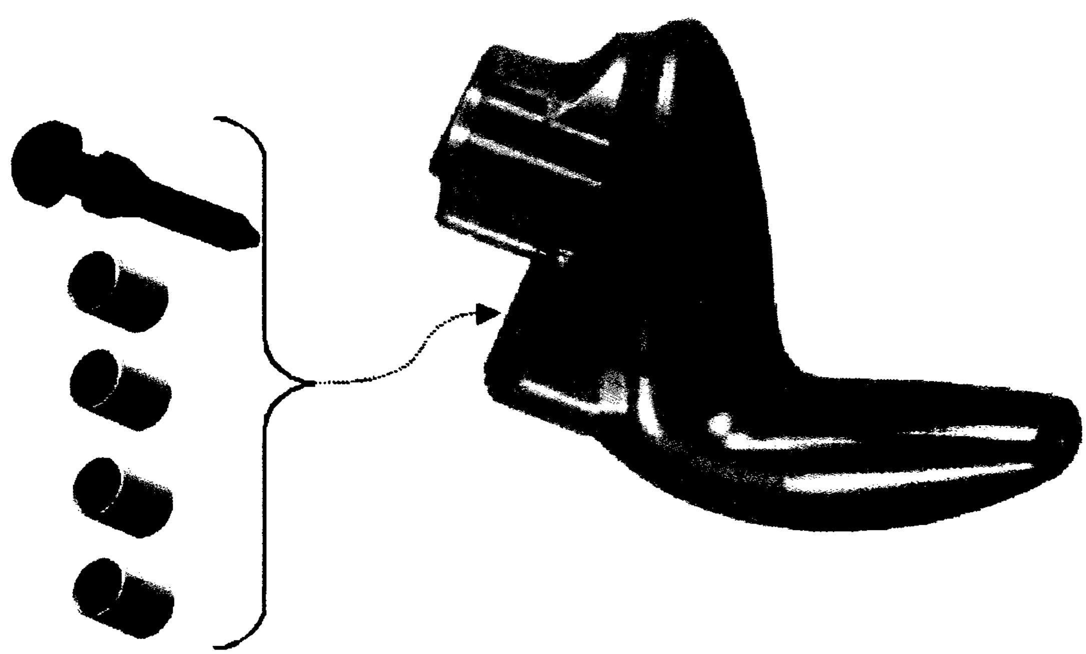

Figure 4 Principe des éléments filtrants interchangeables pouvant être placés dans le canal de mesure du bouchon d'oreille

#### 1.2.2.3 Un système et une méthode de mesure des performances acoustiques

Le système de mesure acoustique (figure 3) se compose d'une source de bruit à large bande (couvrant tout le spectre audible) et d'une sonde microphonique comprenant un microphone externe de référence et un microphone interne de mesure communiquant avec le conduit auditif occlus grâce à un petit canal de traversant le bouchon d'oreille. Il devient alors possible de mesurer de façon précise la différence de niveau de pression acoustique entre ces deux microphones lorsque le protecteur a été placé par le travailleur lui-même (« Subject-fit ») et d'obtenir ainsi une valeur objective et réaliste de l'efficacité de protection du bouchon d'oreille. À partir de cette mesure, présentée en détail dans la problématique scientifique (section 2.3.3), un nouvel indicateur a été proposé par les auteurs (Voix et Laville 2002), le P-PAR (*Predicted Personal Attenuation Rating*, soit Indice d'atténuation personnelle estimée). Le P-PAR est assimilable à un NRR qui serait le fruit d'une mesure objective (et non d'une évaluation subjective), sur un travailleur en particulier (et non sur un échantillon de population) et dans des conditions réalistes de port du protecteur auditif (et non dans des conditions de laboratoire).

### 1.2.3 Problématique scientifique

La problématique scientifique touche trois disciplines scientifiques distinctes qui correspondent aux trois sections de cette partie : premièrement, la modélisation de systèmes physiques pour l'identification des paramètres déterminant du nouveau bouchon ainsi obtenu, deuxièmement, le traitement de signal pour le filtrage sélectif du bouchon et, troisièmement, l'instrumentation et la mesure acoustique pour la détermination de l'atténuation effective du bouchon.

#### 1.2.3.1 Identification des paramètres clefs déterminants les performances d'un protecteur auditif intra-auriculaire

Les protecteurs auditifs supra auriculaire ont depuis longtemps été modélisés sous forme de système mécano-acoustique (Wilkie 1952; Benox Report 1953; Zwislocki 1955; Zwislocki 1955). Plus récemment, les protecteurs auditifs intra auriculaires ont été modélisés plus finement, notamment par la prise en compte des caractéristiques de fuite acoustique (Shaw 1982) et du couplage mécanique avec le conduit auditif (Schroeter and Els 1980; Hahn 1985). Cependant, toutes ces modélisations considèrent le bouchon d'oreille comme une simple masse (modèle de corps rigide) mise en mouvement à l'intérieur du conduit auditif (modèle de raideur et d'amortissement), conduisant à un système classique masse ($m$) - ressort ($k_s$) - amortisseur ($c_s$), tel que présenté sur le schéma de la figure 5. Ces modèles considèrent que le matériau utilisé pour le protecteur est suffisamment rigide, dense ou visqueux pour que la conduction acoustique au travers de ce dernier soit négligeable (Zwislocki 1955). Ce qui était à l'époque vrai pour l'ensemble des bouchons disponibles (Benox Report 1953), composés soit de plastiques relativement rigides, soit de mousses très fortement amorties, n'est plus nécessairement vrai dans le cas d'un bouchon d'oreille composé d'un élastomère de silicone relativement élastique et peu amorti. La nouveauté de l'utilisation de ce produit est probablement la principale explication du fait qu'aucun modèle mettant en évidence un tel phénomène de propagation du son à travers le matériau du bouchon d'oreille n'a pu être trouvé dans la littérature.


Figure 5 Modèle mécano acoustique d'un bouchon d'oreille (à gauche, le modèle discret classique; à droite, le modèle continu envisagé)

La modélisation envisagée s'appuie sur une formulation continue du passage de l'air à un milieu caractérisé par une masse volumique $\rho_p$ et par une célérité des ondes $c_p$; elle est abordée en étroite relation avec des mesures expérimentales; elle doit permettre de répondre aux questions suivantes :

– Selon quel principe mécanique le bouchon d'oreille protège-t-il du bruit ?

– Quels sont les paramètres clefs pour le modèle continu envisagé ?

– Comment prendre en compte les effets dus au couplage mécanique et acoustique avec le conduit auditif ?

#### 1.2.3.2 Systèmes de filtrage sélectifs adaptés au bruit en milieu industriel

L'approche, simple et pragmatique des objectifs de protections en terme de niveau de bruit résiduel (Recommandation EN458 présentée dans la section 2.1.1) est limitée, d'une part, parce qu'elle ne tient compte que des niveaux globaux d'exposition et ne se soucie pas du contenu spectral du bruit résiduel et, d'autre part, parce que les moyens techniques envisagés (présentés dans la section 2.2.2) font appel à des filtres acoustiques passifs dont les caractéristiques fréquentielles sont fixes dans le temps (non adaptatives). Tel que détaillé dans la section 2.1.1, le filtrage envisagé devrait être capable de discrimination entre le bruit indésirable et les signaux utiles (parole, signaux d'alarme), de reproduire fidèlement le contenu spectral du bruit mais, également, d'ajuster automatiquement le degré de protection selon l'exposition du travailleur au bruit, *tout en tenant compte de ses seuils auditifs*[3]. Les pistes de solution associées sont :

1. Le rehaussement de la parole bruitée et l'amélioration de son intelligibilité à l'aide de techniques issues du milieu de la prothèse auditive ainsi que des télécommunications numériques.
2. La détection numérique, le débruitage ou la re-synthèse des signaux d'alarme afin que ceux-ci soient perceptibles en tout temps.
3. L'égalisation fréquentielle du bruit résiduel afin de s'assurer que son contenu spectral et perceptuel est identique à celui d'origine.
4. L'ajustement automatique du filtrage effectué en fonction de l'environnement sonore du travailleur.

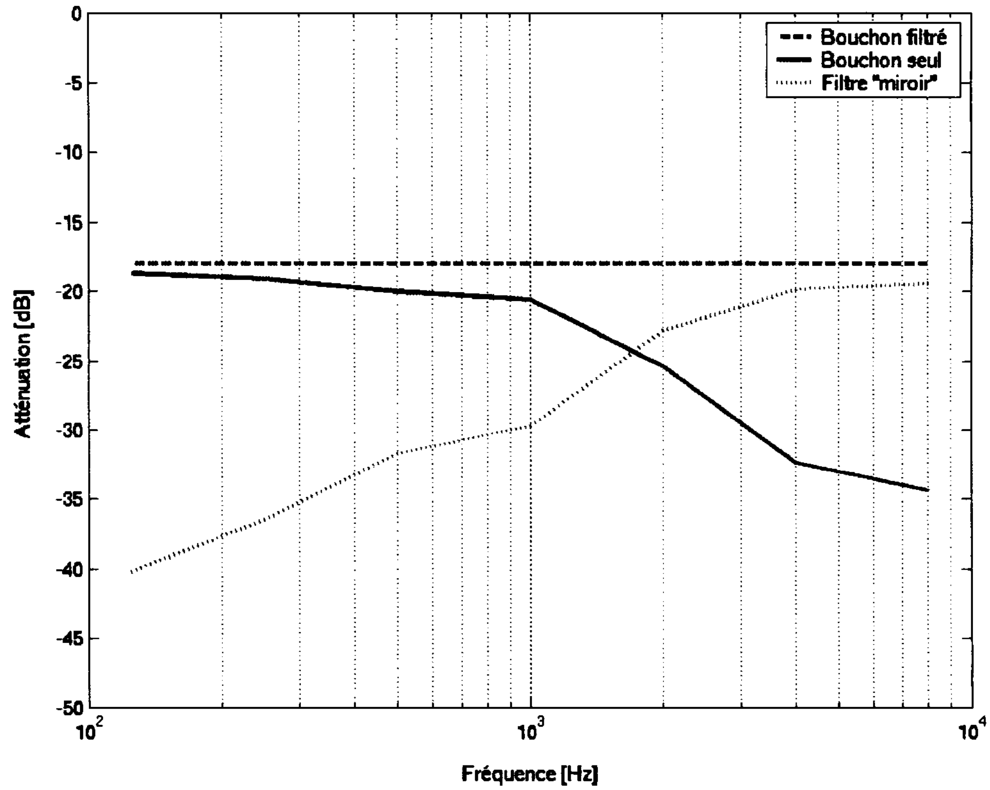


Figure 6 Modélisation de l'atténuation uniforme du bouchon filtré obtenue par l'association du bouchon seul et du filtre « miroir »

Une première approche intéressante serait de concevoir un filtre « miroir » dont la réponse fréquentielle compense parfaitement la réponse du bouchon non filtré afin d'obtenir une atténuation résultante qui soit identique pour toutes les fréquences utiles. Un tel filtre (dont les caractéristiques fréquentielles théoriques sont présentées à la figure 6) conduirait à un bouchon filtré dont l'atténuation serait uniforme et qui permettrait ainsi de conserver le contenu spectral des signaux d'origine. De tels bouchons « à atténuation uniforme » existent sur le marché depuis une quinzaine d'années, tels que les « Musicians Earplugs » de Ethymotic Research (Killion 1989), les « Ready-Fit High Fidelity Earplugs » de Aearo/Ear (Killion, Steward et al. 1992) ou encore les bouchons « Natural Sound Technology » de Bilsom (Hiselius and Nilsson 2002) et il a par ailleurs déjà

[3]La partie en italique est un complément au texte publié ajouté sur demande du Jury.

été prouvé que même si ce système n'a pas recours au rehaussement actif de la parole ou des signaux d'alarme, il permet une meilleur intelligibilité de la parole et des signaux d'alarme noyés dans le bruit (Letowski, Vaughan et al. 1998; Hiselius 2000). Cette solution a l'avantage d'être économique (l'élément clef du filtrage étant une simple membrane plastique), mais elle est limitée en performance et l'atténuation n'est véritablement « uniforme » que lorsque moyennée pour un grand nombre d'individu et uniquement aux quelques fréquences considérées (valeurs centrales des bandes d'octaves de 125 à 8000 Hz). *En outre, même si des travaux récents ( Verbsky 2002) semblent mettre en évidence une amélioration de la perception sonore pour des sujets normaux, sans égard au contenu spectral, il est probable qu'un phénomène de masquage fréquentiel existe et crée une solution non optimale. Par ailleurs, cette même étude a également démontré qu'un tel filtre « uniforme »n'est pas bien adapté pour des sujets ayant déjà des pertes auditives*[4].

Cette première approche du filtre « miroir » est non adaptative (de même que l'était l'approche avec des éléments purement résistifs présentés dans la section 2.2.2), ce qui limite son intérêt pratique car les niveaux de bruit fluctuent au cours de la période de travail; la probabilité est donc grande que le travailleur soit surexposé par moment et surprotégé à d'autres, avec tous les risques que cela implique. Par ailleurs, la prise en compte des conditions auditives du travailleur n'est, à toutes fins pratiques, pas possible avec ces filtres à réponse fréquentielles fixes, ce qui limite donc l'intérêt pratique de telles approches.

Une deuxième approche beaucoup plus complexe, mais au potentiel très prometteur, consiste à utiliser des systèmes de filtrage adaptatif (dont les caractéristiques fréquentielles sont adaptées de façon continue), cela permettrait d'ajuster instantanément le filtrage effectué en fonction de l'environnement sonore du travailleur (en particulier pour des bruits fluctuants). Par ailleurs, ces systèmes adaptatifs permettraient aussi l'utilisation d'algorithmes de rehaussement de parole, de rehaussement des signaux d'alarme et de contrôle

[4]La partie en italique est un complément au texte publié ajouté sur demande du Jury.

actif du bruit. La réalisation de tels filtres numériques hautement miniaturisés est aujourd'hui courante dans le domaine de la prothèse auditive et il deviendrait même envisageable de fusionner ces fonctionnalités de protection auditive (protecteur auditif) à celle d'aide auditive (prothèse auditive), voire même d'interface de communication (captation tympanique de la parole permettant la communication radio ou téléphonique duplex, la commande vocale de machines, etc.).

#### 1.2.3.3 Méthode de mesure objective de l'atténuation effective d'un protecteur auditif intra auriculaire

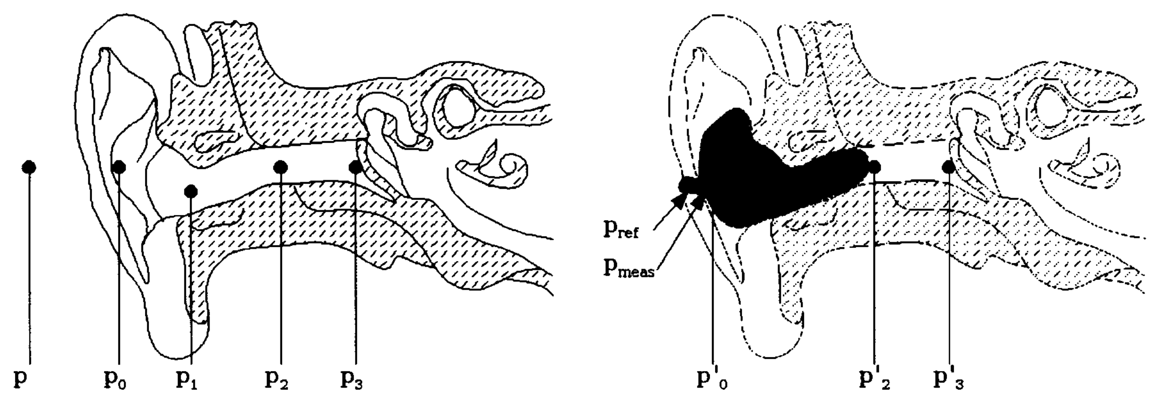


Figure 7 Localisation des points de pression acoustique dans une oreille non protégée (à gauche) et protégée (à droite)

La méthode de mesure envisagée dans la section 2.2.3 est du type « semi objective », puisqu'elle repose sur des mesures microphoniques sur un bouchon placé dans l'oreille du travailleur. Elle doit être en mesure de relier la mesure du NR (Noise Reduction), c'est-à-dire la différence de niveau de pression acoustique entre les microphones externe (pression $p_{ref}$) et interne (pression $p_{meas}$) à l'atténuation REAT (« Real Ear Attenuation at Threshold ») qui serait rapportée par le travailleur s'il était testé par la méthode des seuils audiométriques. La méthode développée par les auteurs (Voix et Laville 2002) s'appuie sur la notion de « compensation » qui est la somme des 5 termes correctifs, présentés dans l'équation 2, reliant le NR au REAT. *Cette méthode ne tient pas compte de la transmission osseuse, puisque ce chemin de transmission, offrant typiquement une atténuation de 40 à*

*60 dB selon les fréquences, peut en tout temps être négligé pour le bouchon développé en section 1.2.2.1.* [5].

$$
\begin{aligned}
REAT &= NR + \\
&\left\{TFOE + 20\log_{10}\left(\frac{p_{mes}}{p'_2}\right) + 20\log_{10}\left(\frac{p'_2}{p'_3}\right) + 20\log_{10}\left(\frac{p}{p_{ref}}\right) + PN\right\}
\end{aligned}
\tag{1.2}
$$

Ces 5 termes correctifs sont respectivement :

1. la fonction de transfert de l'oreille externe, $TFOE$ (*Transfer Function of the Outer Ear*), qui correspond à la différence entre le niveau de la pression acoustique ($p_3$) au tympan et le niveau de la pression acoustique ($p$) au centre de la tête en l'absence du travailleur;
2. la correction entre la mesure microphonique $p_{meas}$ et la pression sur la face interne du bouchon $p'_2$ (comprend essentiellement la correction due à l'effet du tube de mesure);
3. la correction entre la pression sur la face interne du bouchon $p'_2$ et la pression tympanique $p'_3$ (comprend essentiellement la résonance du conduit auditif occlus);
4. la correction entre la pression acoustique en champ libre $p$ et la pression mesurée par le microphone de référence $p_{ref}$ (comprend essentiellement les termes de diffraction de la tête et du torse);
5. le bruit physiologique de masquage $PN$ (Physiological Noise) présent lors des mesures des seuils audiométriques de l'oreille occluse *et incluant l'effet d'occlusion (Occlusion Effect) qu'il est difficile de dissocier.* [6].

Il devient ensuite possible à partir de cette mesure indirecte de l'atténuation de calculer toutes sortes d'indicateurs pour valider l'efficacité du bouchon (Voix et Laville 2004b) et de s'assurer que celui-ci convient bien au niveau global d'exposition du travailleur.

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[5] La partie en italique est un complément au texte publié ajouté sur demande du Jury.

[6] La partie en italique est un complément au texte publié ajouté sur demande du Jury.

## 1.3 État du développement

Un projet de collaboration a été initié en 1999 entre l'École de technologie supérieure et la compagnie SONOMAX SANTÉ AUDITIVE INC. pour le développement d'un bouchon d'oreille « intelligent ». Le premier auteur, étudiant à temps plein à l'ÉTS, consacre précisément son doctorat à la mise au point d'un « bouchon d'oreille intelligent » tel que présenté dans les paragraphes précédents. Ce projet académique a été grandement facilité, dès ses débuts, par la participation régulière de l'étudiant aux activités de recherche et développement de la compagnie et a également permis à l'étudiant de rapidement saisir les enjeux pratiques d'un tel projet de développement. Depuis 2002, un programme de recherche et développement coopérative (RDC) du Conseil national de recherches en sciences naturelles et en génie du Canada (CRSNG) a été initié conjointement entre l'ÉTS et SONOMAX afin de développer des algorithmes de filtrages pouvant être utilisés au sein d'un futur bouchon d'oreille numérique.

### 1.3.1 Synthèse des développements prévus

Le tableau 4 est utilisé pour présenter sous forme synthétique tous les éléments techniques et scientifiques associés à ce projet et pour montrer également les liens entre les différentes problématiques évoquées dans les paragraphes précédents.

### 1.3.2 État d'avancement

Le bouchon d'oreille décrit dans la section 2.2.1, une première génération de filtres acoustiques constituée d'éléments filtrants interchangeables (section 2.2.2) et un système de mesure des performances acoustiques (section 2.2.3) sont commercialisés en Amérique du nord depuis 2002. Ce système répond complètement aux éléments « Confort physique » et « Efficacité réelle connue » de la problématique SST (tableau 4), ainsi qu'aux éléments associés des problématiques techniques et scientifiques. En particulier les éléments « Modélisation du comportement du bouchon » et « Mise au point d'une méthode de mesure » sont en cours de rédaction pour publication dans le cadre du tra-

Tableau IV

Aspect clefs des problématiques associées au développement d'un bouchon d'oreille « intelligent ». Légende : les parties claires correspondent à des développements achevés; les parties gris clair correspondent à des développements pouvant bénéficier d'améliorations par l'utilisation des techniques de filtrage numérique; les parties gris foncé correspondent aux développements en cours.

| | *Problématique SST* | *Problématique technique* | *Problématique et disciplines scientifiques* |
|---|---|---|---|
| Port continu | Confort physique | Bouchon « sur mesure »<br>• adapté à la morphologie individuelle<br>• accepté par l'oreille (biocompatible) | Modélisation du comportement du bouchon **(Modélisation de systèmes physiques)** |
| | Confort de perception (accessibilité aux signaux acoustiques utiles) | Bouchon adaptable à l'exposition sonore | **Développement d'un système de filtrage sélectif (Traitement du signal)** |
| Performance | Efficacité réelle connue | Bouchon aux performances mesurables | Mise au point d'une méthode de mesure **(Instrumentation et mesure acoustique)** |

vail de doctorat du premier auteur. Par contre, la réponse à l'élément « Confort de perception » n'est que partielle car seuls des éléments filtrants passifs sont utilisés. Les travaux en cours consistent à développer des systèmes de filtrage sélectifs adaptés aux bruits en milieu industriel en utilisant des technologies de traitement numérique du signal; une étape technique importante a récemment été franchie par l'intégration de composants électroacoustiques de prothèses auditives « programmables » au sein du bouchon, rendant ainsi possible l'implémentation de n'importe quel filtrage numérique.

## 1.4 Conclusion

Il a été montré que la nocivité de l'exposition au bruit touche une fraction importante des travailleurs dans le monde entier et que les actions de réduction du bruit à la source, quand elles sont techniquement possibles, sont peu souvent mises en oeuvre à cause de problèmes économiques. La protection individuelle, plus économique, reste donc la solution la plus répandue. Malheureusement, les défauts associés aux protecteurs auditifs actuels rendent souvent cette protection peu efficace en pratique. Palier à ces défauts est la motivation derrière le développement d'un bouchon d'oreille confortable et « intelligent ».

Les problématiques présentées sont variées : elles comportent trois niveaux avec chacun trois éléments.

Le premier niveau est celui de la problématique SST. Les deux premiers éléments sont l'inconfort « physique » des protecteurs auditifs et l'inconfort de perception (beaucoup des signaux utiles ne sont plus perceptibles sous un protecteur auditif) qui conduisent à un port non continu des protecteurs, diminuant d'autant leur efficacité. Le troisième élément est que les performances réelles des protecteurs ne sont pas connues et rendent très difficile la sélection adéquate d'un type de protecteur pour un travailleur donné (en fonction de son exposition au bruit, mais également de son éventuelle perte auditive).

Le deuxième niveau est celui de la problématique technique. Aux trois éléments SST correspondent trois éléments de nature technique : le premier est l'adaptation morphologique individuelle du bouchon et son acceptation par les tissus de l'oreille externe, le deuxième est le filtrage adaptatif et sélectif du bouchon afin de laisser passer les signaux utiles et le troisième est la mesure des performances acoustiques du bouchon lorsque porté par le travailleur.

Le troisième niveau est celui de la problématique scientifique où les trois éléments précédents s'inscrivent respectivement dans trois disciplines scientifiques : modélisation des systèmes physiques, traitement du signal, instrumentation et mesure.

Les défis associés à ces problématiques ont été relevés en partie avec le développement d'un bouchon d'oreille sur-mesure ajusté instantanément à l'oreille du travailleur et dont les performances acoustiques sont mesurables lors du port du bouchon grâce à l'introduction d'une sonde microphonique au sein d'un canal de mesure intégré. L'atténuation offerte par le protecteur obtenu peut ensuite être adaptée aux besoins exacts du travailleur grâce à l'insertion de filtres acoustiques passifs laissant simplement passer plus ou moins d'énergie sonore afin d'éviter les cas de surprotection qui empêchent généralement le travailleur de reconnaître la parole dans le bruit.

Un tel produit répond donc assez complètement aux problèmes de l'inconfort physique et de la mesure de ses performances mais répond encore imparfaitement pour l'instant au problème du confort de perception sonore. En effet, le filtre utilisé n'est pas capable de conserver le contenu spectral de l'environnement sonore du travailleur, ni d'ajuster automatiquement le degré de protection selon l'exposition du travailleur au bruit ou de discriminer entre le bruit indésirable et les signaux utiles (parole, signaux d'alarme). La voie choisie pour répondre beaucoup plus adéquatement à ce dernier problème est de passer du filtrage passif au filtrage sélectif actif.

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# ARTICLE 2

# THE OBJECTIVE MEASUREMENT OF INDIVIDUAL EARPLUG FIELD PERFORMANCE

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# The objective measurement of individual earplug field performance

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## Abstract

*This paper presents a Field-MIRE approach for the objective measurement of individual earplug field performance. This approach combines the use of a recently developed Instrumented Expandable Custom Earplug and a method that predicts the individual attenuation from the field measurement of the Noise Reduction through the earplug. The individual attenuation for each octave band center frequency are combined in a single number, the Predicted Personal Attenuation Rating (PPAR) that is the equivalent to the Noise Reduction Rating (NRR) obtained from the classical Real Ear at Threshold (REAT) attenuation testing. The method has been validated experimentally. The quantification of the uncertainty associated with such PPAR measurement have shown that the overall uncertainty is lower than the uncertainty reported in the literature for the subjective REAT attenuation measurement of earplugs. It has also be found that such approach could be successfully used for other type of earplugs (disposable foam plugs, for example) as long as they do incorporate a sound bore for the measurement of the occluded-ear sound pressure level. This approach offers fast and accurate measurement of earplug field performances on an individual basis and has several implications for effective hearing protection practise and for HPD rating and labelling.*

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## 2.1 Introduction

Current standardized methods (like ANSI S3.19 [11]) dramatically fail at predicting the attenuation of *Hearing Protection Devices* (HPD) for individual users in actual application for various well understood reasons [2, 3, 4, 5]. As recommended by NIOSH and many researchers, substantial efforts have been deployed to *"find a laboratory method to estimate the noise attenuation obtained with hearing protectors worn in the field"* [1]. As a result, recent standards (like ANSI S12.6 [12] in 1997, AS/NZ1270 [17] in 2002 or the current draft of ISO 4869-5 [18]) now include a "subject fit" method [10, 11, 12] that provides a better estimate of the attenuation obtained in the field, even if some discrepancies are still found between the laboratory and the field attenuation values [13, 14].

However, even if such laboratory methods better predict average group field performance, it would still be impossible to link an individual field attenuation to this population-based, statistically-derived, laboratory-driven attenuation estimate. One solution to this fundamental problem, as Berger [13] mentioned, would be to perform "Individual Fit Testing"; this process would be *"arguably the best approach to assigning HPD's with the proper attenuation"*. Such an approach would provide the most accurate assessment for an individual user and could also afford an excellent opportunity to train and motivate the employee in appropriate HPD use and fitting.

Unfortunately, very few field measurement methods are currently available (see Franks [15]), even though numerous trials have been made to adapt existing and proved laboratory methods for field measurement use (see Berger [16] and Kusy **??** for a comprehensive list). The FITCHECK™ [18, 19] system is probably the most used and documented [20] field measurement method. It relies on *Real-Ear Attenuation at Threshold* (REAT) test - i.e. the difference between open and occluded-ear hearing thresholds as reported by human subjects. REAT test, sometime referred to as the "gold standard" since it was first standardized in 1957, is now part of many worldwide standards (ANSI S3.19 [11] and

ANSI S12.6 [12], CSA Z94.2 [9], ISO 4869-1 [13], etc.) and takes into account all relevant sound paths to the inner ear. Unfortunately, REAT testing is not only time-consuming and very sensitive to the ambient background noise (making it often incompatible with practical field usage), but it also suffers from two well established [23, 5] limitations: low-frequency masking error (caused by the *Physiological Noise*) leading to an overestimation of the low-frequency attenuation and high variability of the subjective response, which is function of subject selection, training, motivation, and supervision.

Among the various laboratory methods available to measure HPD attenuation (see Berger [5] for an extensive list, while two additional techniques are mentioned in a 2005 paper by the same author [6]), there is one method that would overcome these limitations and still enable an individual measurement: the *Microphone In Real Ear* (MIRE) technique. It consists of inserting a miniature microphone (either wired or in a probe tube form) in the ear to measure the actual sound pressure level at a given location, usually close to the tympanic membrane. The difference between two of these measurements on a given individual at the same location in open and occluded-ear conditions gives the classical *Insertion Loss* (IL). MIRE measurements techniques have being used successfully for earmuff IL (see Mauney [26] for a comprehensive review) and are now normalized for supra-aural or circum-aural HPD [27, 28]. Even if they can not account for the bone conduction sound path, these laboratory MIRE techniques are fast, efficient and reliable and do not suffer from the physiological noise bias.

A field method based on the MIRE approach has been developed for use in the fitting of Hearing Aid devices which may be adaptable to HPD attenuation measurements. The method is used to determine the so-called "Insertion Gain" and is sometimes referred to as the "Substitution Method" (see Madsen [29]). However, existing measurement devices used for the insertion gain measurement rely on a microphone probe inserted around the device and can usually not be used when measuring insertion loss for HPD, as the soft tube of the probe microphone is not protected against outside noise contamination (i.e.

the measurement is affected by the sound source itself, an effect sometimes described as "flanking pathway" [6]), and the probe tube usually breaks the acoustic seal of the HPD, as experienced by the authors and others [6]. Recent studies conducted on the use of MIRE as a field measurement device for earmuffs [26, 30, 31] or for earplugs [17] demonstrate promise for in-field implementation of alternative attenuation tests, but as mentioned by Mauney [26], up to now, the equipment used is delicate lab equipment unsuited for regular field use and the procedure is complex, requiring that the subject be fitted and the microphone placed by a professional to avoid misplacement or tympanic injury. It is therefore necessary to develop rugged field-ready equipment with a simple procedure including HPD fit by the subject

This paper presents the needed development of such a field MIRE method. This development was made possible by the recent design of an Instrumented Expandable Custom Earplug by SONOMAX HEARING HEALTHCARE INC (Montreal, Canada). This custom earplug has two particularities: first, it is instantly molded in the wearer's ear by silicone injection for increased physical comfort and, second, it includes a sound bore that can be used either for Field-MIRE measurements or the insertion of filters improving the wearer perceptual comfort. Because custom earplugs are used, the need for a Field-MIRE method could be questioned on the basis that custom earplugs have often been considered to be less prone to mis-fit by users, and it has even been suggested that they would not suffer from the discrepancies usually observed between laboratory and field performance. Such assumption does not withstand closer scrutiny, as reported by Berger [4] who clearly demonstrates that even if custom earplugs have many advantages over traditional HPD, they still merit individual field attenuation measurements.

The *Instrumented Expandable Custom Earplug* is described in section 2.2. The proposed approach for the measurement of individual earplug field performance is formulated in section 2.3. An experimental validation follows in section 2.4 and the calculations of the uncertainty associated with the measurement are detailed in section 2.5. The use of the proposed approach for other types of earplugs is discussed in section 2.6. Conclusions are given in section 2.7.

## 2.2 The Device Used: An Instrumented Expandable Custom Earplug

As mentioned in the Introduction, the developed device meets two objectives: first, increased comfort from both a physical and perceptual point-of-view, and second, the ability to perform MIRE measurements.

The first objective of increased comfort results from the need clearly expressed by NIOSH (National Institute for Occupational Safety and Health) in its recommendation for the development of an effective HPD *"that eliminate troublesome barriers by providing increased comfort to wearers as well as improved speech intelligibility and audibility of warning signals*" [1].

To address the issue of physical comfort, a new concept of a re-usable custom earplug that is instantly fit to the user's ear using the injection of a soft medical-grade silicon rubber between a rigid core and a soft expandable envelope has been proposed, as illustrated in Fig. 1.

Regarding perceptual comfort, the ability to hear speech and warning signals has been partially addressed by adapting the earplug attenuation to the actual noise exposure of the worker [32, 10, 7]. This proposed adaptation is based on a set of acoustic dampers (acoustic resistance resulting from mesh of plastic fibers) that can be placed into the earplug's sound-bore (see Fig. 1) to result in protected exposure level between 75 and 80 dBA, following the current recommendation for proper HPD selection in order to maximize the ability to hear speech and warning signals [8, 9].

The second objective, the ability to perform MIRE measurement, was met via an inner bore of constant length and diameter that permits the temporary insertion inside the generic rigid core of a miniature microphone to measure sound pressure levels in the residual ear-

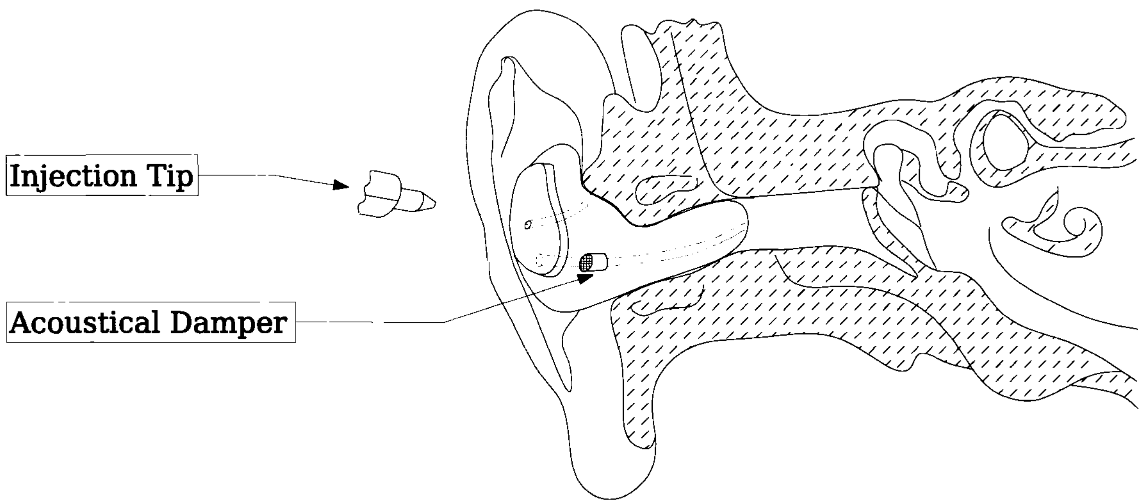


Figure 1 (Color online). The expandable custom earplug filtered with acoustical damper for adapted protection

canal portion beneath the HPD. Attached to the back of this internal pressure microphone, there is an external pressure microphone so that sound pressure level difference across the earplug (Noise Reduction) can be measured while a loud pink noise is generated from an outside reference sound source (frontal incidence, median plan). The *Noise Reduction* (NR) measurement occurs after the end-user removes and replaces the instant-fit earplug on his own in order to perform a "subject-fit" test. This subject-fit NR measurement will later be used to check the proper fit of the earplug (see section 2.3.6 for further details) and to predict the attenuation the user will achieve in the actual use (see section 2.3.5).

The measurement device, dubbed the "SONOPASS™System" [36, 37], is a proprietary DSP-based spectrum analyzer that measures the octave-band Sound Pressure Levels (auto-spectrum's) from both microphones and calculates NR (magnitude of the transfer function between the external "reference" and internal "measurement" microphones) while generating a loud broadband sound (pink noise) through a loudspeaker. It can operate either connected to a computer or as a stand-alone unit (with LED indicators) and has successfully been used in the field since 2002 [38].

Fig. 2 shows the expandable earplug in the ear-canal, the dual microphone probe (external and internal pressure microphones with extended probe tube) as well as the reference sound source.

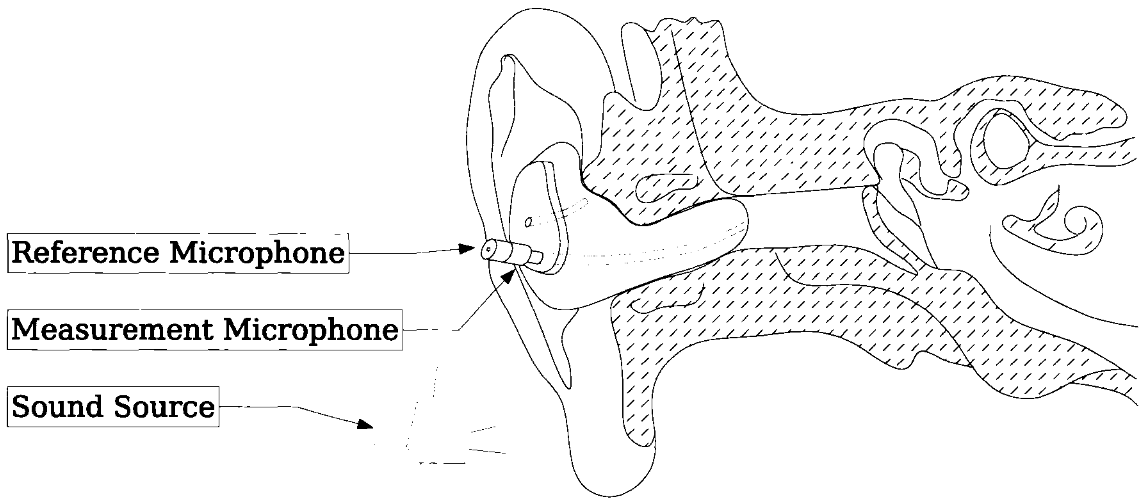


Figure 2 (Color online). The custom earplug instrumented with a dual microphone probe for Noise Reduction measurement

### 2.3 Formulation of the proposed objective measurement of individual earplug field performance

Given that the REAT measurement is the current "gold standard", but that its use as a field test has serious limitations, the proposed approach will rely on the objective measurement of NR to predict the REAT equivalent value. The prediction will be based on the relationship between NR and IL as well as the relationship between IL and REAT (detailed in section 2.3.1).

Estimation of REAT will be obtained by adding a "Compensation" term to the objectively measured NR. Compensation accounts for sound pressure corrections (transfer function) along the occluded, instrumented ear-canal and can be defined using a generic statistical approach. This "Statistical Approach" (detailed in 2.3.4) is derived from the fact that many of the corrections involved are functions of the geometry and dimensions of the human head and can therefore be well represented by a normal distribution: as an example, the use of a statistically averaged *Transfer Function of the Outer Ear* (TFOE) value rather than personal, subject ones has the advantage of avoiding a cumbersome and delicate measurement of tympanic sound pressure level (and makes such approach highly compatible with a practical field usage, as suggested by Mauney [26]) while only slightly increasing the uncertainty associated with the prediction.

Classically, a single number rating is provided by HPD manufacturers to represent the acoustical attenuation of their HPD. The *Noise Reduction Rating* (NRR[3]) per ANSI standards [12, 11] or the *Single Number Rating* (SNR) per ISO standards [40] are both computed with similar expressions from the octave band REAT attenuation reported during a certification test in a laboratory on a limited number of test-subjects. In the proposed approach, the octave band REAT attenuation is predicted from an individual NR measurement and a substitute for the NRR or SNR, the *Predicted Personal Attenuation Rating* (PPAR) will be used and is defined in section 2.3.5. Further calculations used for earplug performance evaluation will be detailled in section 2.3.6.

### 2.3.1 Relationship between Noise Reduction (NR), Insertion Loss (IL) and Real Ear Attenuation at Threshold (REAT)

From figure 3, the *Insertion Loss* (IL) is defined as the ratio of the open tympanic sound pressure $p_3$ over the occluded-ear tympanic sound pressure $p_3'$:

$$\mathrm{IL} = 20\log_{10}\left(\frac{p_3}{p_3'}\right) \tag{2.1}$$

Since IL usually represent a physical “loss”, it is usually a positive value (greater than zero), but can also be plotted as a negative one.

[3]employed by USEPA in 40CFR211 Subpart B [47] and USDOL OSHA in 29CFR1910.95 Appendix B to estimate the effectiveness of hearing protective devices (HPD) for noise-exposed workers

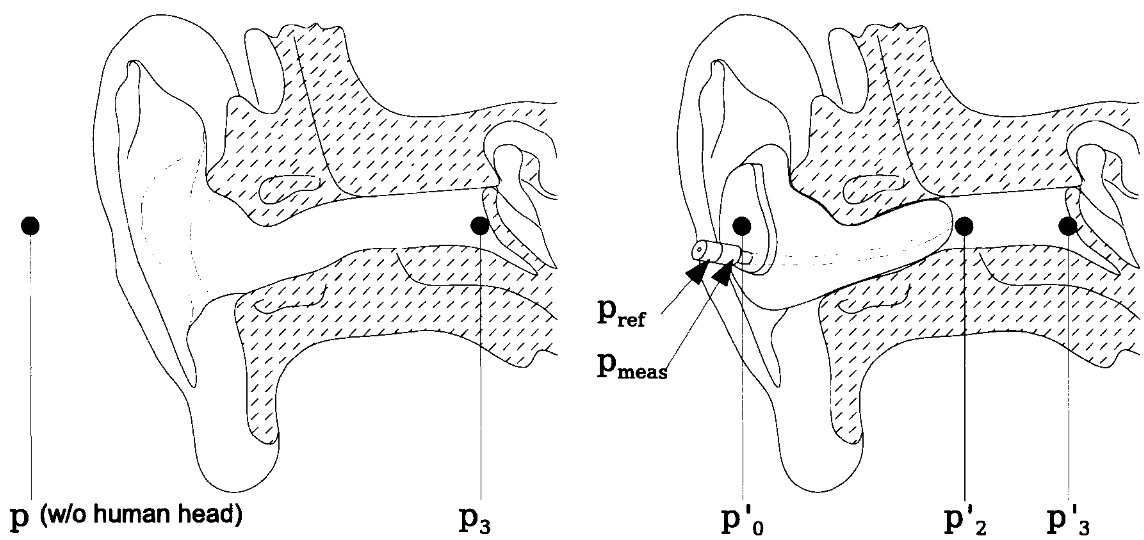


Figure 3 Schematics with sound pressure location for the open ear (left) and for the occluded-ear with the instrumented earplug (right).

The *Noise Reduction* (NR) is defined as the ratio of the free field sound pressure $p$ (at the tympanic membrane location, but without any human subject in place) over the occluded-ear tympanic sound pressure $p_3'$ :

$$\mathrm{NR} = 20\log_{10}\left(\frac{p}{p_3'}\right) \tag{2.2}$$

NR is also a positive value often plotted as a negative one.

The *Transfer Function of the Outer Ear* (TFOE) is defined as:

$$\mathrm{TFOE} = 20\log_{10}\left(\frac{p_3}{p}\right) \tag{2.3}$$

A direct relation between those three quantities is:

$$\mathrm{IL} = \mathrm{NR} + \mathrm{TFOE} \tag{2.4}$$

Such expression for IL is commonly used when objectively measuring the attenuation of HPD at supra-threshold levels. Indeed, for extremely high sound pressure levels (impulse or stationary) the HPD attenuation can no longer be considered to be linear or level-independent (either because of a designed non-linearity of the HPD or because of the intrinsic non linearity of acoustical wave propagation). Many studies [41, 42, 31, 5] rely on such dual step measurement where the NR is measured on the device worn by the user in the field and the TFOE is measured at a different time on the wearer in the laboratory to assess the overall HPD attenuation.

Assuming that the Bone Conduction sound path (typically attenuated by 40 to 60 dB depending on the frequency) is negligible for the earplug under test, the REAT that a subject would report is derived from the IL by adding the *Physiological Noise* (PN):

$$\mathrm{REAT} = \mathrm{IL} + \mathrm{PN} \tag{2.5}$$

The PN has been found [43, 44] to be device related and depends on the residual occluded-ear volume beneath the HPD. In our case, the PN will be considered a correction that includes all human measurement artifacts (occlusion effect, physiological noise, etc.) to be applied for each frequency (even if it mainly occurs in the low frequencies) on an individual basis. Using equations 2.4 and 2.5 lead to:

$$\begin{aligned} \mathrm{REAT} &= \mathrm{NR} \\ &\quad + \mathrm{TFOE} + \mathrm{PN} \end{aligned} \tag{2.6}$$

Unfortunately, the direct measurement of NR in the field is problematic: it requires the measurement of $p'_3$ very close to the tympanic membrane and the measurement of $p$ without the human subject in place. A practical alternative is to measure the NR between the outer and inner faces of the earplug, at pressure locations $p'_0$ and $p'_2$ respectively. In practice, the measurement device used measures $p_{\mathrm{ref}}$ instead of $p'_0$ with the *reference mi-*

*crophone* located 19.5 mm away from the outer face of the earplug ( i.e. approximately 20 mm from the Ear Reference Point defined in ISO11904 [28]) and measures $p_{\text{meas}}$ instead of $p'_2$ with the *measurement microphone* located at the aperture of a 18 mm long, semi-rigid (0.8 mm I.D.) probe tube that slides into the sound bore of the earplug. The NR that is practically measured (denoted $\text{NR}_*$) is therefore defined as:

$$\text{NR}_* = 20\ \log_{10}\left(\frac{p_{\text{ref}}}{p_{\text{meas}}}\right) \tag{2.7}$$

Two corrections factors need to be added to $\text{NR}_*$ to obtain the previously mentioned$\text{NR}$ :

- the use of $p_{\text{ref}}$ instead of $p$ requires the correction $\left(\frac{p}{p_{\text{ref}}}\right)$ that will account mainly for Head and Torso Diffraction and the pinna effect,
- the use of $p_{\text{meas}}$ instead of $p'_3$ requires the correction $\left(\frac{p_{\text{meas}}}{p'_3}\right)$that will account for the occluded ear-canal shifted resonance, the microphone probe and sound-bore tubing effects.

Eq. 2.6 can now be written with those two corrections included:

$$\begin{aligned} \text{REAT} &= \text{NR}_* \\ &\quad +20\log_{10}\left(\frac{p_{\text{meas}}}{p'_3}\right) \\ &\quad +\text{TFOE} + \text{PN} + 20\log_{10}\left(\frac{p}{p_{\text{ref}}}\right) \end{aligned} \tag{2.8}$$

Eq. 2.8 is intentionally presented on three lines: the first line contains the measurement performed in the field, the second line represents the corrections associated with the measurement device that can be determined in laboratory (i.e. probe tube effect, etc.) while the third line contains the corrections related to human factors (i.e. morphology of the ear and psycho-physiology of the hearing). Such three line convention will be used throughout the paper.

The correction $\left(\frac{p_{\text{meas}}}{p'_3}\right)$ can be split in two terms: a first term $\left(\frac{p_{\text{meas}}}{p'_2}\right)$ that would account for the microphone probe tube effect and a second one $\left(\frac{p'_2}{p'_3}\right)$ that would account for the occluded ear-canal resonance. Since this last term is related to the morphology of the wearer and not related to the measurement device itself, it will be presented on the third line, according to the presentation convention defined above. Eq. 2.8 can now be rewritten:

$$\begin{aligned}\text{REAT} = \; & \text{NR}_* \\ & +20\log_{10}\left(\frac{p_{\text{meas}}}{p'_2}\right) \\ & +\text{TFOE} + \text{PN} + 20\log_{10}\left(\frac{p}{p_{\text{ref}}} \times \frac{p'_2}{p'_3}\right) \end{aligned} \tag{2.9}$$

The sound-bore length correction $\left(\frac{p_{\text{meas}}}{p'_2}\right)$, on the second line of Eq. 2.9 is a fixed correction that is only dependent of the overall length of the sound-bore and microphone probe tube. One approach to determining such overall sound bore length correction value is to address it during laboratory measurement and to later refer to this quantity with tabulated values. However, such an approach would assume the use of an ideal microphone probe for which both cells of the dual microphone probe are perfectly equal in sensitivity and frequency response.

There are practical limitations on the knowledge of the sensitivity and frequency response of the microphone cells elements: a first one at the time of the assembly of the dual microphone probe, a second one during the intensive use of the dual microphone probe. The first limitation is that, although the microphone cells are of the same model, they each have a nominal sensitivity that is only guaranteed by the manufacturer to be in a given range.

Typical values are plus or minus 3 dB at 1kHz. For economical and practical reasons, no sensitivity matching could be performed prior to the dual microphone assembly. Although the laboratory determination of the microphone cells response is possible, it would require the end-user to key in the microphones characteristics. The second limitation is that the microphone cells individual frequency response is affected by the ambient atmospheric conditions (temperature, humidity and pressure) and both microphone cells are not always placed in the same environment: the reference microphone cell (outside the ear) is at room atmospheric conditions, while the measurement microphone (in the earcanal below the earplug) is intermittently in a warmer and more humid environment. Because of these two practical limitations and in order for the proposed measurement device to be as simple and rugged as possible, a way had to be found to incorporate ultimately the variation in the frequency response between the two microphone cells: the sound-bore length correction is included together with other corrections that consider the difference between the responses of the microphone cells as well as their response variations over time.

The response corrections are developed by submitting both microphone cells (or their openings at the end of a measuring duct) to the same acoustic pressure field. Three correction scenarios will be presented.

Measured values will be introduced in the equations topped by a *tilde* symbol to distinguish them from exact values. Three systems will be considered, denoted in roman numerals. System $I$ will be the microphone pair alone, system $II$ will be the microphone pair with the probe-tube and system $III$ will be the microphone pair with the probe-tube inserted in the earplug. The quantity $\mathrm{NR}_*$ defined in Eq. 2.7 will be rewritten as the ratio of two measured pressure values for the earplug (index III) in the wearer's ear multiplied by a correction ratio obtained by submitting the two microphone cells to the same pressure field the same day that the field measurement (index $F$) takes place:

$$\mathrm{NR}_* = \left(\frac{p_\mathrm{ref}}{p_\mathrm{meas}}\right)_{\mathit{III}} = \left(\frac{\tilde{p}_\mathrm{ref}}{\tilde{p}_\mathrm{meas}}\right)_{F\mathit{III}} \times \left(\frac{\tilde{p}_\mathrm{meas}}{\tilde{p}_\mathrm{ref}}\right)_{FI} = \widetilde{\mathrm{NR}}_* \times \left(\frac{\tilde{p}_\mathrm{meas}}{\tilde{p}_\mathrm{ref}}\right)_{FI} \tag{2.10}$$

*A first scenario* would consist of performing the measurement of the microphone pair transfer function on a daily basis $\left(\frac{\tilde{p}_\mathrm{meas}}{\tilde{p}_\mathrm{ref}}\right)_{FI}$ and obtaining $\mathrm{NR}_*$. The sound-bore length correction $\left(\frac{p_\mathrm{meas}}{p_2'}\right)$ would be determined in the laboratory (index $L$) by placing the ear plug in an acoustical field giving the same acoustic pressure at both microphone duct openings in free space. This correction is based on the following expression:

$$\left(\frac{p_\mathrm{meas}}{p_2'}\right)_{\mathit{III}} = \left(\frac{\tilde{p}_\mathrm{meas}}{\tilde{p}_\mathrm{ref}}\right)_{L\mathit{III}} \times \left(\frac{p_\mathrm{meas}}{\tilde{p}_\mathrm{meas}}\right)_{LI} \times \left(\frac{\tilde{p}_\mathrm{ref}}{p_\mathrm{ref}}\right)_{LI} \times \left(\frac{p_\mathrm{ref}}{p_2'}\right)_{L\mathit{III}} \tag{2.11}$$

with $\left(\frac{p_\mathrm{ref}}{p_2'}\right)_{L\mathit{III}} = 1$ because of the uniform sound field on the earplug,

and $\left(\frac{p_\mathrm{meas}}{\tilde{p}_\mathrm{meas}}\right)_{LI} \times \left(\frac{\tilde{p}_\mathrm{ref}}{p_\mathrm{ref}}\right)_{LI} = \left(\frac{\tilde{p}_\mathrm{ref}}{\tilde{p}_\mathrm{meas}}\right)_{LI}$ because of the uniform sound field on the two microphone cells.

Such scenario, illustrated in Fig. 4 is unfortunately not well adapted for field usage, since the two microphone cells that are used in the dual microphone probe can not be easily dismounted on a daily basis for the field measurement of the microphone pair transfer function.

*A second scenario* would require no laboratory measurement, as the sound-bore length correction $\left(\frac{p_\mathrm{meas}}{p_2'}\right)$ would be determined via a field measurement conducted by inserting the dual microphone probe in an earplug and positioning the instrumented earplug in a homogeneous sound field. The expression for this second scenario is:

$$\left(\frac{p_\mathrm{meas}}{p_2'}\right)_{\mathit{III}} = \left(\frac{\tilde{p}_\mathrm{meas}}{\tilde{p}_\mathrm{ref}}\right)_{F\mathit{III}} \times \left(\frac{\tilde{p}_\mathrm{ref}}{\tilde{p}_\mathrm{meas}}\right)_{FI} \tag{2.12}$$

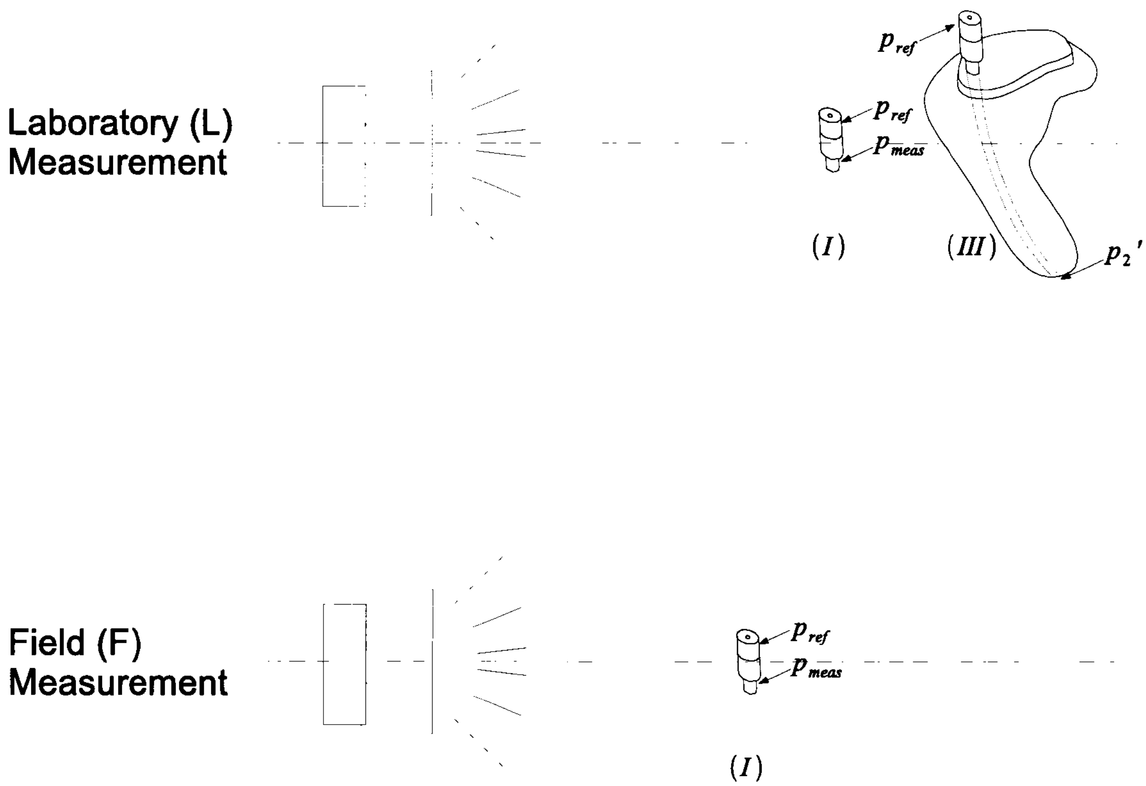


Figure 4 (Color online). First scenario determination of the sound-bore length and microphone sensitivity correction. Top: Overview of the laboratory measurement of $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LI}$ and $\left(\frac{p_{\text{ref}}}{p_2'}\right)_{LIII}$; Bottom: Overview of the field measurement of $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FI}$

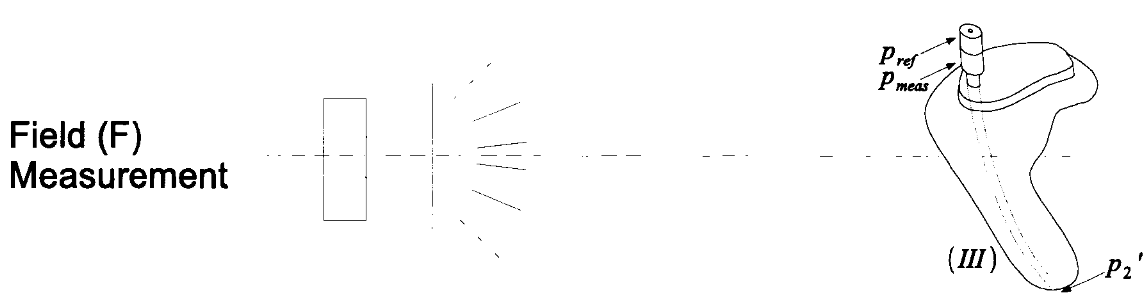


Figure 5 (Color online). Second scenario determination of the sound-bore length and microphone sensitivity correction. Overview of the field measurement of $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FIII}$

This approach would eliminate the need for microphone pair transfer function evaluation as the second term in Eq. 2.12 cancels the second term in Eq. 2.10. This scenario, illustrated in Fig.5 is also unfortunately not adapted for field usage because of the following practical limitations:

- it should be performed on every size of each earplug to be measured (the SONOMAX SONOCUSTOM™earplug is available in three core sizes at this writing);
- the holding of the cumbersome instrumented earplug on the speaker grid is hard to consistently and properly achieve, and has been found to disturb the acoustical field in the vicinity of the loudspeaker;
- the orientation of the instrumented earplug relative to the speaker is critical and difficult to achieve consistently because of the asymmetry of the earplug with respect to the sound bore aperture.

Consequently such measurement can not be performed on a daily basis by a regular user.

*A third scenario* was implemented because it did not have the practical limitations of the two others. This scenario is a variation of the second scenario where the field measurement is performed on the dual microphone probe before insertion in the earplug. Because of its simple geometry and its small size, the probe is easy to position precisely and does not disturb the acoustical field in any critical fashion. However, it requires two additional lab measurements. One measurement is required with the earplug to address the sound bore compensation, and the other with the probe alone to correct for microphone sensitivities that change with time. The measurement setups are illustrated in Fig. 6 . The expression of the sound bore length correction $\left(\frac{p_{\mathrm{meas}}}{p_2'}\right)$ is:

$$\left(\frac{p_{\text{meas}}}{p_2'}\right)_{I\!I\!I} = \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LI\!I\!I} \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LI} \times \left(\frac{\tilde{p}_{\text{meas}(FI\!I)}}{\tilde{p}_{\text{meas}(LI\!I)}} \times \frac{\tilde{p}_{\text{ref}(LI\!I)}}{\tilde{p}_{\text{ref}(FI\!I)}}\right) \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{FI} \times \left(\frac{p_{\text{ref}}}{p_2'}\right)_{LI\!I\!I} \tag{2.13}$$

where $\left(\frac{\tilde{p}_{\text{meas}(FI\!I)}}{\tilde{p}_{\text{meas}(LI\!I)}} \times \frac{\tilde{p}_{\text{ref}(LI\!I)}}{\tilde{p}_{\text{ref}(FI\!I)}}\right) = \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FI\!I} \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LI\!I}$

As in the case of the second scenario, this approach eliminates the need for microphone pair transfer function evaluation as the third term in Eq. 2.13 cancels the second term in Eq. 2.10. The experience with this scenario has confirmed that the measurement of the dual microphone probe response $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FI\!I}$ when placed in a clip in the near-field of the loudspeaker is a simple and reliable measurement to cross-link laboratory and field measurements. The advantages of this approach is that it leads to a very repeatable and reliable measurement. Firstly, it is simply using the "naked" dual microphone probe as used in practice with no special preparation. Secondly, the positioning of the dual microphone probe is very fast and reliable: a "clip" similar to a fuse holder holds the dual microphone probe on the loudspeaker grid. Thirdly, such measurement of dual microphone probe response $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FI\!I}$ clipped at the vicinity of the loudspeaker is not susceptible to ambient noise nor the room acoustics.

Eq. 2.9 can be rewritten using Eq. 2.13 with the same three line presentation convention, with the field NR measurement and its *field correction* on the first line, all the *laboratory corrections* on the second line and a *compensation* on the third line:

$$\begin{aligned}\text{REAT} = {} & \widetilde{\text{NR}}_* + 20\ \log_{10}\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FI\!I} \\ & + 20\log_{10}\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LI\!I\!I} + 20\log_{10}\left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LI\!I} \\ & + \text{TFOE} + \text{PN} + 20\ \log_{10}\left(\frac{p}{p_{\text{ref}}} \times \frac{p_2'}{p_3'}\right)\end{aligned} \tag{2.14}$$

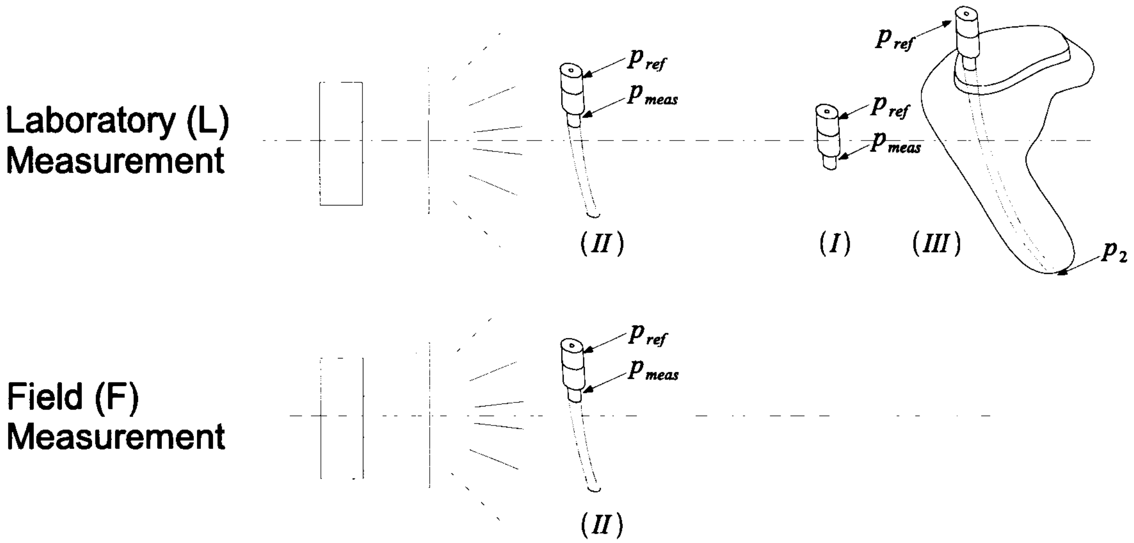


Figure 6 (Color online). Third scenario determination of the sound-bore length and microphone sensitivity correction. Top: Overview of the laboratory measurement of $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LI}$, $\left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LII}$ and $\left(\frac{p_{\text{ref}}}{p_2'}\right)_{LIII}$; Bottom: Overview of the field measurement of $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FII}$

The measurement of the NR field correction $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{FII}$ will be performed prior to the use of the measurement device, to discard any bias that would be introduced (during the measurement of the field Noise Reduction $\text{NR}_*$) by small differences in the microphone sensitivity and frequency response.

To maintain consistency with current attenuation estimation protocols and standards, the REAT will be the value to be predicted. The previous equation 2.14 can therefore also be re-written as the sum of two terms:

$$\begin{aligned} \widehat{\text{REAT}} &= \text{NR}_{\text{C}} \\ &\quad +\text{COMP} \end{aligned} \tag{2.15}$$

The first term, $\mathrm{NR_C}$, is the corrected Noise Reduction, composed of the measured field noise reduction and its field and laboratory correction terms.This estimation of REAT attenuation is a monaural value. Since the NR measurement is performed on both earplugs, a binaural estimation of the REAT is performed, with the " Equivalent Binaural Approach" presented in section 2.3.5.

The second term is the compensation factor COMP, and is composed of the terms in the third line of Eq .2.14. This term will be detailed in section 2.3.4.

### 2.3.2 Measurement of Noise Reduction and its associated corrections

#### 2.3.2.1 Measurement of the field Noise Reduction

The field Noise Reduction $\widetilde{NR}_*$ is obtained from the classical [45] measurement of a *Frequency Response Function* (FRF), using the " $H_3$ approach" (see calculation details in Appendix 2.a, given that $\tilde{p}_{\mathrm{ref}}(t)$ is the input signal $a(t)$ of the system and that $\tilde{p}_{\mathrm{meas}}(t)$ is the output signal $b(t)$ of the system).

The Noise Reduction values at octave band index $i$ , denoted $\widetilde{NR}_*^i$, are obtained from 1/3-octave bands filtered signals centered on the 125, 250, 500, 1000, 2000, 4000 and 8000 Hz frequencies. Such use of 1/3-octave band signals at octave band center frequencies is common practice in the hearing protection measurement field, since the narrow band noise sources used for hearing threshold determination have precisely a 1/3-octave bandwidth (see ANSI [11] or ISO [46] ). The same treatment is applied to all the NR associated corrections and compensations to produce them in 1/3-octave band values at octave band center frequencies.

#### 2.3.2.2 Measurement of the Noise Reduction field correction

The measurement in acoustic near-field of the correction $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$ is performed prior to any use of the measurement device in the field and is part of a *Daily Calibration Check* procedure. This procedure requires the dual microphone probe to be clipped in the center

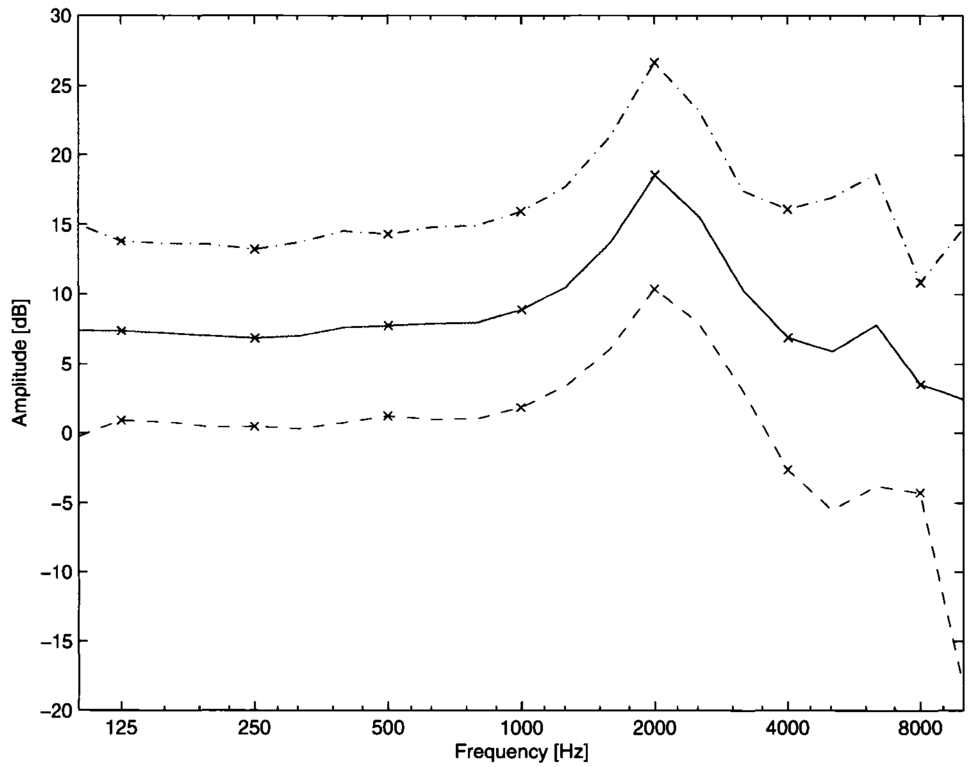


Figure 7 (Color online). Template used to check that the microphones are operating properly. The mean (solid line) and the upper and lower bounds (dashed lines) covering 99.9% of the usual variations were obtained from twenty-six measurements performed with several dual microphone probes in various environmental conditions.

of the Reference Sound Source speaker grid (ensuring an acoustical near-field), and that a Transfer Function (TF) measurement be performed between both microphones while the sound source is generating a moderate level pink noise source (as shown in the bottom of Fig. 6). This procedure will also serve two extra purposes, prior to any use of the measurement device:

1. checking that the sound source is functioning properly (since the Sound Pressure Level measured at the reference microphone must be in a given range of levels),

2. checking that both microphones are working correctly and that the microphone probe is not clogged or altered in any way (since the measured TF magnitude must be within given bounds as represented in Fig. 7 ).

#### 2.3.2.3 Measurement of Noise Reduction laboratory correction $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LIII} \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LII}$

The acoustical length of the overall sound bore is a function of the type of earplug used: for example, in the present case, the earplug is available in three different sizes for the core. Consequently the overall sound-bore length is fixed for a given earplug size. The associated correction has been determined using the laboratory setup illustrated in Fig. 6: the Transfer Function $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LIII}$ is measured in far-field conditions (anechoic chamber) with the microphone probe placed into the earplug two feet away from the loudspeaker (the experimental result of such measurement is presented in Fig. 8). This correction can be tabulated per 1/3-octave band, as presented in Table I.

Table I

Numerical 1/3-octave band values of $\left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LII}$ and $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LIII}$ corrections for sound-bore earplug size #0.5 and #2.5 (in dB).

| Frequency [Hz] | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| $\left(\frac{p_{ref}}{p_{meas}}\right)_{LII}$ | 1.2 | 1.4 | 0.4 | -0.8 | -9.9 | 3.6 | 6.4 |
| $\left(\frac{p_{ref}}{p_{meas}}\right)_{LIII}$ #0.5 | -0.6 | -0.8 | -0.9 | -2.9 | -12.4 | -2.3 | -6.2 |
| $\left(\frac{p_{ref}}{p_{meas}}\right)_{LIII}$ #2.5 | -0.0 | -0.1 | -0.4 | -2.4 | -11.8 | 0.4 | -0.2 |

### 2.3.3 Estimation of the equivalent binaural NR

The estimated attenuation obtained from Eq. 2.15 is a monaural estimation. In common practice, the REAT measurement is binaural with a single value reported by the test subjects. To best match the single attenuation measurement reported under REAT procedures and the two NR measured (one for each ear) using the proposed Field-MIRE protocol,

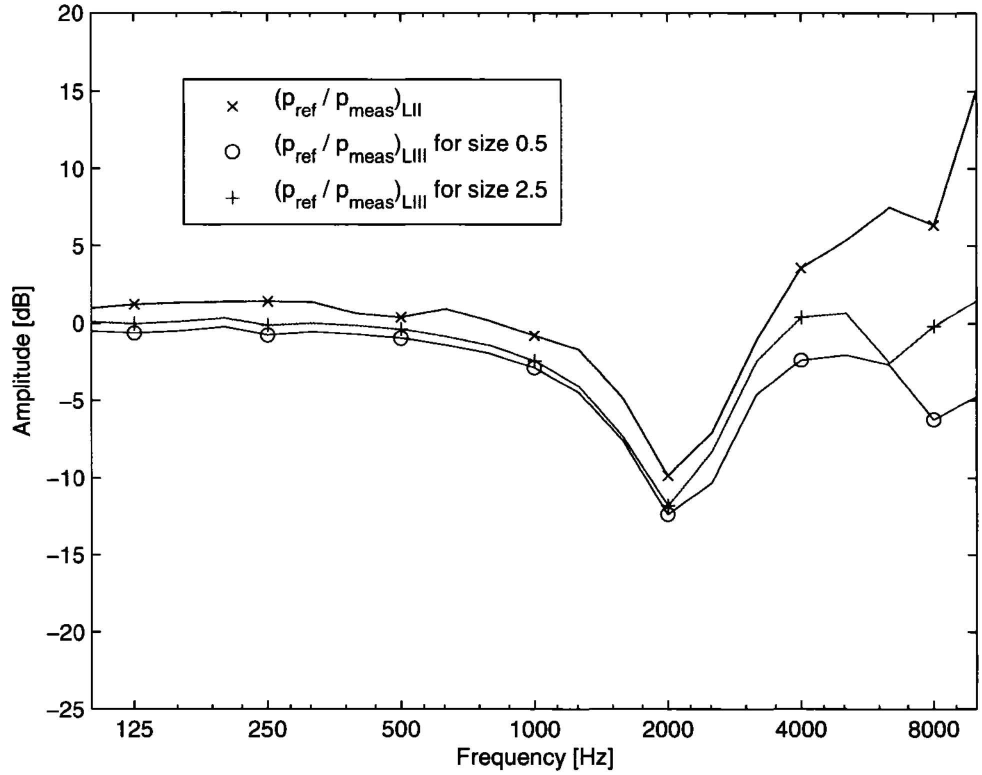


Figure 8 (Color online). 1/3-octave band values of $\left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}}\right)_{LII}$ (upper "x" line) and $\left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}}\right)_{LIII}$ corrections for sound-bore earplug size #0.5 ("o" line) and #2.5 ("+" line).

it has been found that an approach based on the Protected Hearing Threshold gives the best correlation between subjective REAT data and objective NR measurements. Such approach considers that the test subject will be able to detect the audio stimulus (i.e. the test signal used for the hearing threshold determination) through the ear that is presenting a combination of worse HPD attenuation and best hearing level. In practice, this approach consists of computing the protected hearing threshold for each ear by adding the respective hearing thresholds level $A_{\text{R}}$ and $A_{\text{L}}$ of the test subject to the right and left corrected Noise Reduction denoted $\text{NR}_{\text{C(R)}}$ and $\text{NR}_{\text{C(L)}}$; the equivalent binaural NR value to be used, denoted $\mathrm{NR}_{\mathrm{C(B)}}$, is the one that corresponds to the weakest protected threshold. The decision process for ${\mathrm{NR}_{\mathrm{C(B)}}}^i$ value determination is illustrated by the following relationship:

$$\begin{cases} \mathrm{NR}_{\mathrm{C(B)}} = {\mathrm{NR}_{\mathrm{C(L)}}}^i \\ \text{ if } \left({\mathrm{NR}_{\mathrm{C(L)}}}^i + A^i_{\mathrm{(L)}}\right) < \left({\mathrm{NR}_{\mathrm{C(R)}}}^i + A^i_{\mathrm{(R)}}\right) \\ \\ \mathrm{NR}_{\mathrm{C(B)}} = {\mathrm{NR}_{\mathrm{C(R)}}}^i \\ \text{ if } \left({\mathrm{NR}_{\mathrm{C(L)}}}^i + A^i_{\mathrm{(L)}}\right) > \left({\mathrm{NR}_{\mathrm{C(R)}}}^i + A^i_{\mathrm{(R)}}\right) \\ \\ \mathrm{NR}_{\mathrm{C(B)}} = \min\left({\mathrm{NR}_{\mathrm{C(L)}}}^i,\ {\mathrm{NR}_{\mathrm{C(R)}}}^i\right) \\ \text{ if } \left({\mathrm{NR}_{\mathrm{C(L)}}}^i + A^i_{\mathrm{(L)}}\right) = \left({\mathrm{NR}_{\mathrm{C(R)}}}^i + A^i_{\mathrm{(R)}}\right) \end{cases} \tag{2.16}$$

### 2.3.4 Compensation Calculation

The subject-related correction terms on the third line of Eq. 2.14 are $\mathrm{TFOE} + \mathrm{PN} + 20\ \log_{10}\left(\frac{p}{p_{\mathrm{ref}}}\right) + 20\ \log_{10}\left(\frac{p_2'}{p_3'}\right)$. Assuming these terms are all uncorrelated, their wrapping in a single compensation term COMP should lead to a normal distribution for large groups with average value $\overline{\mathrm{COMP}}$ and standard deviation $\sigma_{\mathrm{COMP}}$, denoted:

$$\mathrm{COMP} = \mathcal{N}\left(\overline{\mathrm{COMP}}, \sigma_{\mathrm{COMP}}\right) \tag{2.17}$$

Such assumption is supported by the fact that all the terms included on the third line of Eq. 2.14 originate from morphological or psycho-physiological variables. Furthermore, this assumption will be successfully validated using statistical tests in section 2.4.2.1.5.

Eq. 2.15 can be reverted per octave band index to:

$$\mathrm{COMP}^i = \mathrm{REAT}^i - {\mathrm{NR}_{\mathrm{C(B)}}}^i \tag{2.18}$$

where $\mathrm{REAT}^i$ is the REAT Attenuation reported by the human subject tested per a given standard, while ${\mathrm{NR}_{\mathrm{C(B)}}}^i$ is the Equivalent Binaural Corrected Noise Reduction (detailed in Eq. 2.16 ) as measured on the same subjects, in the same fitting conditions.

The Experimental Protocol for $\mathrm{COMP}^i$ Determination includes four steps:

1. The ${\mathrm{NR}_{\mathrm{C(R)}}}^i$ and ${\mathrm{NR}_{\mathrm{C(L)}}}^i$ measurements were performed on each subject (20 test subjects, per ANSI S12.6) immediately following each of their complete REAT attenuation tests (2 tests per subjects per ANSI S12.6); since the test subjects were instructed not to touch the HPD, and the NR measurement was performed immediately after the REAT tests, the fit of the earplug can be considered to be the same except for the slight effect of the insertion of the microphone probe (probably enhancing the quality of the fit, as the strength applied to insert the probe is towards the ear-canal and tympanic membrane). The same "bias" will be introduced by the microphone insertion for every earplug tested, and consequently, such systematic error will be automatically cancelled later in the Compensation computation. This effect is detailed in section 2.5.2.1;

2. The equivalent binaural NR is then computed per Octave Band using Eq. 2.16;

3. The difference, per Octave Band and per subject between the reported REAT attenuation values and the objectively measured NR, will provide the Compensation values using Eq. 2.18.

4. This per-subject compensation can then be presented, per Octave Band index, as a normal distribution $\mathcal{N}\left(\overline{\mathrm{COMP}^i}, \sigma^i_{\mathrm{COMP}}\right)$, hence this compensation can be given with a confidence interval that will be usefull for the determination of the uncertainty associated with the proposed Field-MIRE measurement.

### 2.3.5 Predicted Personal Attenuation Rating

The Predicted Personal Attenuation Rating (PPAR) is computationally very similar to the existing NRR and SNR: it is a single number, expressed in decibels, that represents the attenuation achieved by the user for a given HPD. But while the NRR is obtained from a subjective REAT measurement on a population sample under laboratory conditions, the PPAR is obtained from an objective NR measurement, on a particular user wearing the hearing protector under realistic conditions. Furthermore, the NRR is computed according to the Environmental Protection Agency requirements [47], by subtracting a two-standard deviation correction from the mean REAT attenuation values in order to estimate the "minimum noise reduction theoretically achieved by 98% of the laboratory subjects" [5] while the PPAR (with its associated uncertainty) is the value that the user will obtain from its own HPD with a given probability $x$ (where $x$ is the expected percentile of measured REAT greater than predicted PPAR).

Per octave band $i$ (from $i$=1 for 125 Hz to $i$=7 for 8000 Hz), the Eq. 2.15 can be written as:

$$\widehat{\mathrm{REAT}}^{i} = \mathrm{NR}_{\mathrm{C}}^{i} + \mathrm{COMP}^{i} \tag{2.19}$$

where $\mathrm{COMP}^{i}$ is the Octave Band Compensation Factor, detailed in 2.3.4.

The left ear, right ear, and equivalent binaural predicted attenuation can be expressed respectively by:

$$\widehat{\mathrm{REAT}}^{i}_{(\mathrm{L})} = \mathrm{NR}_{\mathrm{C(L)}}^{i} + \mathrm{COMP}^{i} \tag{2.20}$$

$$\widehat{\mathrm{REAT}}^{i}_{(\mathrm{R})} = \mathrm{NR}_{\mathrm{C(R)}}^{i} + \mathrm{COMP}^{i} \tag{2.21}$$

$$\widehat{\mathrm{REAT}}^{i}_{(\mathrm{B})} = \mathrm{NR}^{i}_{\mathrm{C(B)}} + \mathrm{COMP}^{i} \tag{2.22}$$

where $\mathrm{NR}^{i}_{\mathrm{C(B)}}$ is the equivalent binaural corrected Noise Reduction computed according to Eq. 2.16.

The PPAR is essentially the REAT value with a protection performance factor $x$. It is therefore obtained from Eq. 2.23 by subtracting $\alpha$-times the uncertainty $u^{i}_{\widehat{\mathrm{REAT}}}$:

$$\mathrm{PPAR}^{i}_{x} = \widehat{\mathrm{REAT}}^{i}_{(B)} - \alpha \times u^{i}_{\widehat{\mathrm{REAT}}} \tag{2.23}$$

The coefficient $\alpha$ is a constant associated with a given protection performance as defined in the ISO4869 standard [40] and is given in Table II as a function of $\alpha$.

Table II

Value of $\alpha$ for various protection performance $x$

| Protection performance $x$,% | Value of $\alpha$ |
|---|---|
| 50 | 0.00 |
| 75 | 0.67 |
| 80 | 0.84 |
| 84 | 1.00 |
| 85 | 1.04 |
| 90 | 1.28 |
| 95 | 1.64 |
| 98 | 2.00 |

The overall PPAR value is derived computationally in a very similar manner as the existing NRR, and is obtained by logarithmically averaging the difference between the C-weighted exposure level and the A-weighted protected exposure level, using the following formula:

$$\mathrm{PPAR}_x = 10\ \log_{10}\sum_{i=1}^{7} 10^{\frac{100+C^i}{10}} - 10\ \log_{10}\sum_{i=1}^{7} 10^{\frac{100+A^i-\mathrm{PPAR}_x^i}{10}} \tag{2.24}$$

where $A^i$ and $C^i$ are respectively the C and A weighting coefficients, defined in table XXI, in Appendix 2.b.a.

In the absence of protection performance $x$ specified, this latter quantity is assumed to be 50 %. The $\mathrm{PPAR}_{50\%}$ will be typically used for symmetrical assessment, for example when it is required to assess the sufficiency of attenuation (trying to avoid overexposure on one side and overprotection on the other). On the other hand, when dealing with asymmetrical assessment, such as the rating test, presented in 2.3.6.2, $\mathrm{PPAR}_{84\%}$ or even $\mathrm{PPAR}_{98\%}$ can be used. The uncertainty associated with the octave band PPAR values will be presented in section 2.5.2 while the uncertainty associated with the overall PPAR value will be presented in section 2.5.3.

### 2.3.6 Performance Tests

From the "subject-fit" NR measurement, three pass-or-fail performance tests are performed to ensure that the earplug delivered to the end-user will be effective against dangerous noise exposures. The first test ("Acoustic Seal Test") ensures that the earplug provides a good acoustic seal; the second test ("Rating Test") ensures that the earplug deserves the NRR it has been officially rated for; the third test will assess the sufficiency of attenuation provided by the earplug once filtered by the acoustical damper.

#### 2.3.6.1 Acoustic Seal Test

The goal of the Acoustic Seal Test is to make sure that the earplug fits the ear-canal properly. The Acoustic Seal Test criteria has been defined empirically (see Technical Reports [48]) to correspond to "good" earplugs that are properly sized and fitted, and therefore provide an effective and comfortable fit; the threshold value was later revisited so that it corresponds to the $98^{th}$ percentile of the $\mathrm{NR_C}$ values measured at 250 Hz ($i = 3$) during an ANSI S12.6 certification test [49].

$$\text{Seal Test}\begin{cases}\text{Passed if } {\mathrm{NR_C}}^{i=3} \geq \left(\mu_{\mathrm{NR_C}}^{i=3} - 2\times\sigma_{\mathrm{NR_C}}^{i=3}\right) \\ \text{Failed else}\end{cases} \tag{2.25}$$

where $\mu_{{\mathrm{NR_C}}^{i=3}}$ and $\sigma_{{\mathrm{NR_C}}^{i=3}}$ are respectively the average and the standard-deviation values of the $\mathrm{NR_C}$ measured in the 250 Hz Octave Band ($i = 3$) on the test subjects involved in the ANSI certification tests [12].

#### 2.3.6.2 Rating Test

The Rating Test ensures that the earplug offers at least the Noise Reduction Rating (NRR) it has been officially rated for, according to current legislation (see EPA [47]). This systematic, individual verification ensures that the earplug really does not need to be "derated"[4]. The Rating Test Criteria used is simply to check that the PPAR reflects attenuation at or more than the published NRR value.

$$\text{Rating Test}\begin{cases}\text{Passed if } \mathrm{PPAR}_{84\%} \geq \mathrm{NRR} \\ \\ \text{Failed if } \mathrm{PPAR}_{50\%} < \mathrm{NRR}\end{cases} \tag{2.26}$$

where $\mathrm{PPAR}_{84\%}$ and $\mathrm{PPAR}_{50\%}$ are respectively the Predicted Personal Attenuation Rating at the 84% and 50% protection performance. For the special case where $\mathrm{PPAR}_{50\%} \geq \mathrm{NRR} > \mathrm{PPAR}_{84\%}$ , the Rating Test Status is on the edge and will be handled in a very specific way.

[4] As mentioned in the Introduction, correlation between laboratory studies and actual HPD performance in the field has been poor, resulting in a range of "derating" systems to try to align laboratory and field performance more closely. OSHA directive CPL 02-02-035 - CPL 2-2.35A - 29 CFR 1910.95(b)(1), "Guidelines for Noise Enforcement; Appendix A " requires a 50% derating when comparing the protection offered by HPD to noise control engineering. NIOSH[1] recommends a variable derating system, with earmuffs derated 25%, formable earplugs 50%, and all other HPD 70%

#### 2.3.6.3 Protection Outcome Test

The Protection Outcome Test ensure the sufficiency of attenuation for the user's individual needs the objective is to avoid under protection as well as over protection. For that purpose, the A-weighted effective sound pressure level when the filtered earplug is worn , $L'_{A_x}$ is calculated using the "Octave Band Method" [40], as:

$$L'_{Ax} = 10\ \log_{10} \sum_{i=1}^{7} 10^{0.1\left(L_{f(i)}+A_{f(i)}-\mathrm{PPAR}_x^i\right)} \tag{2.27}$$

where $L_{f(i)}$ is the sound pressure level of the noise in octave band; $A_{f(i)}$ is the frequency weighting A in accordance with IEC 651 at the octave-band mid-frequency.

The Protection Outcome Test Criteria is presented in Table III, for 50% protection performance.

Table III

Protection Outcome as defined by EN458 recommendation [8] and CSA standard[9].

| | Protection Outcome | Protection Outcome Status |
|---|---|---|
| $L'_{Ax} \geq 85$ | Insufficient | Fail |
| $85 > L'_{Ax} \geq 80$ | Acceptable | Pass |
| $80 > L'_{Ax} \geq 75$ | Ideal | Pass |
| $75 > L'_{Ax} \geq 70$ | Acceptable | Pass |
| $70 > L'_{Ax}$ | Overprotection | Fail |

As mentioned in section 2.2, to avoid over protection, it is possible to insert acoustic dampers in the earplug's soundbore. A computational method has been developed [7, 38] to predict the sound pressure level below the filtered earplug, without having to actually measure with the filter in place. It is therefore possible, right after the "subject-fit" NR measurement to select -among the several acoustical dampers available- the one that will lead to a protected exposure level close to the "optimal" bracket of 75 to 80 dBA.

## 2.4 Experimental Validation of the Proposed Approach

As mentioned in section 2.3, the proposed approach relies on an acoustical measurement by a dedicated device and on a method that aims to predict the earplug REAT attenuation. The complete validation of the approach will consequently consist in validating first the measurement device, and second the proposed method.

### 2.4.1 Validation of the measurement device

The validation of the measurement device consists of laboratory comparison between the measurement output from the measurement device and a supposedly known measurand: in our case the Noise Reduction measured by the device is compared to the Insertion Loss measured by hi-grade laboratory equipment on an *Acoustical Test Fixture* (ATF).

#### 2.4.1.1 Experimental setup

The instrumented earplug is inserted inside the ATF, as illustrated in Fig. 9, while the overall arrangement of the sound source, ATF and microphone is a commonly used one (see for example Kuhn [51]). The laboratory equipment used is presented in Table IV.

Table IV

Hardware used for the validation of the measurement device

| Description | Model | Brand |
|---|---|---|
| Head and Torso Simulator | 4128C | Brüel & Kjær |
| Right Ear Simulator | 4158C | Brüel & Kjær |
| Right Pinna Simulator (soft) | DZ9751 | Brüel & Kjær |
| Real-Time Spectrum Analyzer | 2900B | Larson-Davis |

The measurement steps are the following:

1. the NR measurement is conducted with a laboratory *Real-Time Spectrum Analyzer* (RTA) connected to the regular dual microphone probe to be used by the measurement device,

2. the measurement of the Transfer Function between the sound source and the occluded-ear tympanic pressure $p_3'$ is performed,

3. the measurement of the Transfer Function between the sound source and the pressure at the open-ear tympanic membrane $p_3$ is performed (TFOE measurement).

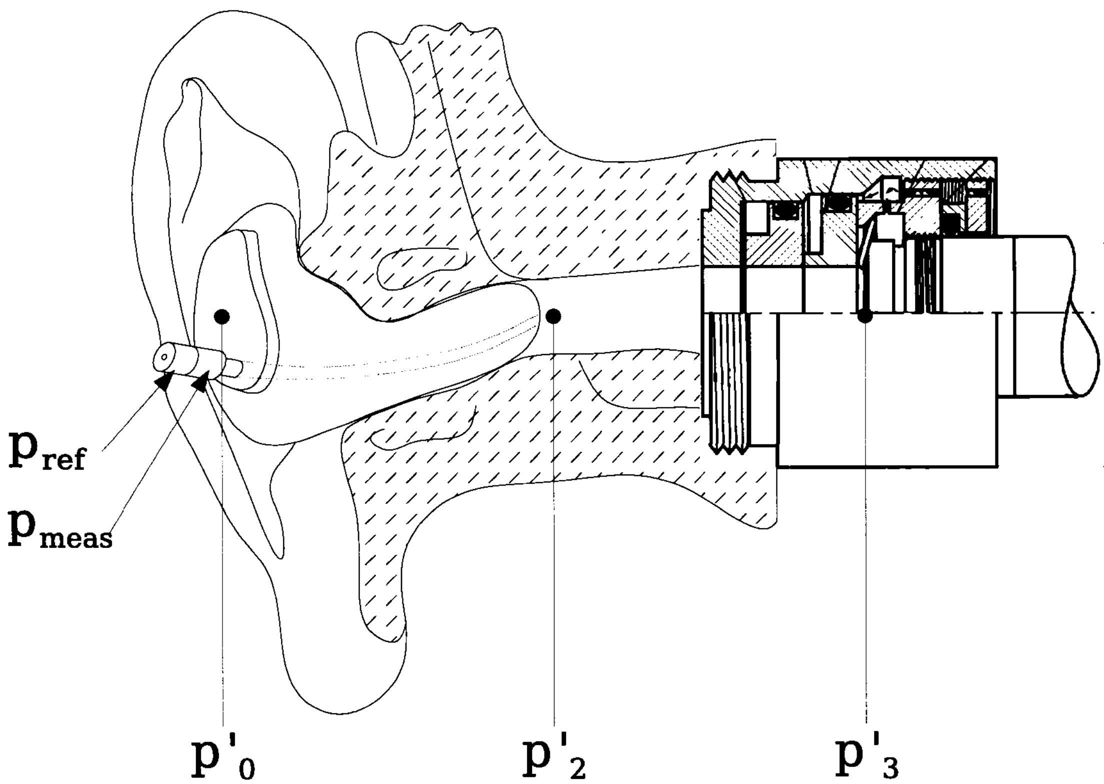


Figure 9 (Color online). The B&K 4158 Ear-Simulator mounted on the ATF B&K 4128C and Sound Pressure Levels Measurement Points

#### 2.4.1.2 Experimental results

The calculation of IL is performed using Eq. 2.1, and the NR (denoted $NR_0$, for that particular validation) is obtained by subtracting the TFOE from this IL, as per Eq. 2.4.

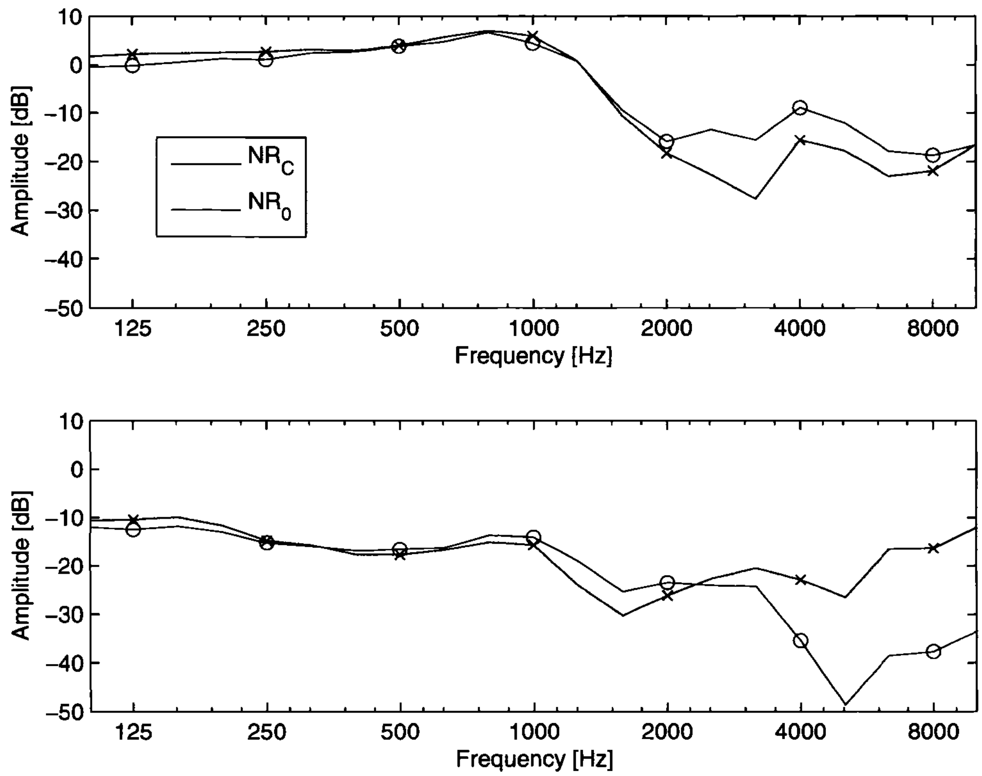


Figure 10 (Color online). Graph showing the $NR_0$ and the corrected field $NR_C$ on the B&K 4128 ATF, for leaky (top) and tight (bottom) SONOMAX SONOCUSTOM™earplugs

The $\widetilde{NR}_*$ measurement is then corrected as per Eq. 2.14 to obtain the field corrected $NR_C$. The quantities $NR_0$ and $NR_C$ have been plotted for a leaky and a tightly fitted earplug in Fig. 10.

It can be seen from Fig. 10 that $NR_C$ and $NR_0$ are close for the frequencies up to 1kHz and that discrepancies arise in frequencies above 2 or 3 kHz. Such concordance reflects well on the process given that the correction terms $\left(\frac{p}{p_{\text{ref}}}\right)$ and $\left(\frac{p_2'}{p_3'}\right)$ from the third line of Eq. 2.14 have not yet been applied. The occluded ear-canal correction $\left(\frac{p_2'}{p_3'}\right)$ that occurs in the high frequency is a function of the residual ear-canal length and consequently varies greatly among human subjects. The measurement of $\left(\frac{p'_2}{p'_3}\right)$ on the ATF is not easy to perform directly (using external miniature probe microphones would modify substentially the system, for example) and the indirect determination of $\left(\frac{p'_2}{p'_3}\right)$ from the current measurement setup would not add any information since it would have been obtained from the subtraction of the $\mathrm{NR_C}$ from the $\mathrm{NR_0}$ . Consequently, the close values observed for $\mathrm{NR_C}$ and $\mathrm{NR_0}$ are a good indication that the measurement device is reliably measuring a physical quantity that is closely related to the Noise Reduction and that nothing unexpected is affecting the acquisition chain.

### 2.4.2 Validation of the prediction method

The prediction method has been validated using results of tests conducted by a third-party research laboratory. Two groups, denoted $\alpha$ and $\beta$ of twenty subjects were tested with the *Instrumented Expandable Custom Earplug* (presented in section 2.2). For each group, the test included two parts:

- the determination of REAT according to the ANSI S12.6-A [11] standard,
- the determination of the field corrected $\mathrm{NR_C}$ according to the measurement setup described in section 2.2 on the same test subjects in the same earplug fitting condition.

Given the importance of accurate, reliable and trusted data for the experimental validation of the proposed approach, the experimental data collected during those tests has been made available for public review [5].

From the test results provided by the third-party research laboratory, the $\mathrm{NR_{C(B)}}$ was determined according to Eq. 2.16. The compensation for group $\alpha$ is evaluated according

[5] See American Institute of Physics Electronic Physics Auxiliary Publication Service (EPAPS) Document No. ????? for an electronic version of the third-party laboratory report. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).

to Eq. 2.18, on seventeen of the twenty subjects (for three subjects the dual microphone probe was impossible to insert properly inside the sound-bore, greatly affecting the NR measurement reliability). This compensation result is used to predict the attenuation of each of the twenty test subject of the group $\beta$ according to Eq. 2.22 (no subject discarded in this validation group).

#### 2.4.2.1 Detailed computation on the two datasets

##### 2.4.2.1.1 Measurement of the REAT

The Octave Band REAT values reported by each of the seventeen test subjects during the first test, $\mathrm{REAT}_\alpha$ is presented in table XXIV in Appendix 2.b.b.

##### 2.4.2.1.2 Determination of the $\mathrm{NR_C}$ for each ear

The $\mathrm{NR_C}$ originally reported by the third-party laboratory comes from a simple subtraction between the reference and measurement sound pressure levels per octave band. In practice, the proposed method relies on the transfer function approach (see section 2.3.2). The $\mathrm{NR_C}$ values havebeen recomputed from the Frequency Response Function that were collected electronically at the time of the experiment. The differences between the initial $\mathrm{NR_C}$ recorded (per the Sound Pressure Level subtraction) and the $\mathrm{NR_C}$ re-computed (per Transfer Function approach) are marginal and can be found in the "Supplement with Experimental Data" [6].

The Noise Reduction measured on right ear of the first dataset, ${\mathrm{NR}_{\mathrm{C(R)}}}^i$ is presented in Table XXV in Appendix 2.b.b, while ${\mathrm{NR}_{\mathrm{C(L)}}}^i$, the Noise Reduction measured on Left Ear is presented in table XXVI in Appendix 2.b.b.

[6]See American Institute of Physics Electronic Physics Auxiliary Publication Service (EPAPS) Document No. ????? for a Supplement with Experimental Data. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).

#### 2.4.2.1.3 Determination of the equivalent binaural $\mathrm{NR_C}$

The right and left ear audiograms of the group $\alpha$ , $A^i_R$ and $A^i_L$ are respectively presented in Tables XXVIII and XXIX in Appendix 2.b.b. Using the formula presented in Eq. 2.16, the equivalent binaural Noise Reduction measured on the group $\alpha$, $\mathrm{NR_{C(B)}}^i$is presented in Table XXVII in Appendix 2.b.b.

#### 2.4.2.1.4 Computation of the Compensation COMP for the first group

The compensation values of the first group is computed according to Eq. 2.18. Individual values of $\mathrm{COMP}^i$ are presented in Table XXX, while the Mean $\overline{\mathrm{COMP}^i}$ and Standard Deviation $\sigma^i_{\mathrm{COMP}}$ are presented in Table XXII in section 2.b.b.

#### 2.4.2.1.5 Normality check of the Compensation factor

The goodness of fit of the Compensation factor to a normal distribution has been successfully validated at a significance level of 5% using the Lilliefors test (similar to the Kolmogorov-Smirnov test, but adjusted for the fact that the parameters of the normal distribution are estimated from the data rather than specified in advance) for both the first and second group sets of experimental data.

The normal probability plot are respectively presented in Fig. 24 and 25 in Appendix 2.c for the two datasets. 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 will be linear. Other distribution types will introduce curvature in the plot. The normal probability plot of the compensation for the two datasets merged is presented in Fig. 26 in Appendix 2.c while its histograms with superimposed normal density are presented in Fig. 27. These plots indicate that the COMP function is a normal distribution and that the hypothesis of section 2.3.4 is valid.

#### 2.4.2.1.6 Computation of $\mathrm{NR}_{\mathrm{C(B)}}$ for the second group

The corrected Noise Reduction measured on right and left ear of the second group, ${\mathrm{NR}_{\mathrm{C(R)}}}^{i}$and ${\mathrm{NR}_{\mathrm{C(L)}}}^{i}$ are presented in Tables XXXI and XXXII in Appendix 2.b.b. The equivalent binaural Noise Reduction measured on the second group, ${\mathrm{NR}_{\mathrm{C(B)}}}^{i}$ is presented in Table XXXIII in Appendix 2.b.b.

#### 2.4.2.1.7 Prediction of the attenuation

Using the compensation values determined on the first group, $\mathrm{COMP}_{\alpha}$ (see table XXX) and the equivalent binaural $\mathrm{NR}_{\mathrm{C(B)}}$ computed on the second group (see Table XXXIII), the predicted values of attenuation $\widehat{\mathrm{REAT}}^{i}$ can be obtained and are presented in Table XXXIV in Appendix 2.b.b.

### 2.4.2.2 Predicted vs. Reported Attenuation

The REAT values reported during forty tests (twenty test subjects tested twice) per ANSI S12.6-A has been compared to the attenuation predicted for those same forty tests using the proposed Field-MIRE approach as implemented in the SONOMAX SONOPASS™measurement system.

The observed prediction errors from a model are the differences between the responses observed at each combination values of the explanatory variables and the corresponding prediction of the response computed using the model. It is defined as:

$$\epsilon = \mathrm{REAT} - \widehat{\mathrm{REAT}} \tag{2.28}$$

If the model fit to the data were correct, the observed prediction errors would approximate the random errors that make the relationship between the explanatory variables and the response variable a statistical relationship. Therefore, if the observed prediction errors appear to behave randomly, it suggests that the model fits the data well. On the other hand, if non-random structure is evident in the observed prediction errors, it is a clear sign that the model fits the data poorly.

#### 2.4.2.2.1 Octave band observed prediction errors

It can be seen from the Normal Probability Plot of the observed prediction errors in Fig. 11 that the distribution of the observed prediction errors is very close to a normal distribution for all the frequency range, with the low-frequency bands showing some curvature in the plot in a very limited number of cases. Such curvature may well be attributed to the low-frequency masking error bias introduced by the Physiological Noise of the subject undergoing the REAT test. Overall, the assumption of a normally distributed observed prediction error appears to be valid and will permit the calculation of the uncertainty associated with the prediction.

Fig. 28 presents the histogram with superimposed normal density for all the observed Octave Band prediction errors $u_\epsilon^i$. The uncertainty component $u_\epsilon$ can be directly asserted from the standard deviation of the observed prediction and is presented in Table V.

Table V

Uncertainty component $u_\epsilon$ obtained from the standard-deviation of $\epsilon$

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean** $\epsilon^i$ | 2.5 | 1.3 | 1.6 | 0.3 | -1.0 | -2.5 | 0.0 |
| **Std.** $\epsilon^i$ | 6.2 | 6.1 | 6.2 | 6.1 | 5.9 | 8.6 | 9.2 |

#### 2.4.2.2.2 Overall observed prediction error

The analysis of the graph in Fig. 12 shows that the overall observed prediction error (as computed using Eq. 2.24 and reported in Table XXIII) is 0.2 dB average with a standard deviation of 4.8 dB.

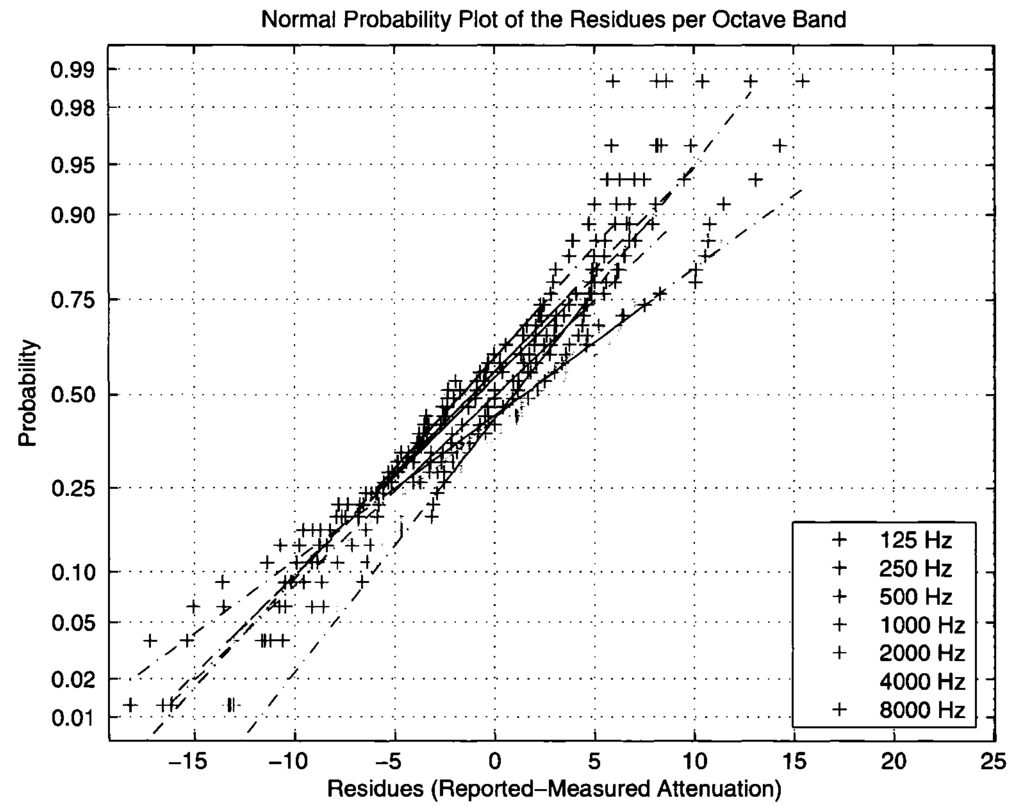


Figure 11 Normal probability plot of the observed prediction error $\epsilon^i$ per Octave Bands

### 2.4.3 Comparison with existing field measurement techniques

Fig. 13 is adapted from [15]: it is reproducing the comparison between the experimenter-fit REAT data ("point" line), the FITCHECK™headphone method ("circle" line), the FITCHECK™in sound field method ("down triangle" line), the bone-conduction loudness balance method ("up triangle") and the ANSI S12.6-1997 Method B subject-fit REAT data ("square" and "plus" lines respectively for day 1 and day 2), for the EAR EXPRESS POD PLUG™earplug. Fig. 14 is a similar comparison between the predicted and reported attenuation with the proposed Field-MIRE approach. The results presented in the cited study are the individual arithmetic means (as used in the ANSI S12.6[12] standard). Consequently, the average and standard deviation for the Field-MIRE are now evaluated on

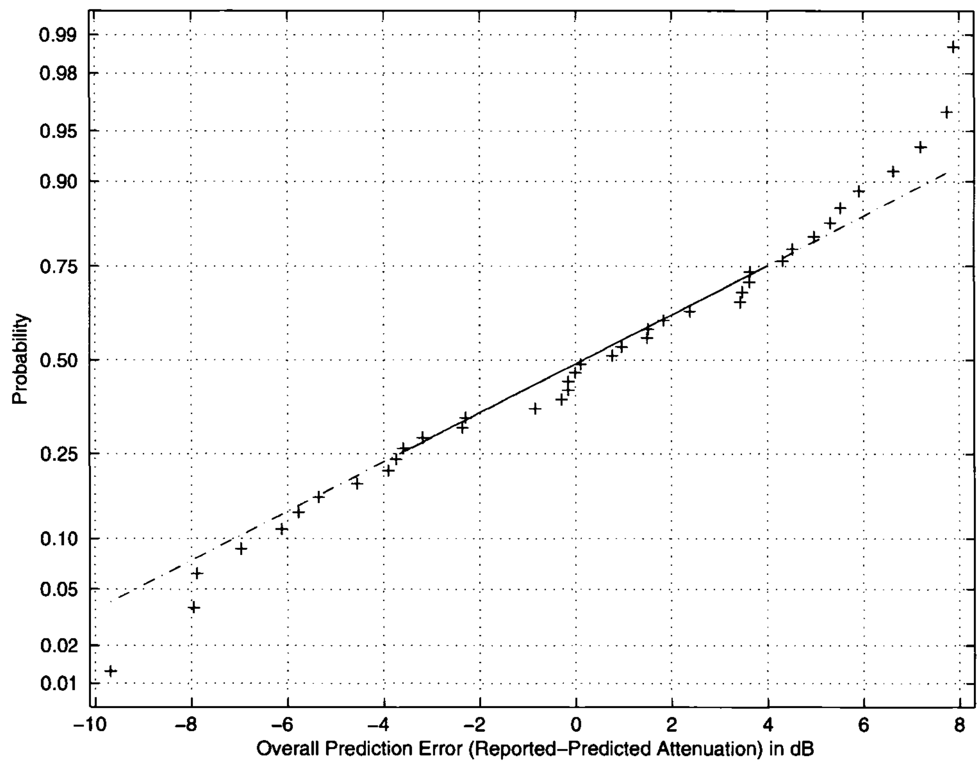


Figure 12 (Color online). Normal probability plot of the overall observed prediction error $u_\epsilon$

twenty individual arithmetic means, rather than on forty test results as in previous normal probability plot in Fig. 12. Some observations can be done when comparing the predicted and reported (REAT) values in Fig. 13 and Fig. 14:

1. It can be seen that the average values predicted for the group with the proposed Field-MIRE approach are as close to the REAT values (Supervised-Fit) than the other existing field measurement approaches are to the REAT values (Experimenter-Fit).

2. It can also be seen that the standard deviation of the group predicted attenuation (using the Field-MIRE) is lower than its counterpart for the other existing field mea-

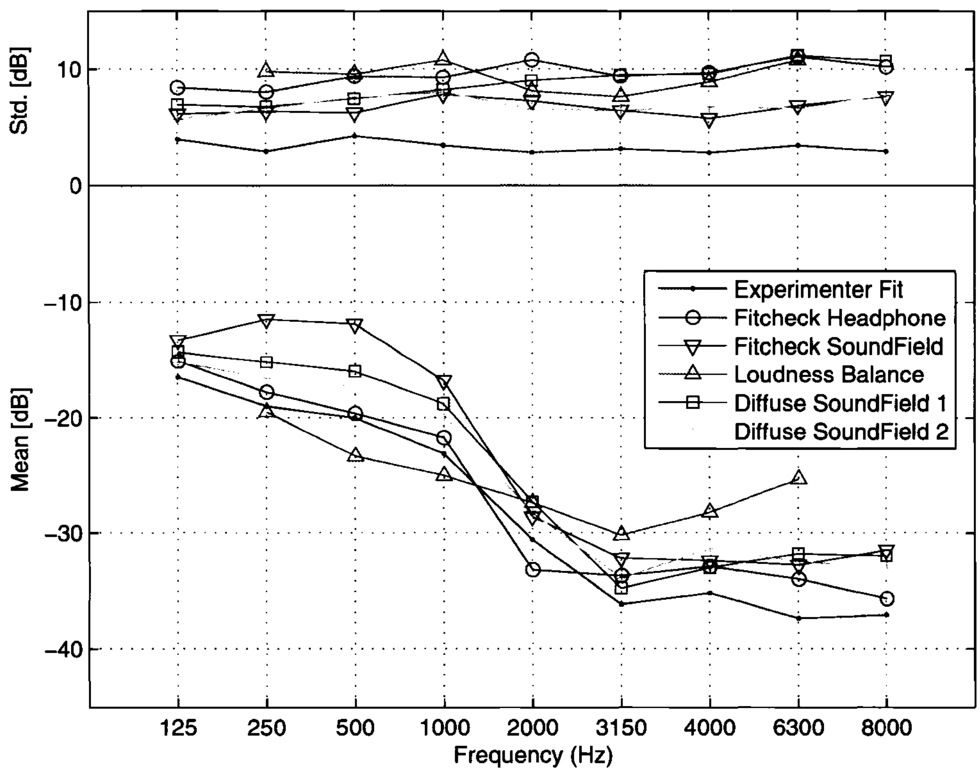


Figure 13 (Color online). Average and Standard Deviation of twenty individual arithmetic attenuation means. Comparison between the experimenter-fit REAT data ("point"), the FITCHECK™headphone method ("circle"), the FITCHECK™in sound field method ("down triangle"), the bone-conduction loudness balance method ("up triangle") and the ANSI S12.6-1997 Method B subject-fit REAT data ("square" and "plus" respectively for day 1 and day 2), for the EAR EXPRESS POD PLUG™earplug.

surement approaches. Since the standard deviation primarily reflects the variability of the earplug attenuation in the group of twenty subjets but does also reflect the variability associated with the measurement device itself, one could think that the proposed Field-MIRE method is indeed introducing less variability than any of the other existing field measurement approaches.

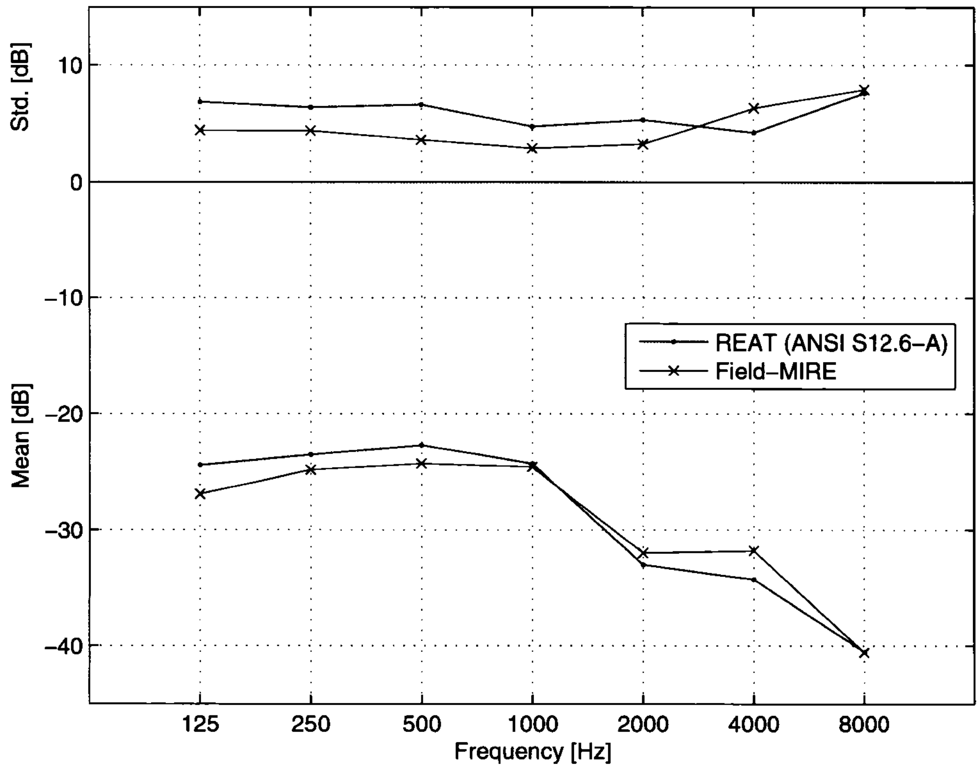


Figure 14 (Color online). Average and Standard Deviation of twenty individual arithmetic attenuation means. Comparison between supervised-fit REAT ("point" line) and Field-MIRE predicted ("x-mark" line) attenuation for the SONOMAX SONOCUSTOM™earplug.

3. Furthermore, the standard deviation of the group predicted attenuation appears to be significantly lower for most octave bands in the case of the Field-MIRE than the one obtained from the REAT test. Such reduced group standard deviation is uncommon, since it is often reported in the literature [5, 44] that standard deviations "*are only marginally less for the MIRE procedure*" [6] but can be explained by the differences between the proposed Field-MIRE and traditional MIRE measurement procedures:

   - In traditional MIRE procedure, two sound pressure levels measurements are performed at two distinctive moments in time, on the same subject: the measurement of the open ear tympanic sound pressure level $p_3$ and the measurement of the occluded-ear tympanic sound pressure level $p'_3$ (see Fig. 3 for illustrations). Moreover, these two sound pressure level measurements can be very easily contaminated by an external disturbance (uncorrelated noise from the measurement setup or induced by the human test subject). Such bias may not be easily noticeable by the experimenter.

- In the proposed Field-MIRE approach, the two related measurements ($p_{\text{ref}}$ and $p_{\text{meas}}$) are performed simultaneously on the same subject greatly reducing the possible variability in the testing conditions. Furthermore, those measurements are based on the measurement of the transfer function between $p_{\text{ref}}$ and $p_{\text{meas}}$. and such measurement is insensitive to the non-correlated noise. Moreover, the coherence function function is available and is a good indicator (for the experimenter) of the validity of the measurement.

All this findings are very promising for the proposed Field-MIRE, but they do come from average and standard deviation values on a group and do not necessary properly reflect the difference between predicted and reported values on an individual basis. Such difference has been plotted on a graph with the reported attenuation (as obtained from the REAT) on the $x$-axis and the predicted attenuation (obtained from the proposed Field-MIRE) on the $y$-axis. Fig. 29 represents the octave band data, while Fig. 30 represents the overall attenuation values. It can be seen that the difference between the predicted and reported attenuation values is never exceeding 10 dB for all the forty tests. Unfortunately, such comparison, on an individual basis, between the predicted and reported attenuation value for other existing field measurement approaches has never been published. Furthermore, the individual error data committed by these approaches is still unavailable despite many attempts from the authors. As a consequence, the detailed analysis of the individual error of the proposed Field-MIRE approach (detailed in section 2.5) will be conducted without comparison to existing field measurement approaches.

## 2.5 Uncertainty associated with the proposed measurement approach

The objective of the proposed Field-MIRE approach is to predict the attenuation of an earplug as worn by the user in the field. As with all physical measurement techniques, the proposed approach would not be complete without an evaluation of its associated uncertainty.

The calculations are based on the recommendations in standards from NIST [55] or ISO [56]. These standards recommend a first step including: (a) Review and validation of the measurement equation used, (b) Classification of uncertainty components, and (c) Representation of uncertainty components. Part a) of this first step has already been accomplished as the measurement equation used for the PPAR computation is presented in Eq. 2.23–2.24 and the details of the PPAR have been explained in section 2.3.5. Part b) and c) of this first step will be the object of section 2.5.1 where the uncertainty components will be defined and classified. The second step in uncertainty assessment will be the evaluation of PPAR uncertainty components in section 2.5.2 using the same experimental data used in section 2.4.2. The third step will be the combination of uncertainty components in section 2.5.3. The fourth and last step will be the calculation of the expanded uncertainty and coverage factor in section 2.5.4.

### 2.5.1 Classification and Representation of uncertainty components for the PPAR

According to Eq. 2.23 and 2.24, the PPAR is computed from ${\mathrm{NR_C}}^i$ and $\mathrm{COMP}^i$. The analysis of the PPAR uncertainty will therefore focus on the two uncertainty components associated with these elements, $u_{\mathrm{NR}}$ and $u_{\mathrm{COMP}}$. These components will be defined and subdivided into elementary uncertainty components in the next two subsections to end-up with the determination of the uncertainties associated with the prediction of the octave band attenuation $\widehat{\mathrm{REAT}}^i$, denoted $u^i_{\widehat{\mathrm{REAT}}}$.

Table VI

Uncertainty components associated with the corrected Noise Reduction : $u_{\mathrm{NR}}$

| Uncertainty source | Variable(s) | Uncertainty |
|---|---|---|
| Transfer Function measurement using a RTA | $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$ and $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{LIII}$ and $\left(\frac{\tilde{p}_{\mathrm{ref}}}{\tilde{p}_{\mathrm{meas}}}\right)_{LII}$ | $u_{\mathrm{TF}_1}$ |
| Disturbances in Noise Reduction measurement | $\widetilde{\mathrm{NR}}_*$ | $u_{\mathrm{TF}_2}$ |
| Transfer Function Measurement in the field using a DSP | $\widetilde{\mathrm{NR}}_*$ and $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$ | $u_{\mathrm{DSP}}$ |
| Earplug fit variability caused by microphone probe insertion | - | $u_{\mathrm{PI}}$ |

#### 2.5.1.1 Uncertainty components associated with the corrected Noise Reduction: $u_{\mathrm{NR}}$

Per Eq. 2.14 , the $\mathrm{NR}_{(\mathrm{B})}{}^i$ is obtained from the measurement of $\widetilde{\mathrm{NR}}_*$ with three corrections $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$, $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{LIII}$ and $\left(\frac{\tilde{p}_{\mathrm{ref}}}{\tilde{p}_{\mathrm{meas}}}\right)_{LII}$ applied.

These three corrections are measured (either in laboratory or in the field) on the dual microphone probe not in the wearer's ear, leading to excellent signal-to-noise ratio and consequently good coherence of the Transfer Function. The uncertainty associated with each of these three TF measurements is $u_{\mathrm{TF}_1}$. The case of the measurement of $\widetilde{\mathrm{NR}}_*$ is somewhat different: it takes place in the occluded-ear leading to a very low sound pressure level at the measurement microphone, sometime even disturbed by the user's physiological noise so that the coherence of the TF for the measurement of $\mathrm{NR}_*$ can be much lower than in laboratory. The uncertainty associated with this measurement is $u_{\mathrm{TF}_2}$. These two uncertainty components $u_{\mathrm{TF}_1}$ and $u_{\mathrm{TF}_2}$ are represented on the first two lines of Table VI.

The measurement that takes place in the field using a Real Time Analyzer (RTA) implemented on a Digital Signal Processor (DSP) chip may suffer from quantification errors due to the Analog-to-Digital converters limited dynamic range and introduces some variability in the measurement. Consequently, the field measurements $\widetilde{\mathrm{NR}}_*$ and $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$ will inherit a DSP uncertainty $u_{\mathrm{DSP}}$. This uncertainty component is represented on the third row of Table VI.

Moreover, each time the dual microphone probe is inserted inside the earplug sound-bore, some pressure is applied to the earplug, affecting its fit inside the ear-canal; the variability introduced by such effect is named $u_{\mathrm{PI}}$ for "Probe Insertion" and affects the value of $\mathrm{NR}_*$. This uncertainty component is represented on the last row of Table VI.

#### 2.5.1.2 Uncertainty components associated with the Compensation factor: $u_{\mathrm{COMP}}$

Per Eq. 2.18, the Compensation factor COMP is the difference of two terms, leading to two uncertainty components, $u_{\mathrm{NR_c}}$ already presented in the previous subsection and $u_{\mathrm{REAT}}$ that results from the subjective REAT measurement and cannot be subdivided into components. Both components are presented in Table VII.

Table VII

Uncertainty components associated with the compensation factor : $u_{\mathrm{COMP}}$

| Uncertainty Source | Variable(s) | Uncertainty |
|---|---|---|
| Determination of corrected Noise Reduction | $u_{\mathrm{NR_c}}$ | $u_{\mathrm{NR}}$ |
| Subjective Sound Attenuation Measurements | REAT | $u_{\mathrm{REAT}}$ |

### 2.5.2 Evaluation of PPAR uncertainty components

#### 2.5.2.1 Evaluation of the corrected Noise Reduction uncertainty component: $u_{\mathrm{NR}}$

The corrected NR uncertainty component $u_{\mathrm{NR}}$ can be expressed as the summation of the uncertainties of the variables that are used for $\mathrm{NR_c}$ determination (first two lines of Eq.

2.14). Practically, using Table VI, the uncertainties in the third column are squared and multiplied by the number of variables in the second column, leading to:

$$u_{\mathrm{NR}} = \sqrt{3 \times u_{\mathrm{TF}_1}^2 + u_{\mathrm{TF}_2}^2 + 2 \times u_{\mathrm{DSP}}^2 + u_{\mathrm{PI}}} \tag{2.29}$$

#### 2.5.2.1.1 Evaluation of the uncertainty component $u_{\mathrm{TF}_1}$

When the Frequency Response Function of an ideal system is estimated from $H_1(\omega)$ or $H_2(\omega)$ and the signals are random noise signals (bandwidth-limited, Gaussian distributed white noise signals) there is a random error in both magnitude and phase [45]. The error upon the number of (independent) averages $n_d$ and the coherence $\gamma^2(\omega)$ in the measurement. The normalized random error for the magnitude of the estimate $|H(\omega)|$ (either $|H_1(\omega)|$ or $|H_2(\omega)|$) is given by:

$$\epsilon_r\left[\left|\hat{H}(\omega)\right|\right] = \sqrt{\frac{1-\gamma^2(\omega)}{\gamma^2(\omega)\; 2\; n_d}} \tag{2.30}$$

The more uncorrelated noise there is in the measurement, i.e. the lower the coherence is, the more averages must be performed to approach a certain statistical accuracy. In practice, the measurement of the Transfer Functions $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{FII}$, $\left(\frac{\tilde{p}_{\mathrm{meas}}}{\tilde{p}_{\mathrm{ref}}}\right)_{LIII}$ and $\left(\frac{\tilde{p}_{\mathrm{ref}}}{\tilde{p}_{\mathrm{meas}}}\right)_{LII}$ are required to have an estimated coherence value $\gamma^2(\omega)$ above 0.8 (a large enough value easily obtained in practise) , while the number of independent averages is $n_d$ =50, thus corresponding to:

$$\epsilon_r\left[\left|\hat{H}(\omega)\right|\right] = \sqrt{\frac{1-0.8}{0.8 \times 2 \times 50}} = 0.05 \tag{2.31}$$

Such requirement on the value of the estimated coherence value means that there would be 68% chance of the true value of $|H_1(\omega)|$ to be within the interval:

$$0.95 \times \left|\hat{H}_1(\omega)\right| \leq |H_1(\omega)| \leq 1.05 \times \left|\hat{H}_1(\omega)\right| \tag{2.32}$$

Table VIII presents the typical value of the estimated coherence $\gamma^2(\omega)$ for each of the three Transfer Function measured.

Table VIII

Typical values for the uncertainty component $u_{\mathrm{TF}_1}$

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Typical Coherence** | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| $u_{\mathrm{TF}_1}$ **[lin.]** | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 |
| $u_{\mathrm{TF}_1}$ **[dB]** | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 | 0.04 | 0.07 |

#### 2.5.2.1.2 Evaluation of the uncertainty component $u_{\mathrm{TF}_2}$

In practice, the average and standard deviation of the estimated Coherence $\gamma^2(\omega)$ has been measured during the Experimental Validation (section 2.4) on the first dataset (n=34, left and right measurements) and given the values presented in Table IX.

Table IX

Typical values for the uncertainty component $u_{\mathrm{TF}_2}$

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Minimun Coherence** | 0.73 | 0.83 | 0.79 | 0.44 | 0.68 | 0.53 | 0.18 |
| $u_{\mathrm{TF}_2}$ **[lin.]** | 0.06 | 0.05 | 0.05 | 0.11 | 0.07 | 0.09 | 0.22 |
| $u_{\mathrm{TF}_2}$ **[dB]** | 0.26 | 0.19 | 0.22 | 0.47 | 0.29 | 0.39 | 0.85 |

#### 2.5.2.1.3 Evaluation of uncertainty components $u_{\mathrm{DSP}}$

To assess the variability of a Transfer Function measurement on the DSP-RTA, thirty consecutive measurements were performed with the DSP-RTA on a well-defined and well-measurable acoustical quantity. This quantity is specifically the correction $\left(\frac{\tilde{p}_{\mathrm{ref}}}{\tilde{p}_{\mathrm{meas}}}\right)_{F\Pi}$ as measured by the DSP-RTA, and is presented in Fig. 15. The variability per octave band, presented in Table X could be further reduced by increasing the number of independent averages, $n$. However, the current value of 50 averages appears to be a reasonable compromise between the test duration and the test accuracy.

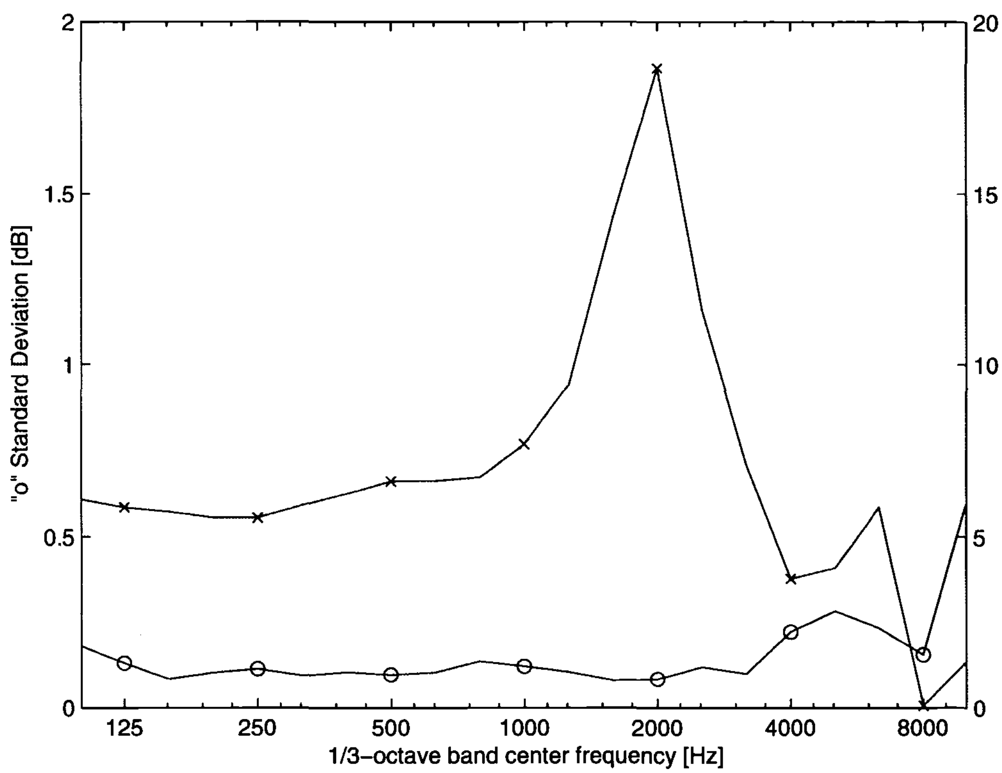


Figure 15 Uncertainty component $u_{\mathrm{DSP}}$: Transfer Function magnitude ("x") and variability ("o"") obtained from thirty consecutive measurements

Table X

Typical values for the uncertainty component $u_{\mathrm{DSP}}$

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\mathrm{DSP}}$ **[dB]** | 0.18 | 0.11 | 0.11 | 0.10 | 0.08 | 0.23 | 0.12 |

#### 2.5.2.1.4 Evaluation of the Probe Insertion uncertainty component $u_{\mathrm{PI}}$

According to the requirements of the ANSI S12.6 [12] Method B ("Subject-Fit") methodology, it is impossible to touch the HPD once it has been fitted by the "naive" human subjects. Accordingly, the only way to measure the NR on the earplugs as it has been fitted is to actually make the measurement after the human subject has been tested for REAT. Each time NR is measured following an REAT evaluation, two manipulations must be performed:

1. the plastic cap occluding the sound-bore (dubbed Full-block) is removed by the experimenter, as illustrated by step 2-3 in Fig. 16 a.

2. the dual microphone probe is inserted inside the earplug sound-bore, as illustrated by step 3-4 in Fig. 16 a.

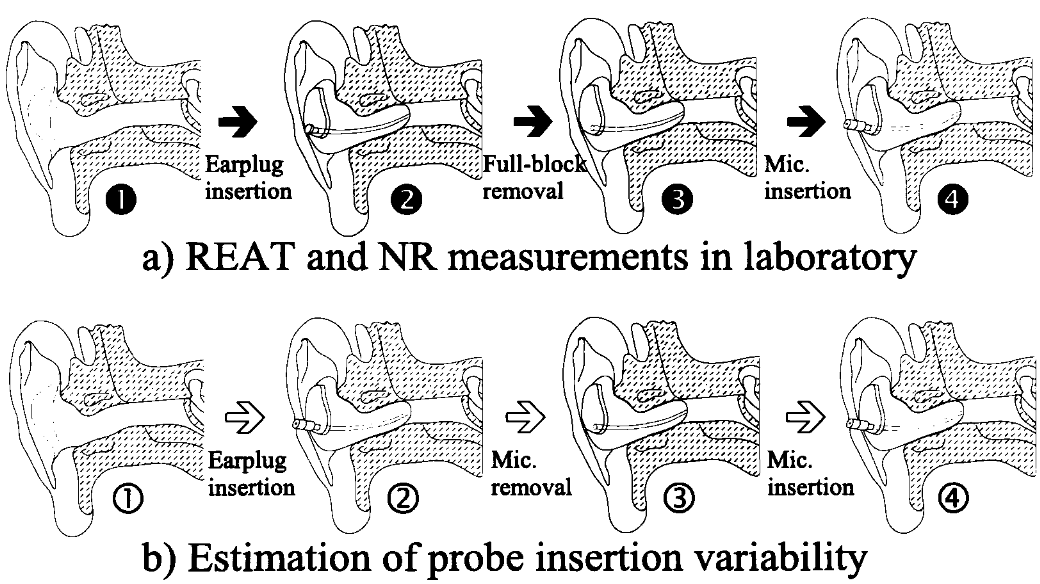


Figure 16 Evaluation of the Probe Insertion uncertainty component $u_{\mathrm{PI}}$ a) Manipulations for REAT (Step 2) and NR measurement (Step 4); b) Manipulations between two consecutive NR measurement (at Step 2 and 4) for estimation of the Probe Insertion Variability.

The strength and strain (caused by the microphone probe-tube insertion and removal of the Full-block) applied to the earplug during those two manipulations introduces some variability in Compensation factor COMP, since the REAT and the NR are indeed evaluated on two slightly different fits of the same earplug. The bias introduced by such manipulation has no effect on the prediction, since that exact order of REAT and NR sequence is kept for the Compensation determination as well as for the individual prediction: in other words, as long as the insertion of the dual microphone probe leads to a consistent shift of the earplug (and a better fit of the earplug), such "enhancement" of the performance is automatically discarded because it was already present during the determination of the Compensation function. Problems arise when the bias caused by the Probe Insertion becomes inconsistent over measurements. In order to evaluate the variability of the bias introduced by the Probe Insertion, the following experimental sequence (illustrated in Fig. 16 b.) has been used:

- inserting the instrumented earplug into the user's ear using the "subject-fit" method (step 1-2),
- measuring the corrected NR, denoted $\mathrm{NR}_{\mathrm{C}}^{(2)}$ (step 2)
- removing the dual microphone probe (step 2-3, this is more disruptive than removing the Full-block as in Fig. 16 a., therefore leading to a slightly overestimated variability)
- reinserting the dual microphone probe (step 3-4),
- measuring the corrected NR, denoted $\mathrm{NR}_{\mathrm{C}}^{(4)}$ (step 4)

The variability introduced by the probe insertion is obtained by computing the difference between $\mathrm{NR}_{\mathrm{C}}^{(2)}$ and $\mathrm{NR}_{\mathrm{C}}^{(4)}$, using:

$$\Delta\mathrm{NR} = \mathrm{NR}_{\mathrm{C}}^{(2)} - \mathrm{NR}_{\mathrm{C}}^{(4)} \tag{2.33}$$

The probe insertion uncertainty component $u_{\mathrm{PI}}$ obtained from the standard deviation of $\Delta\mathrm{NR}$ as measured on human subjects is presented in Fig. 17. and as octave band values in Table XI. The data has been collected in two different consecutive runs:

- A first run where the microphone probe is slightly lubricated (for easier insertion into the earplug's sound bore) only before the second NR measurement (step 4 in Fig. 16 b.); such run is referred to as the "dry" insertion.
- A second run where the microphone probe gets slightly lubricated before the first NR measurement (step 2 in Fig. 16 b.); such run is referred to as the "wet" insertion.

Table XI

Octave band values of the uncertainty component $u_{\mathrm{PI}}$ averaged for "dry" and "wet" insertion of the microphone probe-tube.

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\mathrm{PI}}$ **[dB]** | 2.6 | 2.4 | 2.2 | 2.7 | 2.6 | 2.7 | 4.2 |

#### 2.5.2.1.5 Evaluation of the corrected Noise Reduction uncertainty component $u_{\mathrm{NR}}$

Applying Eq. 2.29 with the evaluated uncertainties $u_{\mathrm{TF1}}$, $u_{\mathrm{DSP}}$, $u_{\mathrm{TF2}}$ and $u_{\mathrm{PI}}$ gives the corrected Noise Reduction uncertainty component $u_{\mathrm{NR}}$ presented in table XII.

Table XII

Device uncertainty component $u_{\mathrm{NR}}$

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\mathrm{NR}}$ **[dB]** | 2.82 | 2.62 | 2.57 | 3.07 | 2.61 | 3.29 | 4.79 |

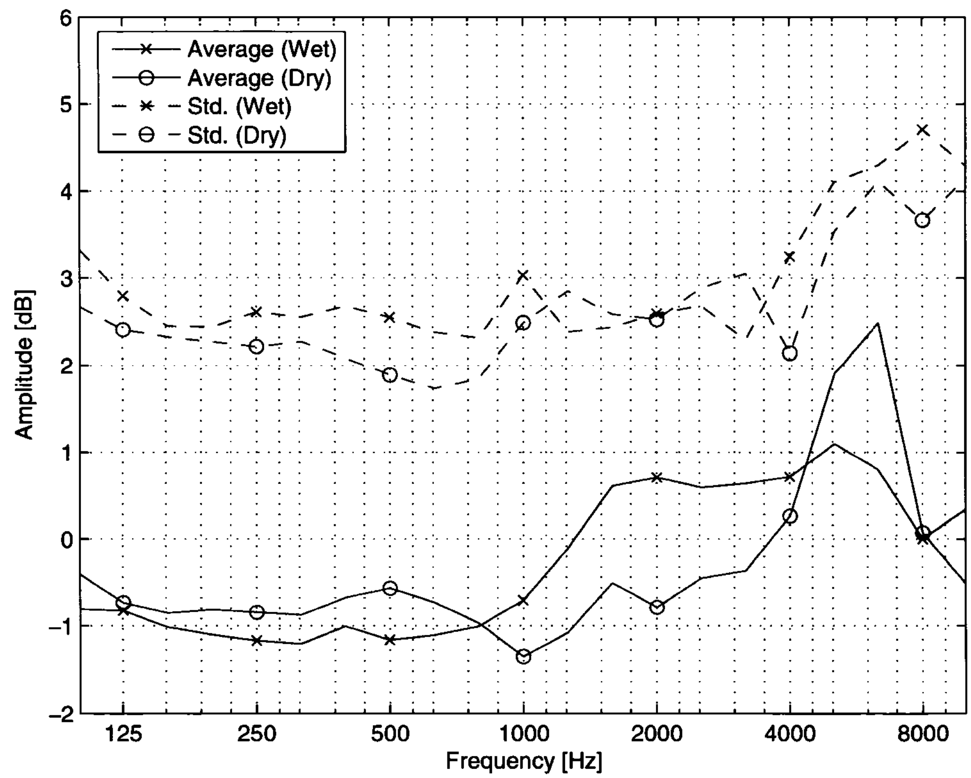


Figure 17 Uncertainty component $u_{\mathrm{PI}}$ obtained from the standard deviation of $\Delta$NR (in dashed line) as measured on human subjects with seventeen "dry" insertion of the microphone probe tube and twenty-one "wet" insertion of the microphone probe tube. Solid lines are average $\Delta$NR for reference.

### 2.5.2.2 Evaluation of the compensation uncertainty component $u_{\mathrm{COMP}}$

The uncertainty component $u_{\mathrm{COMP}}$ can be directly asserted from the standard deviation of the compensation, as established from the experimental validation, in section 2.4.2.1. Table XIII presents the standard deviation of the compensation COMP as established in section 2.4.2.1.

Table XIII

Uncertainty component $u_{\text{COMP}}$ obtained from the standard-deviation of the compensation factor COMP

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\text{COMP}}$ **[dB]** | 5.16 | 4.81 | 5.29 | 5.83 | 5.45 | 7.51 | 8.52 |

### 2.5.3 Combination of PPAR uncertainty components

The uncertainty of the prediction method per octave band is denoted $u^i_{\widehat{\text{REAT}}}$ and can be obtained directly from Eq. 2.15 as:

$$u_{\widehat{\text{REAT}}} = \sqrt{u^2_{\text{COMP}} + u^2_{\text{NR}}} \tag{2.34}$$

The evaluation of the compensation uncertainty component $u_{\text{COMP}}$ is provided in section 2.5.2.2, while the evaluation of the corrected NR uncertainty component $u_{\text{NR}}$ is provided in section 2.5.2.1. The values of the uncertainty of the prediction method are presented in Table XIV. They are found to be very close to the values of the observed prediction error $u_\epsilon$ previously presented in Table V, according to the following expression of $u_\epsilon$:

$$u_\epsilon = \sqrt{u^2_{\widehat{\text{REAT}}} + u^2_{\text{REAT}}} \tag{2.35}$$

This means that the uncertainty of the prediction method $u_{\widehat{\text{REAT}}}$ has probably been overestimated in Table XIV.

Table XIV

Uncertainty component $u_{\widehat{\text{REAT}}}$ obtained from Eq. 2.34

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\widehat{\text{REAT}}}$ **[dB]** | 5.88 | 5.48 | 5.88 | 6.59 | 6.05 | 8.20 | 9.77 |

Differentiating Eq. 2.24 leads to the overall PPAR uncertainty:

$$u_{\text{PPAR}} = \sum_{i=1}^{n} \frac{10^{\frac{100-A^i-\widehat{\text{REAT}^i}}{10}} u^i_{\widehat{\text{REAT}}}}{\sum_{i=1}^{n} 10^{\frac{100-A^i-\widehat{\text{REAT}^i}}{10}}} \tag{2.36}$$

where $\widehat{\text{REAT}}^i$ is the Octave Band Prediction (for example from Table XXXIV in section 2.b.b) and $u^i_{\widehat{\text{REAT}}}$ its associated octave band uncertainty as established in Table XIV.

The overall PPAR uncertainty $u_{\text{PPAR}}$ is presented for the forty tests on twenty subjects of the second dataset used for experimental validation in Table XV.

Table XV

Overall uncertainty components $u_{\text{PPAR}}$ for the forty tests on twenty subjects of the second dataset used for experimental validation (in dB)

| **Subjet #** | | **Trial #** | $u_{\text{PPAR}}$ | | **Trial #** | $u_{\text{PPAR}}$ |
|---|---|---|---|---|---|---|
| **1** | | **1.1** | 4.70 | | **1.2** | 4.65 |
| **2** | | **2.1** | 4.94 | | **2.2** | 4.84 |
| **3** | | **3.1** | 5.88 | | **3.2** | 6.25 |
| **4** | | **4.1** | 6.33 | | **4.2** | 4.80 |
| **5** | | **5.1** | 4.82 | | **5.2** | 4.76 |
| **6** | | **6.1** | 4.80 | | **6.2** | 5.01 |
| **7** | | **7.1** | 4.94 | | **7.2** | 5.74 |
| **8** | | **8.1** | 5.63 | | **8.2** | 4.93 |
| **9** | | **9.1** | 5.02 | | **9.2** | 4.89 |
| **10** | | **10.1** | 4.86 | | **10.2** | 4.93 |
| **11** | | **11.1** | 5.48 | | **11.2** | 4.97 |
| **12** | | **12.1** | 5.06 | | **12.2** | 4.84 |
| **13** | | **13.1** | 4.90 | | **13.2** | 4.91 |
| **14** | | **14.1** | 4.89 | | **14.2** | 6.45 |
| **15** | | **15.1** | 6.12 | | **15.2** | 5.03 |
| **16** | | **16.1** | 5.13 | | **16.2** | 6.35 |
| **17** | | **17.1** | 6.48 | | **17.2** | 4.77 |
| **18** | | **18.1** | 4.85 | | **18.2** | 5.13 |
| **19** | | **19.1** | 5.12 | | **19.2** | 4.86 |
| **20** | | **20.1** | 4.85 | | **20.2** | 5.04 |

#### 2.5.3.1 Discussion on the uncertainty associated with the proposed approach $u_{\mathrm{APP}}$

The use of Eq. 2.34 for the evaluation of PPAR uncertainty is rigorous and conservative, but is not properly reflecting the uncertainty associated the mere Field-MIRE approach that relies on an NR measurement and the use of a statistical compensation factor COMP. Indeed, the compensation factor COMP has been determined using $\mathrm{NR_C}$ and REAT values that are respectively affected by uncertainties $u_{\mathrm{NR}}$ and $u_{\mathrm{REAT}}$, but also from the uncertainty of the proposed approach $u_{\mathrm{APP}}$. The variability of the compensation factor (that has been presented in VII) can be associated with an uncertainty that can be detailled as:

$$u_{\mathrm{COMP}} = \sqrt{u_{\mathrm{APP}}^2 + u_{\mathrm{REAT}}^2 + u_{\mathrm{NR}}^2} \tag{2.37}$$

Using Eq. 2.34 and 2.37, $u_{\mathrm{APP}}$, the uncertainty associated with the proposed approach (and its use of a statistical compensation factor) can be estimated with:

$$u_{\mathrm{APP}} = \sqrt{u_{\widehat{\mathrm{REAT}}} - u_{\mathrm{REAT}}^2 - 2 \times u_{\mathrm{NR}}^2} \tag{2.38}$$

Uncertainties in the measurement of the sound attenuation of a hearing protector using REAT, denoted $u_{\mathrm{REAT}}$, may arise from various sources, such as the uncertainty in the measurement of the threshold of hearing of the test subjects, the uncertainty of the sound pressure level measurements, the uncertainty in the controlling attenuators, etc.

From AS1270[17], the combined standard uncertainty is calculated to be 2.9 dB (whatever HPD is tested). In the most recent draft of ISO 4869, it is calculated to 5.4 and 6.7 dB for earmuffs and earplugs respectively. These latter uncertainty figures supplied for ear muffs and ear plugs are estimated from measurements at the National Acoustic Laboratories (Australia) and from measurements at the NIOSH and are *"considered being representative of the measurements and equipment that would normally be used in hearing protector testing"*.

In order to have a safe estimate of $u_{\mathrm{APP}}$, the lower reported value of 2.9 dB will be used in the calculations of $u_{\mathrm{APP}}$ presented in Table XVI.

Table XVI

Values of the $u_{\text{APP}}$ uncertainty component with an uncertainty value of 2.9 dB for $u_{\text{REAT}}$, as per the AS1270 estimation.

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| $u_{\text{APP}}$ **[dB]** | 3.21 | 2.81 | 3.60 | 4.02 | 3.80 | 6.09 | 6.42 |

#### 2.5.3.2 Discussion on the overall PPAR uncertainty

As we can see in Table XV, for each of the forty test, the value of the uncertainty is lower than the value of 6.7 dB of the uncertainty associated with the REAT measurements for earplugs as specified in the draft of ISO4869[18] standard. It is also important to keep in mind that this overall PPAR uncertainty $u_{\text{PPAR}}$ is associated with the prediction of a REAT value that is itself affected by an uncertainty $u_{\text{REAT}}$. Given that the PPAR uncertainty presented in Table XV does already include the uncertainty associated with the REAT measurement, it is understood that the proposed approach has an uncertainty that is diminished by such amount (using a quadratic summation) and could possibly end-up being lower than the uncertainty of the REAT, the current "gold standard" for HPD attenuation measurement. It should be also noted that two most important uncertainty components for the PPAR are:

- the uncertainty associated with the statistical approach used for the determination of the compensation factor $u_{\text{APP}}$
- the uncertainty associated with the dual microphone probe tube insertion $u_{\text{PI}}$ (evaluated in section 2.5.2.1.4).

Those two uncertainties could be diminished by:

- Computing the compensation factor on an individual basis (rather than on a group) from an analytical model of the occluded-ear: the NR measurement in the occluded-ear allows the identification of some individualized dimensions and characteristics from which it would be possible to reconstruct the required corrections (transfer function) that are part of COMP. As an example, the computational process could identify the exact frequency of the occluded ear-canal resonance, than determine the length and area of the occluded residual ear-canal, from which it would possible to model the exact transfer function of the occluded ear-canal (acoustical duct),
- Designing of a shorter, less intrusive dual microphone probe tube by changes in the sound-bore configuration.

### 2.5.4 Calculation of expanded uncertainty and coverage factor

#### 2.5.4.1 General calculation

The ISO Guide to the Expression of Uncertainties in Measurements (ISO GUM [56]) states that the expanded uncertainty, $U$, should be specified, on the basis that $[\mathrm{PPAR} - U, \mathrm{PPAR} + U]$ covers 95% of the values of PPAR that might reasonably be attributed to the predicted personal attenuation values of PPAR. If we assume a coverage factor of $k = 2$, then $U = k \times u_{\mathrm{PPAR}}$ for the normal probability distribution. The Combined Uncertainty for Predicted Personal Attenuation Rating is thus the value given in Table XV in accordance with the ISO GUM.

#### 2.5.4.2 Specific calculation

The uncertainty statement can be presented in two ways, depending on the goal of the Field-MIRE measurement. If the case where the Field-MIRE measurement aim to predict the *absolute* attenuation that a user would report during an REAT test ( i.e. to predict overall REAT attenuation, to ensure a minimum of REAT attenuation per octave band or to ensure a minimum of overall REAT attenuation (as used for the Rating Test described in section 2.3.6.2), then the PPAR prediction uncertainty $u_{\mathrm{PPAR}}$ or the octave band prediction error $u^i_{\widehat{\mathrm{REAT}}}$ are to be used.

In the case where the Field-MIRE measurement is used for *comparative* purposes (i.e. to predict changes in octave band REAT attenuation, to predict changes in overall REAT attenuation, to monitor the field attenuation of an earplug over time, to check the proper training of a user over time, etc.) the uncertainty statement is no longer subject to the REAT uncertainty $u_{\mathrm{REAT}}$ and the value of $u_{\mathrm{NR}}$ is to be used.

### 2.5.5 Intra-subject earplug "real-world" field performance variability

The proposed Field-MIRE approach makes possible the study of the earplugs performance in "real-world": it becomes easier, for example, to determine if the predicted attenuation changes with a "real-world" field use of the SONOMAX SONOCUSTOM™earplugs. The variability in the "real-world" field performance on an individual basis has been studied separately from NR measurements and the many causes have been quantified independently. These variabilities are grouped in three arbitrary categories:

1. Quality of the *fitting* of the earplug by the subject him/herself: it is reflecting the ease of proper insertion of the earplug and is consequently a function of the earplug design as well as the subject's manual dexterity;

2. Retention capabilities of the outer ear: this reflects the ability of the earplug to stay in place in the ear-canal over the wearing period (usually the length of a work shift); it is mostly a function of the earplug design and initial adjustment to the wearer's ear.

3. Aging of the product: this reflects the long-term integrity of the earplug fit to the wearer's ear-canal; it is a function of the durability of the material used for the earplug as well as changes in size of the ear-canal.

The quantification of the variability of the NR measurement itself (when performed in "real-world") and the three field "real-world" variabilities will be detailled in the next sub-sections.

#### 2.5.5.1 Measurement Variability

The NR measurement variability can be assessed by performing consecutive NR measurements on the same earplug, untouched, repeated over very short time periods (approximately every 2 minutes). The repeated measurements describe a perfect normal distribution and the average and standard deviation (STD) of the deviation from individual means has been presented in Table XVII.

Table XVII

Average and Standard Deviation (STD) of the deviation from individual means due to short term NR measurement variability

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean [dB]** | 0.3 | 0.4 | 0.2 | 0.4 | 0.4 | 0.5 | 0.8 |
| **STD [dB]** | 0.3 | 0.3 | 0.1 | 0.4 | 0.3 | 0.7 | 0.7 |

#### 2.5.5.2 Fitting Variability

Intra-subject variability of fitting has been studied by the authors [57], who found that "naive"subjects (as defined by ANSI S12.6 [11]) exhibit a learning curve in their ability to fit the earplug. It was also found that the slope of this learning curve is a function of the environment of the subject and the training or explanation received. The variability over four consecutive subject-fit insertions is presented below for five subjects tested either in an environment with fitting noise (see table XVIII) or a silent environment, but with some training and explanation (such as the "pinna pull" technique) on the insertion of the earplug (see Table XIX).

Table XVIII

Average and Standard Deviation (STD) of the deviation from individual NR means due to fitting variability of naive subjects with surrounding noise

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean [dB]** | 4.6 | 3.6 | 3.5 | 2.8 | 1.8 | 2.4 | 2.8 |
| **STD [dB]** | 3.6 | 4.0 | 4.0 | 3.3 | 1.9 | 2.3 | 2.5 |

Table XIX

Average and Standard Deviation (STD) of the deviation from individual NR means due to fitting variability of naive subjects with explanations

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean [dB]** | 5.0 | 3.4 | 2.9 | 2.3 | 1.5 | 1.7 | 2.6 |
| **STD [dB]** | 4.4 | 3.7 | 3.0 | 2.0 | 1.7 | 1.5 | 2.4 |

#### 2.5.5.3 Retention Variability

Retention variability takes into account the variability in attenuation of an earplug measured every 20 minutes over a 2 hours period. This two hour period is considered to be representative of most work situations.

Table XX

Average and Standard Deviation (STD) of the deviation from individual NR means due to retention variability over periods of twenty minutes of the earplug worn during two hours

| **Frequency [Hz]** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean [dB]** | 2.0 | 1.4 | 1.4 | 1.4 | 2.5 | 2.6 | 3.0 |
| **STD [dB]** | 1.8 | 1.6 | 1.4 | 0.9 | 1.8 | 1.9 | 2.8 |

#### 2.5.5.4 Aging Variability

In the case of the SONOMAX SONOCUSTOM™ earplug studied, the durability of the material is sufficient for the life-cycle of the product and no degradation of the product is noticeable over a three year period. The natural growth of the outer ear and major changes in weight may affect the quality of the fit of the earplug. In this case, aging variability can be ignored as the devices are intended to be refit at three-year intervals, obviating the changes due to age by replacing the earplugs.

The variability associated with the initial fitting, the measurement and the retention are presented in Fig. 18 and 19 as normal probability plots.

## 2.6 Use of the proposed approach for other types of earplugs

The proposed Field-MIRE approach could be adapted for the measurement of the field attenuation of other types of earplugs, including disposable earplugs. The proof of concept can be performed similarly to the experimental validation on ATF presented in section 2.4.1.

### 2.6.1 Experimental Setup

The earplugs tested are disposable foam earplugs used as auditory testing earpieces [7]. They incorporate a sound-bore that is used to connect the auditory testing equipment (such as inserted earphones). In the present study, special microphone probe adapters have been designed to accommodate the various sound-bore configurations, as illustrated in Fig. 20–21.

### 2.6.2 Experimental Insertion Loss IL vs. Noise Reduction $NR_*$

Fig. 23 presents the comparison between the uncorrected Noise Reduction, $NR_*$ and the IL, as measured on a Head&Torso Simulator (pictured in Fig. 22). A very good agreement can already be found for lower frequencies (below 1 kHz) and the discrepancies observed are not worse than the one observed on the SONOCUSTOM™earplug (detailled in section 2.4.1). The proper sound-bore corrections and Compensation factors (including the TFOE) remain to be determined for each of the earplugs considered, but the objective measurement of individual disposable earplug field performance appears to be definitely possible with the proposed approach and the specific SONOMAX SONOPASS™measurement device.

## 2.7 Conclusions

The presented approach was developed to meet the need to improve earplug field performance prediction accuracy by changing from average group performance prediction to individual performance prediction. The individual earplug field performance is objectively measured by a Field-MIRE method: the individual attenuation is predicted from the field measurement of the Noise Reduction through the earplug. This development was made possible by the availability of a recently designed Instrumented Expandable Custom Earplug. The individual attenuation is first obtained as a set of values for each octave band center frequency and these values are then combined in a single number, the Predicted Personal Attenuation Rating (PPAR) that takes into account the measurement uncertainty. This PPAR is the equivalent to the "individual" Noise Reduction Rating (NRR) obtained from the classical REAT attenuation testing. The method has been validated experimentally on an ATF and using third party REAT testings on two groups of subjects. The sources of uncertainty associated with such PPAR measurement have been studied and the

[7] The exact models used are E-A-R/AEARO E-A-RLINK 3A, HOWARD LIGHT MATRIX BLUE and Nacre PARAT. More information is available on the respective manufacturer's websites: http://www.e-a-r.com, http://www.howardleight.com and http://www.nacre.no

overall uncertainty was found to be lower than the uncertainty associated with subjective REAT attenuation measurement of earplugs reported in the literature. It has also been demonstrated that such an approach could be successfully used for other type of earplugs (disposable foam plugs, for example) if they incorporate a sound bore for the measurement of the occluded-ear sound pressure level.

Such a Field-MIRE approach offers fast and accurate measurement of earplug field performance on a per subject basis and has several implications for effective hearing protection practice and for HPD rating and labelling.

For effective hearing protection practice, the benefits of the proposed approach are three-fold: (a) Fast and reliable measurement: the effective performance of the earplug can be measured quickly using a field-ready, durable, and rugged measurement device; (b) Adaptation of earplug attenuation is now possible. If earplug attenuation is known, it becomes possible to use acoustical filters to match the wearers hearing protection needs. This will allow the wearer's ear to naturally discriminate between noise and speech or warning signals and will maximize speech and warning signals perception; (c) Quick field tests are possible by adopting portions of the field testing protocol described herein (using the acoustic seal criteria, for example) that could be performed in a short time. This has the potential of being a great tool for user motivation and training: such a measurement device could be installed at the entrance of a noisy plant so that exposed wearer can check the fit and efficiency of their HPD prior to sound exposure.

For HPD rating and labelling, changes that would come from standards and regulations updated with this new approach could add significantly to the effectiveness of hearing conservation programs. Easy access to personal measurement of earplug performance on the wearer could completely supercede the current use of a single number rating (like the NRR) as the individual PPAR values are inherently superior to the population-based, statistically-derived, laboratory-driven NRR estimation. Consequently, the rating and labelling of HPD measured using such approach should be changed. A proposal has been written and submitted to the ANSI S12 Working Group WG11 [59]: the HPD product could be rated with average and standard-deviation on a laboratory panel, as currently done in ANSI S12.6- Method B. The measurement device should be rated as well in terms of the uncertainty that is associated with the individual measurement. A new rating and labeling paradigm would therefore contain the typical attenuation value that users can achieve (using a "subject-fit" REAT attenuation measurement), the variability observed on a panel group and the uncertainty associated with the measurement device [60]. In addition to field measurement and rating standards, the proposed Field-MIRE approach shows an equivalent or better uncertainty as compared to the current "gold standard"REAT and may be considered as a reliable alternative for HPD attenuation measurement in laboratory. Such an approach would bring the benefits of an objective measurement (lower measurement uncertainty) while keeping the human factor effect(variation in HPD fit with individuals). It could be integrated into current MIRE or ATF related standards (i.e., ANSI S12.42 [27]).

Future research needs include engineering design of a less intrusive dual microphone probe for reduced probe insertion variability and computing compensation on an individual basis from an analytical model rather than on a group basis from a statistical model.

**Acknowledgments**

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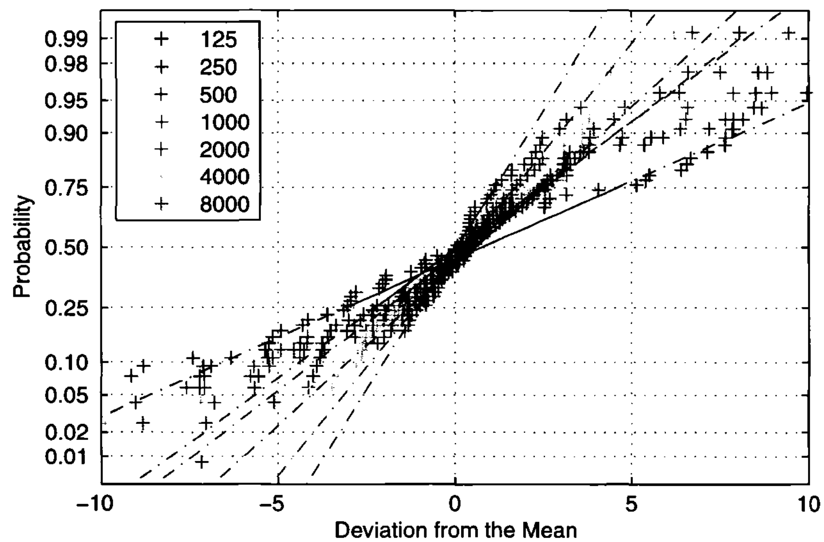


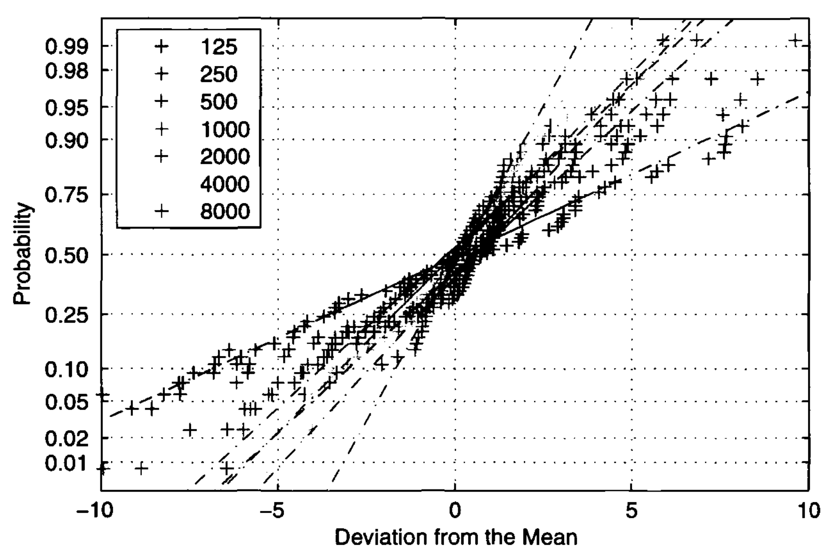
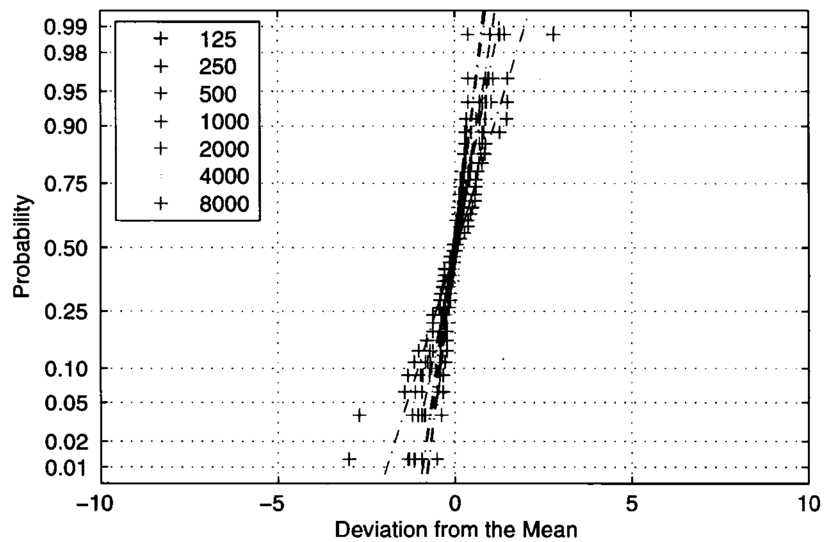




Figure 18 (Color online). Normal probability plots of the field variability associated with the initial fitting, with ambient noise (top) and with explanations (bottom).



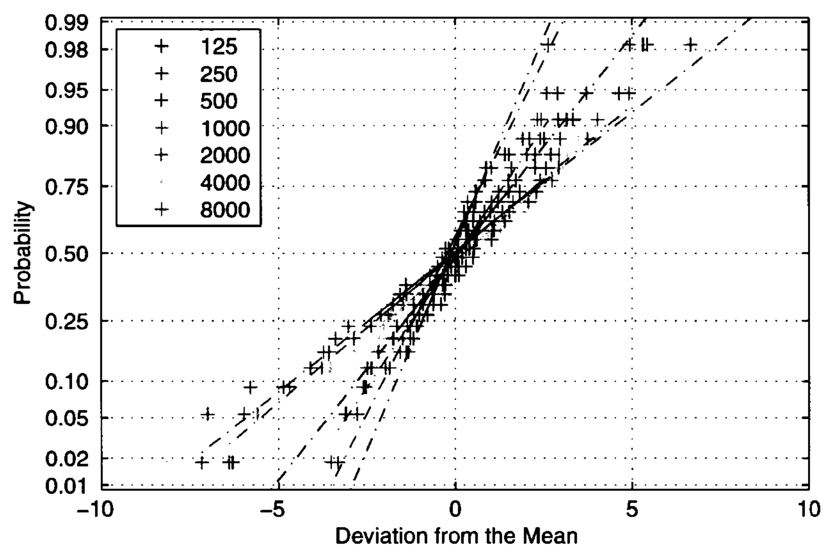




Figure 19 (Color online). Normal probability plots of the field variability associated with the field measurement (top) and the retention of the earplug (bottom)

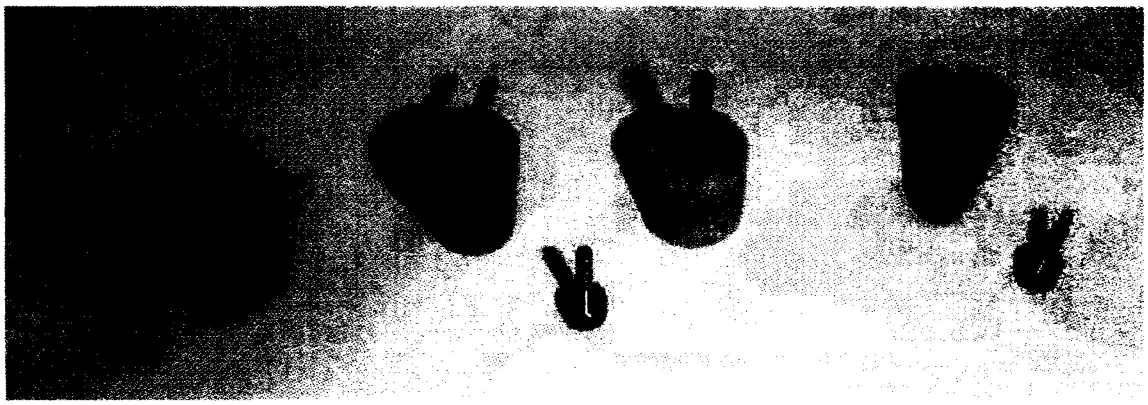


Figure 20 (Color online). The Sonomax custom (far left) and three disposable earplugs instrumented with their respective microphone probe adapters

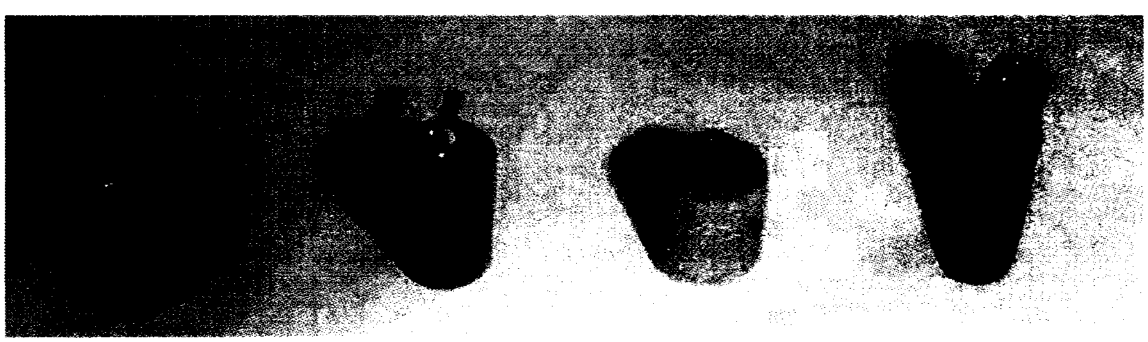


Figure 21 (Color online). The Sonomax custom (far left) earplug and three disposable earplugs instrumented with their respective microphone probe adapters placed inside the sound-bore

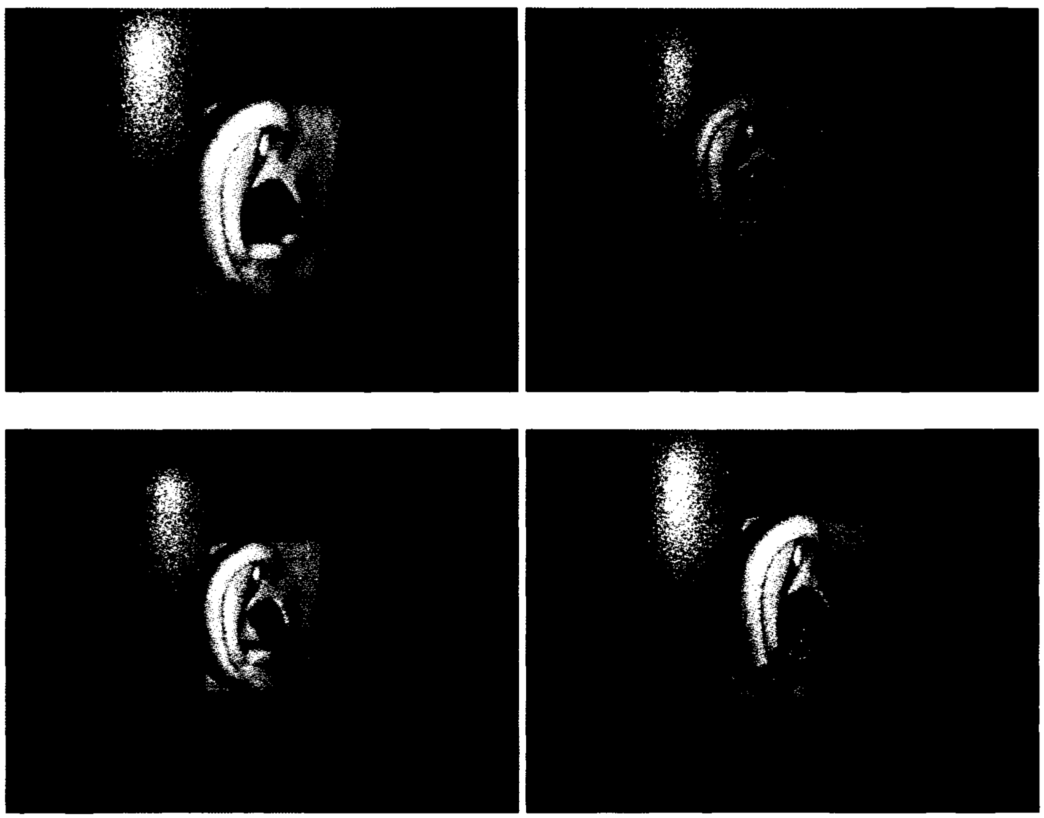


Figure 22 (Color online). The four instrumented (SONOMAX SONOCUSTOM™, Aearo, Bacou-Dalloz and Nacre, clockwise) earplugs fitted in the Head&Torso Simulator

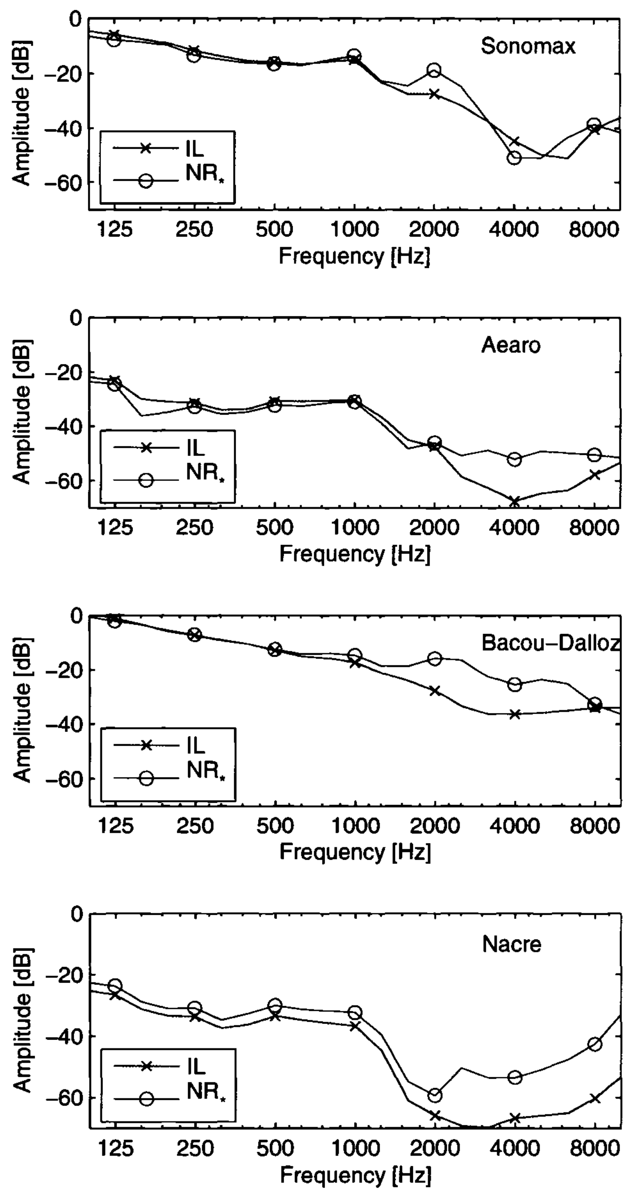



Figure 23 (Color online). Comparison between the Insertion Loss (IL) and uncorrected Noise Reduction ($NR_*$) measurements for the four earplugs tested (SONOMAX SONOCUSTOM$^{TM}$, Aearo, Bacou-Dalloz and Nacre, from top to bottom)

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# Appendix

## 2.a Estimation of the Transfer Function $H_3(\omega)$

The Fourier Transform of a time signal $a(t)$ defines the complex spectrum $A(\omega)$ and is given by:

$$A(\omega) = \int_{-\infty}^{+\infty} a(t)\ e^{-j\omega t} dt \tag{2.39}$$

Likewise, the spectrum $B(\omega)$of the signal $b(t)$is:

$$B(\omega) = \int_{-\infty}^{+\infty} b(t)\ e^{-j\omega t} dt \tag{2.40}$$

The Auto-spectra of $a(t)$and $b(t)$ are then defined by:

$$S_{AA}(\omega) = A^{\star}(\omega) \cdot A(\omega) \tag{2.41}$$

and

$$S_{BB}(\omega) = B^{\star}(\omega) \cdot B(\omega) \tag{2.42}$$

respectively.

The Cross Spectrum $S_{AB}(\omega)$ between the two signals $a(t)$ and $b(t)$ is defined by:

$$S_{AB}(\omega) = A^{\star}(\omega) \cdot B(\omega) \tag{2.43}$$

Let $G_{AA}(\omega)$, $G_{BB}(\omega)$ and $G_{AB}(\omega)$ be the one-sided spectra of $S_{AA}(\omega)$, $S_{BB}(\omega)$ and $S_{AB}(\omega)$ respectively:

$$G_{XX}(\omega) = \begin{cases} 2S_{XX}(\omega) & \text{for } \omega > 0 \\ S_{XX}(\omega) & \text{for } \omega = 0 \\ 0 & \text{for } \omega < 0 \end{cases} \tag{2.44}$$

The Auto-spectrums $G_{AA}(\omega)$and $G_{BB}(\omega)$ are used for the computation of the Octave Band Sound Pressure Levels $SPL^i_{ref}$ and $SPL^i_{meas}$ respectively.

The Coherence Function $\gamma^2(\omega)$ is defined by:

$$\gamma^2(\omega) = \frac{|G_{AB}(\omega)|^2}{G_{AA}(\omega)\, G_{BB}(\omega)} \tag{2.45}$$

To exact Frequency Response Function $H(\omega)$can be estimated using $H_1(\omega)$ and $H_2(\omega)$ defined by:

$$H_1(\omega) = \frac{G_{AB}(\omega)}{G_{AA}(\omega)} \tag{2.46}$$

and

$$H_2(\omega) = \frac{G_{BB}(\omega)}{G_{BA}(\omega)} \tag{2.47}$$

respectively.

The Frequency Response Function can also be estimated by the average value $H_3(\omega)$ defined by:

$$H_3(\omega) = \frac{1}{2}\left(H_1(\omega) + H_2(\omega)\right) \tag{2.48}$$

## 2.b Numerical Tables

### 2.b.a Numerical Tables from section 2.3.2

Table XXI

Octave Band Center Frequencies $\omega_i$, $A_i$ and $C_i$ Weighting Factors (for 1/3-octave filters)

| $i$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $\omega_i$[Hz] | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| $A_i$ | -26.2 | -16.1 | -8.6 | -3.2 | 0 | 1.2 | 1.0 | -1.1 |
| $C_i$ | -0.8 | -0.2 | 0 | 0 | 0 | -0.2 | -0.8 | -3.0 |

### 2.b.b Numerical Tables from section 2.4.2

Table XXII

Mean $\overline{\mathrm{COMP}^i}$ and Standard Deviation $\sigma^i_{\mathrm{COMP}}$ of the Statistical Compensation (n = 34)

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean** | 10.7 | 7.1 | 5.8 | 3.8 | 2.2 | 7.6 | 8.5 |
| **STD** | 5.2 | 4.8 | 5.3 | 5.8 | 5.5 | 7.5 | 8.5 |

Table XXIII

Overall observed prediction error for the second group (n=40)

| **Mean Error** | **Std. deviation of the prediction Error** |
|---|---|
| 0.2 | 4.8 |

Table XXIV

$REAT_\alpha$ : Octave Band Attenuation (REAT) values reported by the seventeen subjects, two trials each, during the first test reported by the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 22.2 | 20.2 | 17.2 | 19.8 | 28.7 | 37.2 | 42.0 |
| **1.2** | 27.3 | 24.0 | 21.5 | 24.3 | 35.8 | 35.7 | 42.8 |
| **2.1** | 23.8 | 18.3 | 21.0 | 17.2 | 33.0 | 32.8 | 44.3 |
| **2.2** | 23.8 | 18.7 | 15.0 | 16.3 | 28.5 | 29.8 | 48.2 |
| **3.1** | 27.8 | 16.7 | 20.8 | 17.3 | 32.7 | 38.8 | 42.8 |
| **3.2** | 29.0 | 23.8 | 22.0 | 21.3 | 34.5 | 30.8 | 39.5 |
| **4.1** | 28.3 | 24.3 | 24.2 | 25.5 | 29.7 | 31.2 | 42.3 |
| **4.2** | 26.2 | 24.7 | 23.5 | 20.5 | 27.3 | 31.0 | 42.0 |
| **5.1** | 22.0 | 22.5 | 21.0 | 21.8 | 33.7 | 28.8 | 41.0 |
| **5.2** | 20.3 | 21.0 | 22.7 | 18.2 | 30.0 | 30.2 | 37.7 |
| **6.1** | 26.2 | 23.0 | 24.0 | 25.5 | 36.7 | 35.0 | 39.8 |
| **6.2** | 36.7 | 29.8 | 29.5 | 23.5 | 37.5 | 34.2 | 38.3 |
| **7.1** | 33.2 | 30.8 | 30.3 | 28.0 | 32.5 | 38.7 | 44.8 |
| **7.2** | 28.5 | 28.8 | 27.0 | 31.8 | 34.8 | 38.3 | 46.7 |
| **8.1** | 31.2 | 31.5 | 33.7 | 30.8 | 40.2 | 34.7 | 37.2 |
| **8.2** | 25.7 | 22.8 | 26.5 | 24.0 | 34.8 | 36.3 | 35.0 |
| **9.1** | 27.0 | 24.7 | 26.8 | 26.3 | 37.3 | 36.3 | 46.3 |
| **9.2** | 22.8 | 26.5 | 27.7 | 27.2 | 28.3 | 27.2 | 41.0 |
| **10.1** | 24.5 | 17.0 | 18.0 | 21.8 | 34.8 | 42.3 | 51.3 |
| **10.2** | 26.0 | 21.8 | 22.3 | 23.5 | 38.2 | 42.7 | 51.3 |
| **11.1** | 36.2 | 30.0 | 31.2 | 30.2 | 34.5 | 31.5 | 44.5 |
| **11.2** | 27.5 | 25.7 | 24.3 | 23.3 | 28.5 | 31.0 | 42.0 |
| **12.1** | 35.3 | 32.7 | 38.3 | 42.8 | 29.3 | 38.3 | 38.7 |
| **12.2** | 29.3 | 31.5 | 31.3 | 35.5 | 22.8 | 32.3 | 39.8 |
| **13.1** | 22.7 | 27.3 | 26.0 | 23.8 | 36.5 | 21.0 | 42.2 |
| **13.2** | 28.8 | 27.2 | 27.0 | 26.2 | 37.7 | 31.0 | 43.2 |
| **14.1** | 18.0 | 18.3 | 17.7 | 21.0 | 35.5 | 33.7 | 44.8 |
| **14.2** | 21.0 | 21.8 | 22.7 | 20.8 | 37.5 | 35.2 | 47.8 |
| **15.1** | 30.5 | 27.3 | 28.0 | 26.0 | 29.7 | 36.2 | 43.2 |
| **15.2** | 25.0 | 22.5 | 23.8 | 20.0 | 25.3 | 32.7 | 35.7 |
| **16.1** | 34.2 | 36.2 | 34.7 | 28.0 | 31.3 | 35.3 | 38.5 |
| **16.2** | 29.0 | 30.8 | 32.5 | 23.3 | 26.8 | 32.2 | 43.2 |
| **17.1** | 28.7 | 26.5 | 19.7 | 28.7 | 33.8 | 35.7 | 40.7 |
| **17.2** | 27.5 | 22.7 | 21.2 | 25.5 | 33.3 | 34.3 | 44.2 |

Table XXV

$NR_R^i$: Noise Reduction measured on Right Ear of the first group, seventeen subjects, two trials each

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 10.5 | 10.2 | 12.8 | 18.6 | 24.3 | 40.2 | 39.9 |
| **1.2** | 12.1 | 12.1 | 15.0 | 22.3 | 28.2 | 44.7 | 36.0 |
| **2.1** | 17.3 | 17.3 | 19.3 | 18.5 | 26.7 | 25.6 | 31.9 |
| **2.2** | 15.7 | 16.1 | 17.5 | 16.4 | 25.7 | 23.8 | 37.0 |
| **3.1** | 13.3 | 14.8 | 13.9 | 16.5 | 34.0 | 36.2 | 41.1 |
| **3.2** | 13.2 | 15.0 | 13.3 | 16.5 | 33.0 | 33.1 | 37.7 |
| **4.1** | 20.2 | 20.8 | 23.9 | 29.4 | 36.5 | 40.7 | 43.9 |
| **4.2** | 18.3 | 18.6 | 20.2 | 24.1 | 29.2 | 40.3 | 41.6 |
| **5.1** | 16.6 | 18.2 | 18.8 | 20.7 | 25.6 | 35.6 | 55.5 |
| **5.2** | 17.6 | 18.1 | 18.7 | 21.1 | 26.0 | 35.4 | 51.3 |
| **6.1** | 26.0 | 27.1 | 28.3 | 28.0 | 35.2 | 19.6 | 34.7 |
| **6.2** | 23.2 | 24.8 | 25.5 | 28.2 | 34.9 | 22.7 | 33.5 |
| **7.1** | 21.1 | 22.2 | 24.1 | 23.4 | 32.7 | 29.4 | 37.0 |
| **7.2** | 21.0 | 21.3 | 22.8 | 22.1 | 28.9 | 29.1 | 36.3 |
| **8.1** | 26.4 | 27.0 | 28.6 | 26.2 | 37.3 | 26.8 | 39.5 |
| **8.2** | 24.4 | 27.4 | 22.4 | 25.2 | 35.8 | 8.9 | 42.3 |
| **9.1** | 18.0 | 20.4 | 20.3 | 21.1 | 30.0 | 25.4 | 38.6 |
| **9.2** | 17.8 | 18.9 | 19.8 | 20.4 | 29.6 | 25.8 | 45.4 |
| **10.1** | 12.7 | 13.5 | 13.1 | 20.4 | 29.2 | 23.5 | 39.4 |
| **10.2** | 12.4 | 13.6 | 13.2 | 18.9 | 30.3 | 14.0 | 33.5 |
| **11.1** | 21.8 | 20.9 | 22.1 | 22.3 | 34.7 | 23.9 | 28.2 |
| **11.2** | 21.8 | 22.2 | 22.7 | 22.1 | 35.3 | 30.4 | 32.8 |
| **12.1** | 20.4 | 19.3 | 24.6 | 24.8 | 33.5 | 33.0 | 49.0 |
| **12.2** | 24.9 | 24.3 | 29.8 | 29.7 | 33.3 | 33.1 | 44.3 |
| **13.1** | 25.6 | 26.0 | 29.2 | 30.7 | 38.7 | 22.6 | 24.7 |
| **13.2** | 27.6 | 27.4 | 29.4 | 29.5 | 38.5 | 21.6 | 32.2 |
| **14.1** | 16.4 | 18.3 | 18.9 | 23.5 | 28.2 | 29.7 | 30.2 |
| **14.2** | 13.0 | 14.1 | 14.8 | 19.8 | 29.0 | 30.2 | 28.2 |
| **15.1** | 17.4 | 18.5 | 20.4 | 20.2 | 30.5 | 32.6 | 33.1 |
| **15.2** | 21.4 | 22.0 | 22.8 | 22.4 | 31.7 | 25.3 | 31.9 |
| **16.1** | 29.7 | 31.5 | 32.1 | 33.4 | 39.7 | 29.4 | 27.1 |
| **16.2** | 36.5 | 39.5 | 36.7 | 27.3 | 35.1 | 27.7 | 25.9 |
| **17.1** | 23.6 | 24.5 | 23.0 | 22.7 | 36.0 | 25.9 | 31.2 |
| **17.2** | 26.0 | 26.6 | 24.9 | 22.7 | 39.3 | 32.5 | 20.8 |

Table XXVI

$NR_L{}^i$: Noise Reduction measured on Left Ear of the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 20.2 | 22.7 | 22.6 | 27.7 | 37.2 | 35.6 | 32.4 |
| **1.2** | 15.4 | 17.8 | 17.8 | 29.7 | 36.4 | 35.3 | 31.1 |
| **2.1** | 15.2 | 16.2 | 17.6 | 17.0 | 24.4 | 33.5 | 38.0 |
| **2.2** | 12.8 | 13.1 | 15.7 | 17.0 | 29.6 | 47.9 | 53.1 |
| **3.1** | 13.4 | 16.6 | 17.8 | 18.7 | 35.3 | 30.5 | 31.0 |
| **3.2** | 12.6 | 15.6 | 16.5 | 18.3 | 35.0 | 30.3 | 41.7 |
| **4.1** | 20.7 | 21.0 | 22.9 | 29.4 | 35.1 | 17.9 | 46.5 |
| **4.2** | 19.7 | 20.3 | 21.9 | 25.1 | 33.9 | 15.1 | 48.4 |
| **5.1** | 15.5 | 17.1 | 18.5 | 19.6 | 28.2 | 35.1 | 45.2 |
| **5.2** | 15.2 | 17.2 | 18.0 | 19.5 | 27.4 | 32.9 | 45.3 |
| **6.1** | 24.7 | 28.2 | 28.9 | 26.5 | 27.3 | 20.7 | 23.5 |
| **6.2** | 25.7 | 27.8 | 28.2 | 29.6 | 36.3 | 25.5 | 37.1 |
| **7.1** | 27.8 | 29.6 | 31.4 | 26.9 | 38.2 | 28.1 | 34.2 |
| **7.2** | 19.4 | 20.5 | 22.7 | 20.6 | 28.9 | 28.0 | 44.3 |
| **8.1** | 13.2 | 13.6 | 16.3 | 15.0 | 27.7 | 34.4 | 38.2 |
| **8.2** | 14.4 | 14.6 | 16.5 | 13.6 | 30.1 | 30.2 | 38.0 |
| **9.1** | 17.5 | 20.6 | 20.2 | 20.5 | 31.1 | 33.9 | 45.4 |
| **9.2** | 15.5 | 18.7 | 19.7 | 20.1 | 29.5 | 26.3 | 44.8 |
| **10.1** | 15.9 | 18.4 | 18.6 | 26.6 | 32.9 | 24.1 | 36.2 |
| **10.2** | 14.0 | 17.5 | 17.4 | 24.0 | 33.0 | 25.2 | 30.5 |
| **11.1** | 13.3 | 16.2 | 15.5 | 15.6 | 27.2 | 27.0 | 44.8 |
| **11.2** | 9.4 | 12.6 | 11.6 | 15.7 | 29.9 | 29.6 | 43.0 |
| **12.1** | 22.1 | 24.9 | 32.6 | 30.3 | 41.5 | 34.5 | 41.5 |
| **12.2** | 18.3 | 19.4 | 25.8 | 26.7 | 40.2 | 45.1 | 44.5 |
| **13.1** | 26.0 | 28.7 | 30.3 | 29.8 | 36.0 | 14.5 | 44.2 |
| **13.2** | 22.9 | 26.0 | 28.9 | 28.1 | 38.7 | 20.2 | 23.5 |
| **14.1** | 16.9 | 17.6 | 19.5 | 20.6 | 32.4 | 31.5 | 37.1 |
| **14.2** | 16.9 | 17.3 | 19.6 | 23.1 | 33.3 | 31.6 | 39.6 |
| **15.1** | 13.6 | 14.8 | 16.3 | 17.8 | 28.2 | 33.3 | 51.8 |
| **15.2** | 14.9 | 16.3 | 17.5 | 16.6 | 26.0 | 31.1 | 51.2 |
| **16.1** | 22.8 | 24.2 | 26.6 | 29.2 | 39.9 | 37.4 | 31.8 |
| **16.2** | 15.5 | 17.5 | 19.4 | 19.2 | 31.0 | 29.3 | 37.5 |
| **17.1** | 17.1 | 19.8 | 19.5 | 20.6 | 36.1 | 34.5 | 42.5 |
| **17.2** | 18.0 | 20.9 | 19.9 | 20.4 | 34.7 | 35.3 | 43.0 |

Table XXVII

$NR_B{}^i$: Equivalent Binaural Noise Reduction measured on right ear of the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 10.5 | 10.2 | 12.8 | 18.6 | 24.3 | 35.6 | 32.4 |
| **1.2** | 12.1 | 12.1 | 15.0 | 22.3 | 28.2 | 35.3 | 31.1 |
| **2.1** | 15.2 | 16.2 | 17.6 | 17.0 | 24.4 | 25.6 | 31.9 |
| **2.2** | 12.8 | 13.1 | 15.7 | 16.4 | 25.7 | 23.8 | 37.0 |
| **3.1** | 13.3 | 14.8 | 13.9 | 16.5 | 34.0 | 30.5 | 31.0 |
| **3.2** | 12.6 | 15.0 | 13.3 | 16.5 | 33.0 | 30.3 | 37.7 |
| **4.1** | 20.2 | 20.8 | 22.9 | 29.4 | 35.1 | 17.9 | 43.9 |
| **4.2** | 18.3 | 18.6 | 20.2 | 24.1 | 29.2 | 15.1 | 41.6 |
| **5.1** | 15.5 | 17.1 | 18.5 | 19.6 | 25.6 | 35.1 | 45.2 |
| **5.2** | 15.2 | 17.2 | 18.0 | 19.5 | 26.0 | 32.9 | 45.3 |
| **6.1** | 24.7 | 27.1 | 28.3 | 26.5 | 27.3 | 19.6 | 23.5 |
| **6.2** | 23.2 | 24.8 | 25.5 | 28.2 | 34.9 | 22.7 | 33.5 |
| **7.1** | 21.1 | 22.2 | 24.1 | 23.4 | 32.7 | 28.1 | 34.2 |
| **7.2** | 19.4 | 20.5 | 22.7 | 20.6 | 28.9 | 28.0 | 36.3 |
| **8.1** | 13.2 | 13.6 | 16.3 | 15.0 | 27.7 | 26.8 | 38.2 |
| **8.2** | 14.4 | 14.6 | 16.5 | 13.6 | 30.1 | 8.9 | 38.0 |
| **9.1** | 17.5 | 20.4 | 20.2 | 20.5 | 30.0 | 25.4 | 38.6 |
| **9.2** | 15.5 | 18.7 | 19.7 | 20.1 | 29.5 | 25.8 | 44.8 |
| **10.1** | 12.7 | 13.5 | 13.1 | 20.4 | 29.2 | 23.5 | 36.2 |
| **10.2** | 12.4 | 13.6 | 13.2 | 18.9 | 30.3 | 14.0 | 30.5 |
| **11.1** | 13.3 | 16.2 | 15.5 | 15.6 | 27.2 | 23.9 | 28.2 |
| **11.2** | 9.4 | 12.6 | 11.6 | 15.7 | 29.9 | 29.6 | 32.8 |
| **12.1** | 20.4 | 19.3 | 24.6 | 24.8 | 33.5 | 33.0 | 41.5 |
| **12.2** | 18.3 | 19.4 | 25.8 | 26.7 | 33.3 | 33.1 | 44.3 |
| **13.1** | 25.6 | 26.0 | 29.2 | 29.8 | 36.0 | 14.5 | 24.7 |
| **13.2** | 22.9 | 26.0 | 28.9 | 28.1 | 38.5 | 20.2 | 23.5 |
| **14.1** | 16.4 | 17.6 | 18.9 | 20.6 | 28.2 | 29.7 | 30.2 |
| **14.2** | 13.0 | 14.1 | 14.8 | 19.8 | 29.0 | 30.2 | 28.2 |
| **15.1** | 13.6 | 14.8 | 16.3 | 17.8 | 28.2 | 32.6 | 33.1 |
| **15.2** | 14.9 | 16.3 | 17.5 | 16.6 | 26.0 | 25.3 | 31.9 |
| **16.1** | 22.8 | 24.2 | 26.6 | 29.2 | 39.7 | 29.4 | 27.1 |
| **16.2** | 15.5 | 17.5 | 19.4 | 19.2 | 31.0 | 27.7 | 25.9 |
| **17.1** | 17.1 | 19.8 | 19.5 | 20.6 | 36.0 | 25.9 | 31.2 |
| **17.2** | 18.0 | 20.9 | 19.9 | 20.4 | 34.7 | 32.5 | 20.8 |

Table XXVIII

$A_R^i$: Right Ear Audiograms of the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 | 20.0 |
| **1.2** | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 | 20.0 |
| **2.1** | 0.0 | 5.0 | 5.0 | 0.0 | 10.0 | 10.0 | 0.0 |
| **2.2** | 0.0 | 5.0 | 5.0 | 0.0 | 10.0 | 10.0 | 0.0 |
| **3.1** | 0.0 | 5.0 | 0.0 | 5.0 | 5.0 | 15.0 | 0.0 |
| **3.2** | 0.0 | 5.0 | 0.0 | 5.0 | 5.0 | 15.0 | 0.0 |
| **4.1** | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 |
| **4.2** | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 |
| **5.1** | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 10.0 | 0.0 |
| **5.2** | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 10.0 | 0.0 |
| **6.1** | 0.0 | 10.0 | 10.0 | 10.0 | 10.0 | 0.0 | 0.0 |
| **6.2** | 0.0 | 10.0 | 10.0 | 10.0 | 10.0 | 0.0 | 0.0 |
| **7.1** | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 10.0 | 0.0 |
| **7.2** | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 10.0 | 0.0 |
| **8.1** | 0.0 | 0.0 | 5.0 | 0.0 | 5.0 | 0.0 | 0.0 |
| **8.2** | 0.0 | 0.0 | 5.0 | 0.0 | 5.0 | 0.0 | 0.0 |
| **9.1** | 0.0 | 5.0 | 5.0 | 10.0 | 5.0 | 5.0 | 0.0 |
| **9.2** | 0.0 | 5.0 | 5.0 | 10.0 | 5.0 | 5.0 | 0.0 |
| **10.1** | 0.0 | 5.0 | 5.0 | 0.0 | 5.0 | 15.0 | 10.0 |
| **10.2** | 0.0 | 5.0 | 5.0 | 0.0 | 5.0 | 15.0 | 10.0 |
| **11.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **11.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **12.1** | 0.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0.0 | 5.0 |
| **12.2** | 0.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0.0 | 5.0 |
| **13.1** | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 | 10.0 |
| **13.2** | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 | 10.0 |
| **14.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **14.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **15.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **15.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **16.1** | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 10.0 |
| **16.2** | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 10.0 |
| **17.1** | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 10.0 | 0.0 |
| **17.2** | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 10.0 | 0.0 |

Table XXIX

$A_L^i$: Left Ear Audiograms of the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **1.2** | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **2.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 0.0 |
| **2.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 0.0 |
| **3.1** | 0.0 | 10.0 | 0.0 | 0.0 | 0.0 | 5.0 | 10.0 |
| **3.2** | 0.0 | 10.0 | 0.0 | 0.0 | 0.0 | 5.0 | 10.0 |
| **4.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **4.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **5.1** | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 10.0 |
| **5.2** | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 5.0 | 10.0 |
| **6.1** | 0.0 | 0.0 | 10.0 | 5.0 | 10.0 | 15.0 | 5.0 |
| **6.2** | 0.0 | 0.0 | 10.0 | 5.0 | 10.0 | 15.0 | 5.0 |
| **7.1** | 0.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0.0 | 0.0 |
| **7.2** | 0.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0.0 | 0.0 |
| **8.1** | 0.0 | 0.0 | 10.0 | 5.0 | 0.0 | 10.0 | 0.0 |
| **8.2** | 0.0 | 0.0 | 10.0 | 5.0 | 0.0 | 10.0 | 0.0 |
| **9.1** | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 | 15.0 | 10.0 |
| **9.2** | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 | 15.0 | 10.0 |
| **10.1** | 0.0 | 5.0 | 0.0 | 0.0 | 5.0 | 15.0 | 10.0 |
| **10.2** | 0.0 | 5.0 | 0.0 | 0.0 | 5.0 | 15.0 | 10.0 |
| **11.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **11.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **12.1** | 0.0 | 10.0 | 15.0 | 10.0 | 10.0 | 5.0 | 15.0 |
| **12.2** | 0.0 | 10.0 | 15.0 | 10.0 | 10.0 | 5.0 | 15.0 |
| **13.1** | 0.0 | 15.0 | 5.0 | 5.0 | 10.0 | 20.0 | 5.0 |
| **13.2** | 0.0 | 15.0 | 5.0 | 5.0 | 10.0 | 20.0 | 5.0 |
| **14.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **14.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **15.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **15.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 |
| **16.1** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 |
| **16.2** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 |
| **17.1** | 0.0 | 0.0 | 5.0 | 10.0 | 0.0 | 15.0 | 5.0 |
| **17.2** | 0.0 | 0.0 | 5.0 | 10.0 | 0.0 | 15.0 | 5.0 |

Table XXX

COMP$^i$: Statistical Compensation Values of the first group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 11.7 | 10.0 | 4.4 | 1.2 | 4.4 | 1.6 | 9.6 |
| **1.2** | 15.2 | 11.9 | 6.5 | 2.0 | 7.6 | 0.4 | 11.7 |
| **2.1** | 8.6 | 2.1 | 3.4 | 0.2 | 8.6 | 7.2 | 12.4 |
| **2.2** | 11.0 | 5.6 | -0.7 | -0.1 | 2.8 | 6.0 | 11.2 |
| **3.1** | 14.5 | 1.9 | 6.9 | 0.8 | -1.3 | 8.3 | 11.8 |
| **3.2** | 16.4 | 8.8 | 8.7 | 4.8 | 1.5 | 0.5 | 1.8 |
| **4.1** | 8.1 | 3.5 | 1.3 | -3.9 | -5.4 | 13.3 | -1.6 |
| **4.2** | 7.9 | 6.1 | 3.3 | -3.6 | -1.9 | 15.9 | 0.4 |
| **5.1** | 6.5 | 5.4 | 2.5 | 2.2 | 8.1 | -6.3 | -4.2 |
| **5.2** | 5.1 | 3.8 | 4.7 | -1.3 | 4.0 | -2.7 | -7.6 |
| **6.1** | 1.5 | -4.1 | -4.3 | -1.0 | 9.4 | 15.4 | 16.3 |
| **6.2** | 13.5 | 5.0 | 4.0 | -4.7 | 2.6 | 11.5 | 4.8 |
| **7.1** | 12.1 | 8.6 | 6.2 | 4.6 | -0.2 | 10.6 | 10.6 |
| **7.2** | 9.1 | 8.3 | 4.3 | 11.2 | 5.9 | 10.3 | 10.4 |
| **8.1** | 18.0 | 17.9 | 17.4 | 15.8 | 12.5 | 7.9 | -1.0 |
| **8.2** | 11.3 | 8.2 | 10.0 | 10.4 | 4.7 | 27.4 | -3.0 |
| **9.1** | 9.5 | 4.3 | 6.6 | 5.8 | 7.3 | 10.9 | 7.7 |
| **9.2** | 7.3 | 7.8 | 8.0 | 7.1 | -1.2 | 1.4 | -3.8 |
| **10.1** | 11.8 | 3.5 | 4.9 | 1.4 | 5.6 | 18.8 | 15.1 |
| **10.2** | 13.6 | 8.2 | 9.1 | 4.6 | 7.9 | 28.7 | 20.8 |
| **11.1** | 22.9 | 13.8 | 15.7 | 14.6 | 7.3 | 7.6 | 16.3 |
| **11.2** | 18.1 | 13.1 | 12.7 | 7.6 | -1.4 | 1.4 | 9.2 |
| **12.1** | 14.9 | 13.4 | 13.7 | 18.0 | -4.2 | 5.3 | -2.8 |
| **12.2** | 11.0 | 12.1 | 5.5 | 8.8 | -10.5 | -0.8 | -4.5 |
| **13.1** | -2.9 | 1.3 | -3.2 | -6.0 | 0.5 | 6.5 | 17.5 |
| **13.2** | 5.9 | 1.2 | -1.9 | -1.9 | -0.8 | 10.8 | 19.7 |
| **14.1** | 1.6 | 0.7 | -1.2 | 0.4 | 7.3 | 4.0 | 14.6 |
| **14.2** | 8.0 | 7.7 | 7.9 | 1.0 | 8.5 | 5.0 | 19.6 |
| **15.1** | 16.9 | 12.5 | 11.7 | 8.2 | 1.5 | 3.6 | 10.1 |
| **15.2** | 10.1 | 6.2 | 6.3 | 3.4 | -0.7 | 7.4 | 3.8 |
| **16.1** | 11.4 | 12.0 | 8.1 | -1.2 | -8.4 | 5.9 | 11.4 |
| **16.2** | 13.5 | 13.3 | 13.1 | 4.1 | -4.2 | 4.5 | 17.3 |
| **17.1** | 11.6 | 6.7 | 0.2 | 8.1 | -2.2 | 9.8 | 9.5 |
| **17.2** | 9.5 | 1.8 | 1.3 | 5.1 | -1.4 | 1.8 | 23.4 |

Table XXXI

$NR_R{}^i$: Corrected Noise Reduction measured on Right Ear of the second group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 9.2 | 11.6 | 15.2 | 18.0 | 24.9 | 30.6 | 34.0 |
| **1.2** | 12.9 | 13.9 | 15.9 | 29.7 | 27.3 | 32.8 | 32.1 |
| **2.1** | 19.9 | 21.2 | 22.6 | 20.8 | 29.3 | 28.2 | 52.1 |
| **2.2** | 23.8 | 24.2 | 25.8 | 22.4 | 29.4 | 25.2 | 47.0 |
| **3.1** | 17.6 | 17.5 | 18.3 | 21.7 | 34.5 | 13.2 | 18.0 |
| **3.2** | 16.0 | 15.8 | 17.7 | 18.9 | 27.6 | 23.3 | 27.2 |
| **4.1** | 14.3 | 16.2 | 14.9 | 19.5 | 31.2 | 20.2 | 36.2 |
| **4.2** | 14.1 | 14.9 | 15.7 | 17.1 | 27.9 | 40.0 | 43.1 |
| **5.1** | 14.2 | 15.0 | 15.7 | 16.7 | 26.6 | 41.8 | 49.9 |
| **5.2** | 13.0 | 14.7 | 17.7 | 21.3 | 22.8 | 30.2 | 43.1 |
| **6.1** | 16.0 | 17.0 | 19.5 | 22.3 | 24.1 | 30.4 | 37.8 |
| **6.2** | 26.6 | 28.9 | 29.6 | 26.3 | 34.7 | 27.4 | 39.3 |
| **7.1** | 22.2 | 23.3 | 23.8 | 22.2 | 31.6 | 26.7 | 34.7 |
| **7.2** | 25.2 | 26.5 | 27.0 | 31.8 | 39.2 | 30.5 | 34.1 |
| **8.1** | 23.6 | 24.0 | 24.4 | 29.5 | 35.9 | 28.8 | 29.0 |
| **8.2** | 16.8 | 17.0 | 16.8 | 19.5 | 28.0 | 27.6 | 30.5 |
| **9.1** | 16.1 | 16.7 | 16.1 | 18.7 | 30.6 | 27.5 | 32.4 |
| **9.2** | 19.9 | 21.1 | 21.5 | 22.8 | 27.4 | 29.8 | 39.4 |
| **10.1** | 21.9 | 22.6 | 22.3 | 24.0 | 31.6 | 37.3 | 40.1 |
| **10.2** | 26.5 | 26.0 | 28.2 | 24.2 | 39.9 | 36.1 | 35.4 |
| **11.1** | 26.7 | 26.2 | 24.4 | 27.9 | 36.4 | 16.8 | 31.8 |
| **11.2** | 14.9 | 17.1 | 16.8 | 17.5 | 28.1 | 23.3 | 31.1 |
| **12.1** | 15.8 | 17.3 | 17.2 | 19.0 | 40.0 | 30.0 | 44.7 |
| **12.2** | 14.4 | 15.8 | 15.8 | 22.2 | 27.2 | 25.5 | 35.8 |
| **13.1** | 13.4 | 15.1 | 15.7 | 16.3 | 27.0 | 24.2 | 38.3 |
| **13.2** | 13.0 | 14.7 | 14.2 | 15.9 | 28.7 | 29.3 | 46.9 |
| **14.1** | 12.7 | 13.7 | 13.0 | 15.5 | 27.5 | 29.4 | 39.6 |
| **14.2** | 21.7 | 20.6 | 23.9 | 24.2 | 35.6 | 35.1 | 34.5 |
| **15.1** | 19.0 | 19.5 | 21.8 | 20.7 | 32.4 | 37.9 | 44.5 |
| **15.2** | 18.9 | 19.1 | 20.7 | 22.4 | 29.9 | 33.3 | 39.9 |
| **16.1** | 17.8 | 18.7 | 20.2 | 22.5 | 29.2 | 28.4 | 30.7 |
| **16.2** | 22.9 | 23.8 | 24.5 | 39.6 | 42.3 | 20.6 | 24.6 |
| **17.1** | 22.9 | 24.4 | 24.5 | 27.7 | 44.8 | 19.6 | 25.4 |
| **17.2** | 14.3 | 19.2 | 18.3 | 25.9 | 31.2 | 31.9 | 33.9 |
| **18.1** | 16.2 | 20.4 | 20.8 | 23.4 | 30.4 | 31.8 | 34.5 |
| **18.2** | 35.4 | 38.3 | 37.2 | 24.4 | 37.3 | 31.0 | 26.3 |
| **19.1** | 29.9 | 32.2 | 31.7 | 30.9 | 36.2 | 28.1 | 25.7 |
| **19.2** | 23.1 | 23.4 | 23.2 | 19.9 | 46.7 | 33.7 | 32.1 |
| **20.1** | 22.8 | 23.2 | 22.9 | 20.8 | 44.1 | 35.2 | 32.0 |
| **20.2** | 14.7 | 17.8 | 17.2 | 18.6 | 36.2 | 22.4 | 36.0 |

Table XXXII

$NR_L{}^i$: Corrected Noise Reduction measured on Left Ear of the second group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 10.2 | 10.8 | 11.9 | 18.6 | 26.2 | 33.5 | 38.0 |
| **1.2** | 12.4 | 14.3 | 12.8 | 25.6 | 31.6 | 31.2 | 35.7 |
| **2.1** | 34.5 | 39.6 | 45.0 | 56.0 | 86.1 | 60.8 | 58.8 |
| **2.2** | 12.6 | 13.2 | 13.7 | 15.3 | 26.3 | 32.4 | 44.3 |
| **3.1** | 1.9 | 3.9 | 10.4 | 16.0 | 23.7 | 9.4 | 6.3 |
| **3.2** | 1.3 | 3.2 | 8.5 | 15.8 | 24.0 | 1.9 | 8.5 |
| **4.1** | 15.7 | 18.2 | 17.1 | 24.0 | 27.3 | 7.0 | 26.9 |
| **4.2** | 17.1 | 18.3 | 20.4 | 26.4 | 34.4 | 33.8 | 39.8 |
| **5.1** | 16.2 | 17.7 | 18.9 | 22.5 | 38.1 | 31.0 | 44.1 |
| **5.2** | 20.7 | 22.4 | 23.2 | 28.2 | 30.3 | 32.8 | 45.9 |
| **6.1** | 19.4 | 20.9 | 22.0 | 25.2 | 32.8 | 34.5 | 48.0 |
| **6.2** | 18.4 | 21.2 | 20.7 | 20.2 | 30.6 | 25.5 | 45.8 |
| **7.1** | 17.7 | 19.5 | 19.5 | 19.8 | 30.4 | 27.2 | 41.7 |
| **7.2** | 30.1 | 31.8 | 31.9 | 31.0 | 25.0 | 18.5 | 35.6 |
| **8.1** | 33.0 | 31.8 | 27.9 | 23.1 | 27.7 | 18.9 | 29.3 |
| **8.2** | 27.2 | 28.9 | 30.0 | 24.3 | 38.5 | 24.8 | 33.2 |
| **9.1** | 25.5 | 26.0 | 26.1 | 25.7 | 42.1 | 21.9 | 37.2 |
| **9.2** | 18.4 | 19.7 | 19.1 | 21.1 | 29.2 | 30.2 | 29.3 |
| **10.1** | 19.2 | 19.9 | 19.5 | 21.7 | 29.0 | 32.0 | 31.3 |
| **10.2** | 23.0 | 24.7 | 26.3 | 22.6 | 39.9 | 36.4 | 41.0 |
| **11.1** | 13.3 | 14.6 | 19.9 | 19.0 | 32.4 | 34.8 | 34.5 |
| **11.2** | 18.0 | 20.8 | 20.5 | 21.4 | 33.1 | 24.0 | 32.4 |
| **12.1** | 16.8 | 19.3 | 17.6 | 20.9 | 38.0 | 22.3 | 31.1 |
| **12.2** | 17.4 | 20.6 | 20.1 | 28.6 | 34.3 | 30.3 | 38.3 |
| **13.1** | 17.4 | 19.8 | 19.5 | 26.6 | 34.8 | 25.7 | 35.0 |
| **13.2** | 13.7 | 17.0 | 16.8 | 18.3 | 30.4 | 23.1 | 32.0 |
| **14.1** | 16.1 | 19.8 | 18.4 | 20.1 | 28.1 | 22.7 | 32.7 |
| **14.2** | 29.4 | 31.3 | 39.4 | 31.2 | 43.2 | 11.7 | 29.3 |
| **15.1** | 31.8 | 31.4 | 41.0 | 33.1 | 44.4 | 13.0 | 32.5 |
| **15.2** | 19.7 | 21.1 | 23.4 | 24.5 | 36.9 | 24.8 | 40.8 |
| **16.1** | 19.8 | 21.6 | 23.4 | 24.6 | 32.7 | 23.2 | 39.8 |
| **16.2** | 23.2 | 25.9 | 26.3 | 26.9 | 37.9 | 16.3 | 21.7 |
| **17.1** | 23.6 | 26.0 | 26.3 | 27.4 | 38.0 | 19.1 | 15.2 |
| **17.2** | 20.1 | 21.1 | 22.0 | 29.1 | 40.6 | 40.0 | 36.9 |
| **18.1** | 19.9 | 21.4 | 21.8 | 26.8 | 40.2 | 37.9 | 36.4 |
| **18.2** | 18.4 | 21.3 | 21.8 | 23.9 | 33.7 | 27.5 | 27.5 |
| **19.1** | 20.3 | 23.1 | 23.4 | 26.2 | 25.3 | 25.9 | 26.2 |
| **19.2** | 16.8 | 19.0 | 18.7 | 19.5 | 38.3 | 33.1 | 39.6 |
| **20.1** | 17.4 | 19.3 | 18.3 | 19.6 | 32.2 | 34.1 | 45.5 |
| **20.2** | 35.8 | 40.2 | 48.3 | 57.7 | 71.9 | 52.8 | 56.7 |

Table XXXIII

$NR_B{}^i$: Equivalent Binaural Noise Reduction measured on right ear of the second group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 9.2 | 10.8 | 11.9 | 18.0 | 24.9 | 30.6 | 34.0 |
| **1.2** | 12.4 | 13.9 | 12.8 | 25.6 | 27.3 | 31.2 | 32.1 |
| **2.1** | 19.9 | 21.2 | 22.6 | 20.8 | 29.3 | 28.2 | 52.1 |
| **2.2** | 12.6 | 13.2 | 13.7 | 15.3 | 26.3 | 25.2 | 44.3 |
| **3.1** | 1.9 | 3.9 | 10.4 | 16.0 | 23.7 | 9.4 | 6.3 |
| **3.2** | 1.3 | 3.2 | 8.5 | 15.8 | 24.0 | 1.9 | 8.5 |
| **4.1** | 14.3 | 16.2 | 14.9 | 19.5 | 27.3 | 7.0 | 26.9 |
| **4.2** | 14.1 | 14.9 | 15.7 | 17.1 | 27.9 | 33.8 | 39.8 |
| **5.1** | 14.2 | 15.0 | 15.7 | 16.7 | 26.6 | 31.0 | 44.1 |
| **5.2** | 13.0 | 14.7 | 17.7 | 21.3 | 22.8 | 30.2 | 43.1 |
| **6.1** | 16.0 | 17.0 | 19.5 | 22.3 | 24.1 | 30.4 | 37.8 |
| **6.2** | 18.4 | 21.2 | 20.7 | 20.2 | 30.6 | 25.5 | 39.3 |
| **7.1** | 17.7 | 19.5 | 19.5 | 19.8 | 30.4 | 26.7 | 34.7 |
| **7.2** | 25.2 | 26.5 | 27.0 | 31.0 | 25.0 | 18.5 | 34.1 |
| **8.1** | 23.6 | 24.0 | 24.4 | 23.1 | 27.7 | 18.9 | 29.0 |
| **8.2** | 16.8 | 17.0 | 16.8 | 19.5 | 28.0 | 24.8 | 30.5 |
| **9.1** | 16.1 | 16.7 | 16.1 | 18.7 | 30.6 | 21.9 | 32.4 |
| **9.2** | 18.4 | 19.7 | 19.1 | 21.1 | 27.4 | 29.8 | 29.3 |
| **10.1** | 19.2 | 19.9 | 19.5 | 21.7 | 29.0 | 32.0 | 31.3 |
| **10.2** | 23.0 | 24.7 | 26.3 | 22.6 | 39.9 | 36.1 | 35.4 |
| **11.1** | 13.3 | 14.6 | 19.9 | 19.0 | 32.4 | 16.8 | 31.8 |
| **11.2** | 14.9 | 17.1 | 16.8 | 17.5 | 28.1 | 23.3 | 31.1 |
| **12.1** | 15.8 | 17.3 | 17.2 | 19.0 | 38.0 | 22.3 | 31.1 |
| **12.2** | 14.4 | 15.8 | 15.8 | 22.2 | 27.2 | 25.5 | 35.8 |
| **13.1** | 13.4 | 15.1 | 15.7 | 16.3 | 27.0 | 24.2 | 35.0 |
| **13.2** | 13.0 | 14.7 | 14.2 | 15.9 | 28.7 | 23.1 | 32.0 |
| **14.1** | 12.7 | 13.7 | 13.0 | 15.5 | 27.5 | 22.7 | 32.7 |
| **14.2** | 21.7 | 20.6 | 23.9 | 24.2 | 35.6 | 11.7 | 29.3 |
| **15.1** | 19.0 | 19.5 | 21.8 | 20.7 | 32.4 | 13.0 | 32.5 |
| **15.2** | 18.9 | 19.1 | 20.7 | 22.4 | 29.9 | 24.8 | 39.9 |
| **16.1** | 17.8 | 18.7 | 20.2 | 22.5 | 29.2 | 23.2 | 30.7 |
| **16.2** | 22.9 | 23.8 | 24.5 | 26.9 | 37.9 | 16.3 | 21.7 |
| **17.1** | 22.9 | 24.4 | 24.5 | 27.4 | 38.0 | 19.1 | 15.2 |
| **17.2** | 14.3 | 19.2 | 18.3 | 25.9 | 31.2 | 31.9 | 33.9 |
| **18.1** | 16.2 | 20.4 | 20.8 | 23.4 | 30.4 | 31.8 | 34.5 |
| **18.2** | 18.4 | 21.3 | 21.8 | 23.9 | 33.7 | 27.5 | 26.3 |
| **19.1** | 20.3 | 23.1 | 23.4 | 26.2 | 25.3 | 25.9 | 25.7 |
| **19.2** | 16.8 | 19.0 | 18.7 | 19.5 | 38.3 | 33.1 | 32.1 |
| **20.1** | 17.4 | 19.3 | 18.3 | 19.6 | 32.2 | 34.1 | 32.0 |
| **20.2** | 14.7 | 17.8 | 17.2 | 18.6 | 36.2 | 22.4 | 36.0 |

Table XXXIV

PPAR$^i$: Predicted Personal Attenuation Rating computed for the second group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 19.9 | 17.9 | 17.7 | 21.8 | 27.1 | 38.3 | 42.5 |
| **1.2** | 23.1 | 21.1 | 18.6 | 29.4 | 29.4 | 38.9 | 40.6 |
| **2.1** | 30.6 | 28.4 | 28.4 | 24.5 | 31.5 | 35.8 | 60.5 |
| **2.2** | 23.4 | 20.3 | 19.5 | 19.0 | 28.5 | 32.8 | 52.8 |
| **3.1** | 12.7 | 11.0 | 16.2 | 19.7 | 25.8 | 17.1 | 14.8 |
| **3.2** | 12.0 | 10.4 | 14.3 | 19.6 | 26.1 | 9.5 | 17.0 |
| **4.1** | 25.1 | 23.4 | 20.7 | 23.2 | 29.5 | 14.7 | 35.4 |
| **4.2** | 24.9 | 22.0 | 21.5 | 20.8 | 30.0 | 41.4 | 48.3 |
| **5.1** | 25.0 | 22.1 | 21.5 | 20.4 | 28.8 | 38.7 | 52.6 |
| **5.2** | 23.8 | 21.8 | 23.5 | 25.1 | 25.0 | 37.8 | 51.5 |
| **6.1** | 26.7 | 24.2 | 25.3 | 26.1 | 26.3 | 38.1 | 46.2 |
| **6.2** | 29.1 | 28.3 | 26.5 | 24.0 | 32.8 | 33.2 | 47.8 |
| **7.1** | 28.4 | 26.6 | 25.3 | 23.6 | 32.6 | 34.4 | 43.2 |
| **7.2** | 36.0 | 33.7 | 32.8 | 34.7 | 27.2 | 26.2 | 42.6 |
| **8.1** | 34.3 | 31.1 | 30.2 | 26.9 | 29.8 | 26.6 | 37.5 |
| **8.2** | 27.5 | 24.2 | 22.6 | 23.3 | 30.2 | 32.4 | 39.0 |
| **9.1** | 26.9 | 23.8 | 21.9 | 22.4 | 32.8 | 29.6 | 40.9 |
| **9.2** | 29.1 | 26.8 | 24.9 | 24.9 | 29.6 | 37.5 | 37.8 |
| **10.1** | 30.0 | 27.0 | 25.3 | 25.5 | 31.2 | 39.6 | 39.7 |
| **10.2** | 33.8 | 31.8 | 32.1 | 26.3 | 42.1 | 43.7 | 43.8 |
| **11.1** | 24.1 | 21.8 | 25.7 | 22.7 | 34.5 | 24.4 | 40.3 |
| **11.2** | 25.6 | 24.3 | 22.6 | 21.3 | 30.3 | 31.0 | 39.6 |
| **12.1** | 26.5 | 24.4 | 23.0 | 22.7 | 40.1 | 30.0 | 39.6 |
| **12.2** | 25.1 | 23.0 | 21.6 | 25.9 | 29.4 | 33.1 | 44.3 |
| **13.1** | 24.1 | 22.2 | 21.5 | 20.0 | 29.2 | 31.8 | 43.4 |
| **13.2** | 23.8 | 21.8 | 20.0 | 19.7 | 30.9 | 30.7 | 40.5 |
| **14.1** | 23.5 | 20.8 | 18.8 | 19.3 | 29.7 | 30.3 | 41.2 |
| **14.2** | 32.4 | 27.7 | 29.7 | 28.0 | 37.8 | 19.3 | 37.8 |
| **15.1** | 29.8 | 26.6 | 27.6 | 24.4 | 34.5 | 20.7 | 41.0 |
| **15.2** | 29.6 | 26.3 | 26.5 | 26.1 | 32.1 | 32.5 | 48.3 |
| **16.1** | 28.5 | 25.9 | 26.0 | 26.2 | 31.4 | 30.8 | 39.2 |
| **16.2** | 33.6 | 31.0 | 30.3 | 30.6 | 40.1 | 23.9 | 30.2 |
| **17.1** | 33.7 | 31.5 | 30.3 | 31.1 | 40.1 | 26.8 | 23.7 |
| **17.2** | 25.1 | 26.4 | 24.1 | 29.7 | 33.3 | 39.5 | 42.4 |
| **18.1** | 27.0 | 27.6 | 26.6 | 27.1 | 32.6 | 39.4 | 43.0 |
| **18.2** | 29.1 | 28.4 | 27.6 | 27.6 | 35.9 | 35.2 | 34.8 |
| **19.1** | 31.1 | 30.2 | 29.2 | 30.0 | 27.5 | 33.5 | 34.2 |
| **19.2** | 27.6 | 26.1 | 24.5 | 23.3 | 40.5 | 40.7 | 40.5 |
| **20.1** | 28.2 | 26.5 | 24.1 | 23.4 | 34.4 | 41.8 | 40.5 |
| **20.2** | 25.4 | 24.9 | 23.0 | 22.4 | 38.4 | 30.0 | 44.4 |

Table XXXV

REAT$^i$: Reported Attenuation for the second group

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1.1** | 16.2 | 16.5 | 11.3 | 14.2 | 25.0 | 32.0 | 38.8 |
| **1.2** | 21.0 | 18.0 | 15.5 | 17.3 | 29.2 | 32.5 | 38.2 |
| **2.1** | 23.0 | 20.2 | 21.0 | 18.2 | 32.7 | 34.3 | 47.0 |
| **2.2** | 29.2 | 27.3 | 23.2 | 22.2 | 33.0 | 39.0 | 45.2 |
| **3.1** | 2.5 | 6.5 | 4.5 | 17.2 | 23.5 | 24.2 | 19.7 |
| **3.2** | 3.7 | 5.0 | 6.5 | 16.3 | 19.5 | 23.0 | 24.2 |
| **4.1** | 31.0 | 28.5 | 18.3 | 26.2 | 34.0 | 43.0 | 46.3 |
| **4.2** | 27.2 | 27.5 | 21.8 | 27.2 | 31.7 | 41.0 | 45.8 |
| **5.1** | 26.2 | 23.7 | 22.8 | 26.5 | 30.7 | 37.3 | 38.5 |
| **5.2** | 26.2 | 23.3 | 20.7 | 22.0 | 29.2 | 37.3 | 42.0 |
| **6.1** | 22.7 | 22.7 | 21.3 | 23.5 | 29.0 | 28.5 | 29.3 |
| **6.2** | 18.2 | 17.0 | 21.8 | 24.8 | 26.3 | 33.8 | 26.2 |
| **7.1** | 9.8 | 12.8 | 14.7 | 14.0 | 29.8 | 31.0 | 39.0 |
| **7.2** | 22.0 | 24.0 | 16.2 | 17.7 | 31.3 | 31.5 | 39.2 |
| **8.1** | 29.2 | 21.8 | 26.7 | 28.7 | 33.3 | 31.7 | 39.0 |
| **8.2** | 27.2 | 21.7 | 24.3 | 26.2 | 36.5 | 30.8 | 39.8 |
| **9.1** | 23.5 | 20.3 | 20.2 | 23.0 | 36.5 | 36.0 | 47.0 |
| **9.2** | 24.0 | 21.5 | 20.7 | 28.0 | 35.7 | 41.0 | 45.7 |
| **10.1** | 20.0 | 18.3 | 16.0 | 17.2 | 30.5 | 32.3 | 47.2 |
| **10.2** | 18.0 | 19.8 | 21.2 | 20.0 | 31.2 | 29.0 | 42.3 |
| **11.1** | 29.3 | 29.0 | 32.0 | 27.5 | 41.7 | 40.8 | 34.3 |
| **11.2** | 25.5 | 26.8 | 27.8 | 24.5 | 43.2 | 42.3 | 29.7 |
| **12.1** | 29.2 | 26.0 | 28.8 | 29.8 | 37.0 | 38.3 | 49.3 |
| **12.2** | 27.2 | 28.0 | 26.0 | 26.7 | 34.0 | 31.3 | 46.2 |
| **13.1** | 23.7 | 21.5 | 25.2 | 27.0 | 39.3 | 37.2 | 54.3 |
| **13.2** | 27.5 | 28.5 | 26.0 | 28.5 | 40.7 | 38.5 | 52.8 |
| **14.1** | 17.2 | 21.3 | 21.7 | 21.5 | 26.7 | 31.7 | 25.5 |
| **14.2** | 22.7 | 21.2 | 21.2 | 19.5 | 31.2 | 30.3 | 32.7 |
| **15.1** | 27.0 | 28.3 | 30.2 | 30.8 | 25.7 | 33.5 | 42.3 |
| **15.2** | 29.8 | 30.5 | 34.2 | 31.3 | 27.2 | 38.0 | 41.8 |
| **16.1** | 26.7 | 22.7 | 22.8 | 20.8 | 28.3 | 32.3 | 40.2 |
| **16.2** | 33.8 | 36.2 | 33.0 | 31.7 | 46.7 | 38.0 | 46.0 |
| **17.1** | 29.2 | 27.7 | 21.8 | 25.5 | 37.7 | 32.5 | 40.7 |
| **17.2** | 28.2 | 25.3 | 20.5 | 28.2 | 41.5 | 32.2 | 46.0 |
| **18.1** | 24.7 | 21.0 | 21.7 | 23.2 | 35.2 | 33.5 | 41.3 |
| **18.2** | 24.5 | 22.8 | 22.7 | 25.2 | 34.3 | 31.3 | 47.0 |
| **19.1** | 35.2 | 38.8 | 34.5 | 29.8 | 35.5 | 38.3 | 43.2 |
| **19.2** | 32.5 | 36.8 | 32.8 | 30.2 | 27.5 | 27.5 | 38.3 |
| **20.1** | 29.8 | 25.8 | 29.2 | 31.7 | 38.2 | 37.3 | 44.8 |
| **20.2** | 31.5 | 26.5 | 27.3 | 28.0 | 40.2 | 36.3 | 44.7 |

Table XXXVI

$\epsilon^i$: Error in the Predicted Personal Attenuation Rating computed for the second group

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1.1** | 3.7 | 1.4 | 6.4 | 7.6 | 2.1 | 6.3 | 3.7 |
| **1.2** | 2.1 | 3.1 | 3.1 | 12.1 | 0.2 | 6.4 | 2.4 |
| **2.1** | 7.6 | 8.2 | 7.4 | 6.3 | -1.2 | 1.5 | 13.5 |
| **2.2** | -5.8 | -7.0 | -3.7 | -3.2 | -4.5 | -6.2 | 7.6 |
| **3.1** | 10.2 | 4.5 | 11.7 | 2.5 | 2.3 | -7.1 | -4.9 |
| **3.2** | 8.3 | 5.4 | 7.8 | 3.3 | 6.6 | -13.5 | -7.2 |
| **4.1** | -5.9 | -5.1 | 2.4 | -3.0 | -4.5 | -28.3 | -10.9 |
| **4.2** | -2.3 | -5.5 | -0.3 | -6.4 | -1.7 | 0.4 | 2.5 |
| **5.1** | -1.2 | -1.6 | -1.3 | -6.1 | -1.9 | 1.4 | 14.1 |
| **5.2** | -2.4 | -1.5 | 2.8 | 3.1 | -4.2 | 0.5 | 9.5 |
| **6.1** | 4.0 | 1.5 | 4.0 | 2.6 | -2.7 | 9.6 | 16.9 |
| **6.2** | 10.9 | 11.3 | 4.7 | -0.8 | 6.5 | -0.6 | 21.6 |
| **7.1** | 18.6 | 13.8 | 10.6 | 9.6 | 2.8 | 3.4 | 4.2 |
| **7.2** | 14.0 | 9.7 | 16.6 | 17.0 | -4.1 | -5.3 | 3.4 |
| **8.1** | 5.1 | 9.3 | 3.5 | -1.8 | -3.5 | -5.1 | -1.5 |
| **8.2** | 0.3 | 2.5 | -1.7 | -2.9 | -6.3 | 1.6 | -0.8 |
| **9.1** | 3.4 | 3.5 | 1.7 | -0.6 | -3.7 | -6.4 | -6.1 |
| **9.2** | 5.1 | 5.3 | 4.2 | -3.1 | -6.1 | -3.5 | -7.9 |
| **10.1** | 10.0 | 8.7 | 9.3 | 8.3 | 0.7 | 7.3 | -7.5 |
| **10.2** | 15.8 | 12.0 | 10.9 | 6.3 | 10.9 | 14.7 | 1.5 |
| **11.1** | -5.2 | -7.2 | -6.3 | -4.8 | -7.2 | -16.4 | 6.0 |
| **11.2** | 0.1 | -2.5 | -5.2 | -3.2 | -12.9 | -11.3 | 9.9 |
| **12.1** | -2.7 | -1.6 | -5.8 | -7.1 | 3.1 | -8.3 | -9.7 |
| **12.2** | -2.1 | -5.0 | -4.4 | -0.8 | -4.6 | 1.8 | -1.9 |
| **13.1** | 0.4 | 0.7 | -3.7 | -7.0 | -10.1 | -5.4 | -10.9 |
| **13.2** | -3.7 | -6.7 | -6.0 | -8.8 | -9.8 | -7.8 | -12.3 |
| **14.1** | 6.3 | -0.5 | -2.9 | -2.2 | 3.0 | -1.4 | 15.7 |
| **14.2** | 9.7 | 6.5 | 8.5 | 8.5 | 6.6 | -11.0 | 5.1 |
| **15.1** | 2.8 | -1.7 | -2.6 | -6.4 | 8.8 | -12.8 | -1.3 |
| **15.2** | -0.2 | -4.2 | -7.7 | -5.2 | 4.9 | -5.5 | 6.5 |
| **16.1** | 1.8 | 3.2 | 3.2 | 5.4 | 3.1 | -1.5 | -1.0 |
| **16.2** | -0.2 | -5.2 | -2.7 | -1.1 | -6.6 | -14.1 | -15.8 |
| **17.1** | 4.5 | 3.8 | 8.5 | 5.6 | 2.4 | -5.7 | -17.0 |
| **17.2** | -3.1 | 1.1 | 3.6 | 1.5 | -8.2 | 7.3 | -3.6 |
| **18.1** | 2.3 | 6.6 | 4.9 | 3.9 | -2.6 | 5.9 | 1.7 |
| **18.2** | 4.6 | 5.6 | 4.9 | 2.4 | 1.6 | 3.9 | -12.2 |
| **19.1** | -4.1 | -8.6 | -5.3 | 0.2 | -8.0 | -4.8 | -9.0 |
| **19.2** | -4.9 | -10.7 | -8.3 | -6.9 | 13.0 | 13.2 | 2.2 |
| **20.1** | -1.6 | 0.7 | -5.1 | -8.3 | -3.8 | 4.5 | -4.3 |
| **20.2** | -6.1 | -1.6 | -4.3 | -5.6 | -1.8 | -6.3 | -0.3 |

Table XXXVII

Reported overall attenuation (PAR), Predicted overall attenuation (PPAR) and Overall observed prediction error for the forty tests on the second group of twenty subjects

| | PAR | PPAR | ERR |
|---|---|---|---|
| **1.1** | 25.0 | 18.8 | -6.1 |
| **1.2** | 27.7 | 22.3 | -5.4 |
| **2.1** | 30.4 | 24.7 | -5.8 |
| **2.2** | 24.6 | 28.2 | 3.6 |
| **3.1** | 18.5 | 14.0 | -4.6 |
| **3.2** | 15.0 | 14.8 | -0.2 |
| **4.1** | 20.7 | 27.9 | 7.2 |
| **4.2** | 26.5 | 30.0 | 3.4 |
| **5.1** | 26.2 | 29.6 | 3.5 |
| **5.2** | 27.7 | 26.9 | -0.8 |
| **6.1** | 29.1 | 26.8 | -2.3 |
| **6.2** | 29.8 | 26.2 | -3.6 |
| **7.1** | 29.3 | 19.7 | -9.7 |
| **7.2** | 30.0 | 23.1 | -7.0 |
| **8.1** | 29.6 | 31.1 | 1.5 |
| **8.2** | 28.0 | 29.8 | 1.8 |
| **9.1** | 27.4 | 27.4 | -0.0 |
| **9.2** | 29.6 | 29.4 | -0.2 |
| **10.1** | 30.4 | 22.5 | -7.9 |
| **10.2** | 33.4 | 25.4 | -8.0 |
| **11.1** | 27.0 | 33.6 | 6.6 |
| **11.2** | 26.9 | 30.5 | 3.6 |
| **12.1** | 28.1 | 34.0 | 5.9 |
| **12.2** | 28.6 | 30.9 | 2.4 |
| **13.1** | 25.8 | 31.1 | 5.3 |
| **13.2** | 25.3 | 33.0 | 7.7 |
| **14.1** | 24.6 | 25.5 | 1.0 |
| **14.2** | 25.6 | 25.3 | -0.3 |
| **15.1** | 25.9 | 30.4 | 4.5 |
| **15.2** | 30.7 | 32.2 | 1.5 |
| **16.1** | 30.2 | 26.4 | -3.7 |
| **16.2** | 29.3 | 37.2 | 7.9 |
| **17.1** | 29.3 | 29.4 | 0.1 |
| **17.2** | 31.8 | 29.5 | -2.4 |
| **18.1** | 31.8 | 27.9 | -3.9 |
| **18.2** | 32.2 | 29.1 | -3.2 |
| **19.1** | 31.1 | 35.4 | 4.3 |
| **19.2** | 29.5 | 30.3 | 0.8 |
| **20.1** | 29.3 | 34.8 | 5.5 |
| **20.2** | 27.9 | 32.9 | 5.0 |

## 2.c Statistical Graphs from section 2.4.2.1.5

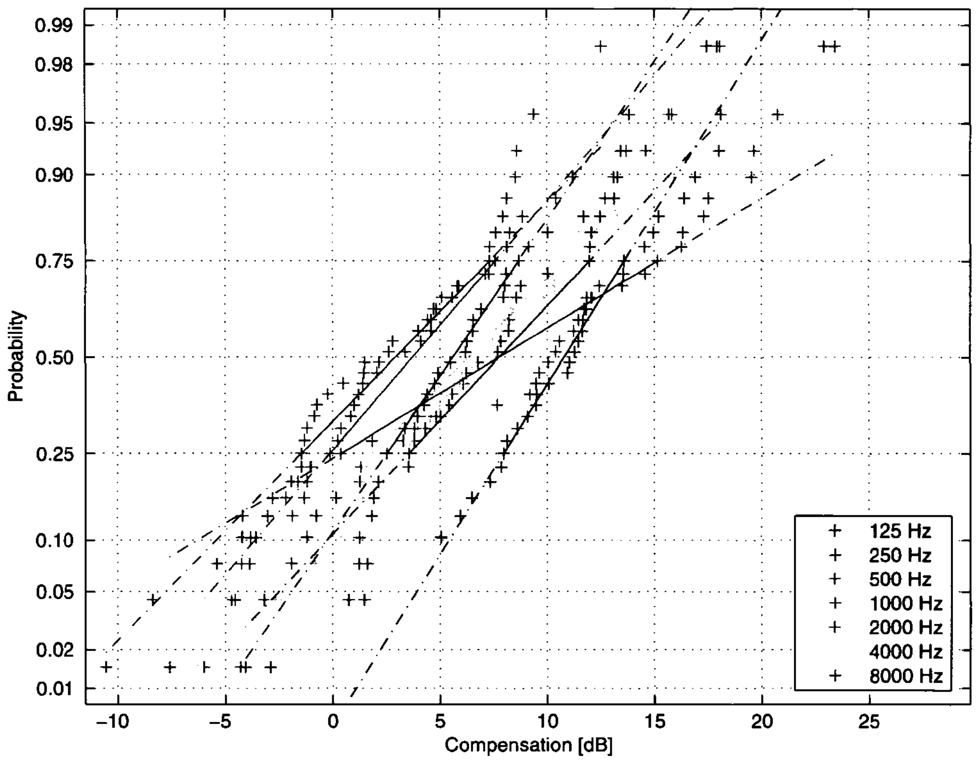


Figure 24 Normal probability plot of the Compensation for the first set of experimental data (n=34)

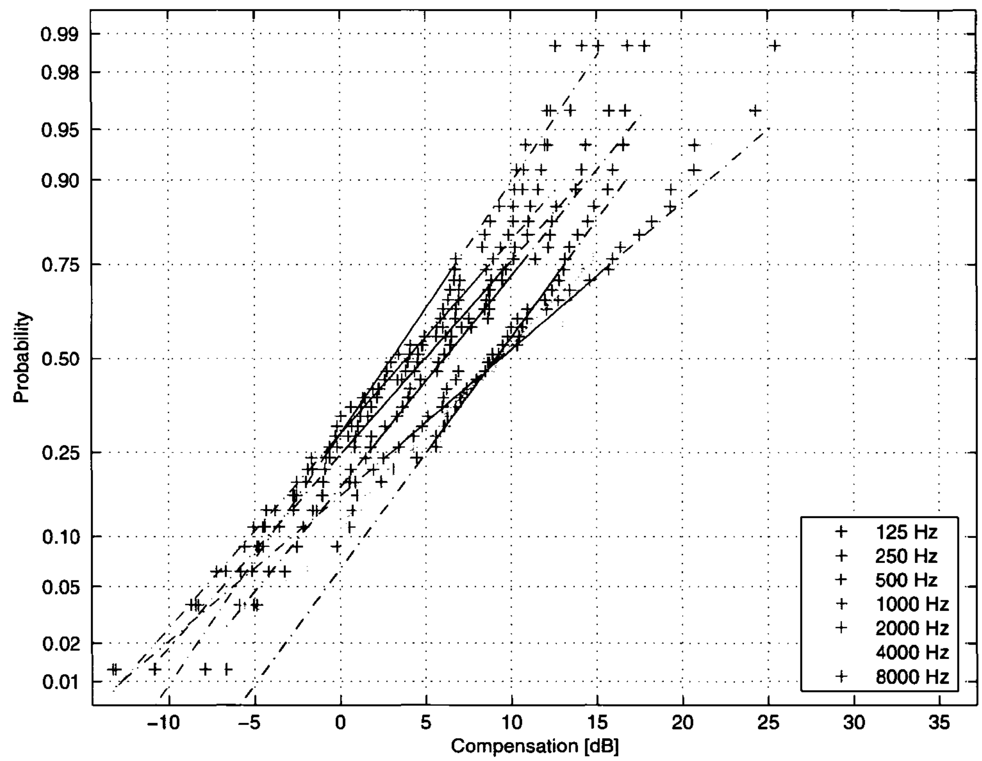


Figure 25 Normal probability plot of the Compensation for the second set of experimental data (n=40)

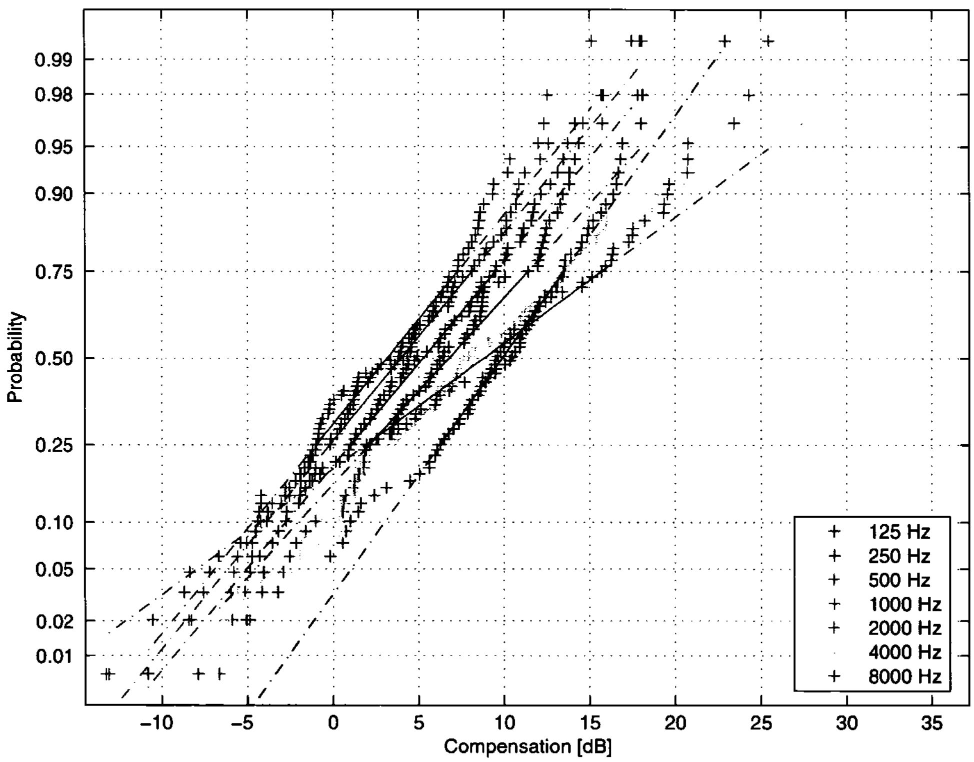


Figure 26 Normal probability plot of the Compensation for the two sets of experimental data merged (n=74)

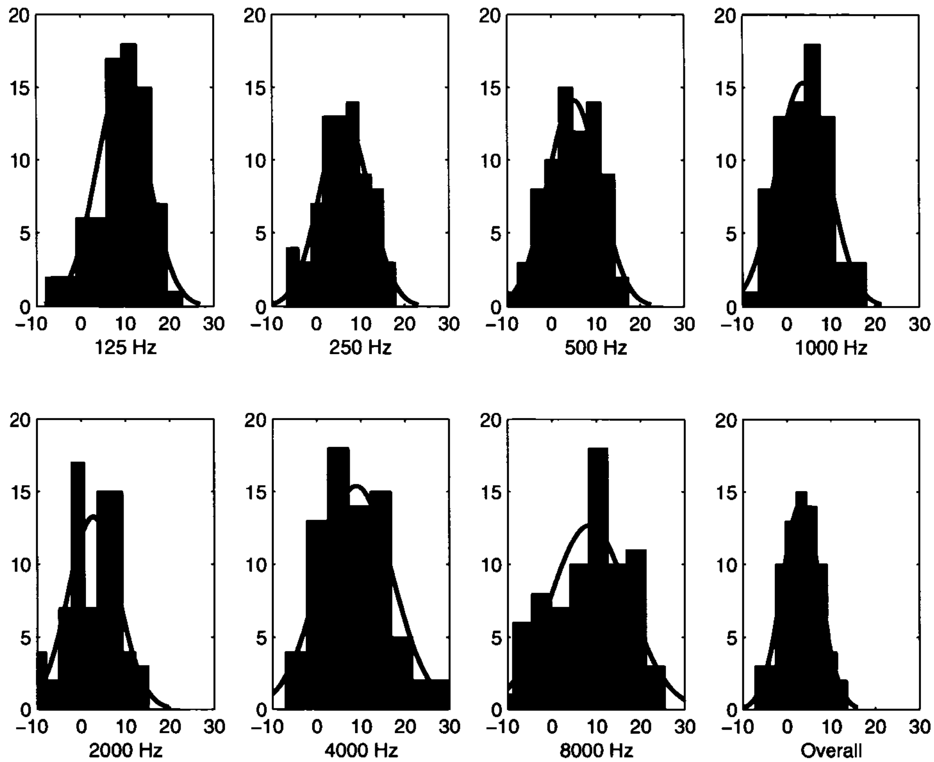


Figure 27 Histogram with superimposed normal density for the Compensation per Octave Bands and as an overall value

## 2.d Statistical graphs from Section 2.4.2.2

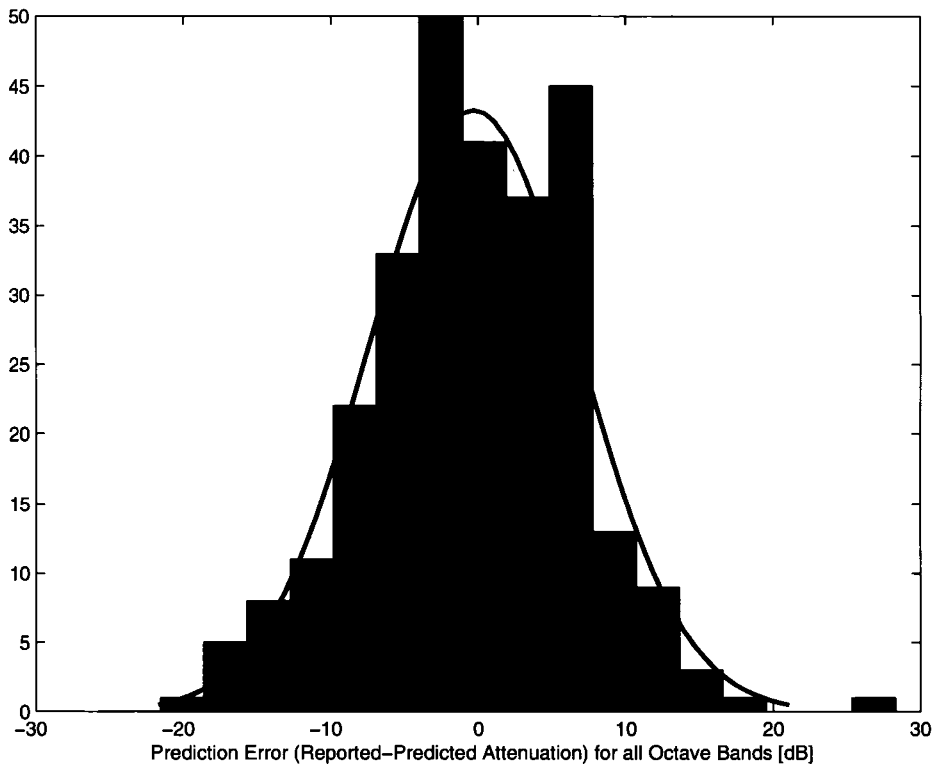


Figure 28 Histogram with superimposed normal density for all the Octave Bands observed prediction errors $\epsilon^i$

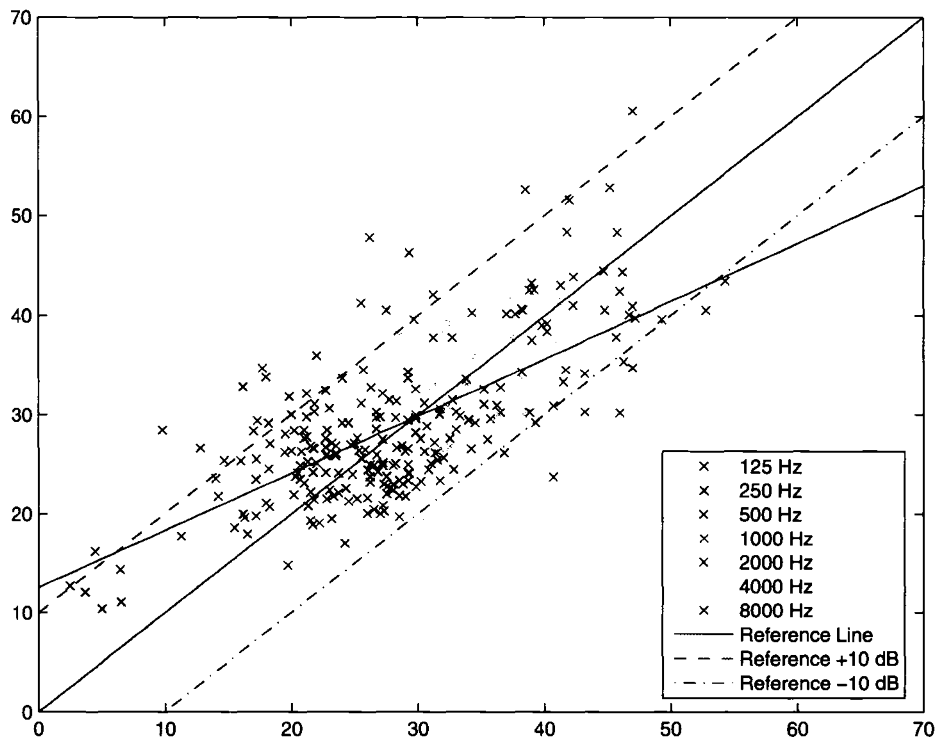


Figure 29 Scattergram of Field-MIRE Predicted vs. REAT reported attenuation per Octave Band Measurements (with Pearson product-moment correlation coefficient of 0.67)

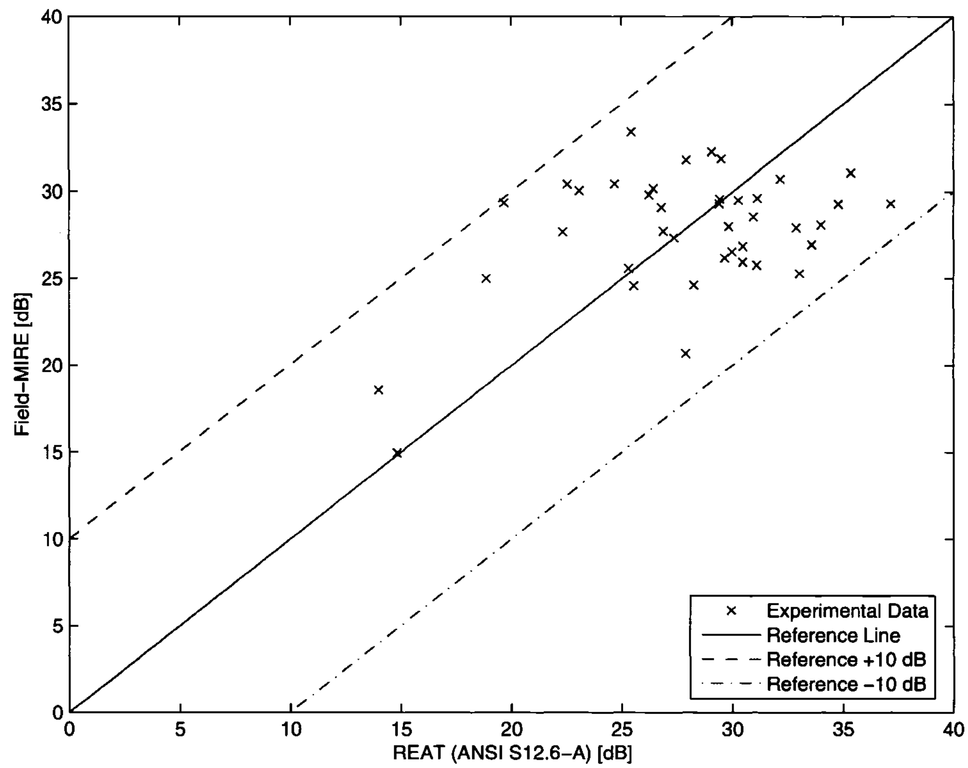


Figure 30 Scattergram of Field-MIRE Predicted vs. REAT reported attenuation per overall value (with a Pearson product-moment correlation coefficient of 0.52) for the second group

# ARTICLE 3

# PREDICTION OF THE ATTENUATION OF A FILTERED CUSTOM EARPLUG

Article tel que soumis à la revue “Applied Acoustics” le 22 décembre 2005.

# Prediction of the attenuation of a filtered custom earplug

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## Abstract

*A model for filtered earplug attenuation has been built based on a transfer function representation of the sound transmission paths and empirical REAT measurement of dampers attenuation contribution. The uncertainty associated with the proposed model has been found to be less related to the variability of the damper acoustical resistance than to the use of an averaged value of damper attenuation contribution without consideration for the wearer's protected ear acoustical characteristics. In an experimental validation, the predictions using the Noise Reduction based measurement of the earplug attenuation combined with the proposed model for the damper attenuation contribution were successfully compared with the direct REAT measurement of the filtered earplug. The uncertainty of the proposed prediction model is equal or lower than the uncertainty associated with the REAT measurement. Therefore, the field implementation of the proposed method can be used for damper selection and earplug adjustment to the desired attenuation.*

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## 3.1 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 perceptual point of view), some manufacturers have recently been offering new *Hearing Protection Devices* (HPD) that are based on a custom earplug for increased physical comfort and that include a passive acoustical filter for increased perceptual comfort: the filter will let some sound energy through, which helps to overcome the problem of the *overprotection* that prevent 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. In the case of the first approach based on filtered earplug modeling, the only attempt found in the literature ([4]) is based on modeling of the filter without taking into account the sound transmission through the rest of the earplug and fails at properly predicting the filtered earplug attenuation. In the case of the second approach based on measurement, a quick field evaluation of the filtered earplug attenuation could be very useful to adjust the filter to the user's attenuation need. 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 device that assesses the attenuation of the solid earplug (for which the soundbore is seal by the probe microphone) and an empirical prediction model that estimates the attenuation contribution of the acoustical filter. Although this approach could be used for the above mentioned "adjustable attenuation HPDs", it has been specifically developed and validated for a new concept of instrumented expandable custom earplug. This re-usable custom earplug, developed by SONOMAX HEARING HEALTHCARE INC (Montreal, Canada), is instantly fitted to the user's ear using the injection of a soft medical-grade silicon rubber between a rigid core and a soft expendable envelope. This expandable custom earplug includes an inner bore of constant length and diameter that permits the temporary insertion inside the generic rigid core of a miniature microphone to measure the sound pressure level in the residual ear-canal portion beneath the HPD. Attached to the back of this internal pressure microphone, there is an external pressure microphone so that the sound pressure level difference across the earplug (Noise Reduction) can be measured while a loud pink noise is generated from an outside reference sound source (frontal incidence, median plan), as illustrated in Fig. 1.

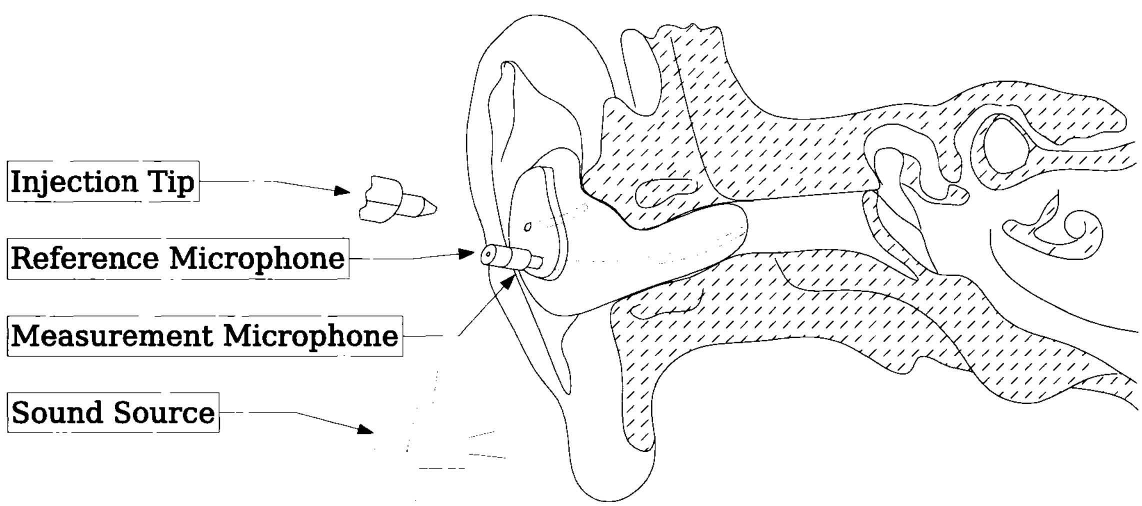



Figure 1 The expandable custom earplug into the wearer's ear: the injection tip used for the inflation of the earplug, the sound source and dual microphone probe for Noise Reduction measurement

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

Table I

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

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

The attenuation of the earplug can be determined using a prediction method (already presented by the authors [10]) that links the Noise Reduction (NR) to the attenuation that the wearer would report if he was tested with the current "gold standard" of attenuation measurement for hearing protection devices, the REAT [9, 11, 12, 13]. The NR measurement is performed after the wearer removes and refit the custom earplug on his own. Such condition corresponds to a "subject-fit" and the attenuation determined will be a quite realistic assessment of the attenuation achieved in "real-world" field use [14].

However, in practice, the damper 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 and it is clearly undesirable to have to repeat the actual NR measurement of the earplug 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 one 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. It is therefore essential to be able to predict the attenuation of the filtered earplug for each of the damper available, without having to actually measure the attenuation of the filtered earplug with each of the available dampers.

The empirical model for the damper attenuation contribution is defined and implemented in section 3.2. The uncertainty associated with the filtered earplug attenuation prediction is evaluated in section 3.3. The experimental validation of the proposed approach is completed in section 3.4. Conclusions are given in section 3.5.

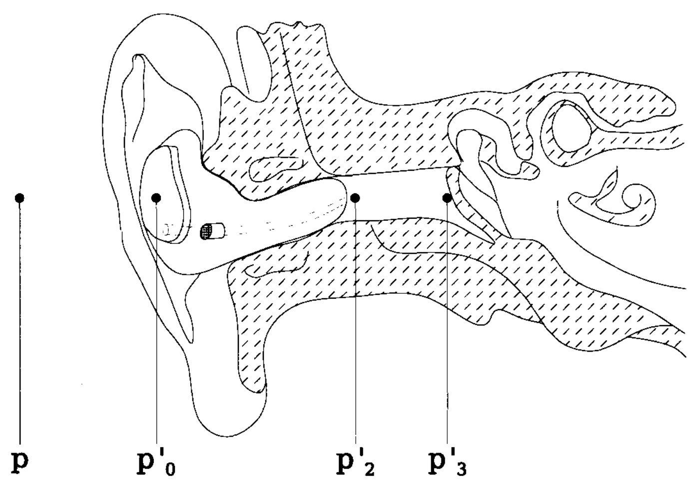



Figure 2 The expandable custom earplug filtered with an acoustical damper for adapted protection and location of the sound pressure level measurement points.

### 3.2 An empirical damper contribution model

#### 3.2.1 Justification, concept 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 modelling separately the solid earplug (with the eventual leak and bone conduction) and the damper and by associating in parallel the two elements. Unfortunately, such transmission matrice approach may not be the optimal approach, in this particular case, for two reasons. First, the overall accuracy of the transmission matrice model depends on the accuracy of the parameters of its constituting elements; however, the exact parameters of the earplug element are not known on an individual basis. Unfortunately, despite some attempts by the authors, no simple method currently exists to extract the pertinent acoustical model parameters from the NR measurement (the only measurement actually available). Obviously the use of typical or average earplug parameters instead of individual parameters would offset all benefits of the accuracy of the transmission matrice approach. Second, such model would require much refinement for the earplug model, whereas the filtered earplug attenuation will be mostly driven by the damper element itself, that constitutes a dominant path, as it will be seen in section 3.2.4.

The proposed model is consequently based on a representation of the sound transmission paths through a filtered earplug as energy summation and is illustrated in Fig. 3. The

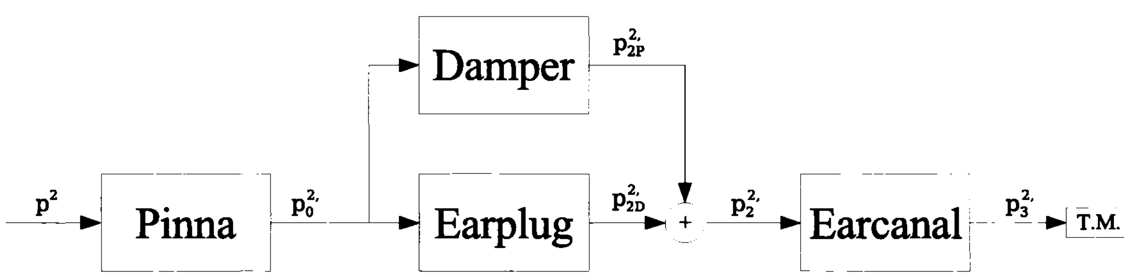



Figure 3 Block diagram of the filtered earplug inside the ear-canal: "Damper" represents the sound path created by the acoustic resistance, "Earplug" represents the combination of all the sound path to the protected ear

sound transmission trough an earplug has been widely presented and illustrated in the literature (see for example a detailed explanation by Berger [16]). The four "classical" sound paths through an earplug are:

1. Air Leaks;

2. Vibration of the HPD;
3. Transmission through the material of the HPD;
4. Bone conduction through the human skull.

For convenience, these four sound transmission paths to the protected ear are grouped in the "Earplug" block that is schematically presented in Fig. 3. They will be referred to as the "*primary*" sound transmission paths. In parallel to these primary transmission paths, the acoustical damper acts as a " *secondary* " sound path and can be viewed as a controlled air leak that actually let more sound energy get to the wearer's protected ear. From this summation diagram, presented in Fig. 3, it is possible to derive an expression that gives the damper attenuation contribution as a function of the measured earplug attenuation. Several earplugs with different acoustical dampers are measured using the REAT method to determine the empirical damper contribution.

The proposed approach, based on sound transmission paths, is using a summation of the energy through the damper element $p'^2_{2D}$ and through the earplug $p'^2_{2P}$ for the prediction of the filtered earplug attenuation $ATT_{Combo}$. Such energy summation may not appear justified at first glance, since the two sources $p'^2_{2D}$ and $p'^2_{2P}$ are originating from the same unique source $p'^2_0$ and are certainly coherent. One could have think that the relative phase of sound pressure signal $p'_{2D}$ and $p'_{2P}$ should have been taken into account and that advanced models (like the Transmission matrices model mentioned earlier) should have been used to properly predict the acoustical interferences that would result from the coupling of two coherent sources. The proposed model indeed requires that the earplug and damper are two independent paths (i.e. $p'^2_{2D}$ and $p'^2_{2P}$ are non coherent sources) and that no impedance coupling exists between the earplug and the damper. This consitutes the H1 hypothesis. According to H1, since no impedance coupling exists between the earplug and the damper, no interference (resonance/anti-resonance) should occur and the use of a damper, by creating an extra sound path from the solid earplug, should always diminish the attenuation of the earplug. Such hypothesis, denoted H2, implies that the filtered earplug attenuation $ATT_{Combo}$ should always be less than the unfiltered earplug attenuation $ATT_{Earplug}$. The validity of H1 and H2 will be examined in section 3.2.4.

### 3.2.2 Formulation of the filtered earplug attenuation prediction

The attenuation of the filtered earplug (denoted "Combo") is modeled with a transmission path approach: the output from the primary sound transmission paths (denoted "Earplug") and the output from the secondary sound path (denoted "Damper"), are considered independent and their energies are simply summed, as illustrated in Fig. 3 where the symbol $p$ denotes a r.m.s. acoustical pressure and $p^2$ its quadratic value. The variable names used through Eq. 3.1–3.3 are directly defined on the diagram of Fig. 3.

The attenuation of the combined primary sound paths is defined as:

$$ATT_{Earplug} = 20\log_{10}\left(\frac{p'_0}{p'_{2P}}\right) \tag{3.1}$$

The attenuation of the secondary sound path is defined as:

$$ATT_{Damper} = 20\log_{10}\left(\frac{p'_0}{p'_{2D}}\right) \tag{3.2}$$

The attenuation of the summed primary and secondary sound paths is defined as:

$$ATT_{Combo} = 20\log_{10}\left(\frac{p'_0}{p'_2}\right) \tag{3.3}$$

From Eq. 3.1, 3.2 and 3.3, it is possible to obtain the attenuation of the filtered earplug $ATT_{Combo}$ using the relation:

$$ATT_{Combo} = -10\log_{10}\left(10^{-\frac{ATT_{Earplug}}{10}} + 10^{-\frac{ATT_{Damper}}{10}}\right) \tag{3.4}$$

where $ATT_{Earplug}$ is the attenuation measured on a blocked earplug (with a plastic cap, dubbed *FullBlock* in the soundbore) and where $ATT_{Damper}$ is determined from the attenuation measurements of a filtered earplug, the attenuation measurements of the same blocked earplug (in which the soundbore is sealed by the probe microphone), and the relation:

$$ATT_{Damper} = -10\log_{10}\left(10^{-\frac{ATT_{Combo}}{10}} - 10^{-\frac{ATT_{Earplug}}{10}}\right) \tag{3.5}$$

In the previous Eq. 3.4–3.5, the attenuation (denoted $ATT$) can be any attenuation type, measured with whatever means, as long as the same measurement method is used consistently for all of the relations. The previous relations are formulated in terms of Noise Reduction, i.e., the ratio of *Sound Pressure Levels* (SPL) between a point located outside the earplug and another beneath the earplug, inside the wearer's earcanal. However, in practice, the measurement methods for the determination of the attenuation of an earplug are limited and the current "gold standard" widely used and standardized is the *Real-Ear Attenuation at Threshold* (REAT) measurement method. The REAT is a psycho-acoustical assessment of the Insertion Loss, that is the difference, at the eardrum location, of Sound Pressure Levels with and without the earplug. Eq. 3.4–3.5 are still valid in the case of REAT measurements because Eq. 3.1–3.3 integrate two additional multiplicative factors: $\left(\frac{p}{p_0'}\right)$ and $\left(\frac{p_2'}{p_3'}\right)$ that disappear in Eq. 3.4–3.5.

The empirical prediction model of the damper attenuation contribution, $\overline{ATT}_{Damper}$, will be the arithmetic average of the damper attenuation values obtained using Eq. 3.5.

The prediction of the filtered earplug attenuation can then be obtained from Eq. 3.4 as:

$$\widehat{ATT}_{Combo} = -10\log_{10}\left(10^{-\frac{ATT_{Earplug}}{10}} + 10^{-\frac{\overline{ATT}_{Damper}}{10}}\right) \tag{3.6}$$

### 3.2.3 Measurement of the averaged damper attenuation contribution $\overline{ATT}_{Damper}$

#### 3.2.3.1 Measurement Methodology

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. The attenuation contribution of these seven dampers was previously evaluated with an IL measurement (similar to the one that will be presented in section 3.3.2.1) and it has been demonstrated that a subset of only four dampers (with nominal values of 4700, 2200, 1000 and 330 Ω) would be sufficient to theoretically insure an *ideal* or *acceptable* "Protection Outcome", as defined in Table I for up to 94.6% of the noise exposure cases in the Canadian workforces (see [7] for details). This subset of four dampers, currently used in the field by SONOMAX, is evaluated in the current section.

The attenuation of the several earplug configurations is measured using the REAT method in an independent third-party laboratory. The attenuation is measured on ten human subjects, three trial each, per the ANSI S3.19 standard [12]. The various configurations of earplug tested are the following:

- the blocked earplug (for which the sound-bore has been blocked by a plastic cap, dubbed "Full-block"), which attenuation is denoted $ATT_{Earplug}$, since it is really the attenuation of the original solid passive earplug
- the earplug filtered with a 4700 Ω acoustical resistance damper,
- the earplug filtered with a 2200 Ω acoustical resistance damper,
- the earplug filtered with a 1000 Ω acoustical resistance damper,
- the earplug filtered with a 330 Ω acoustical resistance damper.

The standard experimental protocol, based on the ANSI S3.19 standard, is completed with these few extra steps:

1. the REAT is first evaluated (three trials per human subject) for the blocked earplug: this lead to REAT values denoted $ATT_{Earplug}$,
2. the Full-block plastic cap is removed and replaced by a given damper, while the earplug remains in the wearer's ear. Great care is used to not alter the initial earplug placement in the wearer's ear,
3. the REAT is estimated (three trials per subject) for the resulting filtered earplug: this lead to REAT values denoted $ATT_{Damper}$,
4. the damper is removed and replaced by another damper of different acoustical resistance value and step 3 is performed again,
5. steps 3 and 4 are reproduced to test the three other dampers available,
6. an objective measurement of the NR is performed at the end of every testing of each of the dampers and compared to the same measurement performed right after step 1: this ensures that the multiple removal and re-insertion of the dampers did not affect the initial earplug placement in the wearer's ear. If such a discrepancy is noticed, all following subject's results are discarded (even if the actual REAT measurements have been completed until the end of the regular ANSI S3.19 test), this will lead to a decreasing number of "*valid fit*" test value with increasing dampers test order (30 "*valid fit*" tests for 4700 Ω damper test down to 21 "*valid fit*" tests for the 330 Ω damper test).

#### 3.2.3.2 Analysis of the data collected

The measured attenuation is reported in Tables XIV–XXI in Appendix 3.a. It sometime happens that a human test subject actually reports more attenuation with the filtered earplug than with the blocked earplug. Such situation is not respecting the H2 hypothesis of the proposed model that states that the damper is always creating an extra sound path and consequently always diminishes the attenuation of the earplug. Such situation is problematic from a conceptual and mathematical point of view. From a conceptual point of view, it correspond to a physical impossible where the damper is a sound path that is actually *removing* some sound energy from the system. From a mathematical point of view, if the filtered attenuation $ATT_{Combo}$ is greater than the blocked attenuation $ATT_{Earplug}$, the equation 3.2 becomes undefined mathematically since it requires to take the logarithmic value a negative number. As it will be demonstrated in section 3.2.4, such situation must be considered as an *outlier* result resulting from the hearing threshold variability and will be discarded accordingly for the computation of the average damper attenuation contribution. However, it is important to note that these outliers are discarded *only* for the building of the damper attenuation contribution model and that they will all be reincorporated for the validation of the model, during the assessment of the model prediction error in section 3.3.1. This clearly means, that if the model assumptions were wrong (i.e. if H1 and H2 were rarely respected), huge values of prediction error would be obtained in section 3.3.1 and therefore unacceptable model uncertainty would be obtained in 3.3. Obviously, this will not be the case, and for the determination of the damper attenuation contribution, the outliers will be discarded according to the following two distinct rejection scenarios:

- on a "per test trial" basis: the complete test (i.e. the seven octave band attenuation data including the other frequencies) is discarded in a given trial if, at one or more frequency in a test trial, the filtered attenuation exceeds the blocked attenuation.
- on a "per subject average" basis: the complete subject data (i.e. the average of the three trials) is completely discarded if, at one or more frequency in an individual arithmetic mean, the averaged filtered attenuation exceeds the averaged blocked attenuation. It was felt that such approach would increase the number of "*valid threshold*" test trials hence improving the estimate of the damper attenuation contribution.

The numbers of "*valid fit*" and "*valid threshold*" results in the "per test trial" or "per subject average" analysis are presented in Table II.

Table II

Amount of "valid fit" tests and "valid threshold" tests for the "per test trial" (left) and "per subject average" (right) analyses

| Damper | "valid fit" | "valid threshold" | "valid fit" | "valid threshold" |
|---|---|---|---|---|
| 4700 Ω | 30 | 11 | 10 | 5 |
| 2200 Ω | 24 | 19 | 8 | 8 |
| 1000 Ω | 21 | 15 | 7 | 7 |
| 330 Ω | 21 | 13 | 7 | 6 |

### 3.2.4 Evaluation of the validity of H1 and H2 hypothesis

#### 3.2.4.1 On Acoustical Test Fixture (ATF)

A careful analysis of the ATF Insertion Loss data plotted in Fig. 4 would not reveal any significant interference aspect between the damper element and the earplug: the attenuation curves of the filtered earplug are strictly following the ranking of the damper resistance values and the unfiltered (blocked) earplug attenuation appear to be always higher than the filtered one. The fact that the filtered earplug has less attenuation than the blocked earplug is a direct validation of H2 hypothesis. It also implies that any coupling effect -if any-are smal and that in practice, the two sound apths can be considered as independent (H1 hypothesis).

#### 3.2.4.2 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. 5 for thirty REAT measurements. It clearly demonstrate that some 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, where the filtered and blocked earplug have average values that are very close. Nevertheless, the normal probability plot shows that the difference

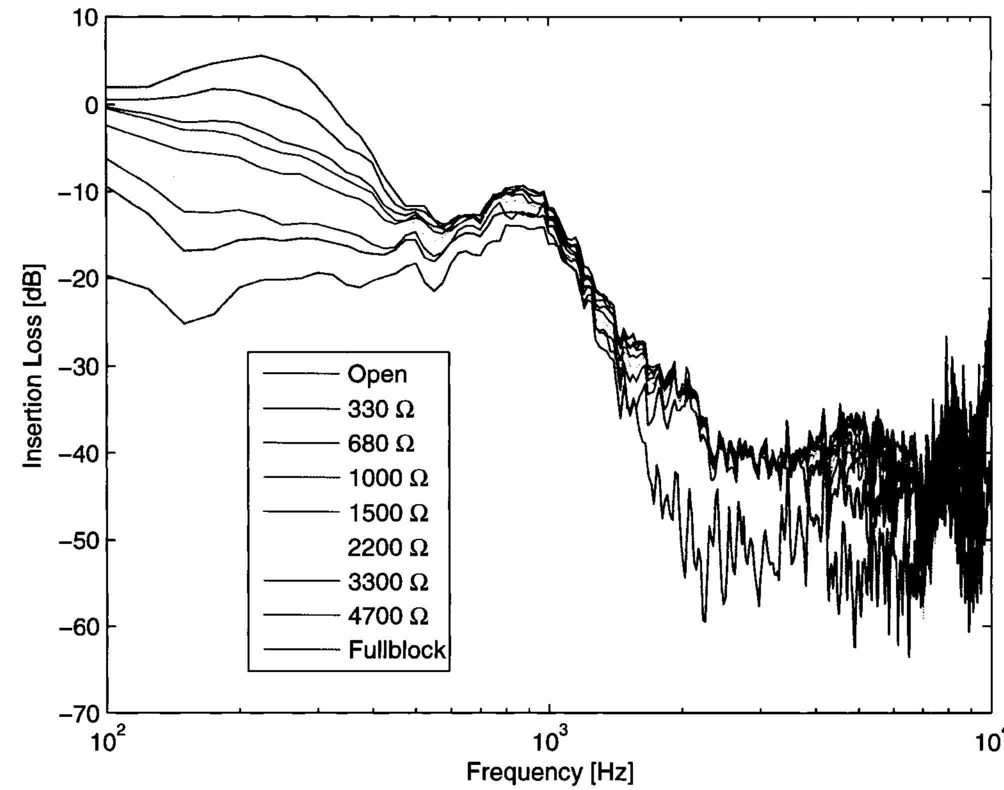



Figure 4 Insertion Loss of the earplug blocked with the Full-block, filtered with the seven available damper elements values and left with the sound-bore open.

is closely following a normal distribution and that the average values of blocked earplug attenuation are greater than filtered earplug attenuation for every octave band. The *outliers* observed previously in section 3.2.3.2 could be seen as the normal spread in the attenuation assessment with REAT method, mainly caused by the variability in hearing thresholds (such uncertainty is estimated to be ranking from 2.9 dB in AS1270 [17] to 6.7 dB in the most recent draft of ISO4869 [18]). The same conclusion as with ATF applies to humna subjects: the fact that the filtered earplug has -on average- less attenuation than the blocked earplug validates H2 which in turn validates H1.

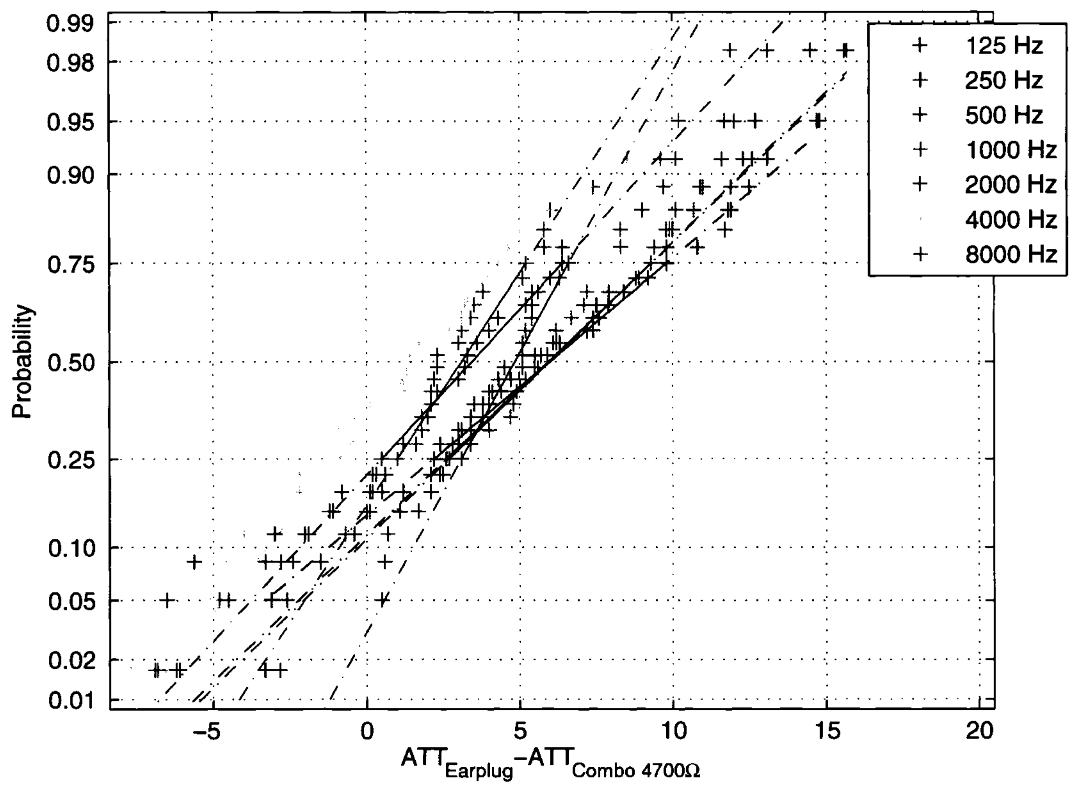



Figure 5 Normal probability plot of $ATT_{Earplug} - ATT_{Combo}$ for the 4700 Ω damper element.

### 3.2.5 Damper attenuation contribution

Using Eq. 3.5 and the measured attenuation data (presented in Tables XIV–XXI), the damper attenuation contribution, $ATT_{Damper}$, is computed for each of the four available dampers, using either the "per test trial" or "per subject average" rejection analysis.

The average and standard deviations of the octave-band $ATT_{Damper}$ values are presented in Fig. 6 and Table III, while the individual data is presented in Tables in Appendix 3.b for the "per test trial" analysis.

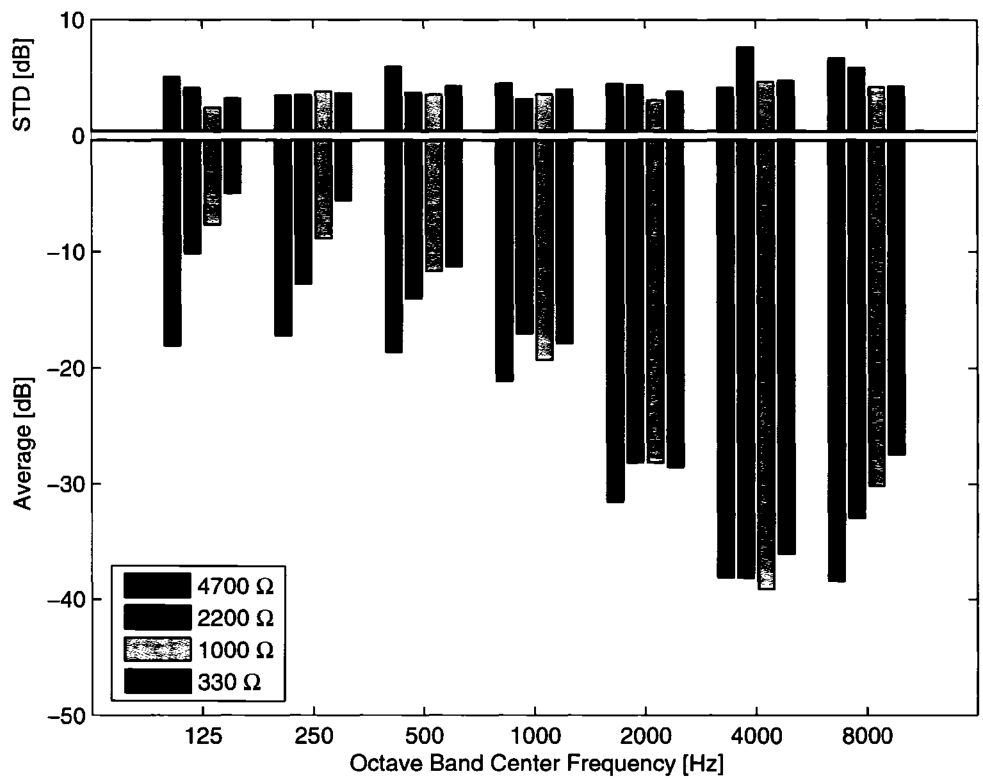



Figure 6 Mean and standard deviation of the octave-band attenuation contribution $ATT_{Damper}$ of available dampers with the "per test trial" analysis.

Table III

Mean and standard deviation of the octave-band attenuation contribution $ATT_{Damper}$ of available dampers with the "per test trial" analysis.

| Frequency | | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|---|
| Mean | **4700 Ω** | 18.1 | 17.3 | 18.7 | 21.2 | 31.5 | 38.1 | 38.4 |
| | **2200 Ω** | 10.1 | 12.7 | 14.0 | 17.1 | 28.2 | 38.2 | 32.9 |
| | **1000 Ω** | 7.6 | 8.8 | 11.7 | 19.3 | 28.2 | 39.1 | 30.2 |
| | **330 Ω** | 5.0 | 5.6 | 11.3 | 17.9 | 28.5 | 36.1 | 27.4 |
| Std | **4700 Ω** | 5.1 | 3.5 | 5.9 | 4.5 | 4.5 | 4.1 | 6.7 |
| | **2200 Ω** | 4.1 | 3.5 | 3.7 | 3.2 | 4.4 | 7.7 | 5.9 |
| | **1000 Ω** | 2.4 | 3.8 | 3.6 | 3.6 | 3.1 | 4.7 | 4.2 |
| | **330 Ω** | 3.2 | 3.7 | 4.3 | 4.0 | 3.8 | 4.8 | 4.3 |

The average and standard deviations of the octave-band $ATT_{Damper}$ values are presented in Fig. 7 and Table IV, while the individual data is presented in tables in Appendix 3.c for the "per subject average" analysis.

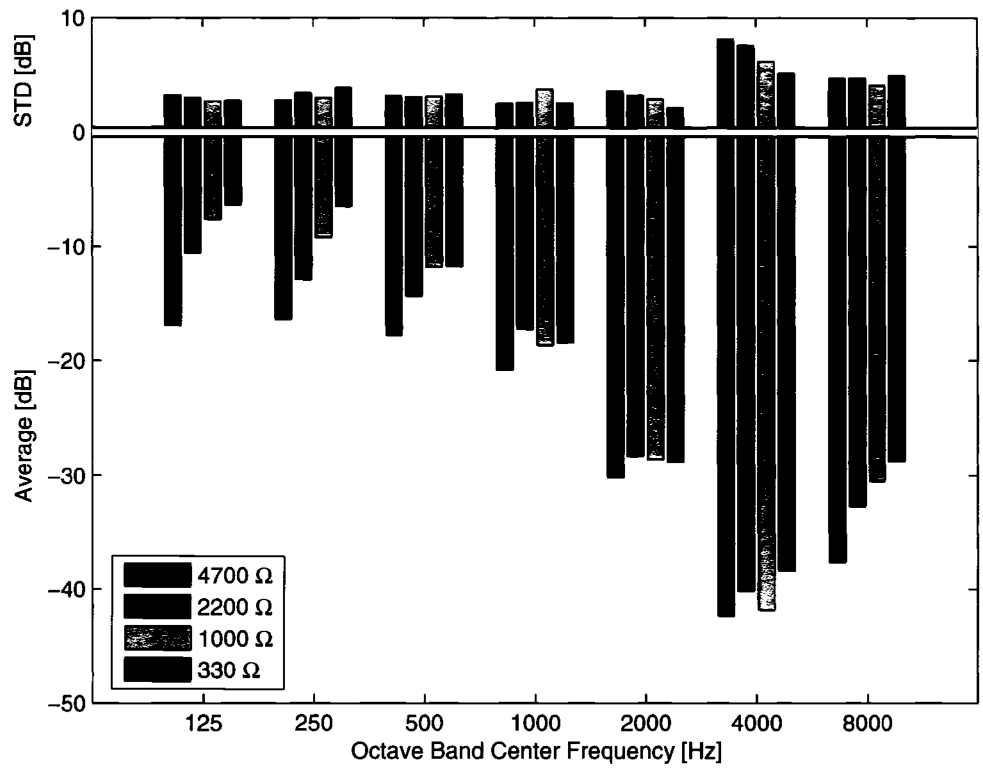



Figure 7 Mean and standard deviation of the octave-band attenuation contribution $ATT_{Damper}$ of valid test with the "per subject average" analysis.

Tables III and IV are presenting the tabulated values of $\overline{ATT}_{Damper}$ to be used for the prediction of the filtered attenuation, per Eq. 3.6. The two analyses, "per test trial" and "per subject average" give averaged values of $\overline{ATT}_{Damper}$ that are very close and even if the "per subject average" is probably more reliable since it does include a larger sample size (for example, in Table II, for the "4700 Ω" damper, five subject averages represent fifteen valid test trials as opposed to only eleven using the "per test trial" analysis), the decision

Table IV

Mean and standard deviation of the octave-band attenuation contribution $ATT_{Damper}$ of valid test with the "per subject average" analysis.

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

to keep the data from one or the other analyses will be postponed until the quantification of the uncertainty in section 3.3.1.

## 3.3 Uncertainty associated with the filtered earplug attenuation prediction

### 3.3.1 Evaluation of the uncertainty associated with the proposed approach

Now that $\widehat{ATT}_{Damper}$ has been established, it becomes possible to predict the filtered attenuation $\widehat{ATT}_{Combo}$ based on the mere measurement of $ATT_{Earplug}$. A direct assessment of the error of the prediction model can be obtained by comparing the predicted filtered attenuation value $\widehat{ATT}_{Combo}$ to the reported one, $ATT_{Combo}$. The global prediction error, denoted $ERR_{Prediction}$ can be defined as:

$$ERR_{Prediction} = \widehat{ATT}_{Combo} - ATT_{Combo} \tag{3.7}$$

where $\widehat{ATT}_{Combo}$ has been obtained from Eq. 3.6 and $ATT_{Combo}$ is the actual filtered attenuation measured with the REAT method.

The computation of the prediction error will be performed, per octave-band, for the "per test trial" and "per subject average" analyses. The average and standard-deviation of the prediction error is presented in Tables V and VI for the "per test trial" and "per subject average" analyses. The uncertainty associated with the prediction model will be estimated from the standard deviation of the prediction error $ERR_{Prediction}$ and is presented in Fig. 8 and 9.

The detailled prediction error for a "per test trial" basis is presented, for the four dampers, in Tables XXXIX, XLI, XLIII and XLV in Appendix 3.d.

The detailled prediction error for a "per subject average" basis is presented in Tables XLVII, XLIX, LI and LIII in Appendix 3.d for the four dampers.

The average prediction error is less than 2 dB (in absolute value) for all the four dampers, at all the octave-band frequencies. The standard deviation of the prediction error presented in Tables V and VI is the highest at high frequencies (8 kHz octave-band) and is increasing

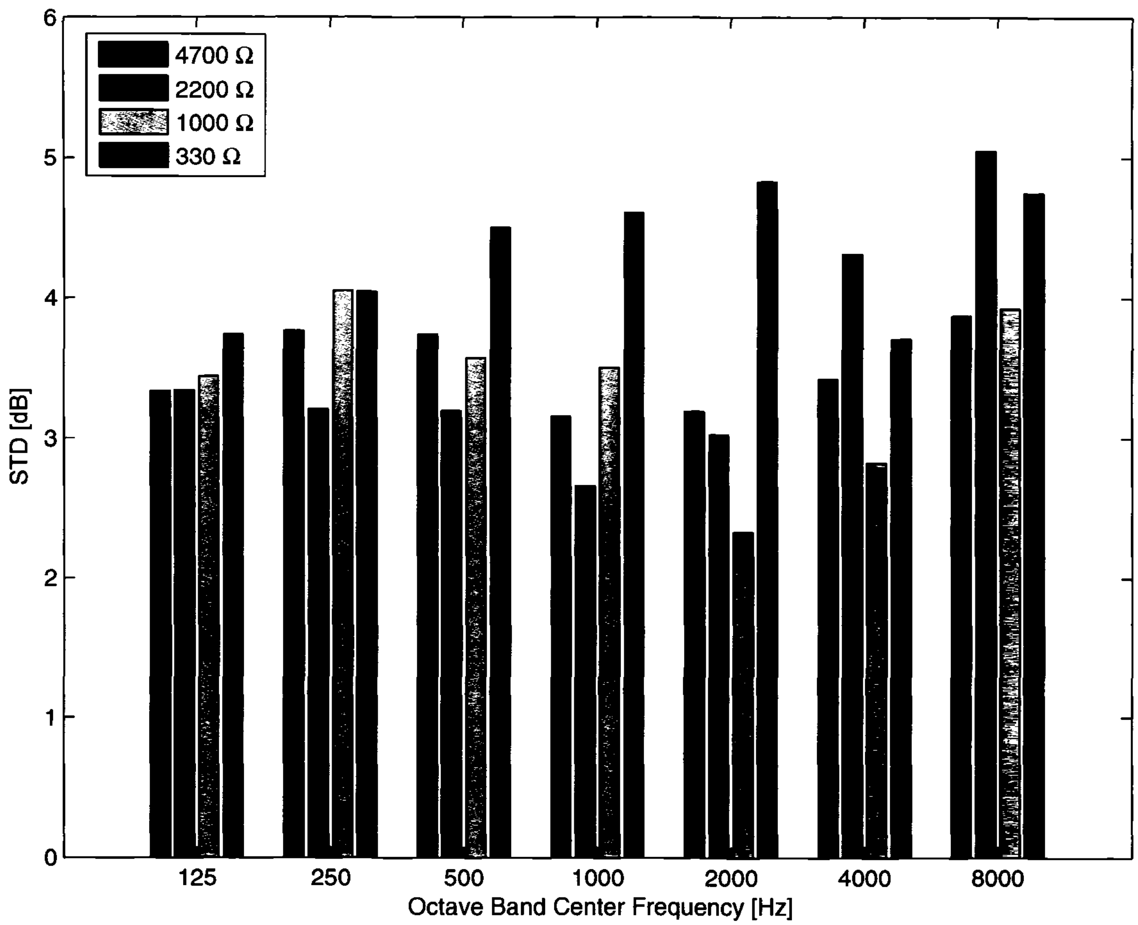



Figure 8 Mean and standard deviation of the prediction error of the octave-band attenuation of the filtered earplug using the valid tests (from "per test trial" analysis)

with the decrease of the nominal acoustical resistance. For example, the largest variability in the attenuation prediction occurs for the "grey" damper (fortunately this"grey" damper would typically be selected when the ambient noise exposure is very low and consequently least hazardous for the hearing protection). It is now clear that the standard deviation of the prediction error is less when using the "per subject average" analysis than with the "per test trial". Consequently, the data from Table IV will be used for the averaged attenuation contribution $\overline{ATT}_{Damper}$ throughout the rest of this paper.

Table V

Mean and standard deviation of the prediction error of the octave-band attenuation of the filtered earplug using the available dampers (from "per test trial" analysis)

| Frequency | | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Mean | **4700 Ω** | -0.2 | -1.4 | -0.9 | -0.9 | 0.9 | -1.4 | -1.2 |
| | **2200 Ω** | -0.3 | -0.1 | -0.2 | -0.1 | -0.2 | -0.2 | 0.1 |
| | **1000 Ω** | 0.0 | -0.3 | -0.2 | 0.6 | -0.3 | -0.7 | -0.5 |
| | **330 Ω** | -1.1 | -1.1 | -1.1 | -0.8 | -1.4 | -1.7 | -1.1 |
| Std | **4700 Ω** | 3.3 | 3.8 | 3.7 | 3.2 | 3.2 | 3.4 | 3.9 |
| | **2200 Ω** | 3.3 | 3.2 | 3.2 | 2.7 | 3.0 | 4.3 | 5.0 |
| | **1000 Ω** | 3.4 | 4.1 | 3.6 | 3.5 | 2.3 | 2.8 | 3.9 |
| | **330 Ω** | 3.7 | 4.0 | 4.5 | 4.6 | 4.8 | 3.7 | 4.8 |

Table VI

Mean and standard deviation of the prediction error of the octave-band attenuation of the filtered earplug using the available dampers (from "per subject average" analysis)

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

This standard deviation of the prediction error is also found to be close or less than the standard deviation of the damper contribution to attenuation presented in Tables III and IV. This indicates that the prediction error variability in the model is mostly caused by the fact that averaged value (obtained from a group of test subjects) are used for the damper attenuation contribution, with no consideration for the individual properties of the acoustical system of the filtered earplug in the wearer's earcanal.

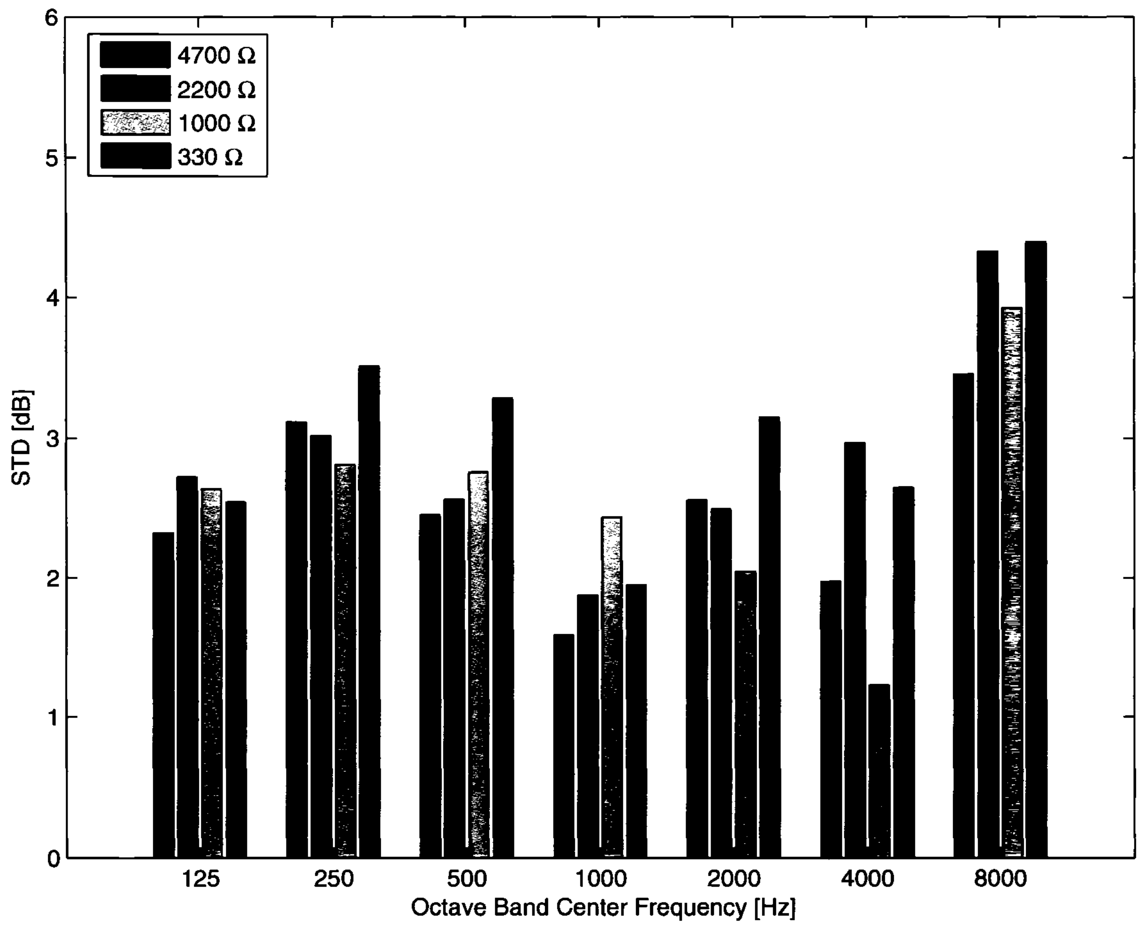



Figure 9 Mean and standard deviation of the prediction error of the octave-band attenuation of the filtered earplug using the available dampers (from "per subject average" analysis)

### 3.3.2 Uncertainty associated with the damper acoustical resistance variability

The prediction of the filtered attenuation $\widehat{ATT}_{Combo}$ is based on the assumption that the damper attenuation contribution $ATT_{Damper}$ remains the same for all the damper of a given nominal acoustical resistance value. Unfortunately, as in all manufacturing processes, theses damper elements may show some variability in their acoustical resistance properties and the manufacturer is only able to insure a given relative tolerance on the acoustical resistance of the damper elements. The variability in the damper attenuation contribution, 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 the damper attenuation contribution 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 a *Artificial Test Fixture* (ATF) appears to be adequate: it has a better 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 reference.

#### 3.3.2.1 IL measurement on several earplug configurations

The experimental setup for the measurement of the Insertion Loss on an ATF of various damper elements is pictured in Fig. 10: the Insertion Loss has been performed in a anechoic room using the B&K 4128 Head&Torso Simulator.

Figure 10 Overview of the B&K 4128 Head&Torso Simulator with the ear simulator occluded with an filtered earplug.

The complete set of the seven damper elements (with nominal acoustical resistance value of 4700, 3300, 2200, 1500, 1000, 680, 330 Ω cgs.) are used in order to increase the number of data point that will later be used to establish the relation between attenuation and acoustical resistance. The earplug with a Full-block and an "open sound-bore" condition were also measured.

The Insertion Loss of the Filtered Earplug, $ATT_{Combo}$, has been plotted in the negative $y$ direction in Fig. 11.

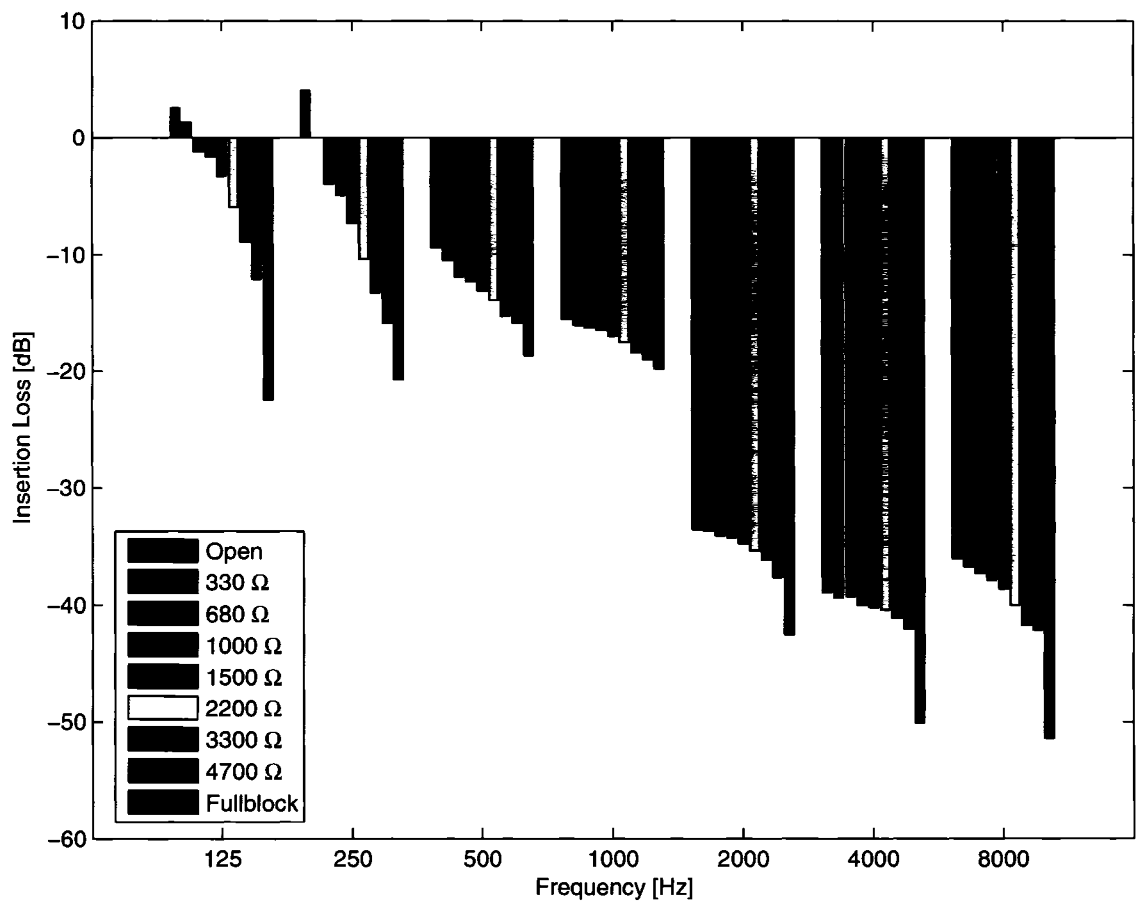



Figure 11 Octave-band Insertion Loss of the earplug blocked with the Full-block, filtered with the seven available damper elements values and left with the sound-bore open.

It is then possible using Eq. 3.5 to compute the damper attenuation contribution for every of the eight filtering elements (including open sound-bore); this is illustrated in Fig. 12.

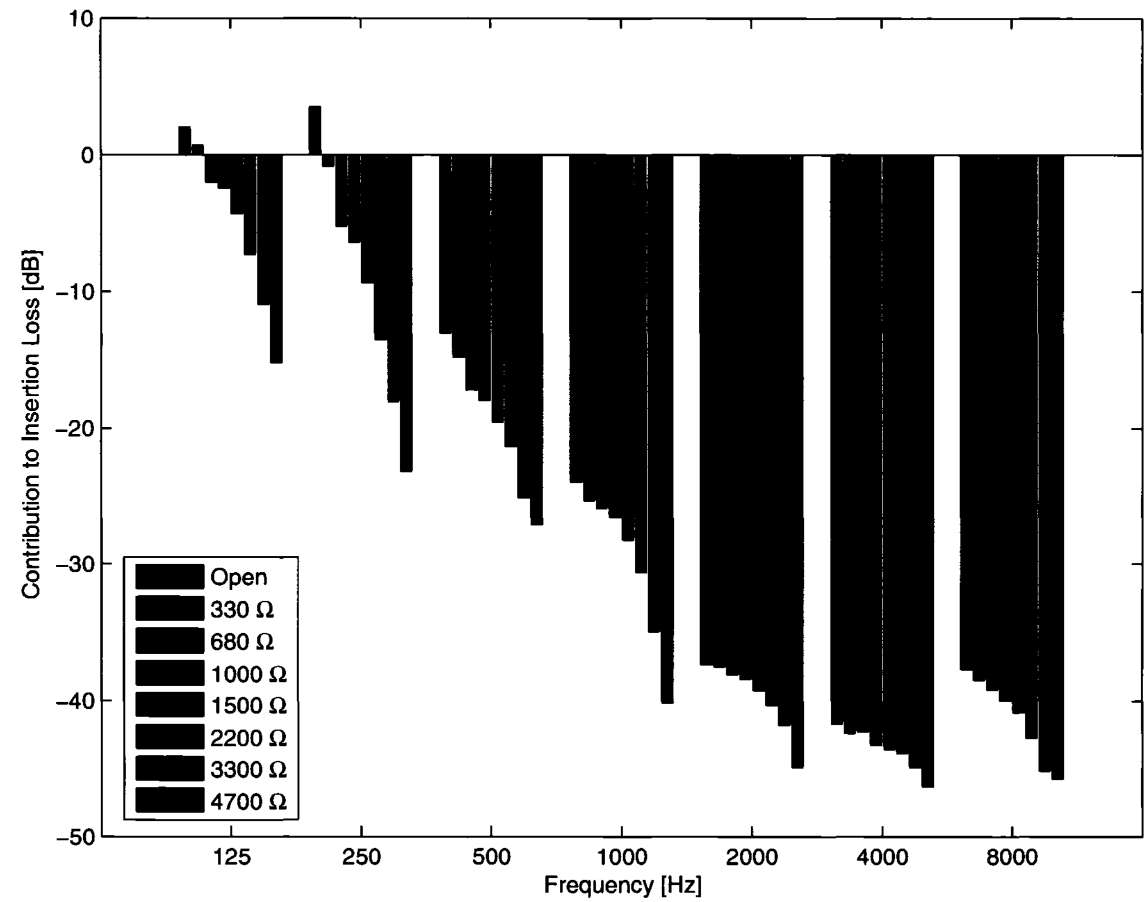



Figure 12 Octave-band Contribution to Insertion Loss of the earplug for the Full-block, the seven dampers and the open sound-bore conditions

### 3.3.2.2 Relationship between acoustical resistance and attenuation

The attenuation (Insertion Loss) of the filtered earplug can be plotted as a function of the damper nominal acoustical resistance value. The linear relation between both quantities is clearly visible in Fig. 13.

It is then 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. Fig. 14 was obtained by removing the initial offset of the previous regression lines in order

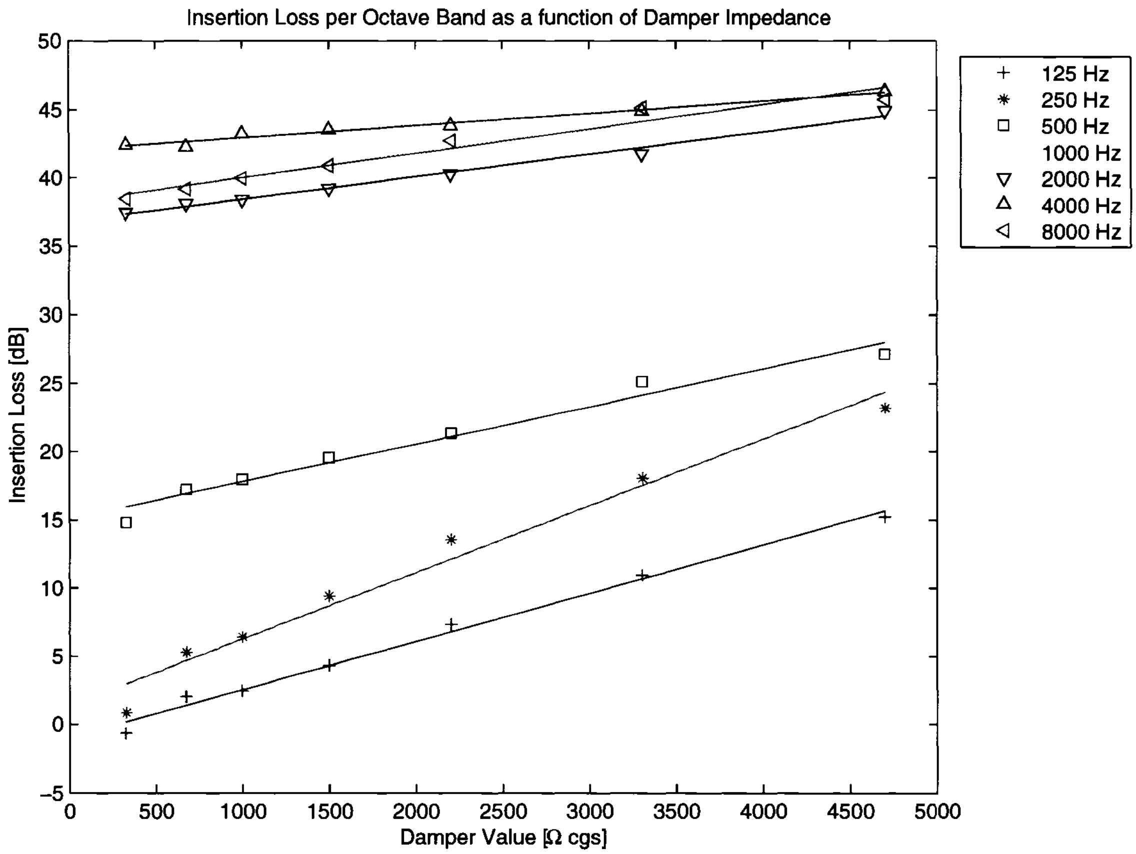



Figure 13 Linear regression curves between the attenuation and the nominal acoustical resistance, for the seven dampers used for the octave-bands from 125 Hz to 8 kHz

to more easily compare their slopes. It can be seen in Fig. 14 that the slopes are generally larger for low frequencies than for high frequencies.

The slopes, in dB/m Ω, of the linear regression curves between the attenuation versus the nominal acoustical resistance are presented in Table VII.

### 3.3.2.3 Variability of the damper attenuation

The manufacturer of the damper elements is insuring[3] the relative tolerances on the acoustical resistance given in Table VIII. Knowing the previous relation between attenuation

[3]From: "Outline and Performance Specification Index", Knowles Electronics Inc. Itasca, U.S.A., June 30th, 1994"

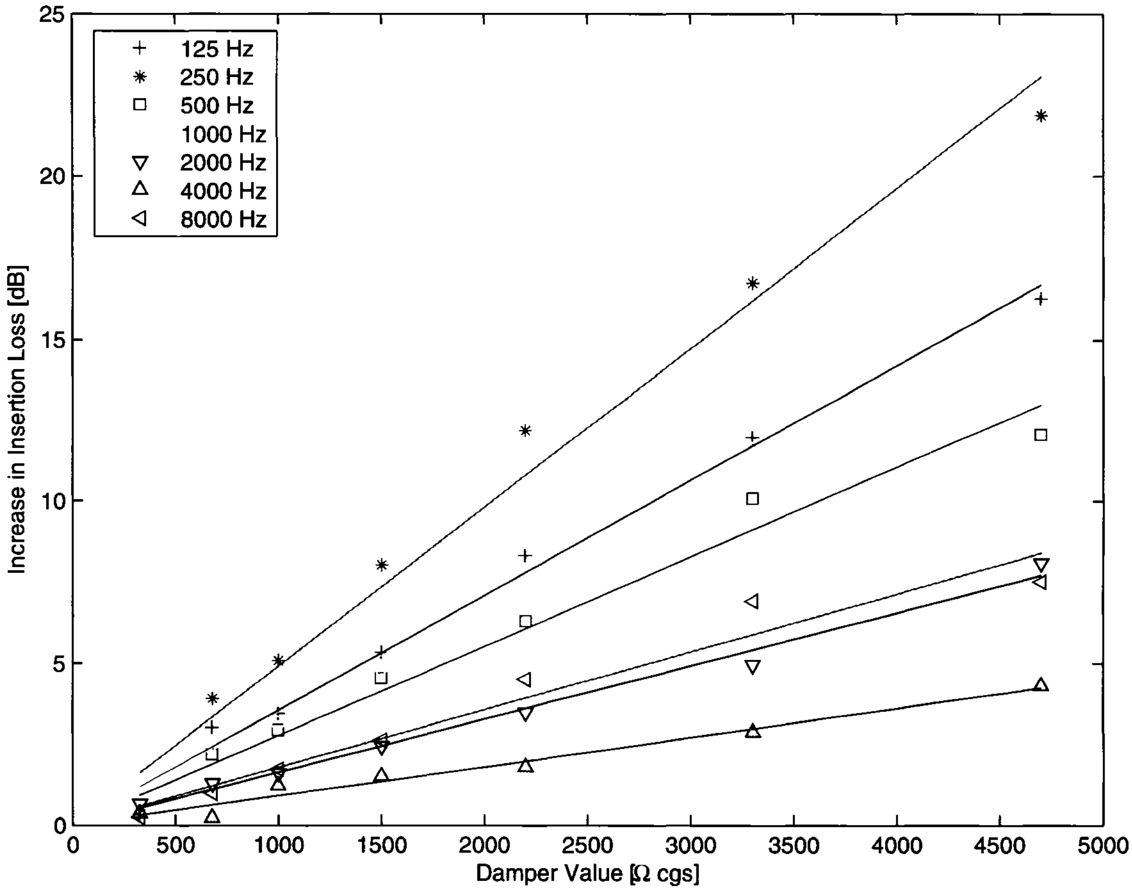



Figure 14 Illustration of the variation in the slopes of the regression curves between the attenuation and the nominal acoustical resistance

Table VII

Slopes of the linear regression curves between the attenuation contribution (Insertion Loss) and the acoustical resistance of the seven dampers per octave-bands.

| **Frequency** [Hz] | **Slope [dB/$m\Omega$]** |
|---|---|
| **125** | 3.55 |
| **250** | 4.91 |
| **500** | 2.76 |
| **1000** | 3.49 |
| **2000** | 1.64 |
| **4000** | 0.90 |
| **8000** | 1.79 |

and acoustical resistance, it is possible to link the variability of the acoustical resistance to the variability in the attenuation contribution of the damper.

Table VIII

Tolerance on the acoustical dampers nominal resistance values

| Model | Color | Acoustic Resistance [Ω cgs] | Tolerance [%] |
|---|---|---|---|
| BF-1923 | Yellow | 4700 | 20 |
| BF-1921 | Red | 2200 | 20 |
| BF-1860 | Brown | 1000 | 15 |
| BF-1999 | Grey | 330 | 15 |

The variability in attenuation contribution caused by the variability of acoustical resistance are presented in Table IX.

Table IX

Uncertainty in attenuation contribution caused by the variability of acoustical resistance for the seven available dampers (in dB).

| **Frequency** | **330 Ω** | **1000 Ω** | **2200 Ω** | **4700 Ω** |
|---|---|---|---|---|
| **125** | 0.2 | 0.5 | 1.6 | 3.3 |
| **250** | 0.2 | 0.7 | 2.2 | 4.6 |
| **500** | 0.1 | 0.4 | 1.2 | 2.6 |
| **1000** | 0.2 | 0.5 | 1.5 | 3.3 |
| **2000** | 0.1 | 0.2 | 0.7 | 1.5 |
| **4000** | 0.0 | 0.1 | 0.4 | 0.8 |
| **8000** | 0.1 | 0.3 | 0.8 | 1.7 |

### 3.3.3 Analysis of the uncertainty sources

The uncertainty associated with the prediction model, denoted $u_{Prediction}$ has been estimated from the standard deviation of the prediction error $ERR_Prediction$ and is presented in Table V and VI, for the "per test trial" and "per subject average" analyses. This prediction uncertainty contains the variability of the method caused by the use of an averaged damper attenuation contribution rather than the individual value. It does also contain the variability induced by the tolerances in the acoustical resistance, since the dampers used during the assessment of this prediction error - described in 3.2.3.1 - were taken out of a normal production lots. The prediction uncertainty $u_{Prediction}$ can be therefore expressed by the following quadratic summation:

$$u_{Prediction} = \sqrt{(u^2_{Resistance} + u^2_{Method})} \tag{3.8}$$

It is possible to use Eq. 3.8 to obtain the value of the method uncertainty independently from the damper variability:

$$u_{Method} = \sqrt{(u^2_{Prediction} - u^2_{Resistance})} \tag{3.9}$$

According to Eq. 3.9, $u_{Method}$ is given in Table X for the "per subject average" analysis that was adopted.

Table X

$u_{Method}$ for the "per subject average" analysis (in dB).

| **Frequency** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **4700 Ω** | - | - | - | - | 2.0 | 1.8 | 3.0 |
| **2200 Ω** | 2.2 | 2.1 | 2.3 | 1.1 | 2.4 | 2.9 | 4.3 |
| **1000 Ω** | 2.6 | 2.7 | 2.7 | 2.4 | 2.0 | 1.2 | 3.9 |
| **330 Ω** | 2.5 | 3.5 | 3.3 | 1.9 | 3.1 | 2.6 | 4.4 |

It can be seen that the uncertainty values found for $u_{Method}$ are close to the values found for the standard deviation of the damper attenuation contribution $u_{Damper}$, as presented in Tables III and IV at the exception of the 4700 Ω damper, for which the uncertainty associated with the acoustical resistance variability is too large (most probably overestimated by the manufacturer) as it is bigger than the prediction uncertainty $u_{Method}$ of which it is only a component. This tends to prove that most of the prediction error actually comes from the uncertainty associated with the method itself and the fact that an averaged value of damper attenuation contribution is used, with no consideration for the wearer's protected ear acoustical characteristics.

## 3.4 Experimental Validation of the Prediction Model

The model aims to predict the attenuation of the filtered earplug, $ATT_{Combo}$ from the blocked earplug attenuation $ATT_{Earplug}$. As mentioned in the Introduction, in the proposed implementation of this method, this $ATT_{Earplug}$ value comes from an objective measurement of the NR rather than a psychophysical REAT test. The main ideas of this experimental validation is to compare the predicted attenuation values of the filtered earplug and the REAT values actually reported by human test subjects. The predicted values are obtained from a measurement system (dubbed SONOPASS$^{TM}$) that performs the NR-based estimation of the earplug attenuation and computes the predicted filtered earplug attenuation using the proposed model. The REAT values are measured (per the AS1270 [17] standard) by an independent third-party laboratory that do also run the above mentioned measurement system on each human subject tested.

### 3.4.1 Experimental process

The experimental process followed by the independent third-party laboratory is detailled below:

1. The test subject is self-fitted with a pair of filtered earplugs, following AS1270 procedure;
2. The subject is tested for REAT in the sound booth, following AS1270 procedure;
3. The subject exits the sound booth, without touching the earplugs (in order to get valid results, the fit of the earplug itself has to remain the same between the REAT and NR measurements);

4. The two damper elements are removed by the experimenter, while both earplugs remain in the subject's ears. In the event that the removal of the filter is not successful, the test has to be restarted from the beginning (ref. step (1));
5. The microphone probe is placed, by the experimenter, inside the sound-bores of the right earplug, while both earplugs remains in the ear;
6. The NR measurement is performed with the SONOPASS™ measurement system on the right earplug and the predicted values of the filtered earplug attenuation is printed, properly identified and signed[4] by the laboratory experimenter;
7. The microphone probe is removed by the experimenter, from the sound-bore of the right earplug;
8. Steps 5 to 7 are repeated for the left earplug;
9. Both earplugs are removed from the subject's ears;
10. Another damper is introduced in the sound-bores of both earplugs. Back to step (2).

### 3.4.2 Experimental Data Reported

All the data collected during the experimental validation is presented in Appendix 3.e:

- Table LIV contains the audiograms. As per AS1270 standard, the 5 subjects are not allowed to have hearing thresholds greater than 20 dB HL at each test frequency (from 125 Hz to 8000 Hz).
- Tables LV, LVI, LVII and LVIII contain the REAT attenuation data for the 4700 $\Omega$ Filter as measured per AS1270 standard on the 5 subjects.

[4]Given the importance of accurate, reliable and trusted data for the experimental validation of the proposed approach, the experimental data collected during those tests has been made available for public review. See American Institute of Physics Electronic Physics Auxiliary Publication Service (EPAPS) Document No. ????? for an electronic version of the third-party laboratory report. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html)

- The NR-based attenuation data that has been predicted by the measurement system and signed-off by a third party is reported in the Tables LIX to LXII.

The predicted attenuation in the Tables LIX–LXII is a monaural estimation. Given that the REAT measurement (presented in Tables LV–LVIII) is binaural and that a single value is reported by the test subjects, a relation has to be established between the left and right NR measurement value and the single REAT value. It has been found [10] that an approach based on the Protected Hearing Threshold gives the best correlation between subjective REAT data and objective NR measurements. Such approach considers that the test subject will be able to detect the audio stimulus (i.e. the test signal used for the hearing threshold determination) through the ear that is presenting a combination of worst HPD attenuation and best hearing level. In practice, this approach consists of computing the protected hearing threshold for each ear by adding the respective hearing thresholds level $A_{\mathrm{R}}$ and $A_{\mathrm{L}}$ of the test subject to the right and left corrected Noise Reduction denoted $\mathrm{NR}_{(\mathrm{R})}$ and $\mathrm{NR}_{(\mathrm{L})}$; the equivalent binaural NR value to be used, denoted $\mathrm{NR}_{(\mathrm{B})}$, is the one that corresponds to the weakest protected threshold. The decision process for ${\mathrm{NR}_{(\mathrm{B})}}^i$ value determination is illustrated by the following relationship:

$$\begin{cases} \mathrm{NR}_{(\mathrm{B})} = {\mathrm{NR}_{(\mathrm{L})}}^i \\ \text{ if } \left({\mathrm{NR}_{(\mathrm{L})}}^i + A^i_{(\mathrm{L})}\right) < \left({\mathrm{NR}_{(\mathrm{R})}}^i + A^i_{(\mathrm{R})}\right) \\ \\ \mathrm{NR}_{(\mathrm{B})} = {\mathrm{NR}_{(\mathrm{R})}}^i \\ \text{ if } \left({\mathrm{NR}_{(\mathrm{L})}}^i + A^i_{(\mathrm{L})}\right) > \left({\mathrm{NR}_{(\mathrm{R})}}^i + A^i_{(\mathrm{R})}\right) \\ \\ \mathrm{NR}_{(\mathrm{B})} = \min\left({\mathrm{NR}_{(\mathrm{L})}}^i,\ {\mathrm{NR}_{(\mathrm{R})}}^i\right) \\ \text{ if } \left({\mathrm{NR}_{(\mathrm{L})}}^i + A^i_{(\mathrm{L})}\right) = \left({\mathrm{NR}_{(\mathrm{R})}}^i + A^i_{(\mathrm{R})}\right) \end{cases} \tag{3.10}$$

This NR-based binaural predicted attenuation data $NR_{(B)}$ is presented in the Tables LXIII, LXIV, LXV and LXVI for the seven octave band frequencies and for a C-A overall value.

### 3.4.3 Validation criteria

In the case of the present experimental validation, efforts have been made to diminish the uncertainty associated with damper acoustical resistance variability, in order to only focus on the validity of the approach. To serve that purpose, two arrangements have been made:

1. the exact same set of acoustical dampers where used and re-used for all the test subjects
2. the damper elements of this special set were individually measured for their acoustical resistance (see [19] for the details) with a limited uncertainty of 5% of the reported value. These damper elements do come from a regular production batch, but are dubbed "gold samples" because their acoustical resistance, presented in Table XI, has been precisely measured rather than simply quality checked.

In such a case, the uncertainty of the prediction becomes:

$$u'_{Prediction} = \sqrt{(u^2_{Gold} + u^2_{Method})} \tag{3.11}$$

where $u_{Method}$ has been previously defined in section 3.3.1 and $u_{Gold}$ is the acoustical uncertainty associated with the measurement of the individual "gold samples" acoustical resistance, that is less than the previous uncertainty $u_{Resistance}$.

Using the measured acoustical resistance of the "gold sample" (Table XI), and the linear regression curves established in section 3.3.2.2, the damper attenuation contribution $ATT_{Damper}$ and the $u_{Gold}$ (Table XII), have been computed.

Table XI

Measured acoustical resistance of the "gold sample" (in Ω cgs)

| | **Left** | **Right** |
|---|---|---|
| **4700 Ω** | 4393.0 | 4912.0 |
| **2200 Ω** | 2164.0 | 2127.0 |
| **1000 Ω** | 972.0 | 946.0 |
| **330 Ω** | 329.0 | 334.0 |

Table XII

Uncertainty $u_{Gold}$ associated with the "gold" damper limited resistance variability (in dB)

| **Frequency** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **4700 Ω** | 1.9 | 2.7 | 1.5 | 1.9 | 0.9 | 0.5 | 1.0 |
| **2200 Ω** | 0.6 | 0.9 | 0.5 | 0.6 | 0.3 | 0.2 | 0.3 |
| **1000 Ω** | 0.4 | 0.5 | 0.3 | 0.4 | 0.2 | 0.1 | 0.2 |
| **330 Ω** | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |

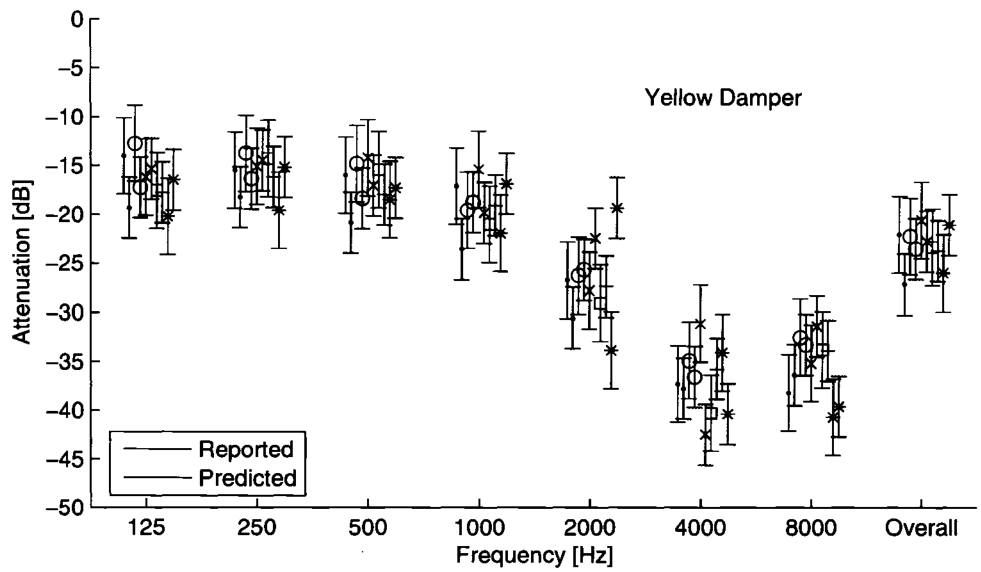
Table XIII

Uncertainty of the prediction method $u'_{Prediction}$ associated with the "gold" damper (in dB)

| **Frequency** | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **4700 Ω** | 2.5 | 3.4 | 2.6 | 1.8 | 2.6 | 2.0 | 3.5 |
| **2200 Ω** | 2.7 | 3.0 | 2.5 | 1.8 | 2.5 | 3.0 | 4.3 |
| **1000 Ω** | 2.6 | 2.8 | 2.8 | 2.4 | 2.1 | 1.2 | 3.9 |
| **330 Ω** | 2.5 | 3.5 | 3.3 | 1.9 | 3.2 | 2.6 | 4.4 |

The proposed criteria to be used for asserting the validity of the prediction method is simply that the range of predicted filtered attenuation values and the range of the reported attenuation values should overlap. The predicted filtered attenuation values have an uncertainty $u_{Prediction}$ presented in Table XIII when using the "Gold Samples". The 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 hearing of the test subjects, the uncertainty of the sound pressure level measurements, the uncertainty in the controlling attenuators, etc. From AS1270 [17], the standard uncertainty is calculated to be 2.9 dB (whatever HPD is tested). In the most recent draft of ISO 4869 [18], it is calculated to 5.4 and 6.7 dB for earmuffs and earplugs respectively. These latter uncertainty figures supplied for earmuffs and earplugs are estimated 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*". In order to raise the validation level, the value of 2.9 dB was used for $u_{REAT}$, as illustrated in graphs on Fig. 15–16. Although such value is mentioned in the AS1270 standard, it is considered to be an underestimation of the effective $u_{REAT}$ that is estimated to be 6.7 dB in the most recent draft of ISO4869.

The results are presented in Fig. 15–16 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.



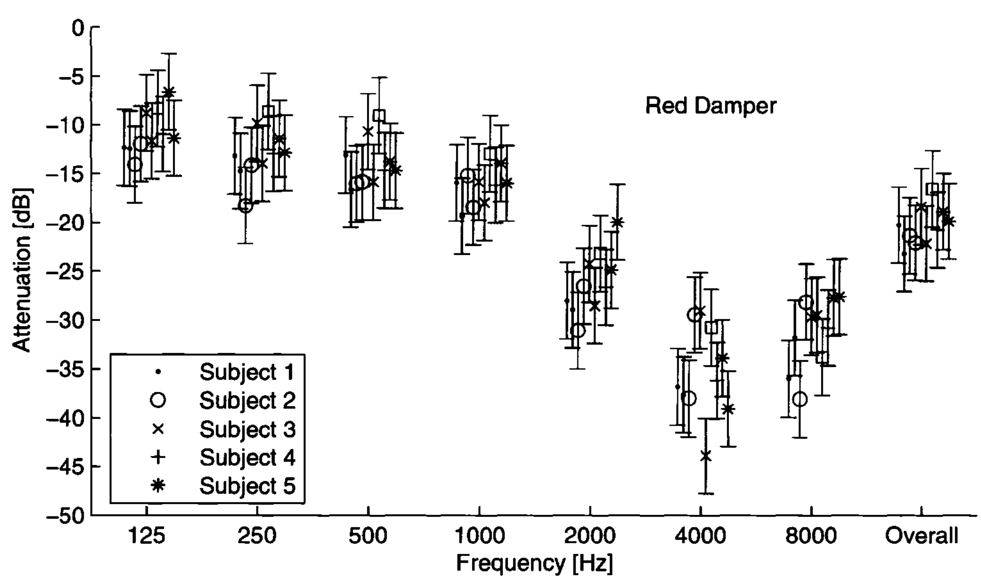




Figure 15 Predicted vs. reported attenuation for the earplug filtered with the 4700 Ω and 2200 Ω dampers

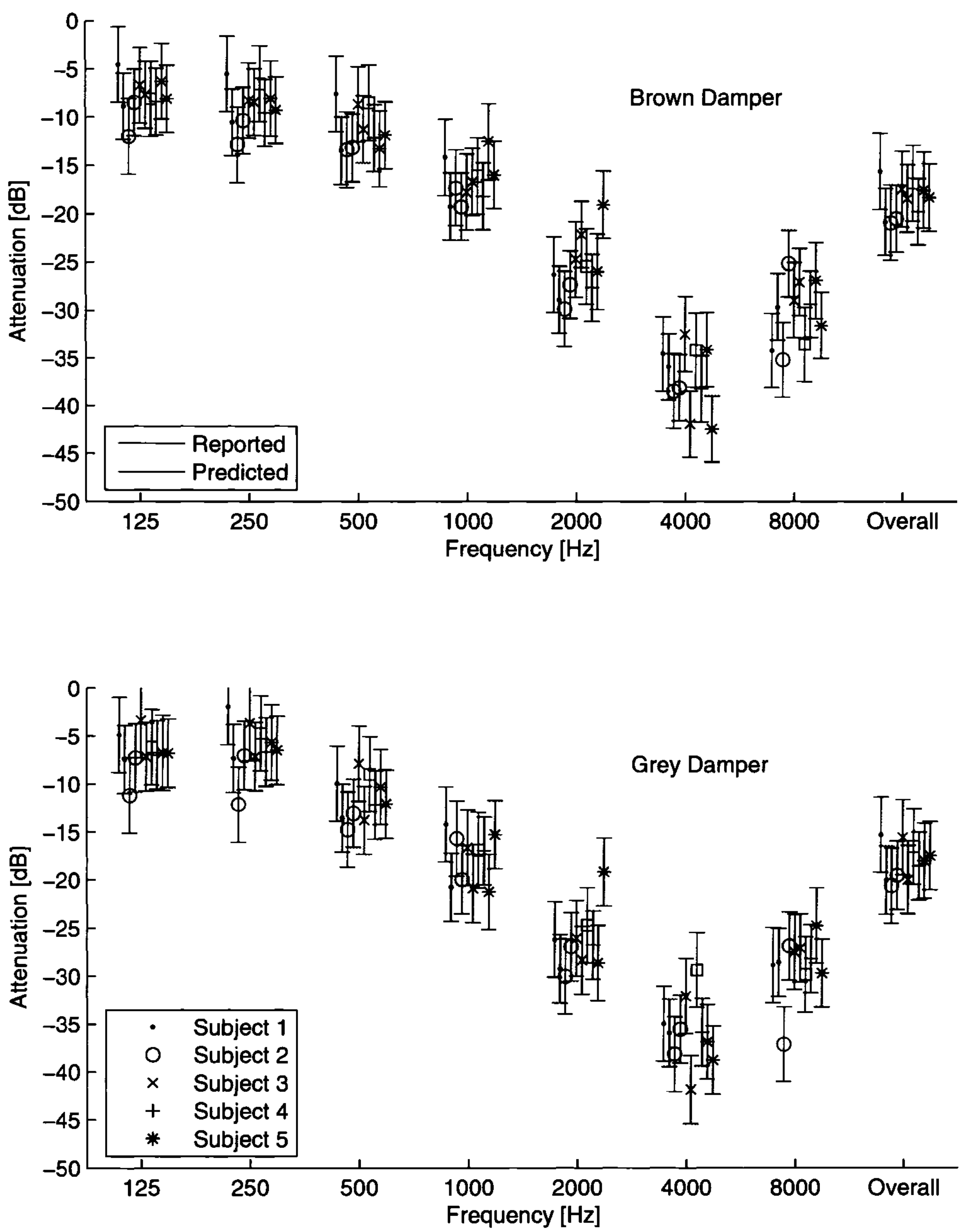



Figure 16 Predicted vs. reported attenuation for the earplug filtered with the 1000 Ω and 330 Ω dampers

### 3.5 Conclusion

A model of the filtered earplug attenuation has been built based on a transfer function representation of the sound transmission paths through a filtered earplug. The damper attenuation contribution has been empirically determined from REAT measurements on several earplugs with different acoustical dampers. The uncertainty associated with the proposed model has been evaluated. A first component, related to the variability of the damper acoustical resistance, appears to have only marginal influence. A second component, related to the fact that an averaged value of damper attenuation contribution is used, with no consideration for the wearer's protected ear acoustical characteristics, seems to be the main uncertainty contributor. An experimental validation of the proposed model was also conducted: an NR-based measurement of the earplug attenuation combined with the proposed model for the damper attenuation contribution was successfully compared with the direct REAT measurement of the filtered earplug. Overall, it appears that the uncertainty of the proposed prediction model is equal or lower than the uncertainty associated with REAT measurements. Therefore, the field implementation of the proposed method can be used for damper selection and earplug adjustment to the desired attenuation.

### 3.6 Acknowledgment

The support of Sonomax Hearing Healthcare Inc, IRSST (Quebec Occupational Health and Safety Research Institute) and NSERC (Natural Sciences and engineering Research Council of Canada) is gratefully acknowledged.

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## Appendix

### 3.a Tables from section 3.2.3

Table XIV

$ATT_{Combo}$ for the 4700 Ω damper as measured on 30 tests

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 7.2 | 14.8 | 15.5 | 14.8 | 32.1 | 34.0 | 34.1 |
| **2** | 18.1 | 17.7 | 17.7 | 15.9 | 30.8 | 35.4 | 37.8 |
| **3** | 16.2 | 21.2 | 16.9 | 20.7 | 28.9 | 28.9 | 33.1 |
| **4** | 17.9 | 14.8 | 12.3 | 17.7 | 24.1 | 36.8 | 39.6 |
| **5** | 11.8 | 14.3 | 19.8 | 16.3 | 28.7 | 38.3 | 37.5 |
| **6** | 12.5 | 17.5 | 16.1 | 17.5 | 27.5 | 36.9 | 37.6 |
| **7** | 21.9 | 21.4 | 19.5 | 20.7 | 30.5 | 39.0 | 40.5 |
| **8** | 17.0 | 20.1 | 20.8 | 20.9 | 29.2 | 37.1 | 34.3 |
| **9** | 22.0 | 20.8 | 18.5 | 19.1 | 32.0 | 38.7 | 42.1 |
| **10** | 11.6 | 14.9 | 15.1 | 21.5 | 26.3 | 36.8 | 34.4 |
| **11** | 13.3 | 12.0 | 17.3 | 19.2 | 28.9 | 35.4 | 30.1 |
| **12** | 13.5 | 14.5 | 12.2 | 18.2 | 23.7 | 32.6 | 33.2 |
| **13** | 18.5 | 15.6 | 15.7 | 18.7 | 28.1 | 37.3 | 41.6 |
| **14** | 14.9 | 16.5 | 16.7 | 23.0 | 23.5 | 36.7 | 41.9 |
| **15** | 16.9 | 17.8 | 18.3 | 22.0 | 21.5 | 34.3 | 40.3 |
| **16** | 18.1 | 20.3 | 16.5 | 12.7 | 25.8 | 35.7 | 44.2 |
| **17** | 13.1 | 26.6 | 14.0 | 25.4 | 16.8 | 32.3 | 48.2 |
| **18** | 18.4 | 20.5 | 16.7 | 13.7 | 20.1 | 36.5 | 41.5 |
| **19** | 15.8 | 16.1 | 17.6 | 18.3 | 30.2 | 34.8 | 33.0 |
| **20** | 14.8 | 13.5 | 8.3 | 9.1 | 26.3 | 29.5 | 37.9 |
| **21** | 18.2 | 15.8 | 16.9 | 18.9 | 27.0 | 29.2 | 34.7 |
| **22** | 21.7 | 13.9 | 11.5 | 19.6 | 27.5 | 37.0 | 32.1 |
| **23** | 14.0 | 12.2 | 19.0 | 21.6 | 27.3 | 43.5 | 34.6 |
| **24** | 17.1 | 16.9 | 15.9 | 22.0 | 32.5 | 40.4 | 34.7 |
| **25** | 19.5 | 18.1 | 19.1 | 21.5 | 34.8 | 34.9 | 39.2 |
| **26** | 21.1 | 17.4 | 18.5 | 23.8 | 35.4 | 34.5 | 41.2 |
| **27** | 20.2 | 23.4 | 18.0 | 20.6 | 31.4 | 32.9 | 41.7 |
| **28** | 15.2 | 14.5 | 19.0 | 19.8 | 29.9 | 35.5 | 36.0 |
| **29** | 16.3 | 16.5 | 22.3 | 20.6 | 29.5 | 38.0 | 33.2 |
| **30** | 13.1 | 19.6 | 20.8 | 20.9 | 29.3 | 34.2 | 34.0 |

Table XV

$ATT_{Earplug}$ for the 4700 Ω damper as measured on 30 tests

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 13.3 | 17.9 | 16.7 | 18.2 | 29.3 | 31.8 | 31.3 |
| **2** | 16.6 | 18.2 | 19.8 | 21.1 | 32.5 | 35.5 | 31.6 |
| **3** | 15.8 | 16.4 | 14.9 | 20.7 | 31.4 | 31.6 | 31.2 |
| **4** | 27.7 | 26.6 | 22.4 | 17.8 | 33.8 | 32.2 | 42.3 |
| **5** | 24.4 | 23.6 | 13.3 | 22.1 | 33.5 | 40.0 | 43.0 |
| **6** | 27.0 | 22.0 | 16.3 | 24.9 | 34.1 | 40.2 | 43.3 |
| **7** | 25.9 | 22.0 | 21.3 | 21.0 | 36.1 | 35.6 | 52.1 |
| **8** | 24.9 | 23.5 | 23.1 | 18.5 | 35.2 | 43.0 | 50.0 |
| **9** | 23.2 | 27.1 | 24.9 | 20.7 | 37.1 | 39.9 | 45.5 |
| **10** | 20.8 | 22.1 | 20.3 | 23.8 | 30.3 | 29.1 | 43.8 |
| **11** | 26.0 | 22.8 | 22.7 | 22.7 | 29.6 | 36.6 | 37.3 |
| **12** | 23.3 | 23.3 | 23.1 | 23.3 | 35.6 | 41.9 | 39.4 |
| **13** | 24.4 | 21.1 | 17.7 | 24.5 | 32.8 | 36.4 | 46.0 |
| **14** | 17.0 | 20.8 | 20.0 | 20.4 | 31.8 | 36.3 | 44.7 |
| **15** | 20.7 | 21.3 | 22.6 | 24.1 | 26.9 | 33.4 | 45.5 |
| **16** | 23.7 | 17.0 | 15.3 | 15.8 | 26.3 | 40.0 | 50.4 |
| **17** | 15.5 | 20.5 | 13.2 | 18.5 | 25.1 | 39.5 | 48.3 |
| **18** | 15.1 | 23.5 | 9.9 | 16.7 | 25.5 | 35.6 | 53.2 |
| **19** | 24.2 | 23.5 | 24.0 | 20.1 | 35.1 | 36.1 | 44.0 |
| **20** | 26.7 | 28.2 | 23.1 | 22.2 | 36.5 | 38.7 | 47.7 |
| **21** | 22.0 | 23.7 | 20.5 | 18.2 | 32.2 | 34.2 | 44.0 |
| **22** | 24.7 | 25.8 | 31.3 | 29.2 | 36.5 | 45.5 | 42.8 |
| **23** | 24.0 | 27.8 | 32.1 | 25.4 | 37.4 | 39.5 | 43.5 |
| **24** | 21.8 | 28.6 | 22.2 | 24.1 | 33.1 | 38.2 | 41.8 |
| **25** | 32.0 | 30.4 | 29.0 | 33.5 | 38.2 | 38.6 | 43.0 |
| **26** | 28.5 | 21.5 | 21.7 | 29.8 | 40.4 | 39.1 | 41.4 |
| **27** | 21.3 | 22.3 | 18.5 | 22.8 | 33.5 | 36.1 | 44.1 |
| **28** | 17.4 | 22.0 | 23.0 | 22.1 | 35.0 | 36.9 | 42.7 |
| **29** | 13.2 | 13.5 | 16.7 | 21.6 | 32.6 | 32.9 | 28.7 |
| **30** | 20.7 | 22.2 | 23.8 | 22.7 | 34.4 | 37.3 | 38.0 |

Table XVI

$ATT_{Combo}$ for the 2200 Ω damper as measured on 24 tests

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 16.1 | 15.3 | 15.9 | 15.7 | 29.2 | 33.7 | 33.3 |
| **2** | 9.9 | 10.6 | 11.0 | 14.5 | 27.9 | 36.8 | 37.8 |
| **3** | 11.1 | 13.9 | 12.6 | 17.8 | 27.2 | 40.1 | 37.1 |
| **4** | 13.3 | 17.5 | 14.7 | 12.2 | 28.4 | 38.6 | 33.0 |
| **5** | 15.7 | 19.0 | 16.4 | 17.5 | 32.1 | 36.3 | 41.2 |
| **6** | 13.4 | 18.5 | 17.2 | 16.1 | 32.9 | 39.3 | 40.2 |
| **7** | 9.9 | 9.9 | 11.6 | 15.4 | 23.8 | 32.5 | 36.4 |
| **8** | 4.8 | 9.7 | 7.9 | 17.3 | 21.6 | 31.1 | 28.6 |
| **9** | 11.8 | 10.1 | 12.7 | 15.0 | 27.6 | 23.6 | 24.2 |
| **10** | 8.8 | 9.4 | 11.5 | 14.5 | 27.1 | 30.4 | 37.2 |
| **11** | 10.2 | 8.8 | 9.0 | 14.6 | 26.5 | 34.0 | 32.1 |
| **12** | 6.1 | 7.8 | 6.8 | 10.0 | 16.1 | 27.9 | 32.2 |
| **13** | 8.1 | 10.8 | 17.0 | 14.0 | 24.8 | 33.3 | 26.9 |
| **14** | 7.1 | 11.2 | 12.4 | 16.3 | 24.6 | 34.5 | 29.9 |
| **15** | 4.7 | 12.4 | 12.0 | 11.6 | 25.3 | 34.0 | 26.5 |
| **16** | 11.9 | 12.0 | 13.1 | 20.0 | 25.8 | 40.4 | 28.2 |
| **17** | 7.1 | 12.6 | 13.4 | 16.1 | 26.1 | 37.0 | 26.0 |
| **18** | 10.3 | 8.3 | 12.5 | 18.0 | 28.8 | 44.1 | 25.1 |
| **19** | 7.4 | 15.1 | 18.3 | 19.9 | 31.0 | 33.1 | 38.0 |
| **20** | 9.7 | 10.0 | 11.5 | 15.9 | 29.8 | 35.2 | 34.9 |
| **21** | 8.2 | 10.6 | 13.0 | 14.2 | 27.8 | 28.7 | 37.1 |
| **22** | 16.1 | 15.9 | 13.4 | 16.5 | 30.8 | 34.5 | 26.5 |
| **23** | 12.0 | 12.1 | 17.9 | 22.6 | 29.2 | 35.2 | 31.2 |
| **24** | 10.6 | 15.0 | 19.9 | 18.6 | 29.2 | 36.7 | 29.6 |

Table XVII

$ATT_{Earplug}$ for the 2200 Ω damper as measured on 24 tests

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 27.7 | 26.6 | 22.4 | 17.8 | 33.8 | 32.2 | 42.3 |
| **2** | 24.4 | 23.6 | 13.3 | 22.1 | 33.5 | 40.0 | 43.0 |
| **3** | 27.0 | 22.0 | 16.3 | 24.9 | 34.1 | 40.2 | 43.3 |
| **4** | 25.9 | 22.0 | 21.3 | 21.0 | 36.1 | 35.6 | 52.1 |
| **5** | 24.9 | 23.5 | 23.1 | 18.5 | 35.2 | 43.0 | 50.0 |
| **6** | 23.2 | 27.1 | 24.9 | 20.7 | 37.1 | 39.9 | 45.5 |
| **7** | 20.8 | 22.1 | 20.3 | 23.8 | 30.3 | 29.1 | 43.8 |
| **8** | 26.0 | 22.8 | 22.7 | 22.7 | 29.6 | 36.6 | 37.3 |
| **9** | 23.3 | 23.3 | 23.1 | 23.3 | 35.6 | 41.9 | 39.4 |
| **10** | 24.4 | 21.1 | 17.7 | 24.5 | 32.8 | 36.4 | 46.0 |
| **11** | 17.0 | 20.8 | 20.0 | 20.4 | 31.8 | 36.3 | 44.7 |
| **12** | 20.7 | 21.3 | 22.6 | 24.1 | 26.9 | 33.4 | 45.5 |
| **13** | 24.2 | 23.5 | 24.0 | 20.1 | 35.1 | 36.1 | 44.0 |
| **14** | 26.7 | 28.2 | 23.1 | 22.2 | 36.5 | 38.7 | 47.7 |
| **15** | 22.0 | 23.7 | 20.5 | 18.2 | 32.2 | 34.2 | 44.0 |
| **16** | 24.7 | 25.8 | 31.3 | 29.2 | 36.5 | 45.5 | 42.8 |
| **17** | 24.0 | 27.8 | 32.1 | 25.4 | 37.4 | 39.5 | 43.5 |
| **18** | 21.8 | 28.6 | 22.2 | 24.1 | 33.1 | 38.2 | 41.8 |
| **19** | 32.0 | 30.4 | 29.0 | 33.5 | 38.2 | 38.6 | 43.0 |
| **20** | 28.5 | 21.5 | 21.7 | 29.8 | 40.4 | 39.1 | 41.4 |
| **21** | 21.3 | 22.3 | 18.5 | 22.8 | 33.5 | 36.1 | 44.1 |
| **22** | 17.4 | 22.0 | 23.0 | 22.1 | 35.0 | 36.9 | 42.7 |
| **23** | 13.2 | 13.5 | 16.7 | 21.6 | 32.6 | 32.9 | 28.7 |
| **24** | 20.7 | 22.2 | 23.8 | 22.7 | 34.4 | 37.3 | 38.0 |

Table XVIII

$ATT_{Combo}$ for the 330 Ω damper as measured on 21 tests

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 5.5 | 1.7 | 10.2 | 15.0 | 27.0 | 37.4 | 30.8 |
| **2** | 3.1 | 0.1 | 9.9 | 13.5 | 28.1 | 35.1 | 27.5 |
| **3** | 6.2 | 4.3 | 9.9 | 14.3 | 23.7 | 32.6 | 28.4 |
| **4** | 12.0 | 10.5 | 13.3 | 16.9 | 29.4 | 36.4 | 40.3 |
| **5** | 10.3 | 12.9 | 14.7 | 16.9 | 30.8 | 37.9 | 36.9 |
| **6** | 11.4 | 13.2 | 16.4 | 13.4 | 30.1 | 40.3 | 34.3 |
| **7** | 7.1 | 4.7 | 6.5 | 19.8 | 30.7 | 32.7 | 28.8 |
| **8** | 0.2 | 4.4 | 12.9 | 15.9 | 26.6 | 34.3 | 25.1 |
| **9** | 2.9 | 2.1 | 4.4 | 14.4 | 21.1 | 29.4 | 28.7 |
| **10** | 2.9 | 6.7 | 11.2 | 19.0 | 26.1 | 32.2 | 31.3 |
| **11** | 7.4 | 1.7 | 4.5 | 16.0 | 25.1 | 28.8 | 29.3 |
| **12** | 8.2 | 5.9 | 11.4 | 15.8 | 23.1 | 27.2 | 29.0 |
| **13** | 0.7 | 3.9 | 12.7 | 13.8 | 29.0 | 36.2 | 26.4 |
| **14** | 0.7 | 7.0 | 13.8 | 9.9 | 30.4 | 37.1 | 22.7 |
| **15** | 12.5 | 12.7 | 22.1 | 31.5 | 46.2 | 40.9 | 31.8 |
| **16** | 6.2 | 3.3 | 5.4 | 18.3 | 27.8 | 35.2 | 23.2 |
| **17** | 8.6 | 5.0 | 8.4 | 22.4 | 30.0 | 36.9 | 23.8 |
| **18** | 5.5 | 8.8 | 17.3 | 23.1 | 28.2 | 38.6 | 27.2 |
| **19** | 2.6 | 6.3 | 15.4 | 18.9 | 27.5 | 35.8 | 27.9 |
| **20** | 7.6 | 10.5 | 14.1 | 15.4 | 28.3 | 34.2 | 20.4 |
| **21** | 3.9 | 11.2 | 15.9 | 17.6 | 32.0 | 35.1 | 21.0 |

Table XIX

$ATT_{Earplug}$ for the 330 Ω damper as measured on 21 tests

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 27.7 | 26.6 | 22.4 | 17.8 | 33.8 | 32.2 | 42.3 |
| **2** | 24.4 | 23.6 | 13.3 | 22.1 | 33.5 | 40.0 | 43.0 |
| **3** | 27.0 | 22.0 | 16.3 | 24.9 | 34.1 | 40.2 | 43.3 |
| **4** | 25.9 | 22.0 | 21.3 | 21.0 | 36.1 | 35.6 | 52.1 |
| **5** | 24.9 | 23.5 | 23.1 | 18.5 | 35.2 | 43.0 | 50.0 |
| **6** | 23.2 | 27.1 | 24.9 | 20.7 | 37.1 | 39.9 | 45.5 |
| **7** | 20.8 | 22.1 | 20.3 | 23.8 | 30.3 | 29.1 | 43.8 |
| **8** | 26.0 | 22.8 | 22.7 | 22.7 | 29.6 | 36.6 | 37.3 |
| **9** | 23.3 | 23.3 | 23.1 | 23.3 | 35.6 | 41.9 | 39.4 |
| **10** | 24.4 | 21.1 | 17.7 | 24.5 | 32.8 | 36.4 | 46.0 |
| **11** | 17.0 | 20.8 | 20.0 | 20.4 | 31.8 | 36.3 | 44.7 |
| **12** | 20.7 | 21.3 | 22.6 | 24.1 | 26.9 | 33.4 | 45.5 |
| **13** | 24.2 | 23.5 | 24.0 | 20.1 | 35.1 | 36.1 | 44.0 |
| **14** | 26.7 | 28.2 | 23.1 | 22.2 | 36.5 | 38.7 | 47.7 |
| **15** | 22.0 | 23.7 | 20.5 | 18.2 | 32.2 | 34.2 | 44.0 |
| **16** | 24.7 | 25.8 | 31.3 | 29.2 | 36.5 | 45.5 | 42.8 |
| **17** | 24.0 | 27.8 | 32.1 | 25.4 | 37.4 | 39.5 | 43.5 |
| **18** | 21.8 | 28.6 | 22.2 | 24.1 | 33.1 | 38.2 | 41.8 |
| **19** | 17.4 | 22.0 | 23.0 | 22.1 | 35.0 | 36.9 | 42.7 |
| **20** | 13.2 | 13.5 | 16.7 | 21.6 | 32.6 | 32.9 | 28.7 |
| **21** | 20.7 | 22.2 | 23.8 | 22.7 | 34.4 | 37.3 | 38.0 |

Table XX

$ATT_{Combo}$ for the 1000 Ω damper as measured on 21 tests

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | -2.1 | 3.5 | 5.6 | 12.5 | 27.8 | 32.6 | 33.9 |
| **2** | 7.1 | 3.7 | 6.2 | 15.1 | 25.4 | 38.8 | 34.1 |
| **3** | 8.8 | 9.5 | 11.2 | 15.1 | 25.9 | 32.5 | 34.8 |
| **4** | 13.6 | 13.5 | 14.5 | 22.0 | 31.0 | 35.9 | 36.3 |
| **5** | 11.4 | 13.4 | 13.5 | 14.9 | 28.6 | 39.8 | 34.8 |
| **6** | 11.1 | 11.8 | 12.3 | 15.2 | 30.2 | 39.9 | 34.6 |
| **7** | 5.2 | 8.5 | 7.7 | 14.4 | 25.6 | 31.7 | 29.3 |
| **8** | 8.7 | 10.6 | 12.2 | 19.5 | 24.8 | 33.8 | 28.7 |
| **9** | 6.3 | 6.0 | 6.3 | 19.5 | 24.0 | 32.2 | 29.0 |
| **10** | 5.7 | -1.0 | 6.0 | 15.8 | 28.4 | 35.7 | 35.5 |
| **11** | 8.1 | 12.9 | 12.2 | 19.0 | 24.0 | 35.0 | 35.0 |
| **12** | 10.6 | 7.9 | 7.5 | 13.6 | 24.1 | 32.0 | 30.3 |
| **13** | 5.3 | 8.9 | 12.2 | 18.5 | 27.9 | 31.5 | 26.5 |
| **14** | 7.6 | 10.1 | 15.0 | 12.8 | 25.2 | 33.1 | 27.8 |
| **15** | 6.0 | 5.4 | 12.7 | 6.4 | 25.0 | 37.9 | 26.5 |
| **16** | 5.6 | 8.4 | 8.1 | 20.1 | 29.3 | 43.4 | 24.3 |
| **17** | 3.8 | 8.4 | 16.1 | 19.8 | 27.7 | 35.6 | 25.1 |
| **18** | 5.5 | 9.3 | 13.4 | 18.0 | 25.8 | 35.7 | 26.3 |
| **19** | 6.1 | 8.8 | 12.4 | 19.4 | 32.7 | 36.1 | 30.9 |
| **20** | 9.8 | 16.0 | 17.6 | 22.8 | 31.1 | 36.3 | 25.8 |
| **21** | 11.2 | 12.6 | 15.3 | 18.5 | 29.1 | 34.5 | 25.1 |

Table XXI

$ATT_{Earplug}$ for the 1000 $\Omega$ damper as measured on 21 tests

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 27.7 | 26.6 | 22.4 | 17.8 | 33.8 | 32.2 | 42.3 |
| **2** | 24.4 | 23.6 | 13.3 | 22.1 | 33.5 | 40.0 | 43.0 |
| **3** | 27.0 | 22.0 | 16.3 | 24.9 | 34.1 | 40.2 | 43.3 |
| **4** | 25.9 | 22.0 | 21.3 | 21.0 | 36.1 | 35.6 | 52.1 |
| **5** | 24.9 | 23.5 | 23.1 | 18.5 | 35.2 | 43.0 | 50.0 |
| **6** | 23.2 | 27.1 | 24.9 | 20.7 | 37.1 | 39.9 | 45.5 |
| **7** | 20.8 | 22.1 | 20.3 | 23.8 | 30.3 | 29.1 | 43.8 |
| **8** | 26.0 | 22.8 | 22.7 | 22.7 | 29.6 | 36.6 | 37.3 |
| **9** | 23.3 | 23.3 | 23.1 | 23.3 | 35.6 | 41.9 | 39.4 |
| **10** | 24.4 | 21.1 | 17.7 | 24.5 | 32.8 | 36.4 | 46.0 |
| **11** | 17.0 | 20.8 | 20.0 | 20.4 | 31.8 | 36.3 | 44.7 |
| **12** | 20.7 | 21.3 | 22.6 | 24.1 | 26.9 | 33.4 | 45.5 |
| **13** | 24.2 | 23.5 | 24.0 | 20.1 | 35.1 | 36.1 | 44.0 |
| **14** | 26.7 | 28.2 | 23.1 | 22.2 | 36.5 | 38.7 | 47.7 |
| **15** | 22.0 | 23.7 | 20.5 | 18.2 | 32.2 | 34.2 | 44.0 |
| **16** | 24.7 | 25.8 | 31.3 | 29.2 | 36.5 | 45.5 | 42.8 |
| **17** | 24.0 | 27.8 | 32.1 | 25.4 | 37.4 | 39.5 | 43.5 |
| **18** | 21.8 | 28.6 | 22.2 | 24.1 | 33.1 | 38.2 | 41.8 |
| **19** | 17.4 | 22.0 | 23.0 | 22.1 | 35.0 | 36.9 | 42.7 |
| **20** | 13.2 | 13.5 | 16.7 | 21.6 | 32.6 | 32.9 | 28.7 |
| **21** | 20.7 | 22.2 | 23.8 | 22.7 | 34.4 | 37.3 | 38.0 |

## 3.b Tables from section 3.2.3.2 , "per test trial" analysis

Table XXII

$ATT_{Dampers}$ for the 4700 Ω damper as measured on 11 tests used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 12.7 | 19.4 | 29.6 | 18.4 | 28.6 | 39.6 | 39.0 |
| **2** | 28.2 | 22.0 | 19.6 | 24.2 | 33.6 | 44.9 | 44.8 |
| **3** | 13.5 | 12.4 | 18.8 | 21.8 | 37.2 | 41.6 | 31.0 |
| **4** | 14.0 | 15.1 | 12.6 | 19.8 | 24.0 | 33.1 | 34.4 |
| **5** | 16.5 | 17.0 | 18.7 | 23.0 | 31.9 | 40.7 | 33.4 |
| **6** | 15.1 | 13.6 | 8.4 | 9.3 | 26.7 | 30.1 | 38.4 |
| **7** | 24.7 | 14.2 | 11.5 | 20.1 | 28.1 | 37.7 | 32.5 |
| **8** | 19.8 | 18.4 | 19.6 | 21.8 | 37.5 | 37.3 | 41.5 |
| **9** | 22.0 | 19.5 | 21.3 | 25.1 | 37.1 | 36.3 | 54.7 |
| **10** | 19.2 | 15.4 | 21.2 | 23.7 | 31.5 | 41.1 | 37.0 |
| **11** | 13.9 | 23.1 | 23.8 | 25.6 | 30.9 | 37.1 | 36.2 |

Table XXIII

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 4700 Ω damper as measured on 11 tests used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 18.1 | 17.3 | 18.7 | 21.2 | 31.5 | 38.1 | 38.4 |
| **STD** | 5.1 | 3.5 | 5.9 | 4.5 | 4.5 | 4.1 | 6.7 |

Table XXIV

$ATT_{Dampers}$ for the 2200 $\Omega$ damper as measured on 19 tests used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 10.1 | 10.8 | 14.9 | 15.3 | 29.3 | 39.6 | 39.4 |
| **2** | 11.2 | 14.6 | 15.0 | 18.7 | 28.2 | 56.5 | 38.3 |
| **3** | 16.3 | 20.9 | 17.4 | 24.4 | 35.0 | 37.3 | 41.8 |
| **4** | 13.9 | 19.1 | 18.0 | 17.9 | 35.0 | 48.2 | 41.7 |
| **5** | 4.8 | 9.9 | 8.0 | 18.8 | 22.3 | 32.5 | 29.2 |
| **6** | 12.1 | 10.3 | 13.1 | 15.7 | 28.3 | 23.7 | 24.3 |
| **7** | 8.9 | 9.7 | 12.7 | 15.0 | 28.5 | 31.7 | 37.8 |
| **8** | 11.2 | 9.1 | 9.4 | 15.9 | 28.0 | 37.9 | 32.3 |
| **9** | 6.3 | 8.0 | 6.9 | 10.2 | 16.5 | 29.3 | 32.4 |
| **10** | 8.2 | 11.0 | 18.0 | 15.2 | 25.2 | 36.5 | 27.0 |
| **11** | 7.1 | 11.3 | 12.8 | 17.6 | 24.9 | 36.6 | 30.0 |
| **12** | 4.8 | 12.7 | 12.7 | 12.7 | 26.3 | 47.5 | 26.6 |
| **13** | 12.1 | 12.2 | 13.2 | 20.6 | 26.2 | 42.0 | 28.4 |
| **14** | 7.2 | 12.7 | 13.5 | 16.6 | 26.4 | 40.6 | 26.1 |
| **15** | 7.4 | 15.2 | 18.7 | 20.1 | 31.9 | 34.5 | 39.7 |
| **16** | 9.8 | 10.3 | 11.9 | 16.1 | 30.2 | 37.5 | 36.0 |
| **17** | 8.4 | 10.9 | 14.4 | 14.8 | 29.2 | 29.6 | 38.1 |
| **18** | 22.0 | 17.1 | 13.9 | 17.9 | 32.9 | 38.2 | 26.6 |
| **19** | 11.0 | 15.9 | 22.2 | 20.7 | 30.8 | 45.6 | 30.3 |

Table XXV

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 2200 $\Omega$ damper as measured on 19 tests used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 10.1 | 12.7 | 14.0 | 17.1 | 28.2 | 38.2 | 32.9 |
| **STD** | 4.1 | 3.5 | 3.7 | 3.2 | 4.4 | 7.7 | 5.9 |

Table XXVI

$ATT_{Dampers}$ for the 1000 $\Omega$ damper as measured on 15 subjects used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 7.2 | 3.7 | 7.1 | 16.1 | 26.1 | 45.0 | 34.7 |
| **2** | 8.9 | 9.8 | 12.8 | 15.6 | 26.6 | 33.3 | 35.5 |
| **3** | 11.6 | 13.8 | 14.0 | 17.4 | 29.7 | 42.6 | 34.9 |
| **4** | 8.8 | 10.9 | 12.6 | 22.3 | 26.5 | 37.0 | 29.3 |
| **5** | 6.4 | 6.1 | 6.4 | 21.8 | 24.3 | 32.7 | 29.4 |
| **6** | 5.8 | -1.0 | 6.3 | 16.4 | 30.4 | 44.0 | 35.9 |
| **7** | 8.7 | 13.7 | 13.0 | 24.6 | 24.8 | 40.9 | 35.5 |
| **8** | 11.0 | 8.1 | 7.6 | 14.0 | 27.3 | 37.6 | 30.4 |
| **9** | 5.4 | 9.1 | 12.5 | 23.6 | 28.8 | 33.3 | 26.6 |
| **10** | 7.7 | 10.2 | 15.7 | 13.3 | 25.5 | 34.5 | 27.8 |
| **11** | 5.7 | 8.5 | 8.1 | 20.7 | 30.2 | 47.6 | 24.4 |
| **12** | 3.8 | 8.5 | 16.2 | 21.2 | 28.2 | 37.9 | 25.2 |
| **13** | 5.6 | 9.4 | 14.0 | 19.2 | 26.7 | 39.3 | 26.4 |
| **14** | 6.4 | 9.0 | 12.8 | 22.7 | 36.6 | 43.8 | 31.2 |
| **15** | 11.7 | 13.1 | 16.0 | 20.6 | 30.6 | 37.7 | 25.3 |

Table XXVII

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 1000 $\Omega$ damper as measured on 15 tests used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 7.6 | 8.8 | 11.7 | 19.3 | 28.2 | 39.1 | 30.2 |
| **STD** | 2.4 | 3.8 | 3.6 | 3.6 | 3.1 | 4.7 | 4.2 |

Table XXVIII

$ATT_{Dampers}$ for the 330 Ω damper as measured on 13 tests used

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 3.1 | 0.1 | 12.6 | 14.1 | 29.6 | 36.8 | 27.6 |
| **2** | 6.2 | 4.4 | 11.0 | 14.7 | 24.1 | 33.4 | 28.5 |
| **3** | 10.5 | 13.3 | 15.4 | 22.0 | 32.8 | 39.5 | 37.1 |
| **4** | 0.2 | 4.5 | 13.4 | 16.9 | 29.6 | 38.2 | 25.4 |
| **5** | 2.9 | 2.1 | 4.5 | 15.0 | 21.3 | 29.7 | 29.1 |
| **6** | 2.9 | 6.9 | 12.3 | 20.4 | 27.1 | 34.3 | 31.4 |
| **7** | 7.9 | 1.8 | 4.6 | 18.0 | 26.1 | 29.7 | 29.4 |
| **8** | 8.5 | 6.0 | 11.7 | 16.5 | 25.4 | 28.4 | 29.1 |
| **9** | 0.7 | 7.0 | 14.3 | 10.2 | 31.6 | 42.2 | 22.7 |
| **10** | 6.3 | 3.3 | 5.4 | 18.7 | 28.4 | 35.6 | 23.2 |
| **11** | 8.7 | 5.0 | 8.4 | 25.4 | 30.9 | 40.4 | 23.8 |
| **12** | 2.7 | 6.4 | 16.2 | 21.7 | 28.4 | 42.3 | 28.0 |
| **13** | 4.0 | 11.6 | 16.7 | 19.2 | 35.7 | 39.1 | 21.1 |

Table XXIX

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 2200 Ω damper as measured on 13 tests used

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean** | 5.0 | 5.6 | 11.3 | 17.9 | 28.5 | 36.1 | 27.4 |
| **STD** | 3.2 | 3.7 | 4.3 | 4.0 | 3.8 | 4.8 | 4.3 |

### 3.c Tables from section 3.2.3.2, "per subject average" analysis

The averaged $ATT_{Earplug}$ and $ATT_{Combo}$ are computed from the three test trials done per individual test subject. Subjects for which one or more frequencies has averaged filtered attenuation greater than averaged blocked attenuation are rejected. The resulting attenuation data is presented in table XXX-XXXVII.

Table XXX

$ATT_{Dampers}$ for the 4700 Ω damper as measured on 5 subject average used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| 1 | 14.3 | 16.2 | 22.0 | 19.1 | 27.7 | 52.5 | 40.1 |
| 2 | 13.2 | 14.4 | 15.8 | 22.1 | 27.7 | 42.1 | 33.4 |
| 3 | 17.0 | 15.6 | 15.0 | 17.2 | 28.9 | 32.7 | 35.7 |
| 4 | 18.9 | 14.6 | 15.7 | 22.6 | 30.2 | 48.2 | 34.4 |
| 5 | 21.2 | 21.2 | 20.4 | 23.0 | 36.4 | 36.4 | 44.8 |

Table XXXI

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 4700 Ω damper as measured on 5 subject averages used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| Mean | 10.6 | 12.9 | 14.3 | 17.2 | 28.3 | 40.2 | 32.8 |
| STD | 3.0 | 3.5 | 3.1 | 2.6 | 3.2 | 7.6 | 4.7 |

Table XXXII

$ATT_{Dampers}$ for the 2200 Ω damper as measured on 8 subject averages used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 12.5 | 13.6 | 15.3 | 17.4 | 29.5 | 45.8 | 37.1 |
| **2** | 14.5 | 19.6 | 17.1 | 17.0 | 32.8 | 43.6 | 38.5 |
| **3** | 9.0 | 10.1 | 11.1 | 16.8 | 25.2 | 30.1 | 30.1 |
| **4** | 8.6 | 8.9 | 9.5 | 13.5 | 24.1 | 32.6 | 34.1 |
| **5** | 6.7 | 11.7 | 14.4 | 15.2 | 25.4 | 37.7 | 27.8 |
| **6** | 10.0 | 11.1 | 13.1 | 18.7 | 27.5 | 49.6 | 26.5 |
| **7** | 8.5 | 12.1 | 14.9 | 16.9 | 30.3 | 33.7 | 37.9 |
| **8** | 15.0 | 16.0 | 19.2 | 22.4 | 31.8 | 48.3 | 30.0 |

Table XXXIII

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 2200 Ω damper as measured on 8 subject averages used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 10.6 | 12.9 | 14.3 | 17.2 | 28.3 | 40.2 | 32.8 |
| **STD** | 3.0 | 3.5 | 3.1 | 2.6 | 3.2 | 7.6 | 4.7 |

Table XXXIV

$ATT_{Dampers}$ for the 1000 Ω damper as measured on 7 subject averages used

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 4.6 | 5.6 | 8.2 | 15.1 | 27.2 | 37.8 | 34.9 |
| **2** | 12.3 | 13.2 | 13.9 | 20.7 | 31.1 | 45.5 | 35.4 |
| **3** | 6.8 | 8.5 | 8.9 | 19.3 | 25.8 | 35.3 | 29.3 |
| **4** | 8.4 | 6.8 | 8.9 | 17.1 | 27.2 | 40.6 | 33.9 |
| **5** | 6.4 | 8.2 | 13.9 | 13.4 | 26.7 | 38.2 | 27.0 |
| **6** | 5.0 | 8.8 | 12.6 | 20.3 | 28.3 | 41.4 | 25.3 |
| **7** | 9.8 | 13.5 | 16.3 | 24.7 | 34.0 | 53.8 | 27.8 |

Table XXXV

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 1000 Ω damper as measured on 7 subject averages used

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean** | 7.6 | 9.2 | 11.8 | 18.7 | 28.6 | 41.8 | 30.5 |
| **STD** | 2.7 | 3.0 | 3.2 | 3.8 | 2.9 | 6.2 | 4.1 |

Table XXXVI

$ATT_{Dampers}$ for the 330 Ω damper as measured on 6 subject averages used

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 5.0 | 2.1 | 10.9 | 15.2 | 27.1 | 38.7 | 29.1 |
| **2** | 11.4 | 12.5 | 15.5 | 17.7 | 31.3 | 44.1 | 37.4 |
| **3** | 3.4 | 3.8 | 8.1 | 17.8 | 27.5 | 34.5 | 27.8 |
| **4** | 6.3 | 4.9 | 9.4 | 18.2 | 26.1 | 30.7 | 30.0 |
| **5** | 6.9 | 5.7 | 10.4 | 22.9 | 29.6 | 39.0 | 24.8 |
| **6** | 5.0 | 9.8 | 16.4 | 19.0 | 31.0 | 43.5 | 23.3 |

Table XXXVII

Mean and Standard Deviation values of the $ATT_{Dampers}$ for the 330 Ω damper as measured on 6 subject averages used

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **Mean** | 6.3 | 6.5 | 11.8 | 18.5 | 28.8 | 38.4 | 28.7 |
| **STD** | 2.8 | 3.9 | 3.4 | 2.5 | 2.2 | 5.2 | 5.0 |

### 3.d Tables from section 3.3.1

Table XXXVIII

$ATT_{Combo}$ for the 4700 Ω damper as predicted for all the subjects

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 12.1 | 14.6 | 14.6 | 16.4 | 27.3 | 30.9 | 30.5 |
| **2** | 14.3 | 14.7 | 16.2 | 18.1 | 29.0 | 33.6 | 30.8 |
| **3** | 13.8 | 13.8 | 13.4 | 17.9 | 28.5 | 30.7 | 30.4 |
| **4** | 17.7 | 16.8 | 17.1 | 16.1 | 29.5 | 31.2 | 36.9 |
| **5** | 17.2 | 16.4 | 12.2 | 18.6 | 29.4 | 36.0 | 37.1 |
| **6** | 17.6 | 16.0 | 14.3 | 19.6 | 29.6 | 36.0 | 37.2 |
| **7** | 17.5 | 16.0 | 16.8 | 18.1 | 30.2 | 33.7 | 38.3 |
| **8** | 17.3 | 16.3 | 17.3 | 16.6 | 30.0 | 36.9 | 38.1 |
| **9** | 17.0 | 16.8 | 17.7 | 17.9 | 30.5 | 35.9 | 37.7 |
| **10** | 16.3 | 16.0 | 16.4 | 19.3 | 27.9 | 28.6 | 37.3 |
| **11** | 17.5 | 16.2 | 17.2 | 18.8 | 27.5 | 34.3 | 34.8 |
| **12** | 17.0 | 16.3 | 17.3 | 19.1 | 30.1 | 36.6 | 35.9 |
| **13** | 17.2 | 15.8 | 15.1 | 19.5 | 29.1 | 34.2 | 37.7 |
| **14** | 14.5 | 15.7 | 16.3 | 17.7 | 28.7 | 34.1 | 37.5 |
| **15** | 16.2 | 15.8 | 17.2 | 19.4 | 25.6 | 32.1 | 37.7 |
| **16** | 17.1 | 14.1 | 13.7 | 14.7 | 25.2 | 36.0 | 38.2 |
| **17** | 13.6 | 15.6 | 12.1 | 16.6 | 24.2 | 35.8 | 38.0 |
| **18** | 13.3 | 16.3 | 9.4 | 15.4 | 24.5 | 33.7 | 38.3 |
| **19** | 17.2 | 16.3 | 17.5 | 17.6 | 30.0 | 34.0 | 37.4 |
| **20** | 17.6 | 16.9 | 17.3 | 18.6 | 30.3 | 35.4 | 38.0 |
| **21** | 16.6 | 16.4 | 16.5 | 16.4 | 28.8 | 32.7 | 37.4 |
| **22** | 17.3 | 16.7 | 18.4 | 20.5 | 30.3 | 37.4 | 37.1 |
| **23** | 17.1 | 16.9 | 18.5 | 19.8 | 30.5 | 35.8 | 37.3 |
| **24** | 16.6 | 17.0 | 17.1 | 19.4 | 29.2 | 35.2 | 36.8 |
| **25** | 18.0 | 17.1 | 18.3 | 20.9 | 30.7 | 35.4 | 37.1 |
| **26** | 17.8 | 15.9 | 16.9 | 20.6 | 31.0 | 35.6 | 36.7 |
| **27** | 16.4 | 16.1 | 15.6 | 18.9 | 29.4 | 34.0 | 37.4 |
| **28** | 14.7 | 16.0 | 17.3 | 18.6 | 29.9 | 34.5 | 37.1 |
| **29** | 12.0 | 12.0 | 14.6 | 18.4 | 29.0 | 31.8 | 28.3 |
| **30** | 16.2 | 16.1 | 17.5 | 18.8 | 29.7 | 34.7 | 35.2 |

Table XXXIX

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 4700 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | -0.2 | -1.4 | -0.9 | -0.9 | 0.9 | -1.4 | -1.2 |
| **STD** | 3.3 | 3.8 | 3.7 | 3.2 | 3.2 | 3.4 | 3.9 |

Table XL

$ATT_{Combo}$ for the 2200 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 10.1 | 12.6 | 13.4 | 14.4 | 27.1 | 31.2 | 32.5 |
| **2** | 10.0 | 12.4 | 10.6 | 15.9 | 27.0 | 36.0 | 32.5 |
| **3** | 10.1 | 12.3 | 12.0 | 16.4 | 27.2 | 36.1 | 32.6 |
| **4** | 10.0 | 12.3 | 13.3 | 15.6 | 27.5 | 33.7 | 32.9 |
| **5** | 10.0 | 12.4 | 13.5 | 14.7 | 27.4 | 36.9 | 32.9 |
| **6** | 9.9 | 12.6 | 13.7 | 15.5 | 27.6 | 35.9 | 32.7 |
| **7** | 9.8 | 12.3 | 13.1 | 16.2 | 26.1 | 28.6 | 32.6 |
| **8** | 10.0 | 12.3 | 13.5 | 16.0 | 25.8 | 34.3 | 31.6 |
| **9** | 9.9 | 12.4 | 13.5 | 16.1 | 27.4 | 36.6 | 32.1 |
| **10** | 10.0 | 12.1 | 12.5 | 16.3 | 26.9 | 34.2 | 32.7 |
| **11** | 9.3 | 12.1 | 13.1 | 15.4 | 26.6 | 34.1 | 32.7 |
| **12** | 9.8 | 12.2 | 13.5 | 16.3 | 24.5 | 32.2 | 32.7 |
| **13** | 10.0 | 12.4 | 13.6 | 15.3 | 27.4 | 34.0 | 32.6 |
| **14** | 10.1 | 12.6 | 13.5 | 15.9 | 27.6 | 35.4 | 32.8 |
| **15** | 9.9 | 12.4 | 13.1 | 14.6 | 26.7 | 32.7 | 32.6 |
| **16** | 10.0 | 12.5 | 14.0 | 16.8 | 27.6 | 37.4 | 32.5 |
| **17** | 10.0 | 12.6 | 14.0 | 16.5 | 27.7 | 35.8 | 32.6 |
| **18** | 9.9 | 12.6 | 13.4 | 16.3 | 27.0 | 35.2 | 32.4 |
| **19** | 10.1 | 12.7 | 13.9 | 17.0 | 27.8 | 35.4 | 32.5 |
| **20** | 10.1 | 12.2 | 13.3 | 16.8 | 27.9 | 35.6 | 32.4 |
| **21** | 9.8 | 12.3 | 12.7 | 16.0 | 27.0 | 34.0 | 32.6 |
| **22** | 9.4 | 12.3 | 13.5 | 15.9 | 27.3 | 34.5 | 32.5 |
| **23** | 8.4 | 10.1 | 12.2 | 15.8 | 26.8 | 31.8 | 27.3 |
| **24** | 9.8 | 12.3 | 13.6 | 16.0 | 27.2 | 34.7 | 31.8 |

Table XLI

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 2200 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | -0.3 | -0.1 | -0.2 | -0.1 | -0.2 | -0.2 | 0.1 |
| **STD** | 3.3 | 3.2 | 3.2 | 2.7 | 3.0 | 4.3 | 5.0 |

Table XLII

$ATT_{Combo}$ for the 1000 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 7.6 | 8.8 | 11.3 | 15.5 | 27.1 | 31.4 | 29.9 |
| **2** | 7.5 | 8.7 | 9.4 | 17.5 | 27.0 | 36.5 | 30.0 |
| **3** | 7.6 | 8.6 | 10.4 | 18.2 | 27.2 | 36.6 | 30.0 |
| **4** | 7.6 | 8.6 | 11.2 | 17.1 | 27.5 | 34.0 | 30.1 |
| **5** | 7.6 | 8.7 | 11.4 | 15.9 | 27.4 | 37.6 | 30.1 |
| **6** | 7.5 | 8.8 | 11.5 | 16.9 | 27.6 | 36.5 | 30.0 |
| **7** | 7.4 | 8.6 | 11.1 | 18.0 | 26.1 | 28.7 | 30.0 |
| **8** | 7.6 | 8.7 | 11.3 | 17.7 | 25.8 | 34.7 | 29.4 |
| **9** | 7.5 | 8.7 | 11.4 | 17.8 | 27.4 | 37.3 | 29.7 |
| **10** | 7.5 | 8.6 | 10.7 | 18.2 | 26.9 | 34.5 | 30.1 |
| **11** | 7.2 | 8.6 | 11.1 | 16.8 | 26.6 | 34.5 | 30.0 |
| **12** | 7.4 | 8.6 | 11.3 | 18.1 | 24.5 | 32.4 | 30.0 |
| **13** | 7.5 | 8.7 | 11.4 | 16.7 | 27.4 | 34.4 | 30.0 |
| **14** | 7.6 | 8.8 | 11.4 | 17.5 | 27.6 | 35.9 | 30.1 |
| **15** | 7.5 | 8.7 | 11.1 | 15.7 | 26.7 | 33.0 | 30.0 |
| **16** | 7.6 | 8.8 | 11.6 | 18.9 | 27.6 | 38.2 | 29.9 |
| **17** | 7.5 | 8.8 | 11.6 | 18.4 | 27.7 | 36.3 | 30.0 |
| **18** | 7.5 | 8.8 | 11.3 | 18.1 | 27.0 | 35.6 | 29.9 |
| **19** | 7.2 | 8.6 | 11.4 | 17.5 | 27.3 | 34.9 | 29.9 |
| **20** | 6.6 | 7.6 | 10.5 | 17.3 | 26.8 | 32.0 | 26.4 |
| **21** | 7.4 | 8.7 | 11.4 | 17.7 | 27.2 | 35.1 | 29.5 |

Table XLIII

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 1000 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 0.0 | -0.3 | -0.2 | 0.6 | -0.3 | -0.7 | -0.5 |
| **STD** | 3.4 | 4.1 | 3.6 | 3.5 | 2.3 | 2.8 | 3.9 |

Table XLIV

$ATT_{Combo}$ for the 330 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 5.0 | 5.5 | 10.9 | 14.8 | 27.4 | 30.7 | 27.3 |
| **2** | 4.9 | 5.5 | 9.2 | 16.5 | 27.3 | 34.6 | 27.3 |
| **3** | 4.9 | 5.5 | 10.1 | 17.1 | 27.5 | 34.7 | 27.3 |
| **4** | 4.9 | 5.5 | 10.9 | 16.2 | 27.8 | 32.8 | 27.4 |
| **5** | 4.9 | 5.5 | 11.0 | 15.2 | 27.7 | 35.3 | 27.4 |
| **6** | 4.9 | 5.5 | 11.1 | 16.1 | 28.0 | 34.6 | 27.4 |
| **7** | 4.9 | 5.5 | 10.8 | 16.9 | 26.3 | 28.3 | 27.3 |
| **8** | 4.9 | 5.5 | 11.0 | 16.7 | 26.0 | 33.3 | 27.0 |
| **9** | 4.9 | 5.5 | 11.0 | 16.8 | 27.8 | 35.1 | 27.2 |
| **10** | 4.9 | 5.4 | 10.4 | 17.1 | 27.2 | 33.2 | 27.4 |
| **11** | 4.7 | 5.4 | 10.7 | 16.0 | 26.9 | 33.2 | 27.4 |
| **12** | 4.9 | 5.5 | 11.0 | 17.0 | 24.6 | 31.5 | 27.4 |
| **13** | 4.9 | 5.5 | 11.0 | 15.9 | 27.7 | 33.1 | 27.3 |
| **14** | 4.9 | 5.5 | 11.0 | 16.5 | 27.9 | 34.2 | 27.4 |
| **15** | 4.9 | 5.5 | 10.8 | 15.0 | 27.0 | 32.0 | 27.3 |
| **16** | 4.9 | 5.5 | 11.2 | 17.6 | 27.9 | 35.6 | 27.3 |
| **17** | 4.9 | 5.5 | 11.2 | 17.2 | 28.0 | 34.5 | 27.3 |
| **18** | 4.9 | 5.5 | 10.9 | 17.0 | 27.2 | 34.0 | 27.3 |
| **19** | 4.7 | 5.5 | 11.0 | 16.5 | 27.7 | 33.5 | 27.3 |
| **20** | 4.4 | 4.9 | 10.2 | 16.4 | 27.1 | 31.2 | 25.0 |
| **21** | 4.9 | 5.5 | 11.0 | 16.7 | 27.5 | 33.7 | 27.1 |

Table XLV

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 330 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | -1.1 | -1.1 | -1.1 | -0.8 | -1.4 | -1.7 | -1.1 |
| **STD** | 3.7 | 4.0 | 4.5 | 4.6 | 4.8 | 3.7 | 4.8 |

Table XLVI

$ATT_{Combo}$ for the 4700 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 13.0 | 13.9 | 14.4 | 17.4 | 27.6 | 32.5 | 30.5 |
| **2** | 16.5 | 15.7 | 14.5 | 18.2 | 28.6 | 36.3 | 36.5 |
| **3** | 16.3 | 15.7 | 16.7 | 17.4 | 29.2 | 37.7 | 37.4 |
| **4** | 16.0 | 15.5 | 16.4 | 18.9 | 27.9 | 35.0 | 35.7 |
| **5** | 15.4 | 15.1 | 15.8 | 18.8 | 27.3 | 34.6 | 37.0 |
| **6** | 14.5 | 14.9 | 11.6 | 15.5 | 24.3 | 36.9 | 37.5 |
| **7** | 16.2 | 15.8 | 16.5 | 17.5 | 28.8 | 35.4 | 37.0 |
| **8** | 16.1 | 16.1 | 17.4 | 19.7 | 29.1 | 38.7 | 36.5 |
| **9** | 16.5 | 15.8 | 16.7 | 20.2 | 29.4 | 36.6 | 36.5 |
| **10** | 14.0 | 14.6 | 16.1 | 18.4 | 28.7 | 34.9 | 34.0 |

Table XLVII

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 4700 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | -0.9 | -2.0 | -1.3 | -1.0 | 0.1 | 0.3 | -1.6 |
| **STD** | 2.3 | 3.1 | 2.4 | 1.6 | 2.6 | 2.0 | 3.5 |

Table XLVIII

$ATT_{Combo}$ for the 2200 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 10.5 | 12.6 | 12.6 | 15.9 | 27.2 | 35.6 | 32.4 |
| **2** | 10.4 | 12.6 | 13.8 | 15.4 | 27.7 | 36.8 | 32.7 |
| **3** | 10.4 | 12.5 | 13.6 | 16.3 | 26.7 | 34.5 | 32.0 |
| **4** | 10.2 | 12.3 | 13.3 | 16.2 | 26.3 | 34.1 | 32.5 |
| **5** | 10.4 | 12.7 | 13.7 | 15.4 | 27.4 | 34.8 | 32.5 |
| **6** | 10.4 | 12.8 | 14.2 | 16.7 | 27.6 | 37.6 | 32.3 |
| **7** | 10.5 | 12.6 | 13.8 | 16.9 | 27.8 | 35.9 | 32.4 |
| **8** | 9.7 | 12.0 | 13.5 | 16.0 | 27.3 | 34.4 | 31.2 |

Table XLIX

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 2200 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.8 | 0.0 |
| **STD** | 2.7 | 3.0 | 2.6 | 1.9 | 2.5 | 3.0 | 4.3 |

Table L

$ATT_{Combo}$ for the 1000 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 7.6 | 9.1 | 10.7 | 16.9 | 27.5 | 36.1 | 30.3 |
| **2** | 7.5 | 9.1 | 11.5 | 16.3 | 27.9 | 37.5 | 30.5 |
| **3** | 7.5 | 9.0 | 11.4 | 17.4 | 26.9 | 34.9 | 30.1 |
| **4** | 7.4 | 9.0 | 11.2 | 17.3 | 26.4 | 34.5 | 30.4 |
| **5** | 7.5 | 9.1 | 11.5 | 16.3 | 27.6 | 35.3 | 30.4 |
| **6** | 7.5 | 9.2 | 11.7 | 18.0 | 27.8 | 38.4 | 30.3 |
| **7** | 7.1 | 8.8 | 11.3 | 17.0 | 27.5 | 34.8 | 29.5 |

Table LI

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 1000 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.5 | -0.0 |
| **STD** | 2.6 | 2.8 | 2.8 | 2.4 | 2.1 | 1.2 | 3.9 |

Table LII

$ATT_{Combo}$ for the 330 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 6.3 | 6.4 | 10.7 | 16.7 | 27.6 | 34.9 | 28.6 |
| **2** | 6.3 | 6.4 | 11.5 | 16.2 | 28.1 | 35.9 | 28.7 |
| **3** | 6.2 | 6.4 | 11.4 | 17.2 | 27.0 | 33.9 | 28.4 |
| **4** | 6.2 | 6.3 | 11.2 | 17.2 | 26.6 | 33.6 | 28.6 |
| **5** | 6.3 | 6.4 | 11.4 | 16.2 | 27.8 | 34.2 | 28.6 |
| **6** | 6.2 | 6.4 | 11.7 | 17.8 | 28.0 | 36.5 | 28.6 |
| **7** | 6.0 | 6.2 | 11.3 | 16.9 | 27.6 | 33.8 | 28.1 |

Table LIII

Mean and Standard Deviation values of the error of the prediction of $ATT_{Combo}$ for the 330 Ω damper as predicted for all the subjects

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **Mean** | 0.2 | -0.2 | -0.6 | -0.3 | -1.1 | -0.3 | 0.2 |
| **STD** | 2.5 | 3.5 | 3.3 | 2.0 | 3.2 | 2.6 | 4.4 |

### 3.e Tables for section 3.4.2

Table LIV

Hearing Thresholds, in dB HL, of the 5 subjects used for the REAT testing according to AS1270 (Right on Top, Left on Bottom)

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| 1 | 0.0 | 0.0 | 5.0 | 5.0 | 5.0 | 0.0 | 15.0 |
| 2 | 0.0 | 0.0 | 5.0 | 5.0 | 0.0 | 0.0 | -10.0 |
| 3 | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 0.0 |
| 4 | 0.0 | 0.0 | -10.0 | 0.0 | 0.0 | -5.0 | 5.0 |
| 5 | 0.0 | 0.0 | 10.0 | 10.0 | 15.0 | 15.0 | 5.0 |

The table LV contains the REAT Attenuation Data for the 4700 Ω Filter as measured per AS1270 standard on the 5 subjects.

Table LV

REAT Attenuation Data for the 4700 Ω Filters measured per AS1270 standard on the 5 subjects

| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | Overall |
|---|---|---|---|---|---|---|---|---|
| 1 | 23.7 | 20.8 | 23.1 | 29.4 | 35.7 | 37.6 | 40.5 | 30.7 |
| 2 | 14.3 | 13.6 | 14.0 | 18.7 | 28.8 | 37.0 | 38.9 | 21.8 |
| 3 | 21.4 | 16.8 | 17.5 | 16.1 | 27.4 | 38.7 | 40.5 | 22.1 |
| 4 | 21.7 | 18.4 | 21.9 | 21.0 | 31.9 | 39.9 | 40.7 | 26.5 |
| 5 | 17.9 | 18.1 | 15.2 | 17.9 | 30.2 | 34.3 | 40.7 | 22.6 |

The table LVI contains the REAT Attenuation Data for the 2200 Ω Filter as measured per AS1270 standard on the 5 subjects.

Table LVI

REAT Attenuation Data for the 2200 Ω Filters measured per AS1270 standard on the 5 subjects

| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | Overall |
|---|---|---|---|---|---|---|---|---|
| 1 | 17.3 | 18.4 | 21.2 | 26.7 | 35.5 | 36.1 | 36.9 | 28.4 |
| 2 | 8.8 | 8.9 | 13.5 | 19.2 | 29.1 | 37.4 | 33.2 | 20.5 |
| 3 | 16.6 | 13.1 | 14.4 | 15.9 | 23.4 | 36.9 | 35.6 | 20.5 |
| 4 | 18.2 | 17.2 | 21.9 | 19.5 | 30.6 | 34.5 | 36.2 | 25.2 |
| 5 | 10.5 | 12.8 | 13.6 | 15.4 | 27.4 | 33.2 | 34.0 | 20.0 |

The table LVII contains the REAT Attenuation Data for the 1000 Ω Filter as measured per AS1270 standard on the 5 subjects.

Table LVII

REAT Attenuation Data for the 1000 Ω Filters measured per AS1270 standard on the 5 subjects

| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | Overall |
|---|---|---|---|---|---|---|---|---|
| 1 | 15.8 | 13.9 | 18.0 | 27.8 | 36.5 | 35.1 | 30.6 | 25.7 |
| 2 | 6.6 | 7.9 | 9.3 | 18.2 | 30.0 | 37.0 | 29.2 | 17.9 |
| 3 | 10.4 | 9.6 | 11.4 | 13.1 | 23.4 | 35.1 | 32.1 | 17.7 |
| 4 | 12.0 | 12.4 | 15.1 | 18.6 | 31.9 | 31.8 | 30.2 | 21.9 |
| 5 | 9.5 | 10.4 | 9.2 | 14.2 | 28.2 | 32.8 | 30.1 | 17.4 |

The table LVIII contains the REAT Attenuation Data for the 330 Ω Filter as measured per AS1270 standard on the 5 subjects.

Table LVIII

REAT Attenuation Data for the 330 Ω Filters as measured per AS1270 standard on the 5 subjects

| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | Overall |
|---|---|---|---|---|---|---|---|---|
| **1** | 8.0 | 8.0 | 15.2 | 27.8 | 35.8 | 33.8 | 27.6 | 21.6 |
| **2** | 1.1 | -0.1 | 8.4 | 17.8 | 29.2 | 36.2 | 27.4 | 14.0 |
| **3** | 8.6 | 5.6 | 8.5 | 15.1 | 25.8 | 33.8 | 31.2 | 16.4 |
| **4** | 13.8 | 8.1 | 15.6 | 17.3 | 30.0 | 29.8 | 26.2 | 20.3 |
| **5** | 3.6 | 4.2 | 8.6 | 15.4 | 30.6 | 33.0 | 27.1 | 15.9 |

The table LIX contains the Predicted Attenuation Data for the 4700 Ω Filter as reported by the SonoPass™ on the 5 subjects.

Table LIX

Predicted Attenuation Data for the 4700 Ω Filter as reported by the SonoPass™ on the 5 subjects (Right on Top, Left on Bottom)

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| **1** | 19.4 | 18.3 | 20.9 | 23.6 | 30.9 | 37.8 | 36.4 |
| **2** | 17.3 | 16.4 | 18.4 | 18.8 | 25.7 | 38.3 | 36.7 |
| **3** | 15.4 | 14.5 | 17.1 | 19.9 | 22.5 | 42.5 | 36.3 |
| **4** | 18.1 | 16.3 | 18.8 | 19.1 | 29.9 | 41.8 | 38.8 |
| **5** | 16.5 | 15.2 | 17.3 | 16.9 | 19.4 | 40.4 | 40.8 |

The table LX contains the Predicted Attenuation Data for the 2200 Ω Filter as reported by the SONOPASS™ on the 5 subjects.

Table LX

Predicted Attenuation Data for the 2200 Ω Filter as reported by the SONOPASS™ on the 5 subjects (Right on Top, Left on Bottom)

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 12.5 | 14.8 | 16.7 | 19.8 | 29.9 | 37.7 | 32.2 |
| **2** | 12.0 | 14.2 | 15.9 | 18.5 | 26.6 | 36.5 | 30.2 |
| **3** | 12.5 | 15.2 | 17.2 | 19.9 | 28.8 | 44.9 | 32.8 |
| **4** | 11.0 | 13.0 | 15.2 | 16.3 | 28.3 | 41.0 | 31.5 |
| **5** | 11.4 | 12.9 | 14.7 | 16.0 | 20.0 | 39.1 | 34.0 |

The table LXI contains the predicted Attenuation Data for the 1000 Ω Filter as reported by the SONOPASS™ on the 5 subjects.

Table LXI

Predicted Attenuation Data for the 1000 Ω Filter as reported by the SONOPASS™ on the 5 subjects (Right on Top, Left on Bottom)

| | **125** | **250** | **500** | **1000** | **2000** | **4000** | **8000** |
|---|---|---|---|---|---|---|---|
| **1** | 8.9 | 10.6 | 13.5 | 19.3 | 29.0 | 37.2 | 30.0 |
| **2** | 8.5 | 10.4 | 13.2 | 19.3 | 27.4 | 38.2 | 30.5 |
| **3** | 7.7 | 8.5 | 11.3 | 16.7 | 22.2 | 42.0 | 30.2 |
| **4** | 8.5 | 9.8 | 12.5 | 18.2 | 28.8 | 39.4 | 29.4 |
| **5** | 8.1 | 9.3 | 11.9 | 16.0 | 19.1 | 42.5 | 31.9 |

The table LXII contains the Predicted Attenuation Data for the 330 Ω Filter as reported by the SonoPass™ on the 5 subjects.

Table LXII

Predicted Attenuation Data for the 330 Ω Filter as reported by the SonoPass™ on the 5 subjects (Right on Top, Left on Bottom)

| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| 1 | 7.5 | 7.4 | 13.6 | 20.8 | 29.3 | 37.3 | 28.8 |
| 2 | 7.3 | 7.1 | 13.1 | 20.0 | 27.0 | 35.6 | 29.2 |
| 3 | 7.2 | 7.2 | 13.9 | 21.5 | 28.4 | 43.4 | 28.2 |
| 4 | 7.0 | 6.7 | 12.3 | 17.0 | 26.8 | 36.6 | 28.5 |
| 5 | 6.8 | 6.5 | 12.1 | 15.3 | 19.2 | 38.8 | 30.0 |

The table LXIII contains the Predicted Attenuation Data for the 4700 Ω Filter as reported by the SonoPass™ on the 5 subjects.

Table LXIII

Predicted Attenuation Data for the 4700 Ω Filter as reported by the SonoPass™ on the 5 subjects

| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | Overall |
|---|---|---|---|---|---|---|---|---|
| 1 | 19.4 | 18.3 | 20.9 | 23.6 | 30.6 | 37.8 | 36.4 | 27.2 |
| 2 | 17.3 | 16.4 | 18.4 | 18.8 | 25.7 | 36.6 | 33.3 | 23.5 |
| 3 | 15.4 | 14.5 | 17.1 | 19.9 | 22.5 | 42.5 | 31.4 | 22.8 |
| 4 | 17.8 | 16.2 | 18.0 | 19.1 | 27.4 | 35.8 | 33.9 | 23.7 |
| 5 | 16.5 | 15.2 | 17.3 | 16.9 | 19.4 | 40.4 | 39.6 | 21.1 |

The table LXIV contains the Predicted Attenuation Data for the 2200 Ω Filter as reported by the SONOPASS™ on the 5 subjects.

Table LXIV

Predicted Attenuation Data for the 2200 Ω Filter as reported by the SONOPASS™ on the 5 subjects

| | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | **Overall** |
|---|---|---|---|---|---|---|---|---|
| **1** | 12.5 | 14.8 | 16.7 | 19.4 | 29.0 | 37.7 | 31.9 | 23.2 |
| **2** | 12.0 | 14.2 | 15.9 | 18.5 | 26.6 | 29.5 | 28.2 | 22.1 |
| **3** | 11.7 | 14.0 | 15.9 | 18.0 | 28.6 | 43.9 | 29.5 | 22.2 |
| **4** | 11.0 | 13.0 | 14.7 | 16.2 | 26.7 | 36.2 | 30.8 | 20.8 |
| **5** | 11.4 | 12.9 | 14.7 | 16.0 | 20.0 | 39.1 | 27.6 | 19.9 |

The table LXV contains the predicted Attenuation Data for the 1000 Ω Filter as reported by the SONOPASS™ on the 5 subjects.

Table LXV

Predicted Attenuation Data for the 1000 Ω Filter as reported by the SONOPASS™ on the 5 subjects

| | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | **Overall** |
|---|---|---|---|---|---|---|---|---|
| **1** | 8.9 | 10.6 | 13.5 | 19.3 | 29.0 | 36.0 | 29.7 | 20.9 |
| **2** | 8.5 | 10.4 | 13.2 | 19.3 | 27.4 | 38.2 | 25.2 | 20.5 |
| **3** | 7.7 | 8.5 | 11.3 | 16.7 | 22.2 | 42.0 | 27.1 | 18.5 |
| **4** | 8.4 | 9.6 | 12.2 | 18.2 | 27.7 | 38.3 | 29.4 | 19.8 |
| **5** | 8.1 | 9.3 | 11.9 | 16.0 | 19.1 | 42.5 | 31.6 | 18.3 |

The table LXVI contains the Predicted Attenuation Data for the 330 Ω Filter as reported by the SonoPass™ on the 5 subjects.

Table LXVI

Predicted Attenuation Data for the 330 Ω Filter as reported by the SonoPass™ on the 5 subjects

| | **125 Hz** | **250 Hz** | **500 Hz** | **1000 Hz** | **2000 Hz** | **4000 Hz** | **8000 Hz** | **Overall** |
|---|---|---|---|---|---|---|---|---|
| **1** | 7.5 | 7.4 | 13.6 | 20.8 | 29.3 | 36.0 | 28.6 | 20.1 |
| **2** | 7.3 | 7.1 | 13.1 | 20.0 | 27.0 | 35.6 | 26.9 | 19.6 |
| **3** | 7.2 | 7.2 | 13.8 | 20.9 | 28.4 | 41.9 | 27.1 | 20.0 |
| **4** | 7.0 | 6.7 | 12.2 | 17.0 | 26.8 | 35.9 | 28.2 | 18.6 |
| **5** | 6.8 | 6.5 | 12.1 | 15.3 | 19.2 | 38.8 | 29.7 | 17.5 |

# CONCLUSION

## PLAN SCIENTIFIQUE

Sur le plan scientifique, les avancées réalisées correspondent directement aux trois objectifs spécifiques du doctorat, à savoir :

1. la formulation détaillée de la problématique associée au développement d'un bouchon d'oreille « intelligent » et l'élaboration de la stratégie technique et scientifique à mettre en oeuvre pour son développement,
2. la mise au point d'une méthode de mesure liant le NR à l'atténuation REAT afin de quantifier les performances acoustiques du bouchon lorsqu'il est porté par le travailleur. La méthode proposée a été validée expérimentalement par des mesures d'un laboratoire indépendant et son incertitude est inférieure à celle rapportée dans la littérature pour la méthode REAT qui est depuis une cinquantaine d'années le standard de facto dans le domaine de la mesure des protecteurs auditifs. Il a également été démontré qu'une telle approche pourrait être appliquée à d'autres types de bouchons d'oreilles (bouchons jetables en mousse, par exemple). Par ailleurs, la rapidité, la précision et le résultat individualisé de la méthode de mesure proposée ont plusieurs implications relatives aux pratiques actuelles de protection de l'ouïe et aux normes actuelles de mesures et d'étiquetage des protecteurs auditifs.
3. la mise au point d'une première stratégie de filtrage acoustique du bouchon, à l'aide d'éléments résistifs interchangeables, permettant d'adapter l'atténuation du bouchon au besoin de protection du travailleur. L'approche développée combine le chemin secondaire de transmission du bruit (constitué par la résistance acoutique) au chemin primaire constitué par le bouchon lui-même et permet de prédire l'atténuation du bouchon filtré. Il devient ainsi possible de sélectionner à l'avance l'élément résistif qui doit être inséré dans le bouchon afin que le niveau d'exposition résiduel du porteur soit situé dans la zone optimale de 75 à 80 dB(A) et permette ainsi à l'oreille

d'effectuer naturellement la discrimination des signaux utiles (paroles, alarmes, etc.) dans le bruit.

**PLAN TECHNOLOGIQUE**

Au plan technologique, les développements effectués répondent en partie aux deux objectifs du projet industriel :

- Un bouchon d'oreille sur-mesure confortable, instrumentable et filtrable a été mis au point et breveté par SONOMAX. Bien que ce bouchon relève essentiellement d'un développement entrepris par la compagnie, la plupart des essais et mesures acoustiques (sélection du matériau constituant le bouchon, preuves de faisabilité du concept d'expansion du bouchon à l'intérieur de l'oreille, tests de pré-commercialisation du protecteur, etc.) ont été effectués sous la responsabilité de l'étudiant au laboratoire de l'ÉTS.

  Une première famille de brevets [1–2] dont les inventeurs font partie de l'équipe de SONOMAX porte sur la caractéristique d'ajustement instantané sur-mesure : ce bouchon est fait d'un caoutchouc de silicone hypoallergénique souple et est ajusté à l'oreille du travailleur par un procédé de moulage instantané utilisant l'expansion d'une membrane souple entourant le bouchon.

  Une deuxième famille de brevets [3] dont les inventeurs sont l'étudiant et son directeur à l'ÉTS porte sur les caractéristiques de mesure et d'adaptation de l'atténuation : le bouchon développé comporte un canal acoustique permettant l'insertion d'une sonde microphonique et la mesure de ses performances dans l'oreille du travailleur; ce même canal acoustique permet l'insertion d'un élément résistif, ce qui rend possible l'adaptation de l'atténuation du protecteur au besoin de protection du travailleur.

[1] I. MCINTOSH et R. SAULCE (2002), "In-ear system" U.S. Patent 6,339,648
[2] I. MCINTOSH et R. SAULCE (2004), "Expandable in-ear device" U.S. Patent 6,754,357
[3] J. VOIX et F. LAVILLE (2004), "Method and apparatus for objective assessment of in-ear device acoustical performance" U.S. Patent Application 20050123146

- Un dispositif de mesure des performances acoustiques du bouchon a été développé dans le cadre du travail de thèse et breveté [4] (à l'origine pour la mesure en temps-réel de l'étanchéité acoustique durant l'expansion du bouchon); il est constitué d'une sonde microphonique, d'un système d'acquisition et d'un procédé d'étalonnage :
  - *La sonde microphonique* utilise deux microphones : Le premier microphone, dit de *référence*, permet la mesure de la pression acoustique à l'extérieur du bouchon, et le deuxième, dit de *mesure*, permet la mesure sous le protecteur. Cette sonde a été spécifiquement développée afin de ne pas perturber le comportement dynamique du bouchon (masse réduite, encombrement limité, etc.) et de limiter l'interférence entre les deux micros afin de mesurer de façon fiable l'atténuation typique d'un bouchon.
  - *Le système d'acquisition, de génération et de traitement de signal* était composé, à la première génération du système d'acquisition, d'une simple carte audio stéréophonique permettant l'acquisition des signaux électriques provenant du doublet microphonique de la sonde ainsi que la génération du bruit large bande nécessaire à la mesure de la fonction de transfert entre les deux microphones. Le traitement de signal, similaire à celui d'un analyseur de spectre, était effectué par le logiciel sur l'ordinateur personnel (PC) d'acquisition. La deuxième génération du système d'acquisition, créée spécifiquement pour cette application, utilise un *processeur numérique du signal* (DSP) pour effectuer l'acquisition, la génération et la majeure partie du traitement du signal nécessaire. Le PC ne sert plus que d'interface usager et le système développé est également capable de fonctionner de façon autonome, en l'absence du PC.
  - *Le procédé de test, d'étalonnage et de traçabilité des systèmes de mesure* a été conçu spécifiquement pour cette application. Le test fonctionnel du système de mesure consiste à déterminer la fonction de transfert du doublet microphonique

[4] J. VOIX et F. LAVILLE (2004), "Method and apparatus for determining in situ the acoustic seal provided by an in-ear device" U.S. Patent 6,687,377

positionné au voisinage immédiat de la source de bruit. L'ensemble des fonctionnalités du système de mesure (génération du bruit par le haut-parleur, mesure acoustique par les microphones et traitement adéquat par le DSP) peuvent ainsi être vérifiées en une seule étape. L'étalonnage du système de mesure consiste à déterminer, à l'aide de sources d'étalonnage, la sensibilité du microphone de référence et celle du *convertisseur analogique-numérique* (ADC). Des certificats de calibration sont alors générés et accompagnent le système de mesure. La sensibilité du microphone de mesure est déterminée relativement à la sensibilité du microphone de référence lors d'une *procédure journalière de vérification*, obligatoire pour l'utilisation du système de mesure. La traçabilité est assurée par l'utilisation d'un numéro de série unique pour chaque système de mesure et l'interconnection du PC utilisé pour l'étalonnage du système de mesure à une base de données.

## RETOMBÉES INDUSTRIELLES

Sur le plan des retombées industrielles, l'ensemble de la solution développée au cours de ce doctorat est commercialisée depuis 2002 sous le nom de SONOMAX'S SOLUTION™ et constitue en soi un important changement du point de vue des pratiques des programmes de protection de l'ouïe. Trois originalités de cette solution sont présentées ci-dessous :

- La première originalité de cette solution réside dans le moulage instantané. Bien que les bouchons d'oreille moulés sur-mesure existent depuis de nombreuses années, ils sont traditionnellement obtenus par un procédé de prise d'empreinte suivi d'un moulage et d'un usinage manuel du bouchon obtenu. Un tel procédé est non seulement long et fastidieux, mais souffre également un taux très élevé d'échec, obligeant de multiples sessions subséquentes de prise d'empreinte, moulage et usinage. À l'opposé, le procédé instantané d'ajustement sur-mesure ramène le délai de livraison de plusieurs semaines à quelques minutes et permet une correction immédiate en cas d'inconfort ou de mauvaises performances acoustiques (grâce au fait que l'évaluation des performances acoustiques fait partie de cette solution, tel qu'indiqué dans le paragraphe suivant).

- La deuxième originalité de la solution développée est la capacité de mesurer objectivement, sur chaque individu, les performances acoustiques du bouchon. L'approche développée repose sur une mesure microphonique de l'affaiblissement acoustique et s'avère non seulement plus simple et plus rapide à mettre en oeuvre que la seule méthode existante basée sur la méthode des seuils audiométriques, mais est également mieux adaptée au milieu industriel, puisqu'elle n'est pas sensible au bruit de fond ambiant, ni à la subjectivité de la méthode des seuils.
- La troisième originalité est l'utilisation d'un filtre acoustique sélectionné en fonction des besoins du travailleur. Même si certains bouchons d'oreille sur-mesure offraient la possibilité d'être filtrés, ce filtre était choisi à l'avance, sans prise en compte pour les besoins exacts de protection du travailleur, ni les performances effectives du bouchon lui-même.

L'approche de mesure proposée, radicalement différente des pratiques actuelles, a un impact direct sur les normes et standards selon lesquels les protecteurs auditifs doivent être testés. L'étudiant a été invité à participer au travaux de groupe d'expert traitant des normes et standards à venir (comités ANSI S12/WG 11 et ISO TC43/SC1-WG 17).

**RECOMMANDATIONS**

Le produit développé répond assez complètement aux problèmes de l'inconfort physique et de la mesure de ses performances mais répond encore imparfaitement pour l'instant au problème de l'inconfort de perception sonore. En effet, le filtre utilisé n'est pas capable de conserver le contenu spectral de l'environnement sonore du travailleur, ni d'ajuster automatiquement le degré de protection selon l'exposition du travailleur au bruit ou de discriminer entre le bruit indésirable et les signaux utiles (parole, signaux d'alarme). La voie choisie pour répondre beaucoup plus adéquatement à ce dernier problème est de passer du filtrage passif au filtrage sélectif actif.

Les travaux en cours dans le cadre d'un projet de Recherche et développement coopérative (RDC) du CONSEIL DE RECHERCHES EN SCIENCES NATURELLES ET EN GÉNIE DU CANADA (CRSNG) en collaboration avec SONOMAX consistent à développer des systèmes de filtrage sélectifs adaptés aux bruits en milieu industriel en utilisant des technologies de traitement numérique du signal; une étape technique importante a été récemment franchie par l'intégration de composants électro-acoustiques de prothèses auditives numériques « programmables » au sein du bouchon, rendant ainsi possible l'implémentation de tout algorithme de filtrage numérique.

Par ailleurs, un projet de recherche conjoint avec l'INSTITUT ROBERT-SAUVÉ DE RECHERCHE EN SANTÉ ET EN SÉCURITÉ DU TRAVAIL (IRSST) portant sur l'évaluation « terrain » de l'efficacité du bouchon développé et d'autres protecteurs auditifs instrumentables, comporte également un volet de modélisation du bouchon. En effet, il a été observé, durant ce travail de doctorat, que les modèles analytiques actuels des protecteurs auditifs ne pouvaient pas s'appliquer sur ce cas particulier de bouchon fait d'un matériau souple et peu amorti. Cependant il est essentiel, pour l'optimisation des performances des bouchons, de bien comprendre et représenter les mécanismes de transmission du son au travers du matériau constituant le bouchon ainsi que le couplage entre le bouchon et la paroi du conduit auditif. L'utilisation de modèle numérique est adaptée à un tel problème et permettrait de plus un avancement des connaissances dans la résolution de deux autres problèmes. Le premier problème est celui du couplage mécano-acoustique entre un protecteur auditif intra-auriculaire (type bouchon d'oreille) et un protecteur circum-auriculaire (type coquille). Il existe en effet très peu de données, autres qu'expérimentales, sur les mécanismes mis en oeuvre lors de l'utilisation d'une *double protection* et les formules permettant de déterminer l'atténuation combinée offerte par un bouchon et une coquille suivent des règles empiriques peu fiables. Le deuxième problème est celui de la prédiction de la réponse temporelle du bouchon qui pourrait être très utile pour modéliser l'atténuation effective d'un bouchon aux bruits impulsifs de forte amplitude.