Measurement of effective hearing protection device attenuation during a workshift in industrial plants

Hugues Nélissea
Jérôme Boutin
IRSST
505 Boul. De Maisonneuve Ouest
Montréal, Québec, CANADA, H3A 3C2

Marc-André Gaudreaub
Frédéric Lavillec
Jérémie Voixd
Département de génie mécanique
École de Technologie Supérieure
1100 rue Notre-Dame Ouest
Montréal, Québec, CANADA, H3C 1K3

ABSTRACT
Discrepancies between labeled noise attenuation data measured in laboratory and field measurements data have been well documented for most types of hearing protection devices (HPD) throughout the years. High “laboratory” attenuation values lead to overestimation of most ratings used for the labeling of HPDs and, subsequently, can cause significant problems when trying to estimate the workers real-world protected levels. This paper presents a field study where unprotected, and protected levels as well as attenuation values were measured as a function of time for full workshifts in different noise environments, for different workers and different HPDs. The acquisition system, based on the F-MIRE technique, is presented. This system was specifically designed to be able to record the unprotected and protected signals at workers ears in a continuous manner using miniature microphones inserted through the HPDs. The system was also designed to be lightweight, comfortable and rugged enough to be able to be worn by workers with minimal disturbance of their working habits. Time data were obtained which allow one to follow the evolution of protection and noise levels as a function of time and to carry out complete signal analysis. Examples of results for different noise environments and different workers are presented and discussed.

a Email address: nelisse.hugues@irsst.qc.ca
b Email address: gaudream@cdrummond.qc.ca
c Email address: Frederic.Laville@etsmtl.ca
d Email address: jvoix@jerevox.com
1. INTRODUCTION
The well-known discrepancies reported over the years\(^1\) between the labeled (laboratory measured) attenuation data and field measurements data for hearing protection devices (HPD) have raised several important questions when dealing with the use of HPDs in “real” working conditions. For example, what is the effective attenuation of a given HPD for a given worker in a specific working environment? Does this attenuation evolve over time during the workshift (in other words, is the worker well protected at all time)? If such variations are observed, what is the magnitude of the changes in the attenuation and what are the parameters that can explain such variations? What are the implications of such variations in the assessment of the performance of the HPD? In this context, the paper presents an attempt to provide answers to some of these questions by measuring HPDs attenuation values in field conditions (industrial plants) using the F-MIRE technique.

Various authors have discussed the merits and drawbacks of different field methods to study the effectiveness of HPDs in real operating conditions\(^2-6\) and various field results obtained using these techniques have been presented and discussed\(^7-12\). Fairly detailed reviews of the existing field methods have been proposed by Franks\(^5\) and recently by Gaudreau et al\(^13\) and Kusy\(^14\). This paper presents field measurements of HPD attenuation values using the F-MIRE (Field-Microphone in the Real Ear) technique. The first part of the paper gives an overview of the technique and the equipment used for the measurements. Secondly, the procedure for the field measurements in industrial plants is presented. Finally some examples of results for different HPDs, workers and workplaces are shown.

2. METHODOLOGY

A. Test setup (F-MIRE)
The F-MIRE technique is based on objective measurements of attenuation by using two microphones: one is placed just outside the HPD thus measuring the un-protected microphone signal while the other one is placed underneath the HPD to obtain the protected microphone signal. Figure 1 shows the microphone arrangements used for the measurements on earplugs and earmuffs. For the study only molded earplugs made by the company Sonomax Hearing Healthcare Inc\(^15\) were considered as they contain, by design, a vented bore that can be used to insert the interior microphone. Knowles\(^16\) microphones of type FG-23742 were used for the exterior sound field while the FG-23652 were used for the protected signals. An attenuation rating can be defined by calculating the transfer function between the signals measured simultaneously by the external and internal microphones. The protected and un-protected time signals were recorded using 16 bit stereo Edirol R-09\(^17\) recorders. This recorder was selected primarily for its recording capabilities (44.1 kHz sampling rate, uncompressed PCM \textit{wav} format, 4 GB storage on SD card), its low weight (160 gr. with batteries) and autonomy (up to 6 hours with AA rechargeable NiMH batteries) which make it very suitable for field measurements on regular working shifts, needing only a battery and card swap during the lunch break. Overall, the measurement system was sufficiently light and rugged to be installed on workers without modifying their normal working habits.
B. Field procedure
Measurements were conducted on a total of 22 workers in 8 different plants. Table 1 gives a summary of the companies and workers who participated to the study.

Table 1: List of participating companies to the measurement campaign

<table>
<thead>
<tr>
<th>#</th>
<th>Company type</th>
<th># tested workers</th>
<th>HPD type</th>
<th>Brand</th>
<th>Approximate measurement time per worker</th>
<th>Age range (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Food transformation</td>
<td>2</td>
<td>Molded earplugs</td>
<td>Sonomax</td>
<td>8 hours</td>
<td>40-50</td>
</tr>
<tr>
<td>2</td>
<td>Petrochemicals</td>
<td>2</td>
<td>Molded earplugs</td>
<td>Sonomax</td>
<td>8 hours</td>
<td>50-60</td>
</tr>
<tr>
<td>3</td>
<td>Wood Furniture</td>
<td>2</td>
<td>Earmuffs</td>
<td>Oris Mustang EM-415S</td>
<td>3 hours</td>
<td>30-40</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum transformation</td>
<td>3</td>
<td>Molded earplugs</td>
<td>Sonomax</td>
<td>8 hours</td>
<td>1 x 55-60; 2 x 25-30</td>
</tr>
<tr>
<td>5</td>
<td>Motorized products assembly</td>
<td>3</td>
<td>Molded earplugs</td>
<td>Sonomax</td>
<td>8 hours</td>
<td>45-50</td>
</tr>
<tr>
<td>6</td>
<td>Wood transformation</td>
<td>3</td>
<td>Earmuffs</td>
<td>Peltor H7A</td>
<td>9 hours</td>
<td>25-50</td>
</tr>
<tr>
<td>7</td>
<td>Aeronautics</td>
<td>3</td>
<td>Earmuffs</td>
<td>Peltor H7A</td>
<td>9 hours</td>
<td>25-30; 35-40; 45-50</td>
</tr>
<tr>
<td>8</td>
<td>Power production – generator</td>
<td>6</td>
<td>Earmuffs</td>
<td>Bilsom Thunder T3 &amp; T3H</td>
<td>30 minutes</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Two members of the research team were always present during each testing day. The measurement procedure used during such day can be summarized as follows:

1. Equipment preparation
2. Recording of reference signals using a calibrator
3. Introductory meeting with workers to explain the procedure for the day
4. Installation of the equipment on the workers and starting of the recorders
5. Lunch break (equipment is removed and batteries & memory cards are changed)
6. Re-recording of the reference signals using the calibrator (safety check 1)
7. Re-installation of the measurement systems & restarting of the recorders
8. End of the workshift (equipment is removed)
9. Re-recording of the reference signals using the calibrator (safety check 2)

Once the measurements were finished, the data was transferred to a hard drive to be afterward post-processed. Figure 2 presents an example of workers equipped with the measurements systems (two per worker) during a typical workshift.

Figure 2: Examples of workers wearing the measurement systems during normal operations with normal earmuffs, earmuffs mounted on a hard hat and molded earplugs

C. Post-processing

The data to process consist, for each ear, in a stereo `.wav` file containing the protected (noted \( x(t) \)) and un-protected (\( y(t) \)) signals. Each file was post-processed using in-house MATLAB routines. The signal was divided into time segments of length \( \Delta t \). For each time segment, the third-octave auto-spectral (\( G_{xx} \) and \( G_{yy} \)) and cross-spectral (\( G_{xy} \)) density functions were computed\(^{18} \). Using these density functions, the indicators given in Table 2 were evaluated. It is important to mention that correction factors were applied to the autospectral density function for the protected signal \( G_{yy} \). These correction factors account for the fact that the interior measurements were performed through small plastic tubes. These factors were measured in laboratory prior to the in-field tests. Additionally, compensation factors were used in order to relate F-MIRE measurements to insertion loss (IL) or REAT-type values (see Berger\(^{19} \)). These compensation factors are related to the transfer function of the open ear (TFOE). In the case of the earplugs, the compensation factors were obtained from Voix\(^{20} \) while for the earmuffs an approximation consisting in using the diffuse-field TFOE at the open entrance of the ear canal was utilized. The attenuation rating calculation scheme was intended to obtain values comparable to standard NRS values (see ANSI S12.68-2007\(^{21} \)) where laboratory attenuation data are generally used the compute the rating.
Table 2: List of indicators used to analyze the results ($W(t)$ is the frequency weighting function ($W(t) = 1$ if no weighting is desired) and $N_f$ is the number of frequency bands)

<table>
<thead>
<tr>
<th>Short description</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-protected (exterior) levels</td>
<td>$L_{ex}^U(t,f) = 10 \log_{10} \left( \frac{G_{ex}(t,f) W(t) \Delta f}{4 \times 10^{-16}} \right)$</td>
</tr>
<tr>
<td>Protected (interior) levels</td>
<td>$L_{in}^P(t,f) = 10 \log_{10} \left( \frac{G_{in}(t,f) W(t) \Delta f}{4 \times 10^{-16}} \right)$</td>
</tr>
<tr>
<td>Transfer functions</td>
<td>$H_0 = \sqrt{\frac{G_{in}}{G_{ex}}}, \quad H_1 = \frac{G_{in}}{G_{ex}}, \quad H_2 = \frac{G_{in}}{G_{ex}}, \quad H_i = \frac{1}{2}(H_{i-1} + H_{i+1})$</td>
</tr>
<tr>
<td>Attenuation</td>
<td>$M_{H_i}(t,f) = -20 \log_{10}(H_n(t,f))$ where $H_n = H_0, H_1, H_2$ or $H_3$</td>
</tr>
<tr>
<td>Attenuation Rating</td>
<td>$AR_{H_3}(t) = 10 \log \left( \sum_{i=1}^{N_f} \frac{L_{ex}^U(t,f)}{10} - \sum_{i=1}^{N_f} \frac{L_{in}^P(t,f) - M_{H_3}(t,f)}{10} \right)$</td>
</tr>
</tbody>
</table>

3. RESULTS

Examples of results for workers wearing earmuffs and molded earplugs are presented, respectively, in Figure 3 and Figure 4. The results are presented for a time step of $\Delta t = 60$ sec. These examples present two cases where relatively good attenuations were obtained. For the two figures, only the results for exterior levels exceeding 80 dB(A) were retained (displayed). In Figure 3, it can be seen that the worker took his lunch break between 12:00h and 12:45h and had one break in the morning (at around 9:30h) and one in the afternoon (around 14:30h). The unprotected levels vary significantly with various zones between 95 and 100 dB(A). The two ears are exposed to similar levels except notably early in the morning and late in the afternoon where the right ear is exposed to higher levels. Significant differences between the two ears are observed for the attenuation rating values. Globally, higher attenuation for the left ear is seen for the entire workshift. The attenuation rating is relatively high although significant variations are observed over time as well as some drop of attenuation in certain zones.
For the worker wearing molded earplugs (Figure 4), the exterior levels vary generally between 85 and 95 dB(A) with some zones above 95 dB(A). Important differences of exposure levels for the two ears are observed after the lunch break, the left ear being exposed to much higher levels. As told by the worker himself, he was working, in the afternoon, on a machine with a very directional source of noise directed directly toward his left ear. Large time variations in the noise levels and attenuations are observed for this worker. More specifically, important differences between the two ears are observed in the attenuation rating before 10:00h in the morning where the attenuation for the left ear is much lower. After the break, the attenuation values for the two ears are much more similar. It is probably due to how the worker is inserting its earplugs after the break.

A last example, presented in Figure 5, illustrate the effect of safety glasses on the attenuation values. For this worker, only about 30 minutes of data was available. Consequently, the time step $\Delta t$ was reduced to 5 sec. In this case, the worker is exposed to very high levels ranging between 110 dB(A) and 115 dB(A). Fairly good and stable attenuation values are observed although differences are observed between the two ears. The worker was asked by the research team to remove its safety glasses at around 20:15h. The attenuation rating values for both ears then increase to reach a plateau, the increase being more important for the left ear and the differences between the two ears becoming much less. These results are not surprising and are consistent with data found in the literature (see for example Lemstad$^{22}$). This illustrates well how the system developed in this study can be used to identify or track time events where the attenuation values are affected.
Figure 4: Time variation of unprotected levels (in dB(A)) and attenuation rating (in dB) for a worker wearing molded earplugs (company #5)

Figure 5: Time variation of unprotected levels (in dB(A)) and attenuation rating (in dB) for a worker wearing earmuffs (company #8)
4. CONCLUSIONS

This paper has presented some examples of results on the measurements of effective attenuation of HPDs during a workshift in different industrial plants. Several workers in 8 different companies were tested. Two types of HPDs were considered: earmuffs and molded earplugs. The small set of data presented here showed large variations in the attenuation rating values over time and important differences between the two ears for some cases.

The large set of time data available reveals a great potential for further analysis. Current work is under way to investigate and explore in more details the data. It includes:

- Defining and analyzing more indicators such as spectral balance, attenuation data, other attenuation ratings scheme and statistics;
- Analyzing frequency content as well as time content;
- Exploring how to compare attenuation values, attenuation ratings and protected levels to values estimated through various existing standards;
- Performing statistical analysis on the various data and indicators;
- Exploring different algorithms for the detection and classification of various time events (speech detection, removal of HPD, etc.).

It is believed that such work will bring significant knowledge on the performance of hearing protection devices in real-world conditions. It will also shed some light on how the F-MIRE technique could be used to assess such performance, in comparison with the existing standards for HPD. Finally, it will help, together with some laboratory work, to understand under which conditions and limitations this technique could eventually be used in a standardized way.

ACKNOWLEDGMENTS

The authors would like to gratefully thank all the companies and the staff who helped organizing the tests and all the workers who participated to the study. The authors would also like to thank Sonomax Hearing Healthcare Inc. for all the logistic support.

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