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1pNSa11. Use of passive hearing protectors and adaptive noise reduction for field recording of otoacoustic emissions in industrial noise

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Distortion Product Otoacoustic Emissions (DPOAEs) can detect noise-induced hearing loss in-field, but their data extraction is very sensitive to background noise. This paper investigates how passive and active noise reduction enhance DPOAE recording based on data collected in white noise from 54dB(A) to 90dB(A). Despite considerable high-frequency attenuation from a proper placed DPOAE probe, 54dB(A) background noise deteriorates the test outcome substantially. More low-frequency attenuation by an extra passive earmuff enables measurements in white noise levels of 70dB(A). The relationship between external sound level and noise recorded by the DPOAE system has been statistically modeled. Additionally, the upper limits of attenuation improvement are analyzed by quantifying residual physiological noise. Furthermore, for an earplug integrating microphone and speakers of the DPOAE measurement probe, adaptive noise reduction processing on the DPOAE signal is used to improve the Signal-to-Noise ratio. The adaptive noise reduction (ANR) is implemented using the NLMS algorithm to filter out the ambiant noise, measured by the first microphone measuring the DPOAE signal, with a second miniature microphone mounted flush with the external faceplate of the isolating DPOAE probe. Simulated data shows that DPOAE response extraction is possible in an environment with noise levels exceeding 70dB(A).

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INTRODUCTION

Despite hearing conservation programs implemented in the workplace, occupational hearing loss is an ongoing problem [4]. Two important factors that may contribute to this is the difficulty to assess workers' actual noise exposure while wearing protectors [18, 15] and each workers' individual vulnerability to a given noise dose [7].

A non-invasive test that can be used to quickly and objectively detect hearing damage due to noise exposure is the measurement of distortion product otoacoustic emissions (DPOAEs) [9], for in-field DPOAE measurements, interfering ambient noise must either be reduced or at least accounted for so that DPOAE responses can be interpreted correctly since background noise found in DPOAE measurements decrease their reliability [10]. Passive noise reduction devices can be included in the OAE setup, but the effect of these measures on DPOAE results have not yet been systematically studied, nor are practical guidelines available.

A way to further increase the signal-to-noise ratio (SNR) of DPOAEs, is a signal processing technique known as Adaptive Noise Reduction (ANR) [2, 6]. ANR and HPD work together so that the gain in SNR from the ANR adds to the attenuation of the HPD, thereby increasing the amount of attenuation [6]. Such processing enables measurement of the DPOAE response in external noise levels typical of industrial environments.

In this study: 1) the effects of passive noise reduction on DPOAE measures are studied and 2) a method of active external background noise reduction is presented. 3) Results demonstrate the effectiveness of the combination of passive and active noise reduction. 4) The outcome of these results are argued in the discussion and conclusion.

MATERIAL AND METHODS

Study of the effects of passive noise reduction

The experimental setup used to study the effects of passive noise reduction on DPOAE measurements is thoroughly discussed in our accompanying paper [3], of which the main aspects are summarized here.

For interfering ambient noise, seven white noise fragments ranging from 54 dB(A) to 90 dB(A) were created using sound editing software and emitted in random order through an Adam Audio S1X loudspeaker. The fragment levels were first registered with a Svantek 959 sound analyzer located at the subject's position 78 cm in front of louspeaker, without the subject. Three fragments with noise levels of 54 dB(A), 58 dB(A) and 62 dB(A) were presented as such, and for 70 dB(A), 77 dB(A), 83 dB(A) and 90 dB(A) the DPOAE probe was equipped with a passive earmuff on top.

The Peltor Optime I earmuff hearing protector was used (see Table 1 for Real Ear At Threshold (REAT) data from the manufacturer). No specific earmuff design requirements were priorly set, but previous experiments [2] have validated that this commercially available earmuff could be used with a commercial OAE system, and that it would not compromise probe placement.

HPD	Freq (Hz)	63	125	250	500	1000	2000	4000	8000
Earmuff	Mf (dB)	14.1	11.6	18.7	27.5	32.9	33.6	36.1	35.8
	sf (dB)	4.0	4.3	3.6	2.5	2.7	3.4	3.0	3.8
	APV (dB)	10.1	7.3	15.1	25	30.1	30.2	33.2	32.0

TABLE 1: Attenuation data for passive hearing protector: the supra-aural earmuff measured according to the ISO 4869-1:1990 standard [8], Mf is the average attenuation, sf the standard deviation and APV the Assumed Protection Value

While presenting the white noise fragments, DPOAEs were measured with the ILO 292 USB

II hardware and ILO v6 software [16]. A standard measurement routine was applied, except that the noise artifact rejection was increased to 8 mPa and the complete frequency range (second stimulus tone between 841 Hz and 8000 Hz at eight points per octave) was looped four times.

Sixty-two volunteers without history of otological conditions between 18 and 46 years old were tested. For each subject, either the right or the left ear was randomly selected. Routine tympanometry and tonal audiometry was carried out to confirm normal hearing status.

Active external background noise reduction

Intra-aural hearing protection

Passive hearing protection devices such as earmuffs described in the previous section already offers a suitable noise reduction. For this study however, we needed to design a prototype intra-aural passive hearing protection to include all the electronic components into a single device. This earpiece, called setup #2, would include a custom-fit Sonomax earplug [17], in which two wide-band speakers and two miniature microphones have been inserted as in Figure 1. The internal microphone would measure the DPOAE response in the ear canal and the external microphone would measure a reference value indicating external disturbance, or industrial noise. The external microphone is mounted flush with the external faceplate of the isolating DPOAE probe. To ensure optimal performance with the ANR algorithm, the external and internal microphones must be as close as possible and thus, are placed on the same ear that is being tested. The disturbance coming from the industrial noise is measured in both microphones. To better understand how the ANR and intra-aural passive hearing protection work together, the following section will describe the ANR signal processing algorithm.

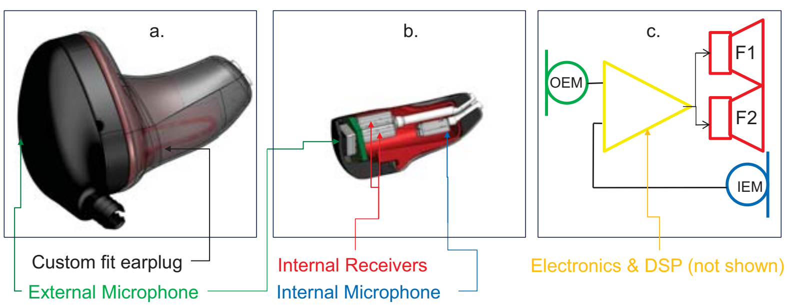


FIGURE 1: Setup #2: Overview of the digital custom earpiece (a), its electro-acoustical components (b), and equivalent schematic (c).

Description of the Adaptive Noise Reduction algorithm

The ANR algorithm presented in Figure 2 uses a normalized least-mean square (NLMS) algorithm [11] to reduce the noise disturbance in the measured DPOAE response. In order to use the NLMS adaptive filter properly, the input signals need to be conditioned a priori. Firstly, the disturbance measured in the internal microphone (IEM) must be in phase with the disturbance measured in the external microphone. Secondly, the stimulus needs to be removed so that the NLMS filter converges for the DPOAE, since their levels are in the range of -20 to 20 dB [6] that is very low compared to the stimulus levels of over 65 dB [6]. To do so, a bandpass filter with a bandwidth of 200 Hz centered at the DPOAE response frequency is used in the primary path of the NLMS filter (internal microphone). The same filter is also used in the secondary path (external microphone) to obtain the same noise disturbance level as in the primary path. The addition of this filter makes the ANR algorithm a filtered-x input NLMS (FXNLMS) algorithm [12]. It is worth noting that there is no acoustic feedback to cancel the noise in the signal as

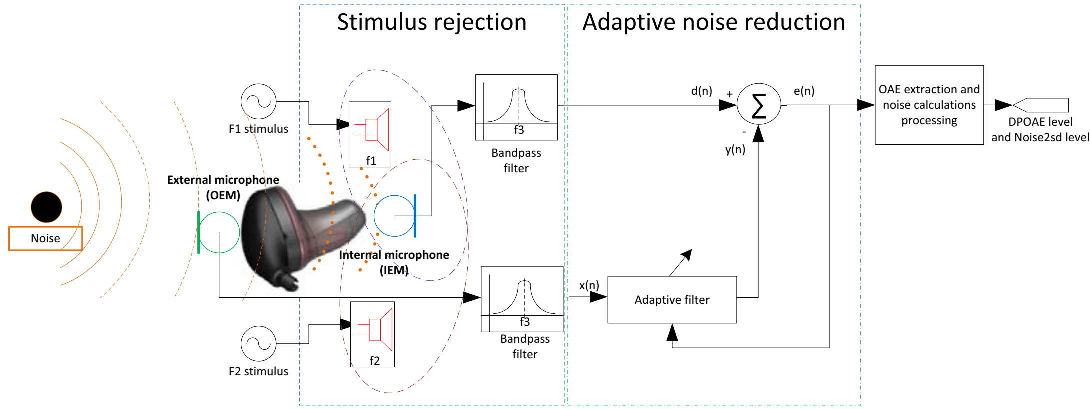


FIGURE 2: Bloc diagram of the proposed Adaptive Noise Reduction algorithm. The purple and brown ellipses represent the acoustic path between the internal microphone and each speaker. The adaptive filter models the noise input *x(n)*, the output of this filter *y(n)* is then subtracted from the desired signal input *d(n)*. The error signal *e(n)* is used to correct the adaptive filter's coefficients in order to model the noise disturbance in the internal microphone accurately.

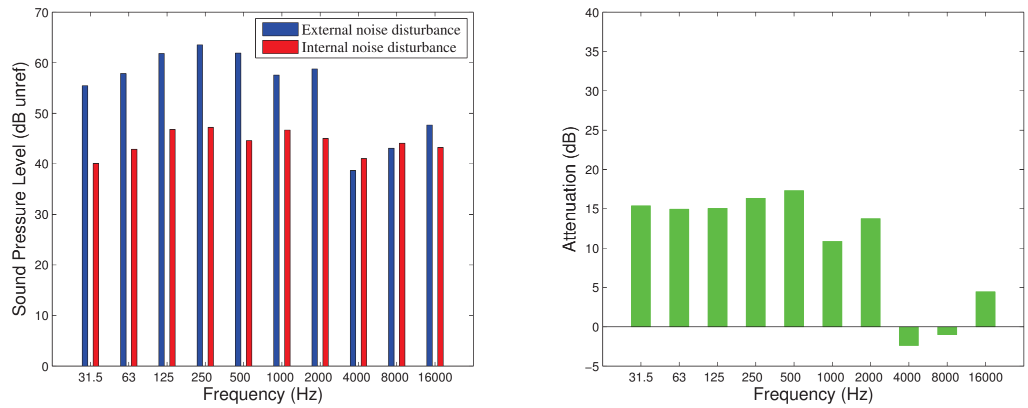
in a traditional Acoustic Noise Cancellation scheme [12]. The noise is reduced by an electronic feedback loop only and this is why the algorithm used is called Adaptive Noise Reduction. In the next section, the simulation setup used to test the ANR algorithm is described.

Simulations setup for the Adaptive Noise Reduction algorithm

To test the signal processing's influence on the DPOAE measurement, the ANR algorithm was simulated in Matlab© [13] using real sound recordings coming from the ILO 292 USB II hardware and ILO v6 software [16] of 8 co-workers who were not included in the passive earmuff experiment. The total number of tested ears is 15, because one participant was only tested for one ear. The recordings were sampled at 96 kHz using a digital recorder (Zoom H4N) [19]. The probe used was an electronic earpiece prototype, known as the Auditory Research Platform (ARP) [5]. A standard eartip is slipped over the DPOAE probe to fit well in the ear canal. Stimuli are presented via the ILO system and simultaneously recorded at the microphone input of the digital recorder.

A proposed approach, that is not the scope of this article, using Amplitude Modulation (AM) was used to extract the DPOAE measurement from the recorded samples. The DPOAE noise recorded by the measuring system is referred to as Noise2sd and Noise1sd, i.e. the average noise level plus respectively two and one standard deviation. The average noise level is calculated over adjacent frequency bins on each side of the DPOAE frequency [6]. The ANR was implemented in Matlab using an NLMS filter function and a bandpass filter function which was centered around the DPOAE measurement frequency.

The ANR algorithm was tested using industrial noise disturbance samples that were recorded during a factory worker's entire shift [14]. Using a Sonomax Sonocustom V3 earplug [17], the sound behind the earplug and outside the earplug were recorded. Upon analyzing the industrial noise samples, as shown in Figure 3a, we observed that the HPD attenuation values were poor, as shown in Figure 3b. The lack of high frequency content also affected the calculation of the measured attenuation in Figure 3b resulting in an underestimation of the earplug's attenuation in high frequencies. The industrial noise behind the earplug, referred to as internal noise disturbance, was added to the DPOAE measurement recordings, which is the desired signal *d(n)*, and the external noise disturbance was used as the reference noise signal, which is *x(n)* in the ANR



(A) **(B)**

FIGURE 3: A) External microphone and internal microphone background noise disturbance level: The following graphic shows the level of industrial noise in dB unreferenced for the external microphone (64 dB(A) noise disturbance) and internal microphone (52 dB(A) noise disturbance) per octave bands. B) Earplug measured attenuation: these attenuation values represent the actual noise reduction per octave bands between the internal and external microphone of the earplug.

scheme found in Figure 2. The value measured for the external microphone is 74 dB(A). To see the effect of the noise level, the same industrial noise sample was reduced by 10 dB and the ANR algorithm was retested.

RESULTS

Potential benefits of passive ambient noise attenuation

To illustrate the benefits of passive noise reduction as measured in white noise for 62 subjects, Figure 4 shows per frequency the outside ambient noise level (without accounting for any extra attenuation) and the DPOAE noise level measured by the commercial ILO probe connected to ILO system. The passive earmuff substantially attenuates the external noise; while background noise conditions (with earmuff) are higher than without, the relative DPOAE noise levels lie closely together. As illustrated in [3], with earmuff, the DPOAE signal-to-noise ratio in 70 dB(A) background noise is comparable to the signal-to-noise ratio in quiet test conditions without added background noise. In contrast, in 62 dB(A) white noise without earmuff, the ambient noise deteriorates the signal-to-noise ratio especially in the lower frequencies.

Figure 4 also reveals that there is room for improvement as the DPOAE noise in quiet conditions is on average markedly lower, especially below 4 kHz. In addition, standard deviations are clearly smaller in quiet test conditions. Here, exact *individual* fitting of the OAE probe and earmuff and obtained attenuation become more important in higher levels of background noise, hence the increase in inter-subject variability for DPOAE noise amplitude.

Subsequently, DPOAE noise level is modeled as a function of external background noise using mixed-model linear regression (statistical software R, lme4 package [1]) with *subject* included as independent random factor. As outcome variable, the *relative* DPOAE noise level has been introduced. Per subject, the difference has been calculated for each frequency between the DPOAE noise level in the respective white noise test conditions and the DPOAE noise level in the baseline condition without added ambient noise. This relative DPOAE noise level then indicates how per subject changes in test conditions—by adding white noise and/or placing an earmuff—*alters* the DPOAE noise level compared to more ideal test conditions, making the model less dependent

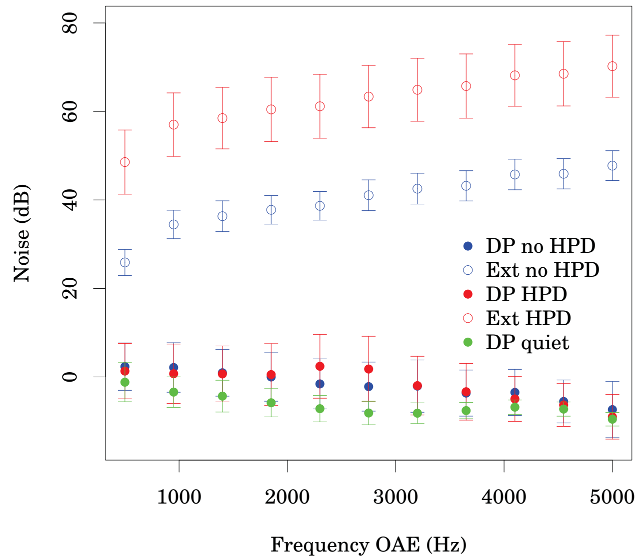


FIGURE 4: Noise levels per DPOAE signal frequency: mean and mean plus/minus one standard deviation. Both external background noise levels (Ext) and DPOAE noise are shown (DP), grouped by presence (HPD) or absence (no HPD) of an earmuff placed on the OAE probe. The DPOAE noise level measured without added background noise (DP quiet) is included as a reference.

Variable	Coeff	p
(Intercept)	-1.640e+01	< 0.001
External Noise	7.372e-01	< 0.001
Frequency DPOAE	-3.051e-03	< 0.001
Gender Male	-1.134e+00	0.04
HPD Yes	8.094e+00	< 0.001
External Noise $*$ Frequency DPOAE	-1.032e-05	0.05

TABLE 2: Coefficients and corresponding p-value of the fixed independent factors included in the mixed-model regression model with relative DPOAE noise level as outcome variable: external noise level (corrected with attenuation earmuff for observations with earmuff), DPOAE signal frequency, gender and use of earmuff (HPD Yes).

on the specific commercial system used for DPOAE registration. For the independent variables, *subject* has been a-priori included as a random factor to take into account that each subject corresponds to different observations.

The coefficients of the fixed factors that significantly reduce the residual deviation are summarized in Table 2. For the test conditions with earmuff, the background noise levels have been corrected with the interpolated assumed protection values given in Table 1. As expected, the relative DPOAE noise level increases with increasing background noise, although this effect is less distinct for higher frequency as can be seen from the negative coefficient for the interaction effect between external noise and frequency. One explanation is that both the OAE probe and the earmuff provide in general sufficient high-frequency attenuation [2] so that the DPOAE noise level is more determined by the setup's noise floor instead of the external background noise. This reasoning is confirmed by Figure 4.

In accordance with the principle of frequency-dependent attenuation, the relative DPOAE noise level decreases with increasing frequencies. This effect is more pronounced in higher levels of background noise, probably because then again the noise level difference between the (more attenuated) higher frequencies and (less attenuated) lower frequencies plays a more important role. Furthermore, relative DPOAE noise levels are higher for women than man, possibly because a man's larger ear canal, pinna and head facilitates the placement of OAE probe and earmuff, thus providing better attenuation.

However, it is clear that pure noise reduction by the earmuff is insufficient to capture its influence on DPOAE noise level, as the categorical variable coding for earmuff placement (yes or no) is still statistically significant. One could hypothesize that placing an earmuff compromises placement of the OAE probe and thus increases DPOAE relative noise levels, but then one would expect overall higher DPOAE noise level with earmuff, which is not the case (see Figure 4). However, the setup does appear to amplify the noise around 1.5 kHz, which corresponds to the resonance frequency of the cavity created between pinna and earmuff cushion (long axis 63.2 mm, short axis 26.9 mm). Another factor is the assumed protection value. As the current test setup and required test time did not allow attenuation measurement per participant, noise reduction had to be estimated from the assumed protection value reported by the manufacturer. Apart from the known differences between laboratory and real-world attenuation, the particular setup with OAE probe under earmuff might have compromised the obtained attenuation.

Benefits of the Adaptive Noise Reduction algorithm

To assess the advantages of the ANR algorithm, several noise conditions have been tested. In the white noise disturbance scenario, the results found in Figure 5 a) and in Figure 5 b) show that white noise fragments are easy to remove from the DPOAE signal because of their high correlation between the simulated IEM signal and OEM signal since they were both simulated and included in the DPOAE signal. A slight offset between the DPOAE response curves with ANR can be explained by the big step-size value of the adaptive filter causing a small error. As mentionned previously the noise samples used to test the attenuation of the earmuffs were white noise signals. It is important to mention that white noise fragments are considered an optimal noise scenario in which the ANR algorithm performs at it's best. Although this white noise scenario does not reflect the reality of the industrial noise fragments which contain less high frequencies due to the origin of the noise source. Also, the attenuation of the HPD (earplug or earmuff) is not uniform, which results in uncorrelated frequency levels in high frequencies in addition to phase problems between the IEM and the OEM, explained by real world disturbances caused by the dynamic movement of the earplug. This inconsistency makes the test conditions suboptimal for the ANR algorithm.

Simulated data found in Figure 5 c) and d) shows that even in industrial noise conditions, the ANR algorithm gives an improvement in SNR ratio for the DPOAE signal. General findings for the ANR algorithm enabled in noisy test conditions are: 1) improved DPOAE signal extraction and 2) decent SNR, at least over 3 dB, for 74 dB(A) ambient background noise.

The residual high frequency noise (over 5 kHz) after the ANR algorithm can be observed by comparing the curves in Figure 5 when the algorithm is on or off. This phenomena could be explained by the physiological noise measured under the earplug or an occluded earcanal resonance with the setup #2. These disturbances are not present in the OEM which makes it impossible to remove. Also, after looking at the frequency spectrum of the internal microphone's disturbance and the external microphone's recording in Figure 3a it seems that, in the industrial noise sampled, there was no high frequency content in the ambient external background noise, therefore no high frequency noise could be removed from the DPOAE response with the ANR algorithm.

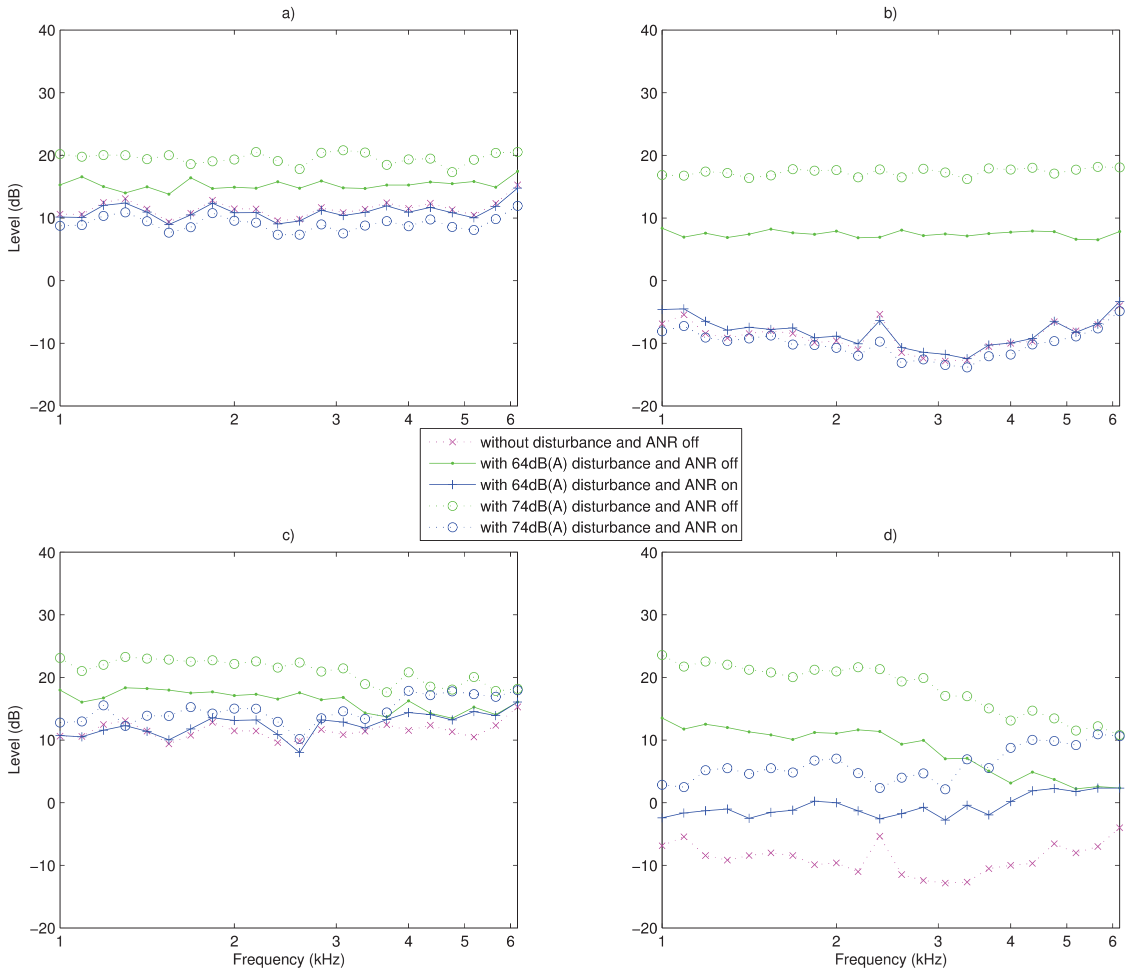


FIGURE 5: Various DPOAE and Noise2sd level curves in noisy test conditions: a) represents the DPOAE level and b) the Noise2sd level both in white noise conditions. c) Shows the DPOAE level and d) the Noise2sd both in industrial noise conditions. The DPOAE level and Noise2sd level without external noise disturbance were included in each graph as a reference.

DISCUSSION

The current paper clearly shows that noise reduction helps to perform DPOAE measurements in suboptimal test conditions caused by external background noise. The fact that these benefits are systematic and reproducible over a larger test sample is an important finding to improve effective hearing conservation in the workplace. The first setup described in this project is quite simple: a typical commercially available earmuff is combined with commercial clinical OAE equipment. This setup can be used by any professional responsible for hearing conservation to improve in-field DPOAE measurements and prevention of noise-induced hearing loss. However, there is room for improvement. One drawback is that the current equipment by no means allows automatic, unsupervised measurements. This makes monitoring labor-intensive and somewhat hampers implementation on a larger scale.

Other issues are related to the use of a passive earmuff as noise reduction strategy. Presumable resonance in the cavity produces noise (around 1.5 kHz), which would not occur if the OAE probe would be integrated in an earplug. Another point is related to passive devices in general: placement and possible air leaks are critical when working in elevated background noise levels. This increases inter-subject variation as to actual noise reduction. Finally, DPOAE measurement could still benefit from more noise reduction than achieved in this setup, especially for the frequencies below 4 kHz.

To provide the necessary improvement in noise reduction, especially for frequencies in which the HPD provides less noise reduction, the ANR signal processing can be used. Knowing that the DPOAE measurement system usually measures DPOAE frequencies between 639 Hz and 3944 Hz, corresponding to a stimulus frequency of f2=1000 Hz to f2=6169 Hz and by looking at the measured attenuation value in Figure 3b, it is clear that the earplug's attenuation will benefit from a better fitting of the envisionned Sonomax earplug. Using the attenuation data of the most recent Sonomax HPD [17], which tends to improve beyond 1000 Hz, and the measured attenuation as seen in Figure 3b it is possible to say that the ANR algorithm along with a properly fitted Sonomax earplug will make it possible to measure DPOAE levels in external noise conditions of over 74 dB(A).

Conclusions

Experiments shown in this paper demonstrate that passive noise reduction alone enhances DPOAE measurements in ambient noise levels of 70 dB(A). Furthermore, an earplug integrating the electronic components found in a DPOAE ear probe along with an adaptive noise reduction algorithm, improves the signal-to-noise ratio, thus giving the opportunity to measure DPOAE levels in noise conditions exceeding 74 dB(A). This improvement would enable industrial workers to measure their DPOAE response during a work day, and even monitor their hearing health condition. Future work will involve the integration of the Auditory Research Platform elements into a better attenuating earplug. The developpement of a calibration method to equalize the frequency response of the speakers and microphones to get a flatter response and minimize errors in the DPgram. Also, involve off-line identification of various transfer functions to model the earplug and the acoustic response of the speakers and microphones to enhance the results with the ANR algorithm. Moreover, a contra-lateral earpiece will be used to reduce residual physiological noise with the help of the second internal microphone this being another major avenue of research involving noise reduction techniques.

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