On the Wavelet-Based Elimination of Stimulus Artifacts in Click-Evoked Otoacoustic Emissions

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Abstract— **Otoacoustic emissions (OAE) are very low-level acoustic responses generated by a healthy cochlea during the normal hearing process. This paper focuses on the detection of click-evoked OAE (CEOAE), using wavelet decomposition, to assist on the diagnosis of possible peripheral hearing disfunctions. A complete wavelet-based modeling procedure for the CEOAE is described, using a powerful toolbox designed for this matter. Simulations indicate that the resulting model reaches correlation levels above 99% with respect to the original CEOAE. Such a match allows an almost-perfect elimination of the stimulus artifact, yielding better detection of the CEOAE and a more precise hearing-system diagnosis.**

I. INTRODUCTION

Despite its importance, understanding of the human hearing process has only began on the second half of the 20th century, with the Nobel-prize winning research by Georg von Békésy. Later, in 1978, an important step was made when Kemp [1] demonstrated that a healthy cochlea generated very low levels of acoustic emissions during the normal hearing process. Such emissions, referred to as the otoacoustic emissions (OAE), act like an active positive feedback signal within a healthy inner ear. Since OAE are very reduced in most damaged hearing systems, detection of OAE becomes the recommended auditory test for possible hearing impairments. Due to its non-invasive procedure, detection of OAE becomes a perfect auditory test for newborns and non-cooperative patients. Early detection of hearing disfunctions can reduce the damage in a child's cognitive development.

One possible way of measuring OAE is by using click-like stimuli. Such stimulus type, however, generates not only the desired OAE but also a passive acoustic echo within the ear cannal, which is commonly referred to as the stimulus artifact. In most cases, the artifact presents a much higher level than the OAE signals themselves. In this paper, we present a wavelet-based technique to isolate the emission signals from this stimulus artifact, thus allowing a more reliable hearing-system diagnosis. The idea is to model the OAE signal through the wavelet transform, using a Matlab-based software tool to perform such procedure. One can then use such a tool to analyze the stimulus response, greatly reducing the spurious artifact within the measured signal. Simulation results indicate that the artifact signals are almost eliminated yielding correlation levels above 99% between the desired (mathematically modeled) and the resulting signals.

The remaining of this paper is organized as follows: Section 2 introduces a classification of the OAE and describes a simple method for reducing the stimulus artifact for CEOAE. Section 3 describes the theoretical aspects for applying the wavelet transform to model the CEOAE and perform subsequent artifact reduction. Section 4 presents the gammatone mathematical model for CEOAE, while Section 5 describes the practical results for the wavelet-modeling procedure of this CEOAE representation. Section 6 includes simulation results using the wavelet CEOAE model to remove the stimulus artifact, allowing improved detection of OAE signals. Finally, Section VII concludes the paper emphasizing its main contributions.

II. OTOACOUSTIC EMISSIONS

As described in [1], the OAE are low level signals provenient from the inner ear as an acoustic response, in general, to an auditive stimulus. These emissions are usually associated to an active tuning system performed by the cochlea during the normal hearing process. The OAE can be classified according to the stimulus type as:

1) Transient-evoked: The stimulus has a short time-duration, and the OAE tends to be separated in time from the stimulus.
2) Distortion product: The stimulus consists of a pair of sinusoids of different frequencies. Due to a nonlinear cochlear behavior, the associated OAE present frequency components other than the input ones.
3) Frequency stimulus: The stimulus consists of a single frequency, and the corresponding OAE is in the same frequency, and can be detected by some phase-delay interactions between the OAE and the stimulus signal.

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4) Spontaneous: The OAE can be generated long after the stimulus has fainted. This type of OAE is referred to as an spontaneous OAE, and, in general, consists of narrowband stationary signals.

This work is focused on the CEOAE, which are a type of transient-evoked OAE where the stimulus consists of an impulse-like peak. In this OAE type, the main interference is the passive echo produced by the ear cannal. Such phenomenon is illustrated in Figure 1, where one can clearly see the click like stimulus, lasting about 1-2 ms, directly followed by the associated stimulus artifact, which lasts approximately 5-7 ms. Figure 2 depicts the general CEOAE aspect, separated from and added to the stimulus signal.

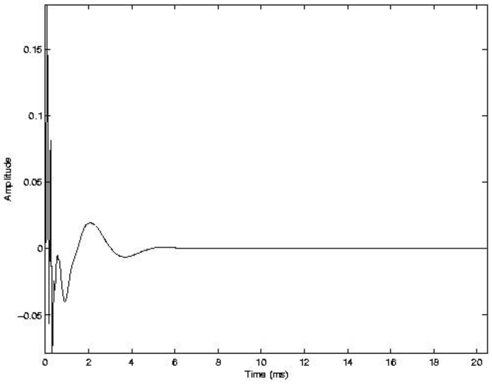


Fig. 1. Click-like excitation signal along with stimulus artifact.

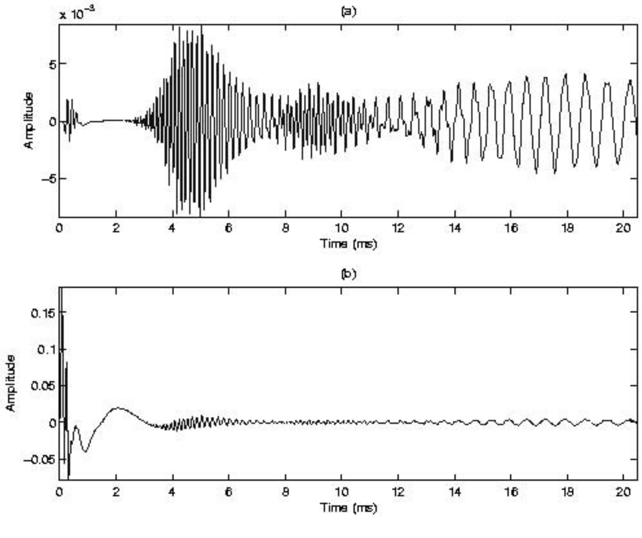


Fig. 2. CEOAE: (a) OAE signal; (b) Measured signal containing click-like stimulus, stimulus artifact, and OAE signal.

Previous methods for dealing with the CEOAE echo artifact include the so-called derived nonlinear response method presented in [3]. In such technique, four impulses are used to generate the OAE, three of them with an amplitude a and the fourth one with amplitude $-3a$. As the stimulus artifact is a linear response of the ear cannal to the input channel, the responses to the four clicks tend to cancel each other. Meanwhile, as the OAE presents a nonlinear behavior with respect to the input amplitude, as reported in the original work by Kemp [1], the corresponding OAE do not cancel each other. Although this method is widely employed in practice, it can be shown to reduce not only the stimulus artifact but some significant portion of the OAE originally present in the measured signal. Therefore, a more efficient artifact-reduction technique is desirable.

III. CEOAE WAVELET MODELING - THEORY

In a proper wavelet domain, the desired short-time duration signal presents significant components only within given wavelet bands, while the other signals tend to spread all over. The denoising process consists of selecting the wavelet bands where the signal of interest is contained and, then, submitting the resulting coefficients to a set of thresholds. This way, one can then significantly emphasize the signal of interest, which is determined by applying the corresponding inverse wavelet transform, after the coefficient shrinkage [4], thus returning to the time domain [5]. Previous works applying the wavelet transform to process CEOAE include reference [6]. In that work, however, no details are given on the selection of the mother-wavelet for CEOAE modeling and subsequent denoising.

A. Performance evaluation criteria

Three criteria are used to evaluate the performance of a specific denoising method:

- The signal-to-noise ratio, defined as

$$\mathrm{SNR}_{\mathrm{dB}} = 10 \log \left\{ \frac{\sum_{k=1}^{L} s^2(k)}{\sum_{k=1}^{L} \left[x(k) - s(k)\right]^2} \right\} \tag{1}$$

  where $x(k)$ is the corrupted signal, which includes the signal of interest $s(k)$ and some additive noise $n(k)$, and L is the total length of that signal.
- The normalized cross-correlation factor R, determined by

$$R = \frac{1}{L} \frac{\sum_{k=1}^{L} \left\{ \left[y(k) - E[y]\right] \left[s(k) - E[s]\right] \right\}}{\sigma_y \sigma_s} \tag{2}$$

  where $E[.]$ denotes the expected value operator, σ_y and σ_s denote standard deviations from the processed signal $y(k)$ and the signal of interest $s(k)$, respectively.
- The amplitude reduction is the percentage difference between the highest peak contained in the original signal $x(k)$ and the highest peak in the processed signal $y(k)$. It denotes the amount of signal peak that is lost through the denoising process.

In practice, it is essential to use more than one criterion in order to have a full idea of the impact of varying the parameters. For instance, in some cases, the SNR may not carry meaningful information on the waveform of the processed signal, whereas the cross-correlation may not retain information on the amplitude of the output signal, and so on. Hence the three criteria described above are jointly used in this paper.

IV. GAMMATONE MODEL FOR CEOAE

To generate a good wavelet characterization of the CEOAE signals, the gammatone model presented in [7] was employed. In such a description, the CEOAE signal, $x(t)$, can be modeled as

$$x(t) = \sum_{i=0}^{N} \gamma(\omega_i, t) \tag{3}$$

where the gammatone functions are defined as

$$\gamma(\omega_i, t) = \omega_i t^3 \mathrm{e}^{-\omega_i t} \cos(\omega_i t) \tag{4}$$

where ω_i is the gammatone central frequency, in rad/s. In [7], it is suggested that $N = 256$, with

$$\omega_i = (1 + 0.02\eta_i)\left(\mathrm{e}^{(\ln \omega_0) + \frac{i}{256} \ln \frac{\omega_1}{\omega_0}}\right) \tag{5}$$

where η_i is a sample of a Gaussian noise with zero mean and unitary variance that models small imperfections of the cochlea, and

$$\begin{cases} \omega_0 = 2\pi 300 \text{ rad/s} \\ \omega_1 = 2\pi 5500 \text{ rad/s} \end{cases} \tag{6}$$

indicate the initial and final gammatone frequency values, respectively. For instance, this gammatone model was used to generate the CEOAE signal depicted in Figure 2(a).

A model for the peripheral auditive system can be found in [8]. Such a model, based on a passive RLC electric network, was used in this work to produce the stimulus artifact shown in Figure 1.

V. CEOAE WAVELET MODELING - PRACTICE

Using the software tool presented in [2], a good wavelet characterization for the CEOAE gammatone model, described in Subsection 2.1, was determined. For this matter, the following wavelet families were considered: Daubechies, Simlets, Coiflets, and biorthogonal. The approach for selecting the most suitable mother-wavelet for representing the signal of interest is based on the higher cross-correlation and lower amplitude reduction criteria.

To better model the CEOAE, the tool presented in [2] was employed. The most suitable family was found to be the Daubechies, for which the CEOAE significant coefficients, using a 9th-level decomposition, were concentrated in scales from 7 to 10 (representing the highest scales). Such coefficient behavior is depicted in Figure 3.

All available wavelet families were tested, but for the sake of simplicity, only the Daubechies family is shown. Figure 4 shows, for instance, the cross-correlation and the amplitude reduction results for the Daubechies 17, generated by the our user-friendly graphical tool. To verify the best order for the mother wavelet, the Daubechies family was tested from order 1 up to 20.

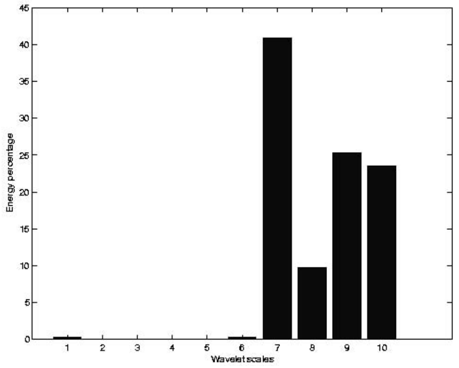
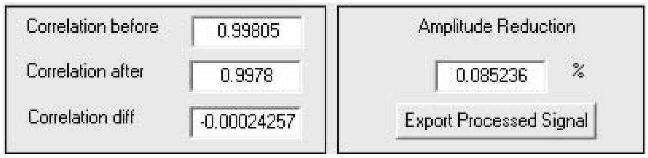


Fig. 3. Wavelet coefficient energy distribution through scales.



Correlation before 0.99805
Correlation after 0.9978
Correlation diff -0.00024257

Amplitude Reduction 0.085236 %

Fig. 4. Information on the cross-correlation and the amplitude reduction results for the Daubechies 17, generated by our user-friendly graphical tool.

Figure 5(a) shows the cross-correlation between the reconstructed signal and the ideal signal and Figure 5(b) shows the amplitude reduction using each one of the mother wavelets contained in the Daubechies family.

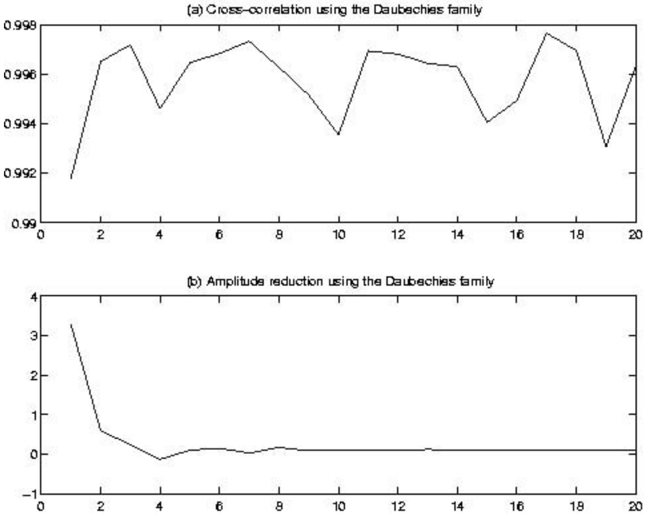


Fig. 5. CEOAE modeling using Daubechies family of wavelets: (a) Cross-correlation between reconstructed signal and signal of interest; (b) Amplitude reduction.

From these figures, one may conclude that the mother wavelet for the CEOAE model is the db17, where the reconstructed signal presents a cross-correlation of $R = 0.997$ and an amplitude reduction of only 0.085%.

VI. STIMULUS ARTIFACT REMOVAL: SIMULATION RESULTS

In the previous section, one was able to determine an excellent wavelet characterization of the CEOAE process. Such wavelet description concluded that the CEOAE is well represented by bands 7-10, using a 9th-level signal decomposition, in the db17 member of the Daubechies family of wavelets.

Using the CEOAE wavelet model obtained before, one is then ready to perform stimulus artifact removal from CEOAE signals. The key is to employ the same coefficient shrinkage procedure as determined above, preserving the bands where the CEOAE is most concentrated, and deleting all other bands where the artifact shall be present. Notice that in this time, the procedure should be applied to the corrupted signal instead on solely the CEOAE signal as before. To avoid stimulus contamination, the first 2 ms were disregarded from all subsequent analyses.

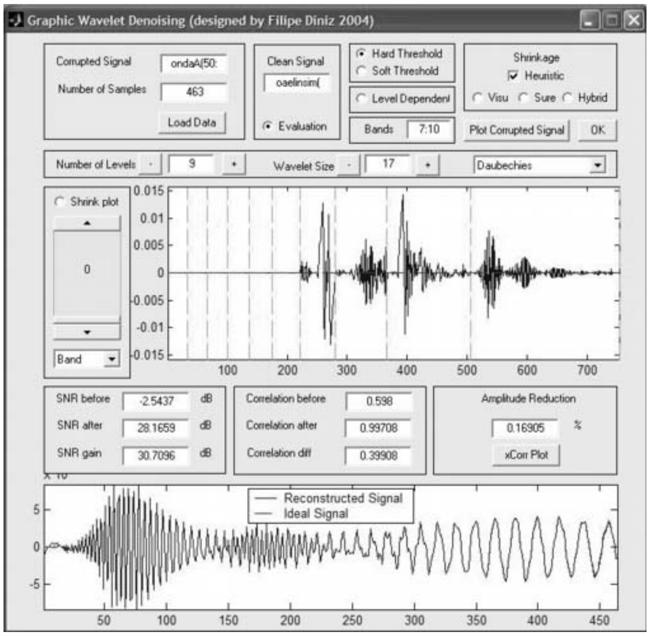

Corrupted Signal: ondaA(50:
Number of Samples: 463
Clean Signal: oaelinsim(
● Evaluation
● Hard Threshold
○ Soft Threshold
○ Level Dependent
Bands: 7:10
Shrinkage: ☑ Heuristic ○ Visu ○ Sure ○ Hybrid
Number of Levels: 9
Wavelet Size: 17
Daubechies
○ Shrink plot
Band
SNR before: -2.5437 dB
SNR after: 28.1659 dB
SNR gain: 30.7096 dB
Correlation before: 0.598
Correlation after: 0.99708
Correlation diff: 0.39908
Amplitude Reduction: 0.16905 %

Fig. 6. Snapshot of the package tool used for performing the denoising process.

The result of this procedure for the complete signal depicted in Figure 2 is shown in Figure 6. In this figure, one can see the wavelet transform of the input signal (in the center of the figure), and the numerical results (shown in the bottom of the figure) obtained with all three figures of merit (SNR, cross-correlation, and amplitude reduction), which are displayed right above the resulting signal.

Two practical examples were tested and the results are shown in Table I. In particular, one can notice that the SNR_{dB} was increased by at least 11 dB, the cross-correlation between the desired signal and the obtained result ended up being approximately 0.997, from an initial value of around 0.6. The amplitude reduction value obtained in Example 2 indicates that the CEOAE signal was attenuated, but its original waveform was preserved as confirmed by the cross-correlation figure of merit.

TABLE I

RESULTS OF TWO WAVELET-BASED PROCESSING EXAMPLES.

	Example 1	**Example 2**
SNR before	-2.5437 dB	0.54591 dB
SNR after	28.1659 dB	11.1055 dB
Cross-correlation before	0.598	0.62755
Cross-correlation after	0.99708	0.99635
Amplitude reduction	0.16905%	29.4545%

In the lower part of Figure 6 the CEOAE signal generated by the gammatone model and the one obtained after the stimulus removal are plotted.

VII. CONCLUSION

This paper described the methodology for using a wavelet-based denoising process for the removal of stimulus artifacts on click-evoked otoacoustic emission signals (CEOAE). First the gammatone model for CEOAE was analyzed in the wavelet domain for several wavelet families and members for each family. It was determined that the Daubechies 17 (db17) was capable of almost-perfectly modeling the CEOAE signals using bands 7-10, in a 9th-level wavelet decomposition. Such fitting allows one to perform artifact subtraction in a very efficient and precise way. The CEOAE wavelet-based modeling and subsequent denoising was simplified by the use of a general-purpose package tool. Results were very encouraging and are currently being tested in real-life signals.

REFERENCES

[1] D. T. Kemp, "Stimulated acoustic emissions from within the human auditory system," *Journal Acoustics Society of America*, vol. 64, no. 5, pp. 1386–1391, 1978.

[2] F. C. C. B. Diniz and S. L. Netto, "A package tool for general purpose signal denoising," *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing*, Pittsburgh, PA, 2005.

[3] P. Ravazzani and F. Grandori, "Evoked otoacoustic emissions: Nonlinearities and response interpretation," *IEEE Transactions on Biomedical Engineering*, vol. 40, no. 5, pp. 500–503, 1993.

[4] D. L. Donoho, I. M. Johnstone, "Threshold selection for wavelet shrinkage of noisy data," *Proc. IEEE Engineering in Medicine and Biology Society*, pp. 24a–25a, Nov. 1994.

[5] P. P. Vaidyanathan, *Multirate Systems and Filter Banks*, Prentice-Hall, 2^{nd} ed., 2000.

[6] M. Yuwaraj and H. Kunov, "Wavelet based reduction of stimulus artifact in evoked otoacoustic emissions testing," *Proc. IEEE Engineering in Medicine and Biology Society*, Montreal, Canada, Sept. 1995.

[7] H. Wit, P. van Dijk, and P. Avan, "Wavelet analysis of real ear and synthesized click evoked otoacoustic emissions," *Hearing Research*, no. 73, pp. 141–147, 1994.

[8] C. Giguère and P. C. Woodland, "A computational model of the auditory periphery for speech and hearing research. Part I: Ascending path" *Journal Acoustics Society of America*, vol. 95, no. 1, pp. 331–342, 1994.