The application of DWT for determining the level of audibility

VINCENZO NIOLA
Department of Mechanical Engineering for Energetics
University of Naples "Federico II"
Via Claudio 21, 80125, Napoli
ITALIA

GIUSEPPE QUAREMBA
University of Naples "Federico II"
Via Pansini 5, 80131, Napoli
ITALY

Abstract: - Normally, the level of audibility is investigated by means of the Evoked Potentials. These patterns are examined by two independent observers in order to define their features. In particular, the threshold value is obtained by calculating, for each ear, the average of the lowest intensity at which the response was revealed and the highest intensity at which the response disappeared. The aim of the work is to objective the determination of threshold of audibility of auditory Evoked Potentials response and their classification in terms of reliability based on the multiresolution analysis performed by wavelets. Actually the analysis performed by wavelet represents an advanced technique of windowing. It concurs to use a long interval in the case the information must be excreted from detailed low frequency signal. A wavelet is, like suggests the name, a small wave. Many physical phenomena show a structure like wavelet. From a methodological point of view, the wavelet technique provides a multiscale analysis of the signal as a sum of orthogonal signals corresponding to different time scales hierarchically organized.

Key-Words: - Wavelet analysis, threshold estimation, evoked potential, deafness index.

1 Introduction

The aim of this paper is to process the data of chinchilla auditory Evoked Potentials (EP) in order to find an objective methodology to measure the deafness index. The chinchilla is a rodent and it is used as model since its acoustic apparatus is very similar to those humans [1].
On the other side, the analysis performed by wavelet represents an advanced technique of windowing. It concurs to use a long interval in the case the information must be excreted from detailed low frequency signal. At the same time, it searches in the high frequency domain if the anomalous signal is covered. A wavelet is, like suggests the name, a small wave. Many physical phenomena show a structure like wavelet. From a methodological point of view, the wavelet technique provides a multiscale analysis of the signal as a sum of orthogonal signals corresponding to different time scales hierarchically organised.
Starting from these considerations some mathematical functions were developed in order to process the signal obtained by EP. A neural network was designed in order to perform an *intelligent* and *soft* denoising of signals. It will be shortly described. Finally, the neural output was analyzed by means of wavelet transform for detecting the presence or not of acoustical stimulus.

2 Preliminaries and Formulation

Mother wavelets are special functions, whose first h moments are zero [2]. Note that, if ψ is a wavelet whose all moments are zero, also the function ψ_{jk} is a wavelet, where

$$\psi_{jk}(x) = 2^{-j/2}\psi(2^j x - k) \quad . \qquad (1)$$

Wavelets, like sinusoidal functions in Fourier analysis, are used for representing signals. In fact, consider a wavelet ψ and a function φ (father wavelet) such that $\left\{\left\{\varphi_{j_0 k}\right\}\right\}$, $\left\{\psi_{jk}\right\}$, k I Z, j = 0, , 2,…} is a complete orthonormal system [3],[4]. By Parseval theorem, for every signal s I $L^2(\mathbf{R})$, it follows that

$$s(t) = \sum_k a_{j_0 k}\varphi_{j_0 k}(t) + \sum_{j=j_0}^{j_1}\sum_k d_{jk}\psi_{jk}(t) . \qquad (2)$$

In particular, the decomposition of signal $s(t)$ performed by means of the Discrete Wavelet Transform (DWT) is represented by the detail function coefficients $d_{jk} = <s, \psi_{ik}>$ and by approximating scaling coefficients $a_{j_0 k} =< s, \varphi_{j_0 k} >$. Observe that d_{jk} can be regarded, for any j, as a function of k. Consequently, it is constant if the signal $s(t)$ is a smooth function, having considered that a wavelet has zero moments. Lemma 5.4 in [5] implies the recursive relations

$$a_{jk} = \sum_{m\in Z} h_{m-2k}\, a_{j+1,m} \qquad (3)$$

and

$$d_{jk} = \sum_{m\in Z} \lambda_{m-2k}\, d_{j+1,m} \, , \quad (4)$$

where $\lambda = (-1)^{k+1} h_{1-k}$; { h_k, k I Z} are real-valued coefficients such that only a finite number is not zero and they satisfy the relations

$$\sum_{k\in Z} h_{k+2m}\overline{h_k} = \delta_{0m} \qquad (5)$$

$$\frac{1}{\sqrt{2}}\sum_{k\in Z} h_k = 1 \qquad (6).$$

The sequence of spaces $\left\{V_j \, , j \in \mathrm{Z}\right\}$, generated by φ is called a multiresolution analysis (MRA) of $L^2(\mathbf{R})$ if it satisfies the following main properties

$$V_j \subset V_{j+1}, \, j \in \mathrm{Z} \text{ and } \bigcup_{j\geq 0} V_j \text{ is dense in } L^2(\mathbf{R}).$$

It follows that if $\left\{V_j \, , j \in \mathrm{Z}\right\}$, is a MRA of $L^2(\mathbf{R})$, we say that the function φ generates a MRA of $L^2(\mathbf{R})$, and we call φ the father wavelet.

The relation (2) is also called a multiresolution expansion of s. This means that any $s \in L^2(\mathbf{R})$ can be represented as a series (convergent in $L^2(\mathbf{R})$), where a_k and d_{jk} are some coefficients, and $\left\{\psi_{jk}, k \in \mathrm{Z}\right\}$, is a basis for W_j, where we define

$$W_j = V_{j+1} - V_j \, , j \in Z \, .$$

$\left\{\psi_{jk}(t)\right\}$ is a general basis for W_j. The space W_j is called resolution level of multiresolution analysis. In the following, by abuse of notation, we frequently write "resolution level j" or simply "level j". We employ these words mostly to designate not the space W_j itself, but rather the coefficients d_{jk} and the function ψ_{jk} "on the level j".

With reference to the neural network, we can say that the perceptron can be thought like a net composed of elementary processors organized in such a way to recreate the biological neural connections. It is able to learn, to recognize and to classify signal in independent way. Observe that the nodes of two consecutive levels are connected by one link (or weight) but no connection exists among nodes belonging to the same level. The level where the nodes of input are present is named input layer, while the level which shows the output is said output layer. The layers which lies between the input and the output layers are named hidden layers[6][7]. For further information on the neural network employed see [8][9].

Finally, for evaluating the impact caused from the noise superimposed to the IC-EP signal, a parameter (Entropy) was defined as follows [10]: given a set S: = {x_i, $i \in$ {1,2,…,n}} and a function c: $x_i \in S \rightarrow c(x_i) \in R$, the entropy $H(\,c\,)$ of c is defined as follows:

$$H(c) := -\sum_{c(x_i)\neq m} \frac{1}{s}\cdot\frac{c(x_i)-m}{M-m}\cdot\ln\left(\frac{1}{s}\cdot\frac{c(x_i)-m}{M-m}\right) (7)$$

where

$$s = \sum_{i\in I}\frac{c(x_i)-m}{M-m} \, , \, (8)$$

$$M := \max \{ c(x_i), i \in \{1,2,...,n\} \},$$

and

$$m := \min \{ c(x_i), i \in \{1,2,...,n\} \},$$

The entropy (H) measures the best ratio between the maximum dynamic showed by noise and the smallest uniformity of signal. Given $|S| = n$, the entropy, as before defined, riches its maximum value at $\ln(n)$ iff, for any $i \in S$, $c(x_i)$ = const. Finally $H(c) = 0$ iff, for any $i \in \{1, 2,…,n\}$, $c(x_i) = S$ and, for any $j \in \{1, 2,…,n\} - \{i\}$, $c(x_j) = 0$.

Calculations were made using MATLAB® 7, The MathWorks, Inc. Natick Mass.

3 Materials and Methods

The data-base used was provided by Prof. D. Henderson (Center for Hearing & Deafness State University of New York at Buffalo) and Prof. Ernesto Quarto (Department of Preventive Medical Sciences Chair of Medical Instrumentation University of Naples “Federico II”).
The data-base was composed of EP response in auditory sensitivity of 5 chinchillas after exposure to impulse noise. The frequency range was 500-16000 Hz and 0-50 dB (for each frequency level).
The level of audibility was determined for each animal before its inclusion into the experimental grouping. Hearing thresholds were measured by means of EP recording by an electrode surgically implanted in the inferior colliculus (IC-EP) [11][12]. The animals were 60 adult chinchillas. Six groups were formed of 10 animals. Each animal had one ear treated, leaving the other ear untreated, so that each animal served as its own control. The auditory evoked response to a burst tone stimulus was recorded from implanted IC electrodes. Responses were sampled at a 10 kHz rate and the sample window was 25 mms, including 2 mms pre-stimulus baseline measurement. The baseline IC-EP thresholds were obtained approximately 7-10 days after treatment, just prior to noise exposure. The EP thresholds were obtained after 1, 7 and 21 days following the noise exposure to impulsive noise condition at 15 min, and 1, 7 and 21 days following noise exposure to continuous noise condition. Measurements following the 21st day were used to determine the so called permanent threshold shift (PTS). [13] [14]

The data base was organized as in the example reported in Tab. 1 below.
In particular, the meaning of the symbols is as follows:

- **Ref.**: chinchilla identification
- **Day**: date of the auditory stimulation
- **F (Hz)**: frequency value of the auditory stimulation employed
- **P (dB)**: value (decibel) of the applied power
- $\mathbf{s_1}$: numerical value of EP signal at time t_1
- $\mathbf{s_2}$: numerical value of EP signal at time t_2
- $\mathbf{s_n}$: numerical value of EP signal at time t_n, $n \in \mathrm{N}$.

Ref.	Day	F (Hz)	P (dB)	s_1	s_2	S_n
3974	1	2000	25	0.39	0.47	…
3974	1	2000	30	0.91	1.35	…
3974	1	3000	20	0.06	0.00	…
3974	10	2000	20	1.78	1.64	…
3974	10	2000	25	2.44	2.71	…
3974	10	3000	15	0.19	0.32	…

Tab. 1 – Example of data-base

Tab. 1, for instance, shows some of the results obtained on the chinchilla identified with the number 3974, by performing the auditory test at the 1st and 10th day. In particular, with s_1 and s_2 were indicated the first two numerical values obtained from the IC-EP test. Consider the IC-EP response as long as a discrete signal composed of 250 values. Note that the IC-EP signal was converted from analogical to discrete signal simply by means of an optimum sampling.

4 RESULTS

On the basis of an objective interpretation of the EP signal, it should be noted that, with the reference to Tab. 1, at 1st day, an effective auditory response was obtained at 2000Hz and 30dB. With reference to the same animal and frequency, an effective response, at the 10th day, was obtained by applying a signal of 2000HZ and 25dB.
Let us observe that, with reference to the 1st day, the fact that at 2000Hz and 30dB, the animal shows an effective auditory response is demonstrated because the next auditory test was set at 3000Hz and 20dB.

Similarly, with reference to the 10th day, after the observation of a positive auditory response at 2000Hz and 25dB, it was studied the auditory response at 3000Hz and 15dB.

The observation of the date-base is useful in order to test the reliability of the proposed signal processing methodology. In fact, by comparing the results obtained with application of DWT to the IC-EP signals to the data-base, it is evident the goodness of the proposed method.

In fact, with the reference to the chinchilla identified with the number 3974, in Fig.1 it is illustrated the shape of the EP obtained at the 1st day with a stimulation of 2000Hz and 25dB. It is evident the presence of noise, at high frequency and small amplitude, due to the electronic components employed for the test.
The Fig. 2 shows the same signal after the application of a soft DWT filter (performed by neural network) in order to perform a denoising process.

The Figures 3 and 4 illustrate the two main families of curves in which the original signal was decomposed by applying the DWT: the approximation curves which are small frequency and large amplitude (Fig. 3) and the detail curves, showing high frequency and small amplitude, with the reference to the first ones (approximation).
Note that the decomposition of the original complex signal, performed by applying the DWT, simplify the analysis, also from a statistical point of view.

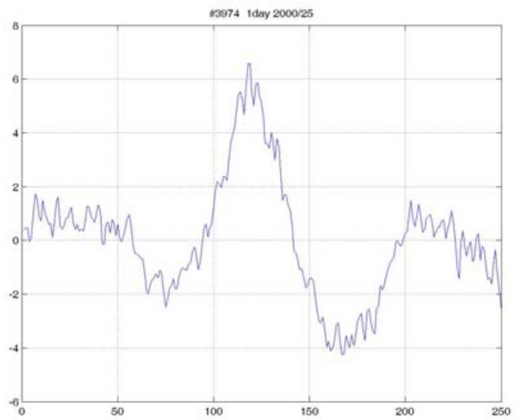

Fig. 1 Original signal

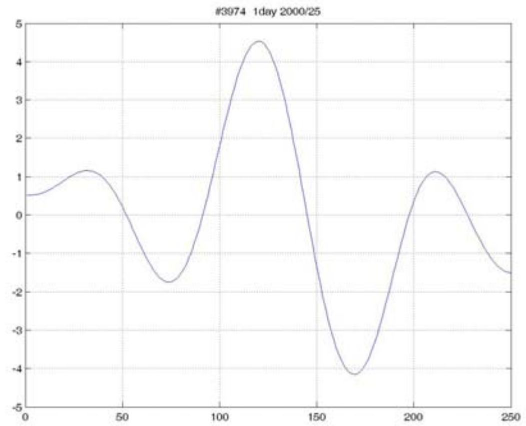

Fig. 2 Denoised signal

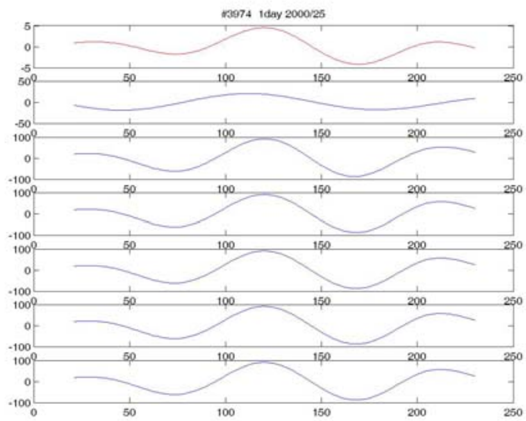

Fig. 3 Approx. components of EP signal

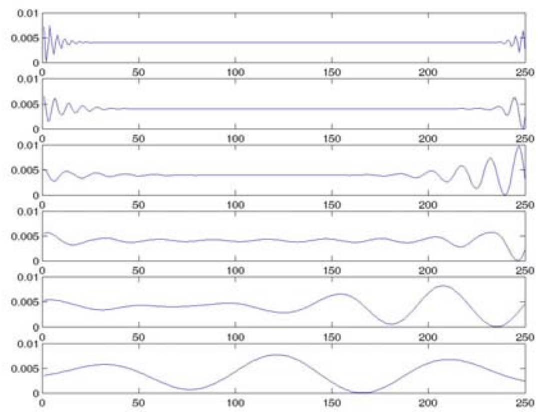

Fig. 4 Detail components of EP signal

As said below, such a decomposition generates two families of complementary curves: Approximation (Fig. 3) and Detail (Fig. 4). Generally, the approximation curves are associated to that part of the original signal which defines the trend. On the other side the detail curves put in evidence the information of the original signal which, usually, are characterized by high frequency and small amplitude. Such information is extremely important for the definition of eventual anomalies or peculiar features living in the signal. Often they are lost or ignored in the case the signal is filtered for eliminating the noise.

In the Fig. 5 it is represented the entropic response obtained from the wavelet analysis applied to the curve of EP showed in Fig. 1. It is evident the absence of a significative residual energetic content (entropy), calculated on D6: the detail decomposition at 6^{th} level, obtained from the wavelet decomposition of EP signal, exceeding 2 times the standard deviation (SD).

It can be deduced that the animal does not perceive any significative auditory signal. Remark that such an energetic response is referred to a stimulation of 2000Hz and 25dB at the first day (see Tab.1).

In the following Fig. 6, it can be observed the features showed by the original EP signal after the denoising process (Fig. 7) and the wavelet decomposition Approximation and Detail (Figg. 8 and 9) respectively with reference to an auditory stimulation of 2000Hz and 30dB, performed at 1^{st} day.

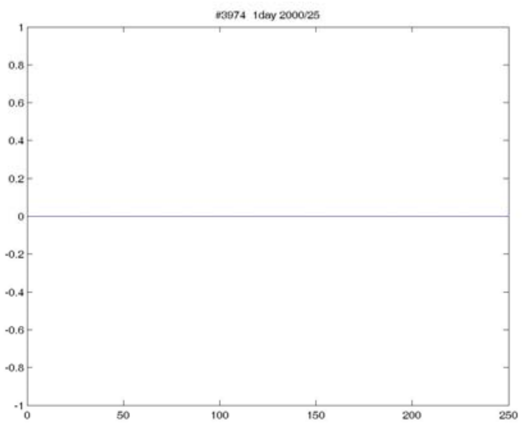

Fig. 5 Response at D6 level (mean $\mp$ 2 SD): *H*=0

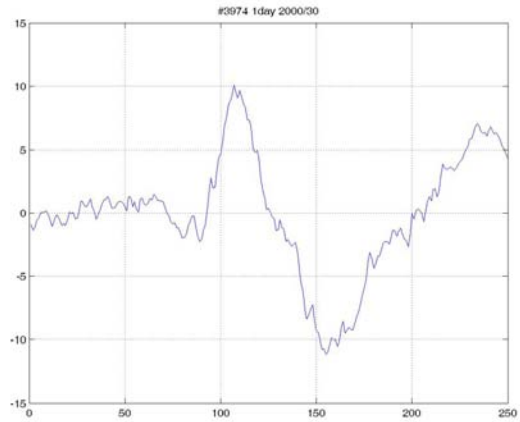

Fig. 6 Original EP signal : 1^{st} day 2000Hz - 30dB

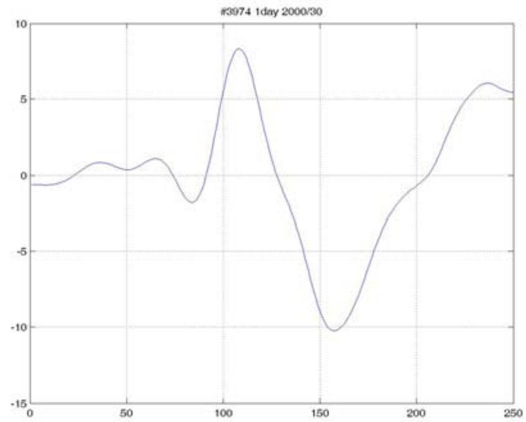

Fig. 7 Denoised signal

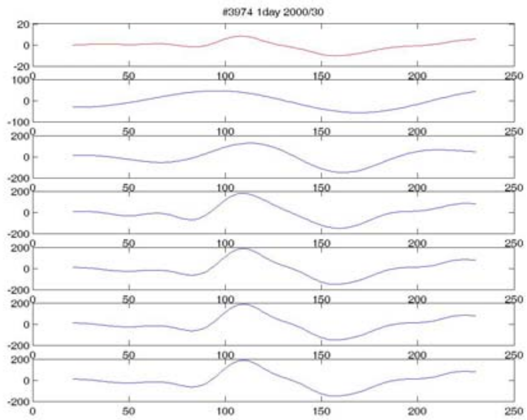

Fig. 8 Approx. components of EP signal

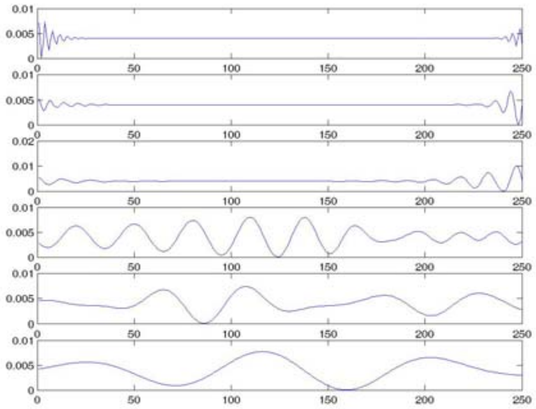

Fig. 9 detail components of EP signal

With reference to the previous curve at 25dB, apparently, no significative differences are visible.
Now, observe that the energetic content of the detail curve at D6 level, obtained by decomposing the original signal at 30dB, puts in evidence the fact that for this auditory stimulation, the animal receives a clear auditory impulse (Fig. 10).
It is also possible to know the area subtended to such a curve and also its temporal position (area = -5.10x10^5, t = 160 mms). It means that it is possible to compare both the energetic answer in terms of area and the auditory power as well as it is possible to define, also, with an optimal precision, the instant in which the animal perceived the auditory stimulus.
The Figg. form 11 to 14 show the original signal, denoised signal, the approximation and the detail curves respectively by applying the wavelet transform to the auditory signal of 2000Hz and 20dB induced to the same animal after 10 days.

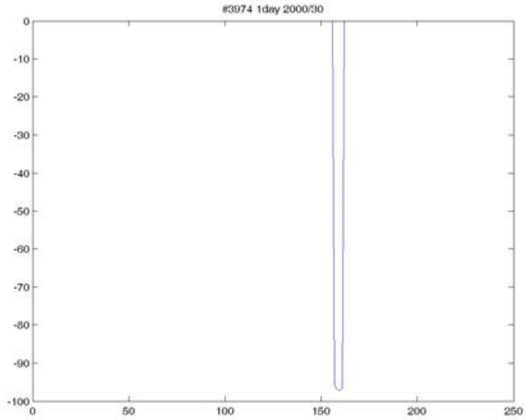

Fig. 10 Response at D6 level (mean $\mp$ 2 SD): *H*= -5.1043x105

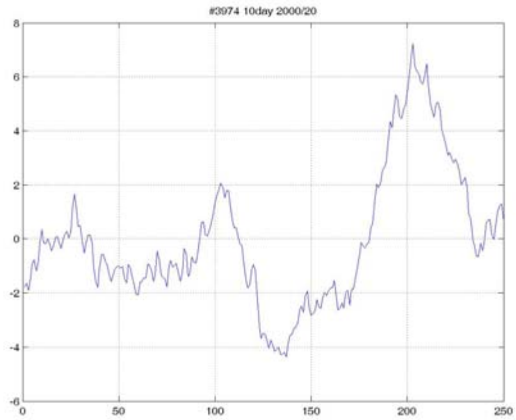

Fig. 11 Original EP signal : 10th day 2000Hz - 20dB

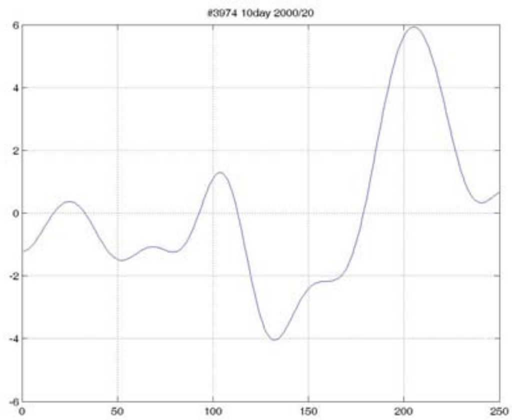

Fig. 12 Denoised signal

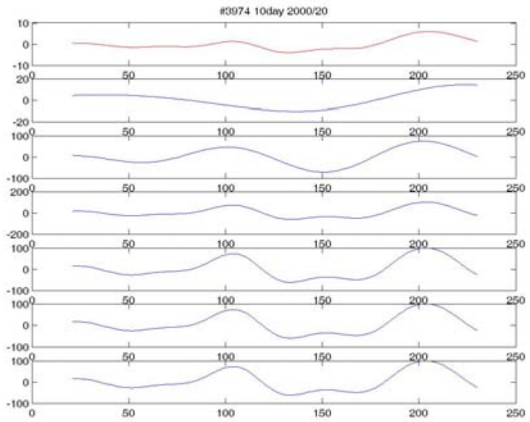

Fig. 13 Approx . components of EP signal

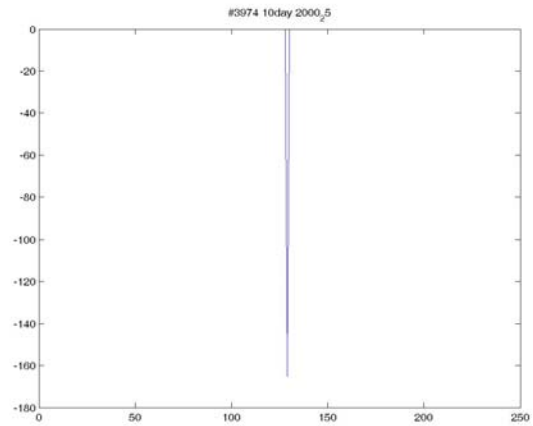

Fig. 15 Response at D6 level (mean ∓ 2 SD): *H*= -2.7819x105

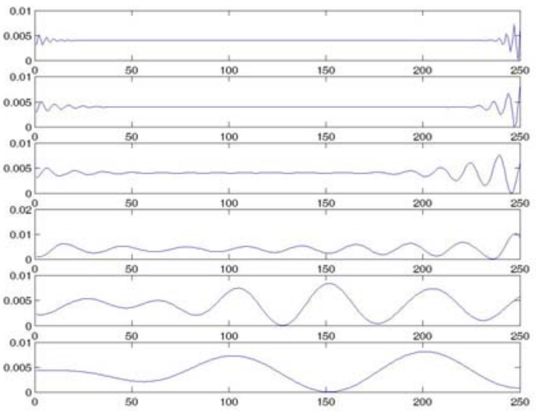

Fig. 14 Detail components of EP signal

In this last case the auditory signal is not perceived and the relative entropic response is similar to the Fig. 5. In the stimulation case, after ten days by applying a signal of 2000Hz and 25dB the entropic response is quite visible (Fig. 15). In this case the calculated area is -2.78x105 and the instant in which the auditory event is allocable is equal to t = 130mms.

By comparing the entropic curves we note that the instants in which the animal perceives the sonorous stimulation show a minor power (25dB rather than 30dB) at 2000Hz and 30dB (at 1^{st} day) and 2000Hz 25dB (at 10^{th} day) with a temporal advance of 130mms rather than 160mms.

5 Conclusions

The results point to validate the decomposition of EP by wavelet analysis in order to allow to us a good identification of the level in auditory sensitivity of chinchillas. A such identification can be performed by the analysis of the residual level of entropy showed from the detailed coefficients obtained by applying the wavelet decomposition to the EP signal.

The reliability of the proposed method might concur to implement a completely automated system, when it is important to coadiuvate the specialist for the identification of small improvements, in particular for some pathologies, where it is essential to study the effect of determined therapies in the time.

This interesting application of DWT to the data has important implications for the preventive medical sciences. So further data collection and analysis is in progress to investigate it further.

Acknowledgments – We are grateful to Prof. Donald Henderson (Center for Hearing & Deafness State University of New York at Buffalo) and Prof. Ernesto Quarto (Department of Preventive Medical Sciences Chair of Medical Instrumentation University of Naples “Federico II”) for providing the data on chinchillas auditory evoked potential.

References:

[1] Davis, R.R., Murphy, W.J., Snawder, J.E., Striley, C.A., Henderson, D., Khan, A., Krieg, E.F., Susceptibility to the ototoxic properties of toluene is species specific. Hearing Research 166, 2002, pp. 24-32.

[2] Teolis A., *Computational signal processing with wavelets*, Birkhäuser, 1988.

[3] Härdle W., Kerkyacharian G., Picard D. and Tsybakov A., *Lecture Notes in Statistics - Wavelets, Approximation, and Statistical Applications*, Springer, 1998.

[4] Ogden R.T., *Essential wavelets for statistical applications and data analysis*, Birkhäuser, 1997.

[5] Daubechies I., Orthonormal bases of compactly supported wavelets, *Comms. Pure Appl. Math.,* Vol.41, No.3-4, 1988, pp.909-996.

[6] L.O. Chua, L. Yang. Cellular neural networks: Applications. *IEEE Trans. Circuits Syst.*, Vo. 35, pp. 1273-1290, 1988.

[7] T. Kohonen, *Self-organized formation of topologically feature maps.* Biol. Cybern., Vol. 43, pp. 59-69, 1982.

[8] Niola, V., Quaremba, G., An application of self-learning neural network for revealing the presence of anomalies of a gear system. *Wseas International Conference ACOMS '05* – March 13–15th, 2005, Prague.

[9] Niola, V, Quaremba G., The object location from images binarized by means of self-learning neural network, *6th WSEAS Int. Conf. on NEURAL NETWORKS (NN'05)*, Lisboa, Portugal, 16 – 18th June 2005.

[10] Niola, V., Quaremba, G. and Oliviero, R., The location of anomalous spikes on a working rotor: a theoretical-experimental test, *Int. J. of App. Mec. and Eng.*, Vol. 9, n.3, 2004, pp. *547 – 556* .

[11] Yang. W.P., Henderson, D., Hu, B.H., Nicotera, T.M., Quantitative analysis of apoptotic and necrotic outer hair cells after exposure to different levels of continuous noise. (in press).

[12] Nicotera, T.M., Hu, B.H., Henderson, D., The caspase pathway in noise-induced apoptosis of the chinchilla cochlea, *JARO*, 4, 2003, pp. 466-477.

[13] Hight, N.G., McFadden, S.L., Henderson, D., Burkard, R.F., Nicotera, T., Noise-induced hearing loss in chinchillas pre-treated with glutathione monoethylester and R-PIA, *Hearing Research*, 179, 2003, pp. 21-32.

[14] Hu, B.H., Henderson, D., Nicotera, T.M., Progression of outer hair cell death in the chinchilla cochlea following traumatic noise exposure. In: Simmons, D.D., Palmer, C., (Eds.), Seminars in Hearing. New Frontiers in the Amelioration of Hearing Loss: Part 2 Hair Cell Development, Regeneration, Protection, and Rescue, Vol. 24. Theime Medical Publishers, New York. pp. 111-114, 2003.