DEVELOPMENT OF A SYSTEM FOR NON STATIONARY MEASUREMENTS OF OTOACOUSTIC EMISSIONS

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Abstract: Otoacoustic emissions (OAEs) are a by-product of sound processing in the cochlea. As such they provide a unique non-invasive insight onto hearing mechanisms. OAEs reflect changes, not only in cochlear physiology, but also in intracranial pressure (ICP). Non invasive assessment of ICP with the help of OAEs is novel. When ICP varies, the spectral contour of OAEs varies as well. As OAEs behave as non-stationary acoustic signals, non-invasive access to ICP requires non-stationary tools for OAE analysis to be developed in the time domain. Time-frequency representations of OAEs have been designed to provide three-dimensional patterns. The Wigner-Ville method proved to be best one for providing high resolution, as well as detection of various drifts in signal properties, representative of ICP. Time frequency representations provided qualitative and quantitative insights into distortion product otoacoustic emission (DPOAE) variations. These representations appear to be useful for calculating and investigating new parameters for classification of ICP signals, for example by neural network methods.

Introduction

Body tilt from upright to head-down position induces an increase in the intracranial pressure (ICP) of the cerebrospinal fluid (CSF) due to gravity [1], [2]. Hearing is also affected and auditory thresholds [3],[4], sound localization [5] and auditory threshold microstructure [6] have been reported to depend on posture. Such changes originate likely either from middle- or inner-ear modifications in relation to body position or CSF pressure. Cochlear changes have been confirmed by objective measurements of cochlear microphonics [7] and auditory brainstem-evoked responses [8]. Otoacoustic emissions (OAEs) have proven to be posture-sensitive, for example stimulus frequency emissions [9], spontaneous OAEs [10] and transient-evoked OAEs (TEOAE, [11], [12]). It has been shown that ICP characteristically influences the phase of DPOAEs around 1kHz, as that ICP fluctuations can be non-invasively inferred from DPOAE recordings. Fast Fourier Transform (FFT) can be used when DPOAE are stationary enough. However, when fast ICP changes are involved, non stationary methods have to be applied to DPOAE analysis in order to extract ICP temporal dynamics.

DPOAEs emerge from the cochlea as combination tones, notably at the cubic combination of frequencies $2f_1$-f_2, in response to a sound stimulation by two pure tones (called primaries) at frequencies f_1 and f_2. Their existence requires some non-linear mechanism in the cochlea and an appropriate mechanical feedback. The so-called outer hair cells (OHC) are sensory cells of prominent importance, responsible for amplifying and filtering sound stimuli, and it is thought that DPOAEs at $2f_1$-f_2 are produced by these cells. DPOAEs decrease or disappear [13] every time OHCs are damaged or absent [14].

The issue of pressure relationships between CSF and DPOAE bears an important clinical potential because it opens the possibility to monitor CSF pressure non-invasively through the ear. The goal of this work is to study and analyse a new method by characterising the posture effect on DPOAE.

Materials and Methods

The data acquisition and stimulation of DPOAE are achieved with the RP2.1 Real-Time Processor from Tucker Davis Technologies (TDT). Where also provides two D/A (digital to analogue channel from RP2.1) channels of integrated stimulus generation of DPOAE therefore the level of each tone has been adjusted with a separate programmable attenuator (SA1 : Stereo power amplifier from Tucker Davis Technology). In this regard, the level of sophistication of the analysing function is examined before acquired the stimulus generations DPOAEs. A graphical user interface RpvdsEx for building the DPOAE circuits (stimulation and acquisition), then to be compiled into control objects (*.rco files) that can then be loaded to RP2.1 via software that supports ActiveX controls. The signals collected by the microphone of RP2.1, this last was amplified 40dB with a preamplifier (ER-10C DPOAE probe), the signals are stored via USB connected with an

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A/D channel (RP2.1) in a *.mat file under Matlab version 6.2. These files present the data base of all the applications and the operations made in the synchronisation system and the signal processing. Noticed that the synchronisation step between the A/D and D/A channel it was very important to create a data base for the signal processing i.e. the input and the output signals must be synchronised to the same clock, for that reason a measure of the delay was calculated between the input and the output signal on the RP2.1 before acquired the DPOAEs signals, this measure of delay is obtained by calculate the difference between the number of samples recorded from the number of samples emitted from the RP2.1, this number mean that the duration of time for which a signal should be sent to the inputs of RP2.1 and sets the duration of time that a signal is recorded from the output channel.

Methods: We described some time frequency representation (TFR) among most known and likely to agree with the analysis of signals, we present TFR of the non parametric group initially the Cohen class of bilinear distributions like Wigner-Ville (WV), Pseudo Wigner-Ville (PWV) and Pseudo Smoothed Wigner-Ville (PSWV); and another type of TFR like Choi-Williams (CW) [19] and Short Time Fourier Transform (STFT). We complete our panorama by the comparison between different methods.

Signals: Two types of signals were processed, the first one was a synthetic signal intended to illustrate the characteristics of each TFR. The second one was a real example selected among DPOAE data acquisitions in human ears.

The Synthetic Signal : The simulated signal (figure 1 and figure 2) applied in Matlab, was a sum of three different signals, two sine waves representing the pair of pure tones at frequencies f_1 and f_2 with primary amplitudes A_1 and A_2, and the combination tone resulting from cochlear non-linearity, with amplitude A smaller than A_1 and A_2, the general equation of the signal is:

$$y_k^i(t) = A_1\cos(2\pi f_{k_1}^i + \phi_1)..+..A_2\cos(2\pi f_{k_2}^i + \phi_2) \\ ...+..A_{dp}\cos(2\pi f_{k_{dp}}^i + \phi_{dp})...+z_k^i(t) \qquad (1)$$

with $i = 1,..., n$ and $k = 1,... , N$

“i” and “k” respectively represent the class of the signal that changes according to the variation of f_1, the realisation and the temporal index, N being the total number of samples.

z(t) represented the background noise level supposed to be a white gaussian noise. In a real ear, its typical level varied between 0 and 5dB, while the DPOAE level varied between 12 and 17dB i.e., in a normal ear, it could exceed the noise level by 12dB.

Converted (1) to complex form the signal was written:

$$y_k^i(t) = A_1\exp(j(2\pi f_{k_1}^i + \phi_1)) + A_2\exp(j(2\pi f_{k_2}^i + \phi_2)) \\ +...+A_{dp}\exp(j(2\pi f_{k_{dp}}^i + \phi_{dp}) + ...+z_k^i(t), \qquad (2)$$

f_2 and f_1 change according to the relation :

$$f_{k_2}^i / f_{k_1}^i = \alpha \qquad (3)$$ (α varies between 1.01 and 1.22)

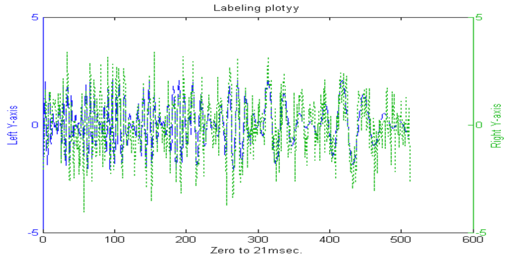

Figure 1: the simulation response with A_1=A_2=1V equivalent to 65 dB

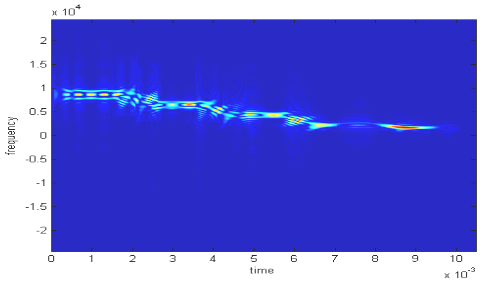

Figure 2 : the same simulation response, when applied a TFR (WV)

From (3), the DPOAE frequency, expressed as a function of α, was :

$$f_{k_{dp}}^i = (2-\alpha) f_{k_1}^i \qquad (4)$$

The acquired signal : The second processed signal was the result of DPOAE acquisition from a real ear utilising the RP2.1.

Protocol : Stimuli for DPOAE were selected in order to compare ICP in two postures "upright" vs. "head-down". It were made of two primary–tone frequencies f_1 and f_2 (f_2/f_1 = 1.20), and were swept with f_2 varying from 6663.785 and 822.542 Hz (5 steps per octave). Primary levels were 60dB SPL at f_2 and f_1. The level and phase of the DPOAE at $f_{dp} = 2f_1 - f_2$ were extracted offline from the *.mat files. The background noise level around frequency f_d was also available. The signal-to-noise ratio was considered to be acceptable when the DPOAE level exceeded the noise level by more than 12dB.

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Results

We know that, there is an infinite number of ways to describe the given data in every signal. A signal's time and frequency distributions are the must useful representation method. When the signal do not have stationary properties, because of the variation of the frequency contents with time, it is more useful to characterise the signal in time and frequency domain simultaneously i.e. by TFR [15], [16], [17], [18] and [19].

The comparison between TFR methods will be made using two types of criteria. The first one is a descriptive, based upon the visual aspect of figures, notable the concentration of the energy distribution around the instantaneous frequency curves. The second criteria will be a quantitative one, obtained by calculating the local maxima of a time-frequency energy distribution [20], [21], then the quadratic error between the obtained results from theoretical and real values of instantaneous energy.

The spectral analysis, is the traditional applied method to DPOAE, assumes stationary signals. Its fundamental tool, the Discrete Fourier Transform (DFT), describes the signal in the frequency domain. To overcome the lack of time resolution of the stationary assumption, some research was started by applying the Short Time Fourier Transform (STFT) method (figure3). A length moving-window is a trade-off between time and frequency, consequently a STFT Spectrogram was obtained, it can be applied to a non-stationary signal. However this method has the inconvenient that the reduction of the window duration deteriorates the frequency resolution. Another disadvantage is the loss of phase information when the square module operation is applied. For this reason, a time frequency distributions of Cohen's class is more available than STFT Spectrogram. This type of representation is given by Cohen [22].

The obtained result is given by the figure 4 and 5 corresponding respectively to two states upright and head-down. In the figure 4, the items 4a, 4b, 4c, 4d and 4e represent respectively the WV, PWV, PSWV, CW and the response of stimulation signal. In figure 5, 5a, 5b, 5c, 5d and 5e represent the same values for the head-down position.

Firstly, we observe that the DPOAE amplitude dependent spectra can be better characterized WV, than the PWV, PSWV and CW. Then we have an important cross-term change between the upright and head-down state in WV, which means that this method is very sensitive to the DPOAE variation, consequently to CSF motion while going from upright (figure 4) to head-down (figure5) and vice versa.

If we calculate the phase after a Fourier application on the signal of the figures 4e and 5e, we can observe that the mean and the standard deviation on the figure5e are slightly different compared to the standard deviation in figure 4e. Now, if we apply the mean and the standard deviation to the WV in the figures 4a and 5a, the difference between them is more important, that is because the cross-term in WV, who which is more sensitive to body tilt than the Fourier transform.

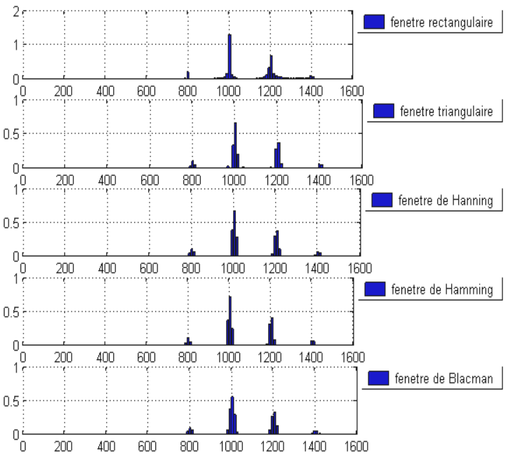

Figure 3: Using the same window length (16 sampling points), Triangular, Hanning and Hamming windowed STFTs appear to offer same resolution, a rectangular STFT offer better resolution with minimum radial basis function.

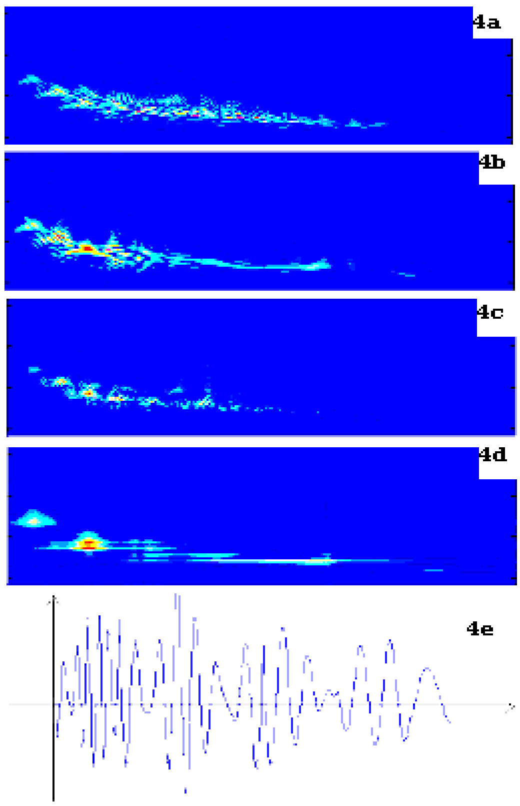

Figure 4: This acquired signal represent the upright posture, the CSF volume is constant. We do not have any variation of ICP, the signal obtained is the reflection of the variation of DPOAE according to OHCs.

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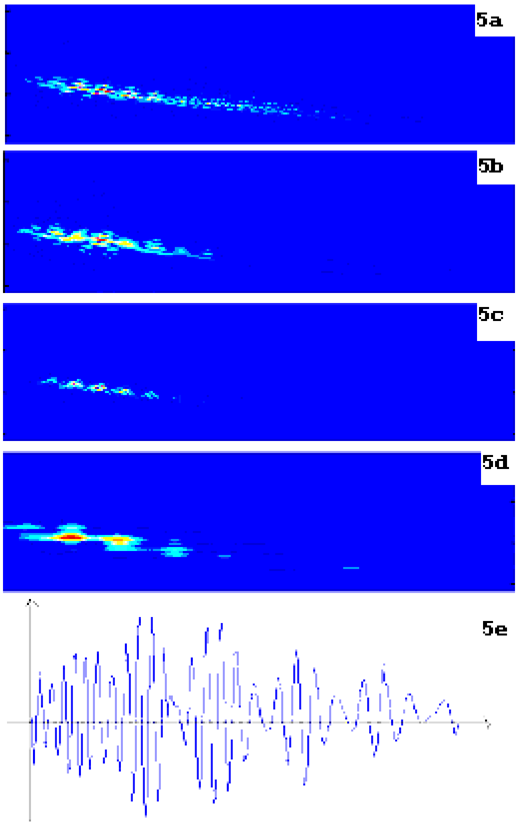

Figure 5: This case is the head-down position, in this figure we have an increased ICP.

Discussions

It has been widely argued that the main drawback of the Wigner distribution is the cross-term interference. But this disadvantage can be also an advantage as far as the DPOAE signal is concerned, because the WV is a real quantity, considered to code phase information in its cross-terms [20]. Moreover, we already saw in the last paragraph, that it has many other properties. The WVs do not require any assumption of local stationary (it uses no window like PWV and PSWV), and do not depend to a chosen parameter (like CW), for offering a good localisation of the energy structures in the time-frequency plan [23].

We have, two concepts of cross terms, internal and external. The distinction between these two concepts was introduced by Hlawatsch [15]. The cross term exists in a distribution of WV, their forms even depend on the nature of the signal. For example, in the sinusoidal signal, like the DPOAE case, the WV distribution leads to an intern structure of cross terms. As the signal constitutes N components, the WV distribution counts N(N-1)/2, it thus is the contribution additional coming from the interaction between these various components. From this formula, we can deduce that, in the synthetic signal applied in these papers, we distinguish three forms of cross terms. Thus the synthetic signal applied constitutes three factors of interference between the two primaries and the DPOAE signal. On the other hand, we cannot say the same thing for the acquired signal by the RP2.1, because the collected signal have more than three components. It constitutes the two primaries and DPOAE signal with $2f_1$-f_2, but also the other components like $2f_2$-f_1, f_1+f_2... from where we discover a disadvantage because the obtained cross terms only due to the interactions of three principal components of the signal. But as the creation of this mechanism is similar to that chair the usual interference phenomena observed for example on physical waves. And already, we know that other components obtained, other that DPOAEs, have negligible values in dB. We can conclude that, their existences do not add important contributions in combinative proliferation. The presence of cross terms in a WV is the normal consequence of a bilinear structure which, in addition, is the reason even of the majority of the good properties of the distribution, like those of localization. We conclude, this presence, which at first sight seems an advantage, is thus a price other investigation.

Conclusion

By using TFR we can describe the energy content at the same time according to time and frequency. Consequently, we can better understanding the cochlear function and how the mechanism of OAEs were generated. The TFR represent the signal without any addition information as for the nature of the signal, but it give us a good redistribution. Therefore it is a tool for removing noise and artefact from the signal.

We have choose WV to study the variation of the ICP signal, and in the second stage, the extraction of its value. these cross-terms have an important utility to understand the nature of variation of the phase [20] in the signal of DPOAE, this method is more sensitive to the change of the signal of the intracranial pressure (ICP). One could of this work seek new descriptor which allow us classification later on. In order to automate the signal and to extract from, a new information concerning the intracranial pressure even the variation of the blood pressure.

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