Time-frequency analysis
Otoacoustic emissions
Adaptive approximations

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ANALYSIS OF OTOACOUSTIC EMISSIONS BY MEANS OF ADAPTIVE APPROXIMATIONS

Otoacoustic emissions (OAE) are low level sounds that can be measured in the ear canal by very sensitive microphone. They are originated in cochlea and arise as an evoked and spontaneous activity.

In present study otoacoustic emissions evoked by short broadband stimuli (Transiently evoked otoacoustic emissions - TEOAEs) were analyzed by means of an adaptive approximations method based on the Matching Pursuit (MP) algorithm. This method is an iterative, nonlinear procedure which decomposes a signal into a sum of known waveforms of well defined frequencies, latencies, time-spans (durations) and amplitudes. It provides also high resolution energy distributions in the time-frequency space.

The MP method made it possible to identify the resonant modes that appear in specific frequencies for a given subject. There are two mian types of these components: short and long-lasting. The second ones are possibly connected with spontaneous activity.

It was found that the parameters of components identified by the MP method - amplitude, latency and time-span - are affected in case of hearing disturbances

The method of adaptive approximations opens new possibilities in the field of investigation of hearing mechanisms and offers new tools for diagnosis of hearing disturbances.

1. INTRODUCTION

Otoacoustic emissions (OAE) were first registered by Kemp [3] and very quickly became an important tool in the diagnosis of hearing impairment. However the mechanisms of their generation are still a matter of a debate. In particular it concerns the role of linear and non-linear effects in shaping the structure of the OAE signal. Spontaneous OAE (SOAE) as well as transiently evoked OAE (TEOAE) exhibit periodic variations in amplitude and phase with frequency, which are called “fine structure” ([5],[8]).

2. MATERIALS AND METHODS

Two data sets were analyzed. In both cases, otoacoustic emissions were recorded using the ILO 292 Echoport system designed by Otodynamics. Responses to 260 repetitions of stimuli were averaged with the “nonlinear” mode of stimulation. The acquisition window had a standard onset at 2.5 ms with a cosine rise/fall of 2.26 ms and flat top up to 20.5 ms.

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The first data set consisted of the OAE recordings from 12 young (20-25 years) adult men. In pure tone audiometry the hearing thresholds were 10-15 dB. For all these subjects, the responses to a click stimulus and a set of tone bursts stimuli of 5 frequencies (1000, 1414, 2000, 2828 and 4000 Hz) and of half-octave bands were measured. The tone-burst stimuli were constructed to cover the same frequency band (850 to 4750 Hz) as the click stimulus.

The second experiment concerned the influence of noise on OAE. Two datasets of click evoked OAEs from 124 ears were recorded. The first dataset was measured from 62 ears of male personnel who serviced aircraft (aged 24-51), thus these individuals were regularly exposed to jet engine noises. The second set, used as the control group, consisted of 62 ears from age-matched males. These subjects were laryngologically healthy with hearing thresholds of 10-15 dB HL. The subjects exposed to aircraft noise had threshold levels that were in average 6.6 dB higher.

The protocol of the experiments was approved by the board of human experimentation.

2.1. MATCHING PURSUIT

The method of adaptive approximations is based on the decomposition of the signal into basic waveforms (called atoms) from a very large and redundant dictionary of functions. Finding an optimal approximation of the signal by selecting functions from a very large and redundant set is a computationally intractable problem. Therefore, sub-optimal, iterative solutions were applied. In practice, Gabor functions (sine-modulated gaussians) are used, since they provide the best time-frequency resolution. This method was described in [2].

Figure 1 illustrates the main features of this approach. The TEOAE signal (Fig. 1 – top) was decomposed into its basic components and the five of the largest energy are presented (Fig 1 – bottom). Their energy distribution in the time-frequency space is illustrated in center of Fig 1. At the left, the spectrum constructed by summation of the atoms energy in time is shown; the frequencies of the components are marked as lines, their heights are proportional to their energy. One can see that the weaker components are hardly visible in the spectrum, however, in case of MP we need not rely on the spectrum, since the spectral components are found by the procedure and parameterized. We can observe that by means of spectra it is not possible to distinguish components of close frequencies (e. g. 3rd and 4th waveforms on Fig. 1).

In this paper we used a dictionary consisting of 10^6 Gabor functions, with these functions being described by the following parameters: frequency, latency, time-span, amplitude, and phase. The decomposition was performed until fitted waveforms explained 99.5% of the signal energy. The parameters of main interest were amplitude, frequency, latency, and time-span. The amplitude was determined as the maximum of the modulus of the waveform of a certain frequency, whereas the latency was measured from the stimulus onset to the maximum of the envelope of the waveform. The time-span parameter was defined as half the width of the TEOAE envelope and can be understood as the atom’s duration in time.

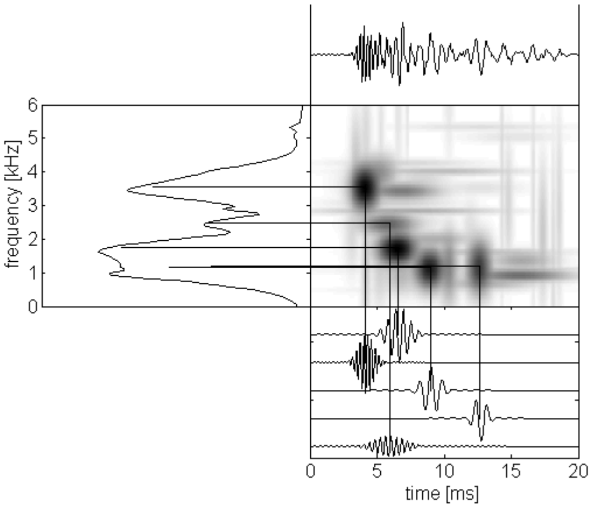

Fig. 1. Illustration of matching pursuit (MP) decomposition. Upper plot: OAE signal. Center plot: energy density (illustrated by shades of gray) in the time-frequency plane. Left: the spectrum. Bottom: waveforms fitted in the first five iterations, connected by lines with corresponding structures in time-frequency plane and corresponding peaks in the spectrum.

3. RESULTS

Tone and click evoked OAE were decomposed by means of the MP algorithm and the parameters of the components were found. In most cases the basic features of the click evoked OAE are reproduced by the first 15 waveforms, which account for 95% of the energy of the signal. When the components of the signal are known, it is straightforward to construct the time-frequency distribution of the energy density (Figures 1, 2).

The time-frequency (t-f) representations of the tone evoked OAE are presented in Fig .2. Usually the atom of the highest energy was closest to the frequency of the stimulation. It can be observed that the frequency of the tone stimulus is not exactly reproduced in OAE and the response depends on the individual features of the subject’s cochlea. Namely for each subject there are some privileged frequencies, which appear to a higher or lower degree for different frequencies of the stimulus. E.g. in Fig. 2 a component of frequency of around 2 kHz appears at stimulation frequencies of 1414, 2000 and 2828 Hz. It followed from our studies [2] that not only each person, but each ear has its preferred frequencies, which are resonant modes of cochlea.

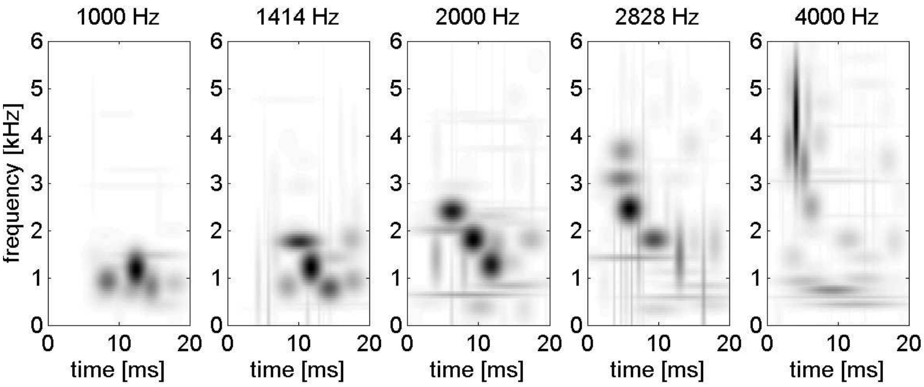

Fig. 2. Time-frequency distributions of energy for an OAE signal evoked by tone burst stimuli (from 1000 to 4000Hz) for one subject. Frequency of the stimulation is given above the maps.

In the literature resonant TEOAEs had sometimes different meaning, namely they were connected with the long lasting (slow decay) components [8]. Among resonance modes found by us there were also components of long duration and very narrow frequency span. In Fig. 3 a histogram of time spans of resonant modes is shown. It has a bi-modal character with a distinct minimum at 12 ms. It seems that there are some short-time resonant modes as well as long–time resonant modes.

In some papers [7] the long lasting components of TEOAE were associated to the considerable degree with SSOAE. For sake of comparison in Fig. 4 SSOAE spectra are shown together with time-frequency maps of TEOAEs. The two examples illustrated in Fig. 4 show that correspondence between SSOAE and long lasting components is visible, but not in all cases.

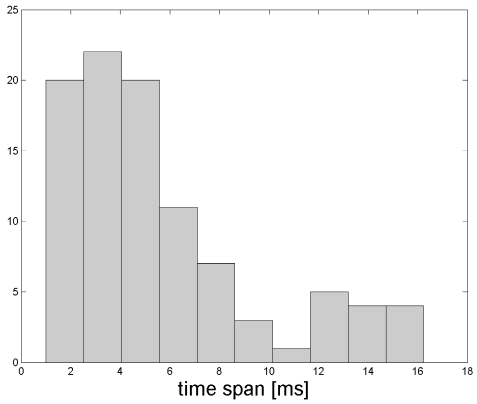

Fig. 3. Histogram of the time spans of the atoms which can be considered as a resonant modes. Time span is defined as the half-width of the Gabor function.

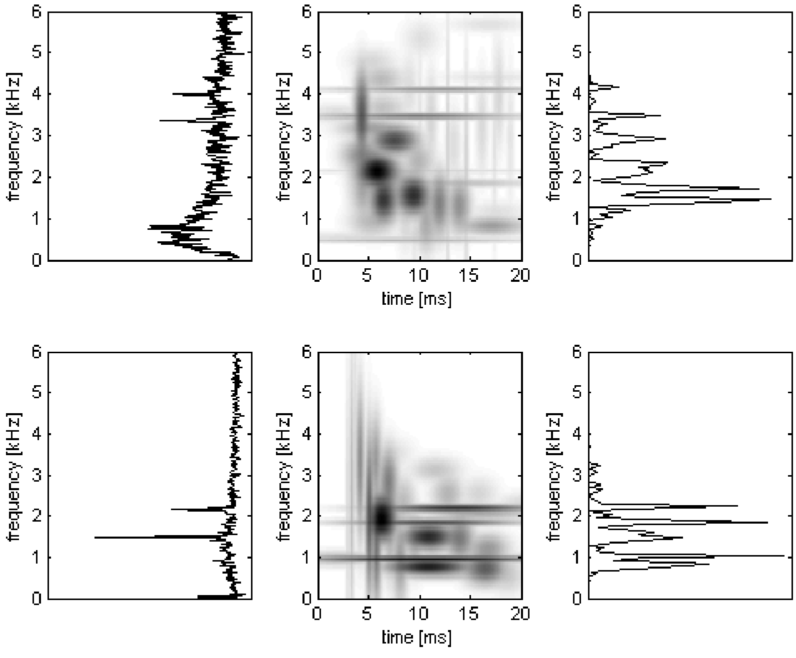

Fig. 4. Comparison of SSOAE with TEOAE of the same ear for two persons A and B. From the left: SSOAE spectrum obtained by ILO 292, time-frequency map of TEOAE, spectrum obtained by Fourier transform from TEOAE response.

The method of OAE analysis described in this paper proved to be adequate not only for investigations of the OAE nature, but also in assessment of hearing disturbances. Parametric description of the signal components makes easy statistical analysis of the data. In order to make statistical comparison between the groups exposed and not exposed to noise atoms, obtained in decomposition procedure, were grouped in half-octave bands. Only the highest energy components for each subject in each band were selected for further analysis. Frequency-latency dependence as shown in Fig. 5A is logarithmic, which is a consequence of the cochlear structure. For the band up to 1414 Hz, there were no significant changes in the exposed group, but for higher frequencies, there was a significant shift towards longer latencies.

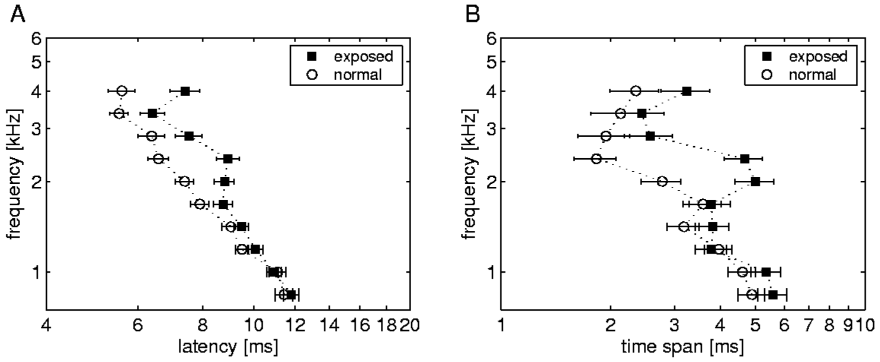

Fig. 5. A: Quarter-octave average latencies of waveforms fitted to the TEOAE signals for non-exposed (circle) and exposed subjects (rectangle). B: Quarter-octave average time-span (durations in time) of waveforms fitted to the TEOAE signals for non-exposed (circle) and exposed subjects (rectangle).

The time span parameter proved to be the least influenced by exposure of subjects to jet-engine noise. In Fig. 5B the trend can be observed that in all bands the duration of components of TEOAEs from ears exposed to noise was longer than in the non-exposed case. However, the difference between the two datasets was found to be statistically significant only for the 2000 Hz and 2379 quarter-octave band.

4. DISCUSSION

Application of adaptive approximations by the MP algorithm allowed for identification of OAE intrinsic components, which eluded conventional methods of signal analysis. This was possible in virtue of the high time-frequency resolution of MP and the parametric description of the components by parameters with a clear meaning, namely: their latencies, frequencies, time spans and energy (or amplitude). Usually most of the energy of the signal is described by a few components only.

The MP method is especially suitable in respect of studying of mechanisms of the OAE generation. In particular it helped in elucidating the presence of the effects connected with the fine structure of OAE. The observation that for different frequencies of stimulation the same preferred response frequencies appeared in OAE indicates the presence of resonance modes in OAE, which can be associated with the sharply tuned emission generators situated in specific areas of the organ of Corti as suggested by Elberling et al. [2].

In earlier OAE works, which used filtration to determine latency (Prieve et al. [4]), no significant differences between latency in OAEs of normal and impaired ears were found. This outcome was probably due to a poor resolution and a high bias of the filtration method. In their study of a group affected by impulsive noise, Sisto and Moleti [6] detected, by wavelet method, a shift towards longer latencies in the frequency range from 1-2 kHz with no changes in the 4.4 kHz band. The results of the present work show shifts in frequencies higher than 2 kHz. Changes in latencies observed here for the higher frequency region are compatible with the decreasing amplitude and also with the fact that the cochlear structures responsible for high-frequency perception are more prone to damage.

The time-span of a component is a parameter not available in the other analysis methods. For healthy subjects, it had values from 2 ms for 4 kHz, to 4.5 ms for 1 kHz. We have also observed components with very long time-spans that are possibly connected with synchronized spontaneous activity.

ACKNOWLEDGMENT

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