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USE OF DOUBLE-PHASE-SENSITIVE DETECTION TO MEASURE DPOAE SIGNALS

Wojciech MICHALSKI(1), Wojciech DZIEWISZEK(2), Marek BOCHNIA(2)

(1)Wrocław University of Technology
Institute of Telecommunications, Teleinformatics and Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
e-mail: Wojciech.Michalski@pwr.wroc.pl

(2)Medical University of Wrocław
Clinic and Department of Otolaryngology
T. Chałubińskiego 2, 50-368 Wrocław, Poland
e-mail: Dziewisz@fa.am.wroc.pl

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This paper presents a new method of measuring distortion product otoacoustic emissions (DPOAE) induced by a two-tone acoustic wave. The method is based on double-phase-sensitive detection whereby it is possible to precisely measure DPOAE signals whose acoustic pressure level is even below -15 dB. Exemplary experimental results for guinea pigs are given.

Keywords: phase-sensitive detection, DPOAE.

1. Introduction

Phase-sensitive detection allows one to measure very weak (even below the noise and other disturbing signal level) AC periodic signals. If the measured signal is a harmonic signal, then its RMS value is measured. If the measured signal is a more complex periodic signal, then the RMS value of its first harmonic is measured.

The measurement of a weak signal in the midst of noise and strong disturbing signals is possible only because it takes place in a very narrow band – in the order of 0.1 Hz. The midband frequency is the frequency of the measured signal. Such a narrow measurement band (even in the range of frequencies as low as single hertz) can be obtained thanks to the use of phase-sensitive detection. This kind of detection occurs in the presence of another signal called a reference signal. The frequency of the reference signal must be the same as that of the measured signal. Also any random instantaneous fluctuations of this frequency must be correlated with the measured signal frequency fluctuations. This condition is satisfied because both the measured signal and the reference signal originate from the same signal generator.

The condition that measured and reference signal fluctuations must be correlated is not necessary when measurements are performed using double-phase-sensitive detection.

The authors of this paper used double phase-sensitive detection to measure signals associated with distortion product otoacoustic emissions (DPOAE) [1]. Such signals are produced by two tones having different frequencies f_1 and f_2 and different decibel levels. The internal ear's response to such excitation is a return acoustic signal generated by the motions of the external hair cells (otoacoustic emission – OAE). OAE contains signals having different combination frequencies, including the strongest with frequency $f_3 = 2f_1 - f_2$.

Traditionally, the DPOAE signal has been measured using time-averaging and Fast Fourier Transform (FFT) [2, 3]. In that method continuous recording of the DPOAE signals is not possible. Measurements of rapid changes of DPOAEs are very difficult. The method proposed by us is free from these disadvantages. It is described in detail below and preliminary measurement results are given.

2. Fundamentals of dual phase-sensitive detection

A block diagram of a system for measuring AC signals by the double-phase sensitive detection method is shown in Fig. 1.

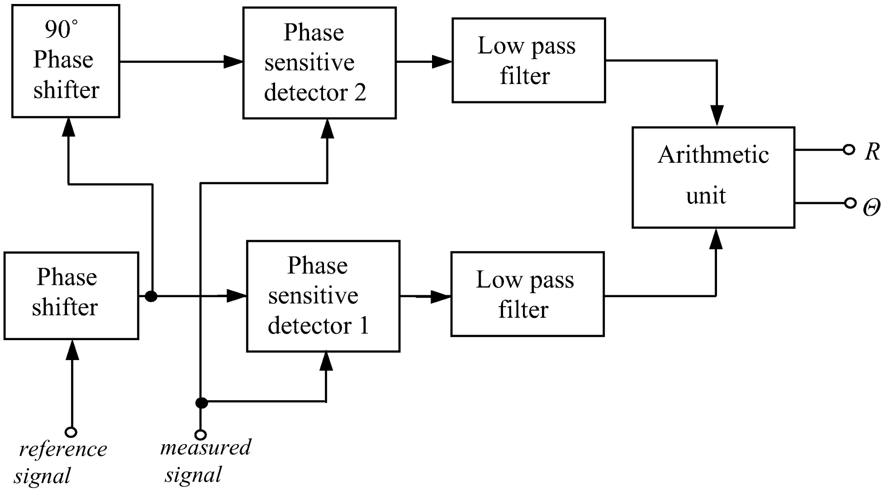

Fig. 1. Block diagram of double-phase sensitive detection.

Let us assume that the measured signal is harmonically variable over time and so it can be desribed by the expression

$$U_s = A_s \cos \omega t. \tag{1}$$

The reference signal has the same frequency but a different amplitude (A_r) and it can be shifted in phase by a certain angle α. Thus the reference signal can be described by the formula

$$U_r = A_r \cos(\omega t + \alpha). \tag{2}$$

The signal at the output of phase-sensitive detector no. 1 (PSD1) is

$$U_{\mathrm{o}1} = A_s \cos \omega t \cdot A_r \cos(\omega t + \alpha) = \frac{1}{2} A_s\, A_r \cos \alpha + \frac{1}{2} A_s\, A_r \cos(2\omega t + \alpha). \tag{3}$$

A reference signal shifted in phase by 90° relative the reference signal fed to PSD1 input is fed to the input of phase-sensitive detector no. 2 (PSD2). Hence the signal at PSD2 output can be described by the formula

$$\begin{aligned} U_{\mathrm{o}2} &= A_s \cos \omega t \cdot A_r \cos\left(\omega t + \alpha + 90^\circ\right) \\ &= \frac{1}{2} A_s\, A_r \sin \alpha + \frac{1}{2} A_s\, A_r \cos\left(2\omega t + \alpha + 90^\circ\right). \end{aligned} \tag{4}$$

The signal at both PSD outputs is made up of a constant component and a variable component whose frequency is twice higher than that of the measured signal. The low-pass filters remove the variable components and as a result the signals at the arithmetic unit's two inputs are constant

$$U_{\mathrm{c}1} = \frac{1}{2} A_s\, A_r \cos \alpha \quad \text{and} \quad U_{\mathrm{c}2} = \frac{1}{2} A_s\, A_r \sin \alpha. \tag{5}$$

The following mathematical operations are performed in the arithmetic unit

$$R = \sqrt{U_{\mathrm{c}1}^2 + U_{\mathrm{c}2}^2} = \frac{1}{2} A_s\, A_r \quad \text{and} \quad \theta = \tan^{-1}\left(U_{\mathrm{c}2} / U_{\mathrm{c}1}\right). \tag{6}$$

The arithmetic unit has two outputs. At one of them there is constant voltage R proportional to the amplitude of the measured signal while at the other there is voltage proportional to phase difference θ between the measured signal and the reference signal. It is significant that in double phase-sensitive detection output signal R does not depend on phase difference θ. Accidental, not necessarily correlated, fluctuations of the phases of both signals (the measured signal and the reference signal) have no effect on the value of R. But the condition of equality between the frequencies of both signals or if the frequencies of both signals are different, the condition of concurrency between changes in the frequencies, still must be satisfied.

The latter case occurs when nonlinear distortions introduced by, for example, an acoustic amplifier are measured by the phase-sensitive detection method. A harmonic signal having frequency f is fed to the amplifier's input. The amplifier introduces distortions whereby besides the signal with frequency f higher harmonics appear at its output. In order to measure, for example, the 2nd harmonic one should multiply the frequency of the input signal fed to the amplifier's input by two and use it as the reference signal.

In earlier papers [4, 5] the authors showed that the phase-sensitive method can be applied to investigate the cochlea's electrophysiological activity in experimental animals. Further below more measurement possibilities offered by the double phase-sensitive detection method are presented.

3. Experimental set-up

Paper [5] describes a phase-sensitive method of measuring cochlear microphonics (CM) induced by two-tone excitation. In the above method for the first time phase-sensitive detection was used in a situation when the measured signal was not generated directly in the generator (as were the exciting signals), but by the external hair cells. The cells excited by tones with two different frequencies: f_1 and f_2 generated a tone having, among others, frequency $f_3 = 2f_1 - f_2$. Using the phase-sensitive method one could receive CM signals having frequency f_3 from the cochlea of a guinea pig (the guinea pig was under general anaesthesia). This was possible because frequency f_3 of the reference signal and frequencies f_1 and f_2 of the signals exciting the cochlea's electrical function were closely correlated.

The authors decided to take one step further and apply a double-phase sensitive detection method to the reception of signals that are products of induced otoacoustic emission. Figure 2 shows the concept of the measuring system.

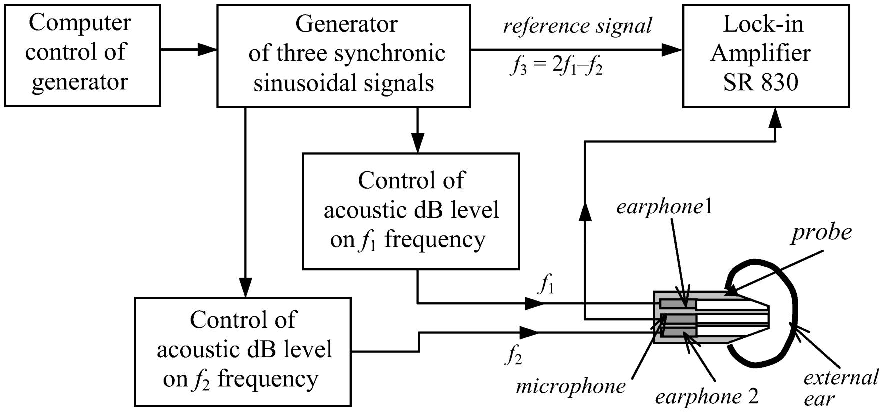

Fig. 2. Block diagram of measuring system.

The measuring system's main component is a digital generator which is a source of three synchronic harmonic signals. The computer controlling the generator allows one to set a specific frequency of each of the signals. At the generator's two outputs there are circuits allowing one to adjust the amplitude of the electrical signals indirectly exciting cochlear function and the amplitude adjustment translates into specific decibel levels of the acoustic waves induced in the external auditory canal.

The acoustic waves are induced by two earphones in a probe located in the external auditory canal. The probe also contains a microphone which picks up the weak return signal generated by the external auditory cells. Besides receiving the weak acoustic signal of induced otoemission, the microphone receives much stronger exciting acoustic signals. One should note that the difference between the acoustic levels of the exciting waves and the otoemission signal amounts to 40–50 dB. Thanks to phase-sensitive detection only the signal whose frequency is the same as that of the reference signal is picked up.

4. Preliminary results

The concept of measuring DPOAE signals by the double-phase-sensitive detection method (Fig. 2) was tested on five guinea pigs with retained Preyer's reflex. Acoustic excitations by two tones having different frequencies f_1 and f_2 and different intensity levels were applied. The microphone output signal with frequency $f_3 = 2f_1 - f_2$ (a signal with such a frequency was fed as the reference signal) was subject to phase-sensitive detection.

As an example, Fig. 3 shows the measured RMS values of the DPOAE signal (in μV) having frequency $f_3 = 1987$ Hz versus $k = f_2/f_1$ (from 1.10 to 1.40 with a step of 0.05) for seven different pairs of levels (in dB) of the exciting tones. The values have been obtained for one ear of a chosen quinea pig.

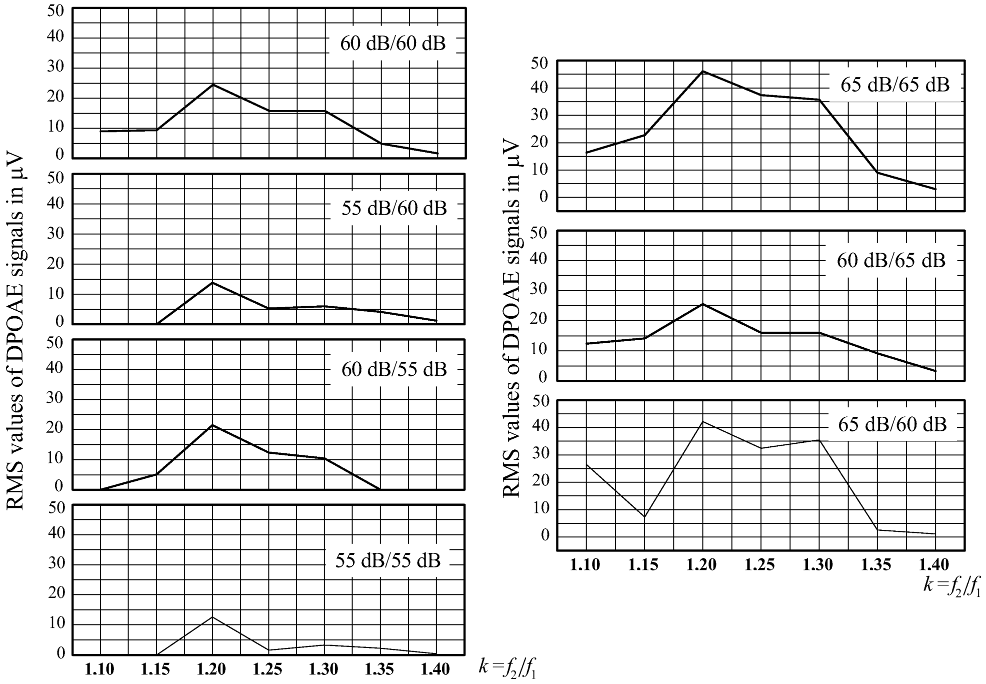

Fig. 3. Measured values of DPOAE signal versus f_2/f_1.

The above example attests to the well-known fact that the DPOAE signal RMS value is a function of the frequencies (i.e. f_1 and f_2) of the signals exciting acoustic waves in the external auditory canal and of the intensity levels of the two excited waves. It confirms that the strongest DPOAE signals are excited at ratio $k = f_2/f_1 = 1.20$.

The measured DPOAE signal values (in μV) can be converted to decibel levels if the relation between the microphone output voltage and the sound intensity level [dB] for frequency $f_3 = 1987$ Hz is known. In the example, the relation (measured by means of an artificial ear) can be described by this formula

$$\log U_{[\mu\mathrm{V}]} = 0.0503\, p_{[\mathrm{dB}]} + 0.74211.$$

Using the formula one can plot a graph of the acoustic pressure of the DPOAE signal picked up by the microphone versus the RMS value of the signal's voltage. The graph is shown in Fig. 4.

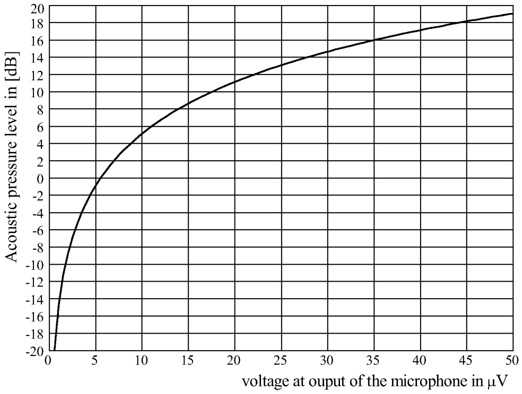

Fig. 4. Acoustic pressure level of DPOAE signals (in dB) versus voltage at output of the microphone for frequency of 1987 Hz.

The graph indicates that in the considered case excited DPOAE signals with a level as low as below −10 dB were measured.

5. Conclusion

The double-phase-sensitive detection method has proved to be highly useful for measuring DPOAE signals. Particularly noteworthy is its high sensitivity whereby it is possible to measure very weak DPOAE signals and to precisely measure changes in the values of the signals under the influence of various external factors. A patent was applied for the method and on 19.06.2006 the latter was registered under number P 379972 [6].

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