Simultaneous Measurement of the DPOAE Signal Amplitude and Phase Changes

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Although the phenomenon of otoacoustic emission has been known for nearly 30 years, it has not been fully explained yet. One kind of otoacoustic emission is distortion product of the otoacoustic emission (DPOAE). New aspects of this phenomenon are constantly discovered and attempts are made to interpret correctly the obtained results. This paper discusses a new method of measuring DPOAE signals based on double phase-sensitive detection, which makes possible a real-time measurement of the DPOAE signal amplitude and phase. The method was applied for measurements of DPOAE signals in guinea pigs. Sample records are presented and the obtained results are discussed.

Keywords: signals, double-phase-sensitive detection, guinea pigs.

1. Introduction

Otoacoustic emission was predicted by GOLD as early as in 1948 (KIMBERLEY, 1999). Thirty years later KEMP published a paper (KEMP, 1978) in which he described experiments proving the existence of this phenomenon. He used clicks of 0.2 ms duration at a repetition rate of 16/s. Between the successive pulses he recorded (with an electret microphone) acoustic wave pressure fluctuations at the outlet of the external acoustic duct. Applying an averaging procedure to

the two-minute recordings, he was able to reduce the noise level to 0 dB SPL and reveal the backward signal which originated from the cochlea stimulated by the click. A large number of works has been published on this subject since the first paper of Kemp, e.g. (Dhar *et al.*, 2005; James *et al.*, 2005; Plinkert, Wagner, 1998; Relkin *et al.*, 2005; Schneider *et al.*, 2001; Scholz *et al.*, 1999; Withnell *et al.*, 2003; Ziarani, Konrad, 2004). New experimental data are reported but their interpretations are not always explicit and mutually consistent (e.g. Ren, 2004).

There are two kinds of otoacoustic emission: spontaneous and stimulated. One form of stimulated emission is the distortion product otoacoustic emission (DPOAE). The stimulation consists of two tones with different frequencies, f_1 and f_2, and different intensity levels. The result of such stimulation of the inner ear is the presence of backward acoustic signals with different intermodulation frequencies in the external auditory meatus; the strongest of the signals has the frequency $f_3 = 2f_1 - f_2$. The level of the latter signal may be as much as 60 dB below that of the excitation signals.

The present authors have been using for a few years a lock-in amplifier with double phase-sensitive detection (Michalski *et al.*, 2000; 2005; 2006a; 2006b; 2007). The amplifier allows to measure not only the rms signal of frequency f_3, but also its phase. During the experiments it was observed that as the excitation parameters were changed, not only the amplitude of the DPOAE signal, but also its phase changed. The real-time simultaneous recording of the DPOAE signal amplitude and phase provided a deeper insight into the character of the changes. This paper describes the measuring system used, presents sample records and an interpretation of the results.

2. Measuring system and technique

The amplitude and phase of the DPOAE signals depend on the excitation conditions defined by four parameters: the frequencies and intensities of the two primaries. In most of the papers published, the DPOAE signals are induced in such a way that the intensities of the primaries are fixed at a constant level and their frequency is changed in a certain peculiar way. For example, one can fix one of the primary frequencies f_1 or f_2 and sweep the other one over a range of frequencies (Harris *et al.*, 1989; Wagner *et al.*, 2008). Another way is to determine a few values of frequency f_3 and measure the DPOAE signals for different frequency ratios f_2/f_1 and different levels of intensity of the two primary frequencies (Michalski *et al.*, 2007). The latter way has been used in the experiment.

The measuring system used in the experiments is described in the paper (Michalski *et al.*, 2006a). A digital generator of three synchronous electric signals with independently regulated frequencies and amplitudes, a probe inserted into the external ear canal during measurements and a lock-in amplifier are

the three main elements of the experimental setup. During measurements, electric signals with frequencies f_1 and f_2, a precisely specified amplitude and the same phase were fed into the probe earphones whereby a two-tone acoustic wave with exactly specified intensity levels was induced in the external acoustic duct. A third signal with frequency $f_3 = 2f_1 - f_2$ was the reference signal for phase-sensitive detection. The week backward signal with frequency f_3 was measured by a DSP lock-in amplifier SR 830 made by Stanford. The amplifier has two BNC outputs. At one output there is a voltage signal proportional to the measured rms signal while at the other output there is a voltage signal proportional to the measured signal phase. The two analogue signals were fed into the BNC inputs of an NI USB-9215 card connected to a PC. The data acquisition was performed by an application running in Labview 7.1. The recorded data were processed by means of the graphic program Origin 7.5.

The experiments were carried out on five coloured guinea pigs (10 ears) each weighing 500–650 g, which were under general ketamine/xylazine anaesthesia (15 mg/kg and 10 mg/kg body weight, respectively). According to the literature, this kind of anaesthesia has no effect on the DPOAE signal emission (SMITH *et al.*, 2008). A Homoth measuring probe was placed in the external auditory meatus of the animals. The probe contains two mini earphones and a standard microphone. Prior to measurements, the probe was graduated in a Brüel&Kjaer artificial ear 4144, using a measuring amplifier 2607 made by the same company. Thanks to the graduation, it was determined for each measuring frequency what voltage must be applied to each of the probe earphones to obtain an acoustic wave with a given intensity. Also the microphone voltage response-frequency dependence was measured.

The measurements were carried out for five fixed intermodulation frequencies f_3: 1321, 1875, 2671, 3142 and 5342 Hz. Each of the five frequencies were obtained for seven different ratios $k = f_2/f_1 = 1.10, 1.15, 1.20, 1.25, 1.30, 1.35$ and 1.40. All the used measuring frequencies are shown in Table 1.

Table 1. Measuring frequencies.

Measuring frequencies [Hz]		Values of parameter $k = f_2/f_1$						
		1.10	1.15	1.20	1.25	1.30	1.35	1.40
$f_3 = 1312$	f_1	1458	1543	1640	1749	1874	2018	2187
	f_2	1604	1774	1968	2186	2436	2724	3062
$f_3 = 1875$	f_1	2083	2206	2344	2498	2678	2885	3125
	f_2	2291	2537	2813	3121	3481	3895	4375
$f_3 = 2671$	f_1	2968	3142	3339	3561	3816	4109	4452
	f_2	3265	3613	4007	4451	4961	5547	6233
$f_3 = 3749$	f_1	4166	4411	4686	4998	5356	5767	6248
	f_2	4583	5073	5623	6247	6963	7785	8747
$f_3 = 5342$	f_1	5936	6285	6678	7123	7631	–	–
	f_2	6530	7228	8014	8904	9920	–	–

After any of the five frequencies f_3 was fixed and a given frequency ratio k was selected 140-second recordings of changes in amplitude and phase were made. The changes were effected by changes in the intensity of the individual stimulating tones. The following tone intensity pairs were used: 1 – (55 dB, 55 dB), 2 – (55 dB, 60 dB), 3 – (60 dB, 55 dB), 4 – (60 dB, 60 dB), 5 – (65 dB, 60 dB), 6 – (60 dB, 65 dB) and 7 – (65 dB, 65 dB). In each of the combinations, the dB SPL of primary f_1 is in the first place.

3. Measurement results

In four ears no DPOAE signals were detected in the external acoustic duct. Hence the considered series of measurements is only for six ears. In total, a few tens of double records (amplitude and phase) for different values of frequency f_3 and ratios k were obtained. Some of the records for 3749 Hz DPOAE are shown in Fig. 1.
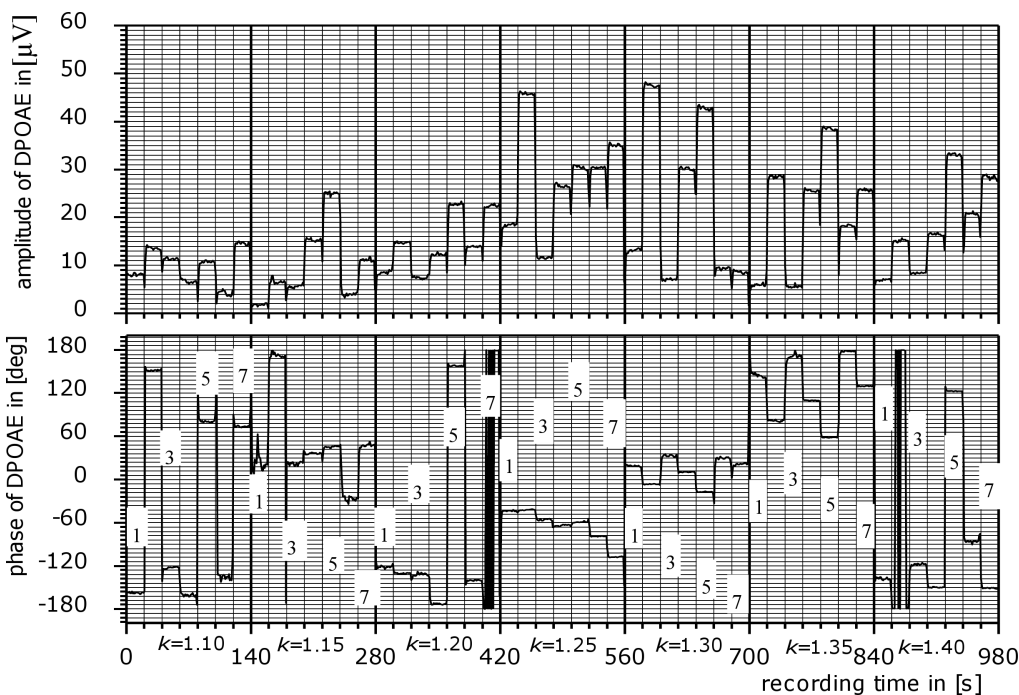

Fig. 1. Records of simultaneous changes in amplitude and phase of DPOAE signals for $f_3 = 3749$ Hz and seven different $k = f_2/f_1$ ratios.

Each record (lasting 980 s) was obtained for one of the five frequencies f_3. A single 980 s long record contains seven 140 s periods, each of them obtained for a different f_2/f_1 ratios. The seven dB SPL primary pairs mentioned above

were used in each 140 s period. The amplitude and phase of DPOAE signals
were recorded in microvolts and volts, respectively. In order to obtain a DPOAE
phase in degrees, the conversion rate 1V= 18 degrees was used. Phase recording
was possible in a voltage range of $[-10V, +10V]$ corresponding to a degree range
of $[-180°, +180°]$.

A diagram of DPOAE amplitude and phase changes caused by the dB SPL
primaries was drawn on the basis of recordings similar to that shown in Fig. 1.
In order to get an idea what the acoustic wave intensity level in [dB] was, ap-
propriate curves from the artificial ear measurements were used. As an example,
the dB sound pressure level $[L_{dB}]$ for the DPOAE amplitude in microvolts ($U_{\mu V}$)
and frequency $f_3 = 3749$ Hz was calculated from the formula

$$L_{dB} = -16.3 + 19.8 \ \log U_{\mu V}.$$

Other formulas were used for DPOAE frequencies of 1312 Hz, 1875 Hz,
2671 Hz and 5342 Hz. An exemplary diagram for some of the data presented
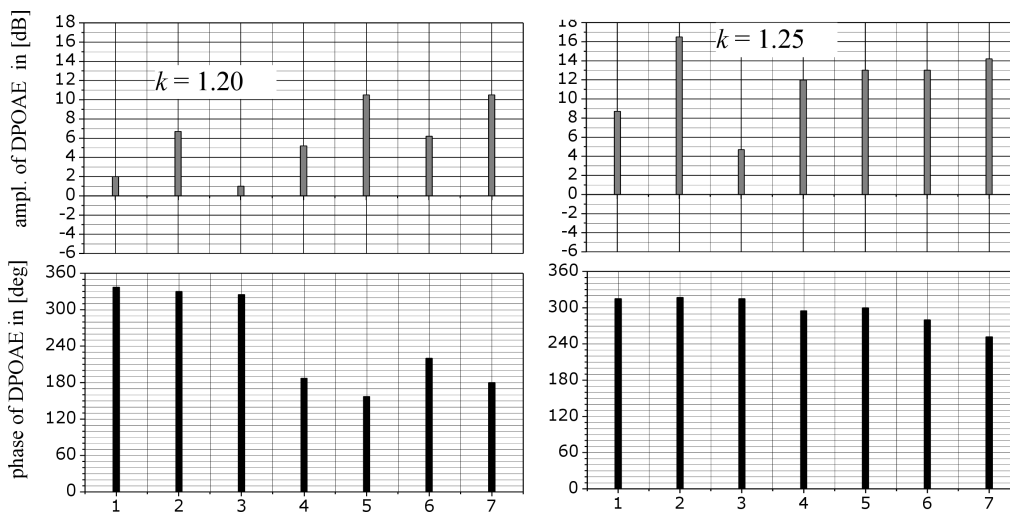in Fig. 1 is shown in Fig. 2.

Fig. 2. Amplitude and phase of the 3749 Hz DPOAE signal for different pairs of dB SPL
primaries.

It was found in all the measurements that each change of the dB SPL primary
frequencies causes a change in the amplitude and phase of the DPOAE. Both
amplitude and phase may either increase or decrease. During each 20-second pe-
riods when the excitation parameters remain unchanged, the two quantities can
have a constant or a slightly changing value. Each dB SPL primary pair change
causes phase and amplitude jumps regardless of the tested ear number. However,
the magnitude of an abrupt increase or decrease in phase showed individual dif-
ferences.

Table 2. Amplitude and phase of 3749 Hz DPOAE signals at one of the two dB SPL primary levels fixed.

$f_3 = 3749$ Hz

k = 1.10

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	4.5	238		55	6	151
60	-0.4	200		60	-0.4	200
65	-4.0	225		65	4.0	80

k = 1.15

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	-1.5	25		55	-0.4	173
60	7.0	30		60	7.0	30
65	-4.5	-25		65	11.1	45

k = 1.20

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	1.0	325		55	6.7	330
60	5.1	188		60	5.1	188
65	6.1	220		65	10.4	158

k = 1.25

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_1 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	4.7	314		55	16.5	318
60	12.0	295		60	12.0	295
65	13.0	280		65	13.0	300

k = 1.30

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	4.8	313		55	16.4	318
60	12.0	294		60	12.0	313
65	13.0	280		65	13.0	300

k = 1.35

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	0.4	170		55	16.8	81
60	13.0	110		60	13.0	110
65	1.0	180		65	16.0	59

k = 1.40

$L_1 = 60$ dB				$L_2 = 60$ dB		
L_2 [dB]	ampl. [dB]	phase [deg]		L_1 [dB]	ampl. [dB]	phase [deg]
55	0.3	170		55	16.8	81
60	13.0	110		60	13.0	110
65	1.0	180		65	16.0	59

In order to assess which of the two dB SPL primaries has a bigger influence on the DPOAE amplitude and phase, the experimental data were processed in the way shown in Table 2 for the DPOAE frequency of 3749 Hz. For particular f_2/f_1 ratios, the table shows the amplitude and phase of DPOAE first for fixed $L_{1\,\text{dB}} = 60$ dB SPL and $L_{2\,\text{dB}} = 55$, 60 and 65 dB and next for $L_{2\,\text{dB}} = 60$ dB and $L_{1\,\text{dB}} = 55$, 60 and 65 dB. Similar tables were compiled for the other DPOAE frequencies.

4. Discussion of results

In all the published research papers known to the authors, otoacoustic emission phenomena recorded in the external acoustic duct are referred to the electromechanical function of the cochlear as the sole source of such signals, including DPOAE signals. This means that the fact that the week backward signal travels the same distance (but in the opposite direction) as the excitation signals and so it is not taken into account that the system of auditory ossicles and the drum membrane may have an effect on the amplitude and phase. The above ear components take part in the transmission of strong excitation signals to the cochlea. Theoretically, changes in dB SPL primaries can depend on the transmission parameters of the auditory ossicles and the drum membrane. The discussion below is based on the assumption that changes in the amplitude and phase of DPOAE can be directly referred to the cochlea.

The experiment discussed here consisted of series of measurements. In each series the frequencies of the excitation tones were fixed while the intensities of the tones changed. In the experiment set up in this way, the places of the DPOAE signal origin did not change. According to the literature, there are two such places on the basilar membrane , i.e. the generation regions of maximum primaries overlap and the component is reflected from the characteristic frequency region of the DPOAE (wave-fixed and place-fixed mechanisms) (JOHNSON *et al.*, 2007; WILSON, LUTMAN, 2006; WITHNELL *et al.*, 2003). As the intensity of the excitation tones changes, the excitation area of each of the travelling waves changes as well. As the result, not only the amplitude, but also the phase of each of the waves changed. The backward acoustic wave with frequency f_3 recorded by the microphone is a result of the simultaneous action of the two travelling waves on the stapes base.

If each of the travelling waves acting directly on the oval window (on its inner side) is written as respectively

$$A_{1m}\cos(\omega_3 t + \alpha_1) \qquad \text{and} \qquad A_{2m}\cos(\omega_3 t + \alpha_2),$$

then the resultant wave is a vector sum of contributions arising from the f_2 and $2f_1 - f_2$ regions and can be expressed by the formula

$$A_{3m} = \sqrt{A_{1m}^2 + A_{2m}^2 + 2A_{1m}A_{2m}\cos(\alpha_2 - \alpha_1)}\cos\left[\omega_3 t + (\alpha_2 - \alpha_1) + \kappa\right], \quad (1)$$

where

$$\kappa = \operatorname{a} \tan \left(\frac{\sin(\alpha_2 - \alpha_1)}{\dfrac{A_{1m}}{A_{2m}} + \cos(\alpha_2 - \alpha_1)} \right). \tag{2}$$

The double phase-sensitive detection method used by us enables independent measurements of the DPOAE signal's amplitude A_{DPOAE} and phase Ω_{DPOAE} in the ear canal, which, according to the earlier assumption, are proportional to the amplitude and phase of the resultant wave on the oval window:

$$A_{\mathrm{DPOAE}} \approx A_{3m} = \sqrt{A_{1m}^2 + A_{2m}^2 + 2A_{1m}A_{2m}\cos(\alpha_1 - \alpha_2)}, \tag{3}$$

$$\Omega_{\mathrm{DPOAE}} \approx (\alpha_1 - \alpha_2) + \kappa. \tag{4}$$

According to the formulas (3) and (4), the resultant amplitude and phase are functions of the amplitude of the two component waves and the phase difference between the waves. When the intensity of the excitation tones increases, then the amplitude of each of the excited travelling waves may increase. However, the phase difference may be such that the resultant amplitude will decrease. To sum up, the irregular changes in the amplitude and phase of the DPOAE signals, observed when the intensities of the excitation tones are changed, confirm that in the perilymph there are two travelling waves arising in two different places of the cochlea's basement membrane.

A similar experiment was described by HARADA *et al.* (2001). In the experiment, the effect of changes in the stimulus level on the phase of the DPOAE in five normal hearing adults was measured. Changes in dB SPL primary f_1 and dB SPL primary f_2 had different effects on the DPOAE phase. However this is not confirmed by our results (see Table 2), which may be due to the fact that we examined guinea pigs.

5. Conclusion

In all the records, regardless of the individual differences, a jump in both the amplitude and phase of the DPOAE signals was observed as the intensity level of the excitation signals was changed at fixed signal frequencies. This may corroborate the theory that two sources of the travelling wave with frequency $f_3 = 2f_1 - f_2$ exist. Changes in dB SPL primary f_1 at constant dB SPL primary f_2 and changes in dB SPL primary f_2 at constant dB SPL primary f_1 show the same effect on the phase of the DPOAE signal.

It is apparent that the simultaneous recording of both amplitude and phase changes offers over time new possibilities for the investigation of the DPOAE signal generation mechanism and the real-time analysis of the behaviour of this

signal. The presented experimental research should be considered as a preliminary one. Further experiments on a larger group of test animals are planned.

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