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Ellipsoidal reflector for measuring oto-acoustic emissions

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ABSTRACT

A truncated prolate ellipsoidal reflector having the ear canal of a listener at one focal point and large-diaphragm low-noise microphone at the other focal point is proposed for free-field recordings of oto-acoustic emissions. A prototype reflector consisting of three pieces is presented, which enables measuring the response of the system with different truncations. The response of the system is measured with a miniature loudspeaker, and proof-of-concept measurements of oto-acoustic emissions are presented. The effect of truncation and other physical parameters to the performance of the system are discussed.

1. INTRODUCTION

Oto-acoustic emissions (OAE) are faint sounds emanated by the ear drum (Geisler 1998). The emissions are thought to be a by-product of the active processes in the inner ear enhancing the frequency-resolution and sensitivity. The processes are active when sound vibrations enter the cochlea, and also spontaneously without external sound. The processes produce non-linear distortion components to the vibration of basilar membrane, which are transducted through the middle ear into the ear drum (a.k.a. tympanic membrane), which finally generate the emissions. These signals are generally low in level (around 0 dB SPL), depending on the type of the OAE. Oto-acoustic emissions are interesting in the research of functioning of the cochlea itself, and they are used routinely for screening of new-born babies.

The OAEs are typically measured using a miniature microphone inserted in the ear canal. Due to the small diameter of the microphone membrane, the induced self-noise is relatively high, and sound generated by the body of the subject may disturb the recording, such as breathing noise and body movements. The driving idea of this work is to use a reflector to focus most of the sound emanating from ear canal to a large-capsule microphone with low self-noise. When the microphone is not in the ear canal, and when the ear canal is not sealed, the acoustical load of the inner ear towards the ear canal is more realistic compared to closed-ear measurements. In addition, having the microphone detached from the listener reduces the level of sounds generated by the subject, and hence improves the quality of the recordings.

The problem geometry has thus a small source (the ear canal) and a relatively small receiver (the microphone). An ellipsoidal reflector can be used to collect the acoustic rays after traveling equal distance, where the ear canal is at one focal point, and the microphone at the other focal point, as shown in Fig. 1. Ellipsoidal acoustic reflec-

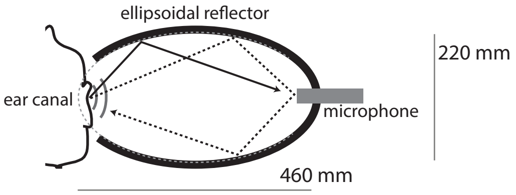

Fig. 1: General idea of using a truncated ellipsoid reflector in recording of oto-acoustic emissions. The ear canal and the microphone capsule are at the focal points of the reflector. The distance between the focii is 404 mm.

tors have earlier been used to focus pressure pulses in medical applications (Wright and Blackstock 1997), or in under-water acoustics (Sommerfeld and Müller 1988). The sound emanated by the ear canal will thus be largely captured by the microphone. Another phenomenon that affects the effectivity of the system is the impedance mismatch between ear canal and the free field, which decreases the level of radiation depending on frequency, similarly as in sound radiation from vocal tract to free field (Rabiner and Schafer 1978). The quantification of the responses measured with this system is thus a bit complicated as the geometry of the ear of the subject affects the results. We will discuss in this paper the implementation of such reflector in the context of distortion-product OAEs, and will also show responses that quantify the acoustical properties of the reflector.

2. DESIGN AND IMPLEMENTATION OF THE ELLIPSOIDAL REFLECTOR

The reflector should gather as much as possible of the sound emanated by the ear, which suggests that the ellipsoid should be truncated as little as possible. On the other hand, the frequency response of the reflector should naturally be flat, and the impulse response should be as short as possible. If a minimally-truncated ellipsoidal reflector is used, it is clear, that the sound will at least partly be reflected back to the ear canal and then back to the microphone due to reflections from the subject and diffraction from the edge of the reflector, as shown with dashed line in Fig. 1. Such reflections cause a longer impulse response, and create modes in frequency response. It is possible to truncate the ellipsoid more prominently, i.e., use only a smaller part of the surface of the ellipsoid. In this case the sound would reflect less sound energy back to the ear, and consequently the impulse response would be shorter, and the modes would be less present in the frequency response.

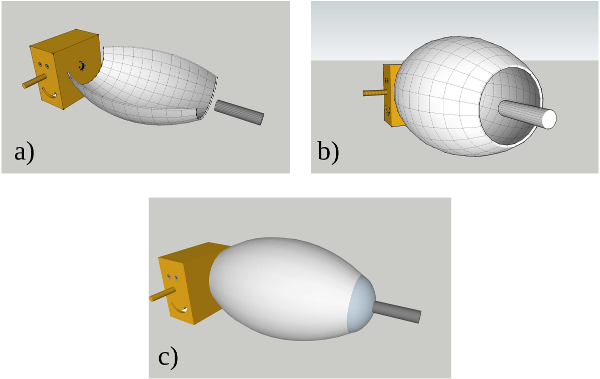

Fig. 2: Ellipsoid reflector designs for oto-acoustic emission measurements with the ear canal at one focal point and the microphone in the other. a) One-side reflector. b) Two-side reflector. c) Closed reflector.

To test these ideas in practice, we constructed the reflector in a modular structure to be able to put together an ellipsoid with only one side, with two sides, or with both sides and closed end, as shown in Fig. 2. The physical reflector was build using a computer-controlled cutting machine (CNC router). The material to be carved was selected to be polyurethane board with density of 400kg/m^3, which was assumed to be dense, thick and hard enough for this purpose. The geometry of the carved reflector follows prolate ellipsoid, as shown in Fig. 1 with the dimensions of the device.

The carved reflectors were painted with glossy spray paint with hardening agent to smooth small irregularities in the surface, and to further increase the reflection coefficient of the material. The constructed pieces and the 1-inch low-noise microphone are shown in Fig. 3.

3. RESPONSE MEASUREMENTS

Ideally, we should measure the transfer function from ear canal to the microphone. This is not straight-forward, as the measurement loudspeakers can not be inserted into the ear canals. For this study we simply used a miniature loudspeaker as sound source with area of the driver of about 1cm^2 which roughly corresponds to radiating area of the ear canal.

The measured frequency responses are shown in Fig. 4 for different versions of the reflector. As reference curves, the free-field response measured at the microphone position of the reflector, and the response of the

Fig. 3: Constructed reflectors. Up: all pieces separately. Down left: two sides together. Down right: the head piece and microphone together.

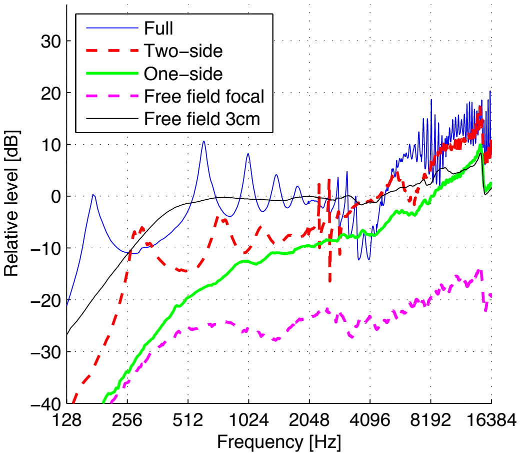

Fig. 4: Frequency response of the reflector measured with a miniature loudspeaker.

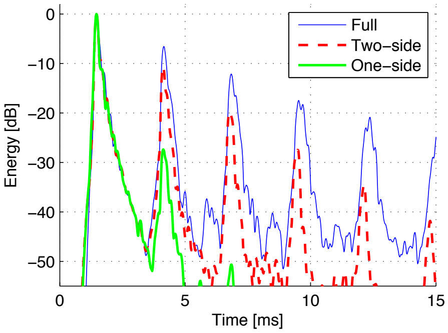

Fig. 5: Energy decay curves smoothed by convolution with 0.2ms Hann window. The curves show the responses with different versions of the reflector measured with miniature loudspeaker at the focal position.

microphone at 3cm distance from the miniature loudspeaker are shown. It can be seen, that with closed reflector the response follows roughly the response of the microphone in 3cm, however with some strong modes at low frequencies, a notch in response near 3kHz, and higher and rippled response at frequencies above 6kHz. The response of the two-sided reflector shows slightly less pronounced modes, though with lower magnification at frequencies below 2kHz and less ripples in the response in general. In the case of single-side reflector, the gain of the system is lower at low frequencies, and the frequency response does not show such ripples as with other variants.

The measured energy decay curve is shown in Fig. 5 for different versions of the reflector. With fully-closed reflector, the impulse response shows prominent reflections spaced by about 2.7ms in time, with decay between consecutive reflections only of about 6dB. This clearly limits the use of such reflector in time-domain measurements, such as in the case of transient-evoked oto-acoustic emissions. If the reflector was made larger, the reflections would be more separated in time. For example, if 10ms time window would be needed for measurements, the reflector diameters should be made four times larger. Such long temporal response can also be avoided by using more truncated reflector, which is shown in measurements. With two-side reflector, the decay between consecutive reflections is about 10dB, and with one-side reflector the reflections decay very fast within few ms. The impulse response of one-side reflector would be ideal for temporal-domain measurements, unfortunately the lower

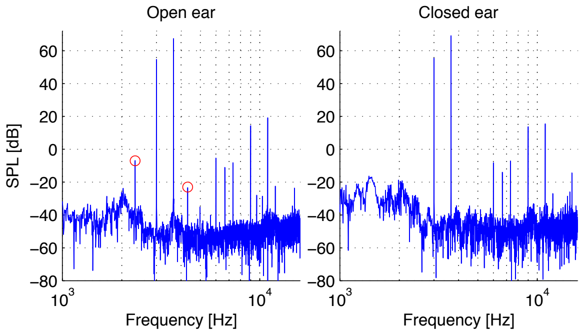

Fig. 6: Sound spectra measured with reflector with two loudspeakers producing sinusoids at 3kHz and 3.66 kHz and subject lying under the reflector with ear canal approximately in focus point. Left: response with open ear canal, with most prominent oto-acoustic emissions marked with red circles. Right: response with closed ear canal, where the oto-acoustic emissions are not present.

amplification in low frequency domain may limit its applicability. Nevertheless, the closed reflector may still be used for measurements where the temporal response is not critical, such as with distortion-product oto-acoustic emissions, where two continuous sinusoids are used as stimulus.

4. MEASUREMENT OF DISTORTION-PRODUCT OTO-ACOUSTIC EMISSION

To make an initial test of the system, a measurement of oto-acoustic emissions produced by two sinusoids with frequencies $f_1 = 3$kHz and $f_2 = 3.66$kHz generated with two loudspeakers was conducted with a real subject. The subject was lying under the reflector, and two active loudspeakers were emitting the sinusoids, producing about 65 dB SPL in the position of the ear of the listener. The length of stimulus was 65s. 360 subsequent frames with length of 166.6 ms were averaged in temporal domain, and the result was analyzed with FFT.

The measured responses with closed ear show clearly the frequency components, and also some distortion components of the loudspeakers. When the ear canal is open, some oto-acoustic emissions are clearly shown, most prominent ones of them at frequencies corresponding to $2f_1 - f_2$ and $2f_2 - f_1$. This suggests that the system can be used for oto-acoustic emission measurements. Note, that the levels in the figure can not directly be interpreted as absolute SPL values. The transfer function neither from the loudspeakers nor from the ear canal to the microphone are not known per se, and thus the absolute SPL in the ear canal are not known. The level difference between loudspeaker sound components and oto-acoustic emission components is exaggerated, as the loudspeaker sound leaks directly to the microphone, whereas the emission is measured only after being radiated from the ear canal. Absolute measurement of the SPL in ear canal is reserved as future work.

5. CONCLUSIONS

This engineering brief shows a design of ellipsoidal reflector to capture oto-acoustic emissions. A prototype was constructed that can be dissected to three parts to measure their performance separately and/or together in the task. The system was found to amplify the sound especially at frequencies above 6 kHz with all tested cases. At lower frequencies prominent amplification was found at mode frequencies with least truncated ellipsoidal reflectors. The level of truncation also affects the impulse response of the system, with higher degree of truncation shorter impulses are obtained, and vice versa. Oto-acoustic emission measurement was conducted with a real subject, and the results show a proof-of-concept that the system can be used for measurements of distortion-product oto-acoustic emissions.

6. ACKNOWLEDGMENTS

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