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Development, validation and application of a generator for distortion product otoacoustic emissions

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ABSTRACT

The application area of distortion product otoacoustic emissions (DPOAEs) is expanding beyond clinical routines, towards new measurement environments, protocols, wearable hardware and more robust algorithms. To enable systematic assessment of the performance of commercial and prototype OAE equipment under various measurement conditions without a need for recruitment of the test subjects, a DPOAE generator that produces a reliable and stable response is proposed. This article suggests simple design for such generator that is easy to reproduce by third parties. This design uses an approximate model for middle and inner ear dynamics focusing on typical operational conditions. The DPOAE generator is embedded in a head and torso simulator enabling testing for various probe fitting and also residual ear canal volume effects. Measurement of the DPOAE generator response with clinical equipment shows that the response obtained falls within the range of human normative data. It is also shown that the generator is applicable outside the clinical routines and is able to highlight differences in measurements obtained with different clinical OAE measurement devices.

1. Introduction

Otoacoustic emissions (OAEs) are low-level signals, primarily originating from outer hair cell activity located in the cochlea inside the inner ear. These OAE signals propagate back from the inner ear to the external ear canal where they can be observed using distortion-free recording and refined signal processing. Evoked OAEs (EOAEs) are OAEs in response to an external acoustical stimulus. Spontaneous OAEs (SOAE), on the other hand, occur without stimulus and are usually more rare in the human population. Within the EOAEs, the two most commonly used types are transient evoked OAEs (TEOAEs), evoked by click stimuli and distortion product (DPOAEs), evoked with pure tone stimuli [1,2].

Both TEOAEs and DPOAEs are frequently used to monitor the status of the cochlea and detect potential outer hair cell damage. For example, EOAEs are now frequently used for diagnostic purposes and newborn screening [3,4]. For this and other clinical applications, protocols are developed to assure measurement reproducibility [5]. Also, technical standards for the electronic components in OAE equipment are available [6]. However, the field of application of OAE measurements is currently expanding. As an example, OAE measurements are also suggested as a tool for early detection of occupational and/or recreation noise-induced hearing damage, or for indirect monitoring of real exposure under hearing protector [7,8]. New devices are being developed to withstand the difficult measurement conditions that might occur outside the clinical environment. Manufacturers use different techniques to detect the OAEs and noise levels as the technology evolves. Developing new devices and test protocols requires extensive testing and validation.

At the moment, validation of OAE devices and their parameters is mostly done by repeated measurements with human test subjects. Due to inter-subject and individual temporal variability of OAE responses, the test groups need to be sufficiently large and many repetitions are required. This imposes practical constraints on the number of measurement conditions that can systematically be compared. For this purpose, an OAE generator that produces realistic but time-invariant EOAE responses, would be useful. This generator has to be generic with respect to the various designs of the OAE equipment. All OAE devices, therefore, can operate on the generator as they would on human subjects.

The proposed design was intended for simulating DPOAE responses, since DPOAEs are well established in clinical practice, but are also more commonly used for in-field DPOAE measurements outside clinical routines [8]. The proposed DPOAE generator was developed starting from a standard head-and-torso simulator (HATS). Such HATS based DPOAE simulator enables a human-like

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measurements setup including realistic probe placement in the outer ear canal. Also, it accounts for the influence of the head and torso on the sound propagation in elevated background noise levels. DPOAEs are generated in real time in response to stimuli sent by the OAE equipment. Within this hardware setup, various models could be implemented in signal processors for the fundamental DPOAE generation mechanisms—such as advanced models by Liu et al. [9], Neely et al. [10], Rapson et al. [11] and How et al. [12]. However, since the focus is on designing a generic tool, useful for the development and testing of OAE devices and protocols, a less complex DPOAE generator algorithm is proposed in this paper. The design is easy to reproduce by the third parties and it has low computational requirements.

The simulator produces $2f_1 - f_2$ DPOAE frequency component in responses to the primary frequencies f_1 and f_2. DPOAE responses are seen at multiple distortion products of f_1 and f_2, but numerous studies and clinical practice have focused on $2f_1 - f_2$ DPOAEs. Especially in humans, it is the strongest distortion component for a wide range of stimulus parameters [14]. There are no further restrictions or hypothesis that would limit the operational range of the proposed generator. However, to reduce the complexity of the generator model and to focus on hardware design, the following additional assumptions are made. The ratio f_1/f_2 is assumed to be around 1.22. In practice, this frequency ratio is the most adopted [13], as it assures that DPOAE amplitude at each frequency is still within 3 dB of its optimal value [5,14]. Furthermore, it is assumed that the proposed generator is intended to replicate DPOAE signals which are result of active cochlear processes observed for moderate stimuli levels ($\leqslant$70 dB (SPL)) [5] in subjects with normal hearing. Moderate stimuli levels are used in conventional clinical protocols for hearing screening, as low level stimuli enhance the sensitivity of DPOAE responses to cochlear dysfunction [5,13], while high level stimuli can lead to false-high DPOAE responses due to the system distortion [15]. The generator is further simplified by assuming that the level of the tone produced at frequency f_1 (L_1) is significantly higher (e.g. 10 dB) than the level produced at frequency f_2 (L_2). This level difference is known to lead to the optimal levels of the DPOAE responses [16].

The basic principles of the proposed DPOAE generator have already been introduced by authors in [17]. The design is explained in detail in Section 2. Sections 3 and 4 describe the methodology and results of an extensive validation of the DPOAE generator responses with normative data obtained with the human subjects in the quiet clinical conditions [18]. For this purpose, a newer type of OAE equipment is used compared to the one used in [17]. In addition, Sections 3 and 4 explain two examples of use of the DPOAE generator. As the first example, DPOAE responses are measured in elevated background noise conditions. The results are also compared with reported data on the human subjects [19]. Another example of the applicability compares the DPOAE responses measured by two different commercial OAE devices. Finally, the performance of the proposed DPOAE generator is analyzed and discussed in Section 5.

2. Design of the DPOAE generator

2.1. Hardware components

The proposed DPOAE generator is integrated in commercially available HATS with middle and outer ear simulator, in casu Brüel & Kjær HATS type 4128C (Fig. 1, Brüel & Kjær, Denmark). The OAE measurement device under test (DUT) and its OAE probe generate primary tones and record the DPOAE responses. Stimuli sent by the OAE probe are picked up by the sensitive microphone of the HATS, passed through the HATS pre-amplifier and are further routed through the Field-Programmable Gate Array (FPGA) interface to a personal computer where the fundamental mechanisms of DPOAE responses are simulated (see Section 2.2). Note that the FPGA is used solely for acquisition and playback and can be replaced by any high quality audio card. Subsequently, the DPOAE responses are evoked with a mid-frequency exciter, type VISATON EX 45 S (VISATON, Germany), attached to the ear simulator block inside the HATS (Fig. 1).

In this configuration, the generated DPOAE responses are altered by the propagation from the exciter via the ear simulator block to the ear canal. The transfer function between the exciter and the HATS microphone in the ear canal (H in Fig. 1) depends on the hardware that is used and can be rather complex (see Fig. 2). To compensate for it and to preserve the desired DPOAE levels in the ear canal, a digital filter is included in the DPOAE response generation path (H^{-1} in Fig. 3). If another type of the HATS, middle ear simulator, exciter and/or probe placement is used, the compensation filter (H^{-1}) is automatically adapted. Therefore, this compensation procedure allows for flexible adaptation to and independence of the choice of hardware fixture.

The compensation filter (H^{-1}) is identified prior to the DPOAE measurement using an adaptive normalized least mean square (NLMS) technique. The inverse transfer function (H^{-1}) is implemented as a Finite Impulse Response (FIR) filter of order $N = 1024$ with a delay of 500 samples for a sampling frequency of 50 kHz. By compensating for the hardware-related transfer function in this way, the desired DPOAE signals are produced in the ear canal. The physical transfer function (H in Fig. 1) and its electronically identified inverse transfer function (H^{-1} in Fig. 3) are shown on the Fig. 2.

During the design process of the DPOAE generator, different exciter models and exciter positions have been tested in terms of output levels and frequency response. A miniature loudspeaker placed directly in the ear canal was also considered as a possibility. However, adding the loudspeaker in the ear canal would alter the impedance in the ear canal and hence the working conditions of the OAE probe in the generator compared to human subjects.

2.2. DPOAE generation algorithm

The block diagram of the DPOAE generation algorithm proposed in this paper is shown in Fig. 3. Here, the middle ear filter (MEF) represents the influence of the middle ear on the DPOAE response. This influence has to be accounted for since the middle ear affects both the stimuli signals propagating from the ear canal to the inner ear via the middle ear, and the DPOAEs generated by the cochlea, propagating back via the middle ear to the ear canal. Therefore, the middle ear influence is addressed as a two port system with a forward and backward function [20]. In our model, these functions are represented by two FIR filters (MEF: M1, M2) of the same order $N = 1024$. The filters approximate the average forward (M1) and backward (M2) middle ear pressure gain, measured on thawed ears of human cadavers [20] and are shown in Fig. 4.

The part of the block diagram in-between the middle ear filters models the inner ear. In the proposed design, the DPOAE response at frequency $2f_1 - f_2$ is generated using a third power function (X^3). This function is the lowest integer power that produces the distortion product at the frequency $2f_1 - f_2$. In addition, it can easily be implemented in analog electronics if one desires a more compact hardware design.

The third power function introduces a supralinear increase in DPOAE magnitudes with stimulus magnitudes. Hence, a compression factor is included in the algorithm, accounting for the compression mechanisms found in healthy human cochleas [15]. The compression factor is set at 0.3 dB/dB according to the results