Late Breaking Results: Can You Hear Me? Towards an Ultra Low-Cost Hearing Screening Device

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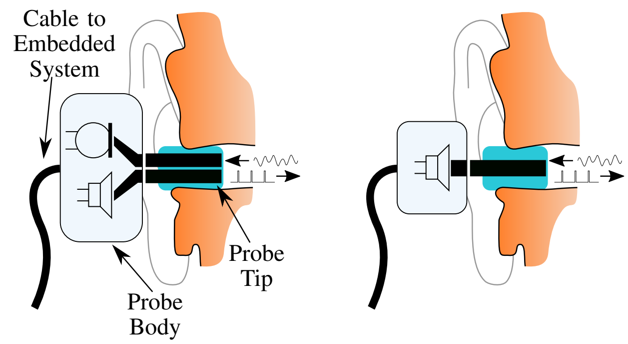
***Abstract*—Hearing screening devices emit an acoustic signal in the outer ear, which invokes a specific response from a healthy inner ear. However, the high cost of such devices prevents widely deploying them in schools or private homes, especially in developing countries. In this paper, we for the first time show that such tests are also feasible with a device that consists of only one speaker for emitting the signal and using the same speaker – now as a microphone – for also recording the response. Existing devices rely on a speaker and microphone pair, which makes them significantly more complex and costly. We further outline the embedded systems and signal processing challenges that such a setup entails. If successful, it has the potential to make hearing screening available to a much wider population in developing countries.**

I. Introduction

Four out of every 1,000 children born in India were found to suffer from severe to profound hearing loss, with a larger number being at risk [1]. Early detection of hearing loss is crucial for speech development, especially because most hearing impairments can be treated. However, devices for hearing screening are expensive and often unavailable, especially in the rural areas of developing countries.

Detecting Hearing Loss: For detecting hearing loss of infants, the measurement of otoacoustic emissions (OAE) has become the gold standard. OAEs are an epiphenomenon of the active amplification process in the inner ear, which relies on both intact middle ear function and healthy sensory cells. Therefore, the absence of OAEs is a very strong indicator for a significant hearing loss, which needs further action. Figure 1(a) shows a schematic sketch of a conventional OAE probe for measuring transient-evoked OAEs (TEOAEs). Here, a click noise is created in a specific pattern through a speaker, while a microphone records the OAE response. For distinguishing the minuscule OAEs from the noise, a large number of click patterns are averaged over time. The probe is *the* critical component in an OAE hearing screening system. It needs to accommodate a microphone and speaker in a small form-factor housing and connect them to the ear canal through two separate acoustic channels. This requires a precision design, making the probe complex and expensive. However, compared to the high-end devices used in diagnosis and screening by clinicians, there is an urgent need for low-end inexpensive devices that can be used at the first level of screening. Such devices can then be much more widely deployed compared to the screening devices that are currently available.

Low-Cost Probe Design: In this paper we for the first time propose a probe design that consists of only one speaker, which is used both for stimuli generation and also for response detection (Fig. 1(b)). After a click stimulus has been generated in the ear canal, the OAE response is emitted shortly



(a) Typical TEOAE probe (b) Our proposed probe

Fig. 1: (a) Typical TEOAE probe. Its housing consists of a speaker and a microphone with separate acoustic channels. (b) Proposed speaker-only probe with single channel.

afterwards. Within this time, the role of the speaker has to be reversed into that of a microphone. We then measure the vibrations of the speaker's membrane as an electrical signal. Omitting the microphone also simplifies the mechanical design of the probe tip significantly, as now only one acoustic channel is required for the connection to the ear canal. We show that detecting OAEs with such a setup is still feasible. We also claim that the resulting probe is more amenable to low-cost mass production, in contrast to the current probes that need expensive manual assembly because of their complex design. If we would be able to integrate the embedded system directly into the probe housing itself, cost-effective mass-production techniques can be used to manufacture our proposed design. A design based on a single printed circuit board (PCB) including the speaker could drive down cost by an order of magnitude, as manual assembly would no longer be necessary. A standard TEOAE probe currently retails for several hundred dollars, while we expect our probe to be manufacturable below $ 10.

Embedded Systems Challenges: Compared to conventional probes with a separate microphone, the signal acquired by the speaker's membrane is expected to be much worse: the sensitivity of speakers when used as microphones is generally very low. Combined with the already faint OAE signal, a much better signal processing is required, compared to when a standard OAE probe is used. Furthermore, the circuits for signal generation and recording need to be alternately connected within a very short time-frame, while at the same time introducing only a limited amount of switching interference. Since the resulting signal quality falls short of that of existing probes, additional effort needs to be taken for designing the embedded hard- and software processing this signal.

II. Probe Evaluation

We evaluated probes based on five different general purpose speakers, with similar specifications. For each of them, we manufactured a housing using a stereolithography (SLA)-based 3D printer. In particular, we evaluated the following properties. (1) broadband frequency response at the ear drum while driving the speaker, based on a calibrated sound level meter and an ear simulator; (2) settling time in the ear simulator by generating a transient of $80\,dB\,peSPL$ with the prototype probe [2], which is a typical level for TEOAEs; (3) broadband frequency response of the speaker membrane and the generated signal, by using a custom calibrator [3]. Based on this evaluation, we found that three out of five probes did not exhibit suitable acoustic properties (viz., probes based on *CUI CDM-10008*, *Soberton RC-1206S*, *PUI SMS-1508MS*), despite having similar specifications in the data sheet.

We used the following measurement setup based on a National Instruments PXI-4461. In this configuration, its inputs are specified to have an idle noise of $-115\,dBV_{rms}$. A typical sensitivity of $-75\,dB\,V/Pa$ was found in the prototype probes at $1\,kHz$. Assuming OAEs sound pressure at $10\,dB\,SPL$ ($-84\,dBPa$), the signal is expected to have an amplitude of $-159\,dB\,V$. Thus a low noise preamplifier of $50\,dB$ was used.

The analog input channel and analog output channel were connected in parallel to the loudspeaker. To lose as little sensitivity for the recording as possible, the analog output was connected to the loudspeaker with a $1\,k\Omega$ series resistor. However, due to the noise coming from the analog output, the noise floor increases in this configuration.

III. Experimental Results

To verify the feasibility of OAEs using speaker-only probes, a small study with four adults with unimpaired hearing was conducted. Our measurements were done following the standard non-linear pulse protocol described by Kemp et al. [4]. A pulse sequence consists of four pulses, $15\,ms$ apart. To reduce noise, multiple pulse sequences were recorded and averaged. We recorded 1000 pulse sequences per measurement. We assigned a number to every pulse sequence and averaged even recordings to a buffer a and uneven ones to a different buffer b. A simple OAE evaluation is done by comparing both buffers. If the correlation between a and b was high, the measurement was stable. Noise was estimated by taking the difference of a and b and calculating the RMS value: $RMS(\frac{a-b}{2})$. Similarly, signal strength can be calculated as $RMS(\frac{a+b}{2})$. A summary of the recorded data is shown in Table I. Typically, if a signal-to-noise ratio (SNR) of at least $6\,dB$ is reached, the OAE is considered present. This was achieved in most cases.

Figure 2 shows the recording of the first measurement in Table I. The OAE is expected in a window of $5\,ms$ to $13\,ms$ after the click. The similarity of the a and b buffer can be observed and their amplitude is well above their difference (i.e., the noise), thus indicating the presence of an OAE. In this example, the measurement could be reduced to 400 pulse sequences to achieve this SNR threshold, which corresponds to a measurement time of $23\,s$.

Two more measurements were made using an ear simulator, which does not exhibit an active behavior, such as OAEs. The resulting SNR and correlation show that our system is also able to detect the absence of an OAE.

TABLE I: Experimental results data overview.

DUT	Signal dBV	Noise dBV	SNR dB	Correlation
CUI CDS-16098A	-113	-123	10	0.83
	-115	-122	7	0.66
	-116	-121	5	0.51
	-111	-118	7	0.69
	-111	-119	8	0.70
	-111	-119	8	0.73
	-108	-120	12	0.90
	-109	-122	13	0.90
Mallory PSR20N08AK	-117	-121	4	0.41
	-117	-121	4	0.44
	-112	-119	7	0.70
	-113	-118	5	0.59
	-110	-119	9	0.76
	-108	-121	13	0.91
Ear simulator AEC304				
CUI CDS-16098A	-120	-121	1	0.18
Mallory PSR20N08AK	-121	-121	-1	-0.08

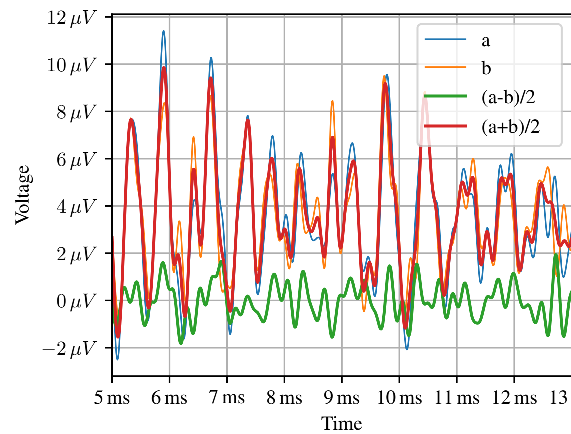


Fig. 2: TEOAE recording of a normal hearing adult using a speaker only probe built around a *CUI CDS-16098A*.

IV. Concluding Remarks

We for the first time demonstrated that acquiring OAEs with probes consisting of only one transducer, which is used as speaker and as microphone, is feasible. This paves the way for producing ultra-low-cost OAE devices in the future, which might become as natural as a clinical thermometer at home. While our paper provides a proof of principle, further research on the actual probe design is necessary, before it can be tested in clinical trials. However, our research will especially need to focus on the embedded systems challenge of this problem. We need to design an embedded system, that is capable of doing the required signal processing, while still being low cost.

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