Designing a Single Speaker-based Ultra Low-Cost Otoacoustic Emission Hearing Screening Probe

Nils Heitmann
Chair of Real-Time Computer Systems
Technical University of Munich, Germany
nils.heitmann@tum.de

Thomas Rosner
PATH medical GmbH
Germering, Germany
rosner@pathme.de

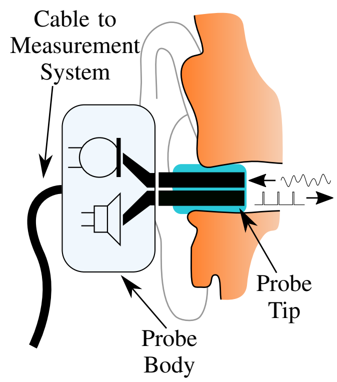
Samarjit Chakraborty
University of North Carolina at
Chapel Hill (UNC), USA
samarjit@cs.unc.edu

***Abstract*—Hearing impairment is one of the most widespread disabilities world wide. Early detection and treatment of hearing loss in neonates and small children is necessary for normal speech development. Also early detection of hearing loss in adolescents and adults will improve treatment possibilities. However, comprehensive hearing screening is not easily accessible everywhere and is too expensive for mass usage, especially in developing countries. While there are solutions for smartphone based self-administered tests, these cannot be used for neonates and small children. We propose a simplified low-cost ear probe, to measure otoacoustic emissions (OAEs), which can be used for objective hearing screening, without feedback from the subject. In this paper we built five different prototype probes and characterize them. Finally we selected two probes and demonstrate the feasibility in a small study.**

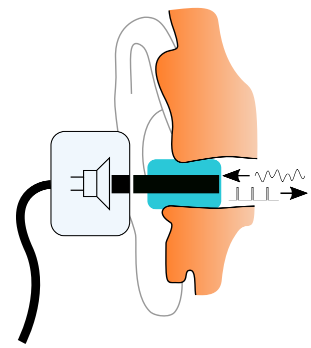
I. Introduction

Hearing impairment is one of the most widespread disabilities world wide [1]. It can have a vast personal impact on communication, well-being, quality of life and health. Especially for neonates and small children, proper hearing is important for speech development. In many regions around the world, a universal neonatal hearing screening program has been implemented. Despite these efforts, there still is a lack of coverage, especially in developing countries and even rural areas of newly industrialized countries, such as India [2]. In those regions, childbirth will often not take place in maternity hospitals, but at home, where access to objective hearing screening tests is limited. Further, skilled maternal and newborn health workers are also often unavailable [3]. In many cases detection of the hearing loss comes to late, although treatment is possible and available. Another prevalent form of hearing loss is noise-induced hearing loss (NIHL) [4]. In many situations the affected person will not immediately be aware of the hearing loss. Increasing the availability of low-cost and easy to use tests, would allow more widespread screening.

The most common hearing screening test, is based on otoacoustic emissions (OAEs), which are active emissions from the inner ear. Figure 1a shows a typical configuration of an ear probe used in such tests. A built in speaker is used to emit a specific stimulus and a microphone will record the response. We intent to provide a hearing screening test based on OAEs, which may be as normal to have as a medical thermometer, for a health worker or even at home. To achieve that, not only is the cost relevant, but also the ease of use.



(a) Typical TEOAE probe



(b) Proposed TEOAE probe

Fig. 1

Here we will present our work on a simplified OAE probe, which only consists of a single transducer, shown in Figure 1b. With this simplification, the construction of the probe will be significantly less complex. While fewer components are needed and fewer electrical connections need to be made, we see the advantages mostly in the mechanical buildup: The probe tip needs fewer details, since only one acoustic channel is needed. This allows for a more robust construction, which may be less prone to mishandling and clogging with cerumen. Our proposed probe may cost \$10 USD, compared to the several hundred dollars retail price of commercially available probes, which are usually hand assembled. The cost savings may be achieved by utilizing existing mass-manufacturing processes, which already exist for in-ear headphones.

In the following chapter we will highlight related work, that also intents to provide more ubiquitous hearing screening. Afterwards we will give a basic introduction to hearing screening with OAEs. Then we present how we constructed and characterized our prototype probes. Finally we demonstrate a proof of concept with a complete OAE measurement.

II. Related Work

The need for hearing screening is widely accepted and is reflected, for example, in universal neonatal hearing screening. The problem of unavailability of hearing screening, due to cost, lack of trained personnel or unawareness has also been addressed before.

As smartphones are ubiquitous for many people around the world, their use in low cost medical applications became of interest. These device are highly accessible and often include powerful audio interfaces. This allows self administered hearing screening tests utilizing smartphones and any in-ear or over-ear headphone. Na et al. [5] presented a subjective test with pure tone audiometry and correction of environmental noise levels. This test requires a calibration of the sensitivity of the smartphone used. A subjective smartphone based digit-in-noise test was demonstrated by Potgieter et al. [6], which has been successfully validated [7].

For hearing screening of neonates, calibrated noise makers have been investigated by Ramesh et al. [8]. These device are intended to be used by medical practitioners and administering the test requires a certain amount of training.

Low cost devices based on auditory brainstem response (ABR) have also been considered by Singh et al. [9]. The advantage of brainstem based screening, is the full coverage of the auditory system. However placing and cleaning electrodes may prove difficult in practice and an ABR test usually takes longer to complete, compared to an OAE based test.

With our novel probe design, we intent to close the gap in the unavailability of low-cost hearing tests, based on OAEs, which is an objective and clinically well known method.

III. Hearing Screening with OAEs

Hearing screening may be categorized as subjective and objective hearing tests. A common subjective test is pure tone audiometry. This method requires comparatively little equipment and can identify the hearing thresholds well. However, it requires active participation of the patient during the examination. In contrast, a number of objective hearing tests are used in medical practice today, that do not require any interaction with the patient. The analysis of OAEs is probably the most widely used objective hearing screening test. Hearing screening tests, in contrast to hearing diagnostics, usually do not give full results, but only “pass” or “refer”: hearing level is adequate or refer to a medical professional for further diagnosis.

Figure 2 shows an overview of the human peripheral auditory system. The inner ear is receptive for different frequencies at different locations on the basilar membrane. Close to the oval window, at the base of the cochlea, high frequencies will be detected and lower frequencies are detected closer to the apex. An active process, the cochlear amplifier, will amplify the acoustic signals on the basilar membrane, with the outer hair cells (OHC) being the main component. Those active processes may by themselves emit an acoustic signal. This signal will then travel backwards trough the cochlea and middle ear into the ear canal and can there be observed as an OAE. OAEs are categorized into spontaneous and evoked OAEs, where evoked OAEs are stimulated with an external acoustic signal. In diagnostics and research, many types of OAEs are used. However, in hearing screening only two evoked OAE procedures are commonly used: Distortion product OAEs (DPOAEs) and transient evoked OAEs (TEOAEs).

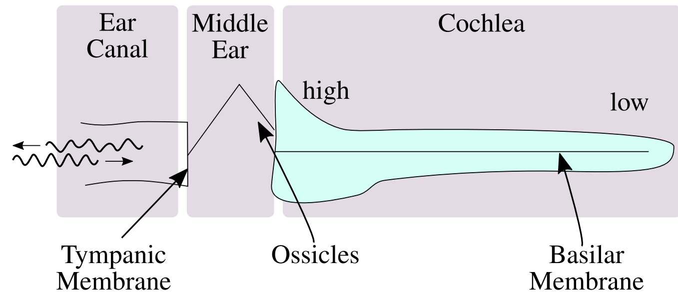


Fig. 2: Schematic overview of the peripheral auditory system, with the cochlea “rolled out”.

While both procedures can be used for screening, we exploit the temporal separation of stimulus and response in TEOAEs for our probe design. Here the stimulus is a transient, often referred to as click, of $80\,\mu s$ to $100\,\mu s$ duration. The clicks are presented as a sequence of three clicks of positive polarity followed by a click of an inverse polarity with an intensity three times higher than the positive clicks [10]. The stimulus intensity is set such that the TEOAE recordings originate from saturated cochlear generators, i.e. around $85\,dB$ sound pressure level (SPL). The TEOAE will be measurable in the ear canal right after the click onset of the stimulus. Due to the frequency-location dependency in the inner ear, the high frequency response will arrive first. Typically a window of $20\,ms$ after the click is recorded and analyzed.

Figure 1a shows a typical probe used for measuring TEOAEs. A speaker is used to emit the clicks. The response is recorded shortly after by means of a sensitive electret microphone. Both transducers need to be connected to the ear canal by separate acoustic channels.

Since the TEOAEs represent the OHC pulse response along the basilar membrane, the response occurs according to the delay of the basilar membrane. By exploiting this delay we propose our new probe, which can be seen in Figure 1b. This probe will be much simpler in mechanical construction and will be easier to assemble, thus substantially reducing manufacturing cost. Due to the much simpler probe tip, now only consisting of one acoustic channel, the mechanic interface for the replaceable probe tips will need much less complexity. This will make replacing probe tips easier and the consumables will cost less.

The main challenge in our proposed probe design is the much lower sensitivity when recording from a speaker, compared to a microphone. Since the OAE signal is extremely weak, a dedicated microphone is usually considered indispensable.

IV. Prototype Probe Design

To evaluate our proposed probe design, we built several prototypes. The design was oriented on the earlier mentioned goals of reducing cost and easy handling.

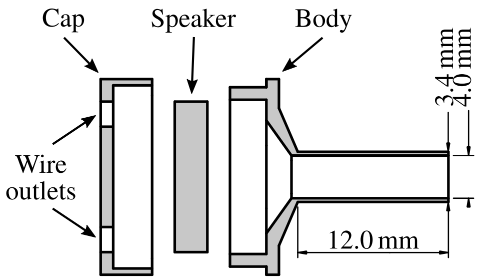


Fig. 3: Exploded-view drawing of the *Soberton RC-1206S* prototype probe.

A. Objectives

For achieving the overall goal of providing a low cost probe design, the components must be low cost. However, the construction and manufacturing process must be as well. Therefore, the probes should be kept as simple as possible. The selection of speakers for this paper was based on physical size, specified frequency behavior, part cost, mounting options and sound port layout. The overall performance of TEOAE probes is dominated by acoustic properties which are largely dependent on mechanical design. A well performing probe should have a flat frequency response for emitting sound and recording. It must seal the ear-canal, so that as much sound energy, coming from the tympanic membrane, can be captured by the probe. Especially low frequencies will otherwise be lost. A good seal from the ear canal to the environment is also necessary, so that as little outside sound as possible will interfere with the measurement. This seal is usually implemented with a soft probe tip, which presses against the ear canal. Consequently a good probe design has to fulfill other requirements besides the acoustical properties. The probe tip needs to be easily replaceable, since it should be disposed after measuring each patient. As mentioned above, hearing screening in infants and newborns is of particular significance, so the probe and probe tip need to be small enough to fit into a newborn's ear. Achieving the two last mentioned objectives, is expected to be much easier with a single speaker probe, since designing a small probe with only one component is much simpler.

B. Approach

All prototype probes presented and measured in this paper where manufactured using a stereolithography (SLA) 3D printer. This process allows for very detailed features and a good surface quality. Overall five prototype probes where built, using five different speakers. The design of our prototype probes aimed at keeping the parts and assembly as uncomplicated as possible. Figure 3 shows an exploded-view drawing of one of the prototype probes. The design of the other prototype probes was kept very similar, where the dimensions of the speaker seat in the body part is adjusted and the cap is changed to fit accordingly. The body also forms the acoustic channel, that connects the ear canal to the sound port of the speaker.

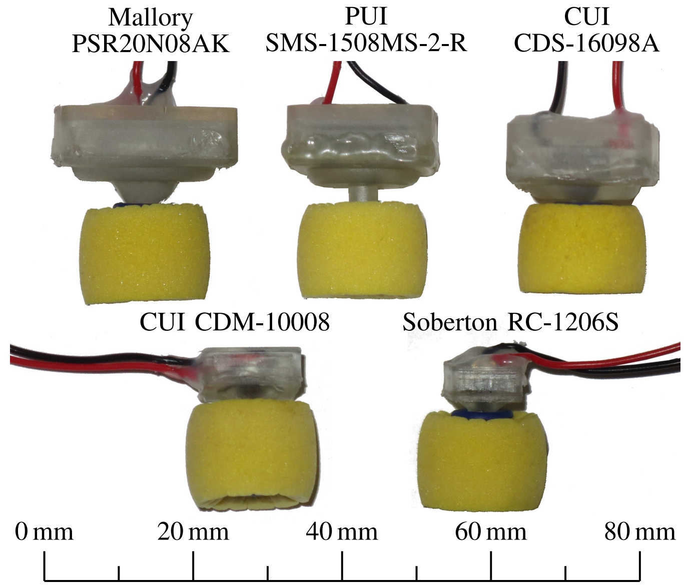


Fig. 4: Picture of the prototype probes.

The wall thickness of the probe tip is $0.3\,mm$. The probe tip dimension was kept the same for all our prototype probes, to allow easier comparison. Finally, to close the gap between the probe tip and the ear canal, commercially available ear tips were used, which can be slid on. The backsides of our prototype probes were closed off with a cap, which had the required holes to feed the wires trough, that lead to the speaker. The cap and the wires were glued in place during assembly to create an airtight seal in the probe itself. The finished prototype probes can be seen in Figure 4.

V. Probe Characterization

To evaluate the performance of our prototype probes, they were acoustically characterized. Their behavior when driven as speakers and recorded from as microphones are measured independently. All measurements were done with an *National Instruments PXI-4461* sound card. Reference for all measurements of acoustic properties is a *Larson Davis 824* sound level meter (SLM) system, including a *2540* free field microphone, a *AEC304* occluded ear simulator and a *CAL 200* $94\,dB\,SPL$ $1\,kHz$ calibrator.

A. Speaker Response

The frequency response of our prototype probes, while driving the speaker, was measured in an *AEC 304* ear simulator. This ear simulator replicates the acoustical properties of an ear canal of an human adult. The sound pressure measured by the built in microphone corresponds to the sound pressure at the ear drum. Therefore, we measure which electric level at the speaker results in which sound pressure level at the ear drum. However, for each ear canal and each time the probe is inserted, the acoustic properties change slightly. An ear simulator offers high repeatability of measurements, but the results can usually not be generalized directly. During an

OAE screening measurement a specific sound pressure at the ear drum is needed within a certain margin. This means in practice, that the level of the stimulus has to be adjusted for each insertion into an ear canal by doing an in-ear calibration.

In this experiment, a linear chirp is used to measure the frequency response. The level of the stimulus is adjusted for each prototype probe, so that the sound pressure is roughly the same in all measurements. The stimulus is given as electrical voltage to the speaker of the prototype probe. The immediate response is the electrical voltage recorded from the ear drum microphone of the ear simulator. All calculations are done in frequency domain and only the magnitude is considered. The sensitivity function of the prototype probes in Pa/V can now be calculated:

$$S_{Speaker} = S_{EarSimulator} * \frac{U_{Response}}{U_{Stimulus}}$$

Where $S_{EarSimulator}$ is the sensitivity of the ear simulator, assumed flat and calibrated at $94\,dB\,SPL$ at $1\,kHz$ with the *CAL 200* in units of Pa/V. $U_{Stimulus}$ is the frequency response of the linear chirp stimulus used. $U_{Response}$ is the frequency response of the signal recorded by the ear simulator. Finally $S_{Speaker}$ is the resulting sensitivity function of the prototype probe tested. The chirp can be repeated multiple times to lower noise in less sensitive frequency regions by averaging recordings.

Figure 6a shows the results of this measurement for each prototype probe. The click stimulus during a TEOAE measurement should ideally activate the full spectrum equally at all frequencies. Consequently a flat frequency response would be best. However since TEOAEs are most effective on frequencies below $5\,kHz$, an attenuation at higher frequencies is acceptable. At low frequencies, a high attenuation will result in insufficient stimulation and thus the OAE response will not be measurable. Thus the results already show problems with the *CUI CDM-10008* and *Soberton RC-1206S* prototype probes. Finally, an absolute shift in sensitivity can easily be compensated by adjusting the level of the stimulus.

B. Settling Behavior

The click stimulus in a TEOAE measurement has a duration of typically $100\,\mu s$. A few milliseconds after, the TEOAE will arrive at the probe. At this point in time, if the speaker membrane is still resonating from emitting the stimulus, it will disturb the measurement. This effect is also referred to as "ringing" and may also occur in conventional TEOAE probes, where the settling oscillation of the speaker membrane can be measured in the ear canal. In this measurement, we compare the settling behavior of our prototype probes to each other using the AEC 304 ear simulator. The probe under test is set up to emit a pulse of $100\,\mu s$ duration. The output amplitude is adjusted, such that a level of $80\,dB\,peSPL$ can measured at the ear simulator microphone [11]. These settings are similar to actual TEOAE measurements.

To compare the prototype probes to each other, the root mean square (RMS) value of the measured signal at the ear simulator microphone in the window of $4\,ms$ and $8\,ms$ after the click is calculated. Table I shows the results, listing the required output (stimulus) level and the measured settling RMS value. The *PUI SMS-1508MS-2-R* probe shows excessive activity of almost $1\,mV$ and the *CUI CDM-10008* probe has a similar behavior. The other probes perform well enough, as a certain settling activity can be compensated by the non-linear pulse protocol used during TEOAE recording. Additionally, the output level required for each prototype probe to achieve the given sound pressure level corresponds to the findings in the previous broadband measurement.

C. Recording Response

All measurements so far have only evaluated the stimulating (speaker mode) performance of our probes. To accurately evaluate the the recording properties, the prototype probes need to be excited by an external source. In a standard probe OAE probe, one can connect it to an ear simulator and use the built-in speaker of the probe to generate the stimulus. This usually works well with low frequencies. However, at higher frequencies (3 to $5\,kHz$), standing waves in the cavity will lead to variation in the sound pressure. This leads to different sound pressures at the ear-drum microphone of the ear simulator and the probe microphone. Consequently this is also an issue when doing the in-ear calibration before an actual OAE measurement.

One possible calibration setup for OAE probes was proposed by Siegel [12] and refined by Rasetshwane et al. [13]. Here, a hard walled tube (8 mm syringe) is used to form a cavity, representing the ear canal. On one opening a sound source is inserted. On the other opening a tube microphone is radially inserted. This leaves the second side open, to insert a reference microphone from a calibrated SLM. After the first step of calibration, the SLM is removed and the probe to be tested is inserted. For accurate results, the tube microphone needs to be on the same plane in the cavity as the SLM or the probe under test. Also, exact placement and repeatable insertions are necessary for reproducible measurements.

To achieve that, a custom calibrator was designed and manufactured using the same SLA 3D printer as for the probes. The resulting device can be seen in Figure 5. The sound source is realized with a *CUI CDM-10008* speaker and the radially mounted tube microphone is a *Knowles EM-23346-C36*. The opening on the right fits a standard ½ inch microphone and is sealed by an o-ring. When an OAE probe is inserted, a appropriate probe tip has to be used.

The speaker of the calibrator is used to generate a broadband signal. We used a linear chirp with constant amplitude. Other broadband signals may also be used, especially if one wants to emphasize certain frequency regions. The used stimulus will later cancel out, however uniform excitation is necessary for good results. If the resulting recordings are noisy, the measurements may be repeated several times and averaged in time domain to lower the noise floor.

The procedure for calibrating OAE probes consists of two steps. First, a calibrated SLM microphone, is inserted.

TABLE I: Summary of the properties of the prototype probes.

Speaker	Impedance	Pulse amplitude for $80\,dB\,peSPL$	Settling RMS	Sensitivity $1\,kHz$
	Ω	mV	$dB\,V$	$dB\,V/Pa$
CUI CDM-10008	8	12.6	-70	-86
CUI CDS-16098A	8	10.2	-84	-80
Mallory PSR20N08AK	8	11.5	-79	-67
PUI SMS-1508MS-2-R	8	8.2	-62	-78
Soberton RC-1206S	32	39.8	-88	-101

The sound pressure in the cavity is recorded by the tube microphone and the calibrated SLM microphone (reference microphone). The transfer function between the reference microphone and the tube microphone is:

$$H_{ref/tube\,1} = \frac{U_{ref}}{U_{tube\,1}}$$

Where U_{ref} and U_{tube1} are the frequency transformed recordings and $H_{ref/tube1}$ is the resulting transfer function. In the second step, the reference microphone is removed and the process is repeated with the probe under test inserted. The transfer function is accordingly:

$$H_{probe/tube\,2} = \frac{U_{probe}}{U_{tube\,2}}$$

To get the sensitivity function of the probe under test S_{probe}, one has to calculate the transfer function from the reference microphone to the probe and multiply that by the sensitivity of the reference microphone S_{ref}:

$$S_{probe} = H_{probe/ref} \times S_{ref} = \frac{H_{probe/tube\,2}}{H_{ref/tube\,1}} \times S_{ref}$$

The sensitivity function of the reference microphone is flat in our SLM and the offset is measured in Pa/V with a $1\,kHz$ acoustic calibrator.

The results can be seen in Figure 6b. In our case, we recorded from our prototype probes with an additional $40\,dB$ amplifier on the input of the sound card, to sufficiently raise the signal levels from the noise floor. This gain was subtracted before plotting.

Similar to the speaker response, a flat frequency response during recording is desired. Besides the used speaker in the probe, most of the acoustic behavior is governed by the mechanical properties of the probe body. Therefore, many features will be visible independently of if a speaker is used to emit sound or record. Of the evaluated prototype probes, the *CUI CDS-16098A* performs best. In the most important frequency regions for TEOAE the sensitivity is adequate, however it declines fast above $4\,kHz$. For reference, a electret microphone based probe would have a sensitivity of about $-30\,V/Pa$.

Finally, to cross check the findings of this measurement, all prototypes probes were measured in a fixed frequency acoustical calibrator (*Larson Davis CAL200*). It emits a sine of $94\,dB\,SPL$ $(1\,Pa)$ at $1\,kHz$. The results can be seen in Table I and match the measurements in our custom calibrator.

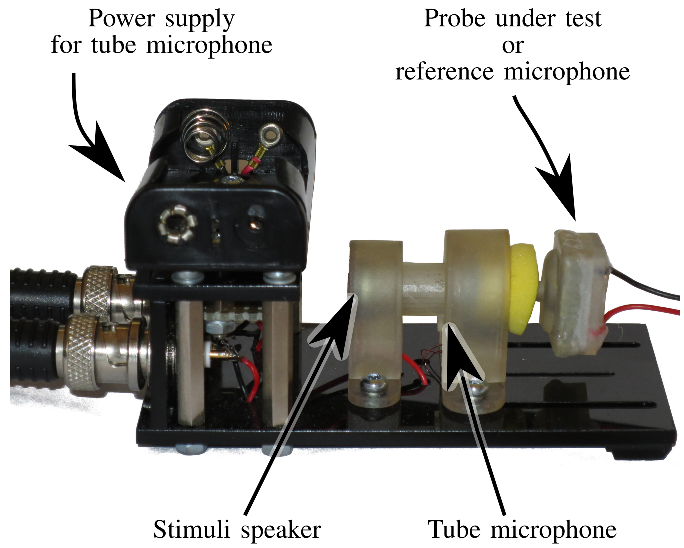


Fig. 5: Custom calibrator for OAE probes.

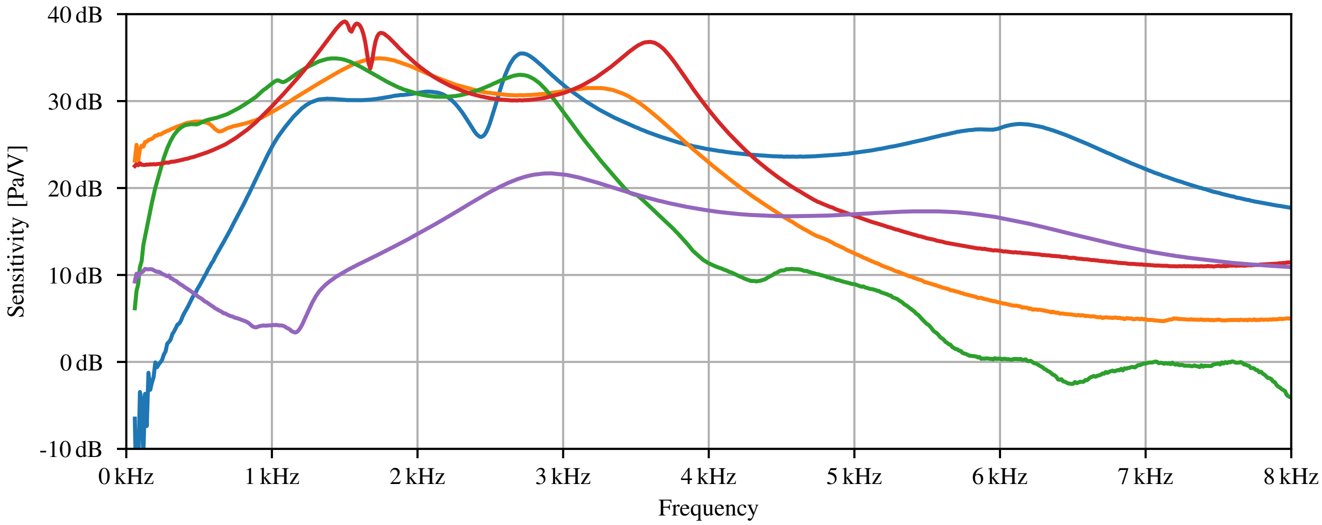
VI. Measurement Setup

The probe characterization measurements show, that measuring TEOAEs with our simplified probe design is possible. To verify, we implemented a measurement system using the same sound card as was used for the previous measurements. Unlike the previous measurements, where the speaker was either driven or recorded from, we now need to do both simultaneously. So the main challenges are the overall low sensitivity when recording and the concurrency of input and output. With the results of the prototype probe characterization in mind, we will go forward and design our system around the *CUI CDS-16098A* and *Mallory PSR20N08AK* prototype probes.

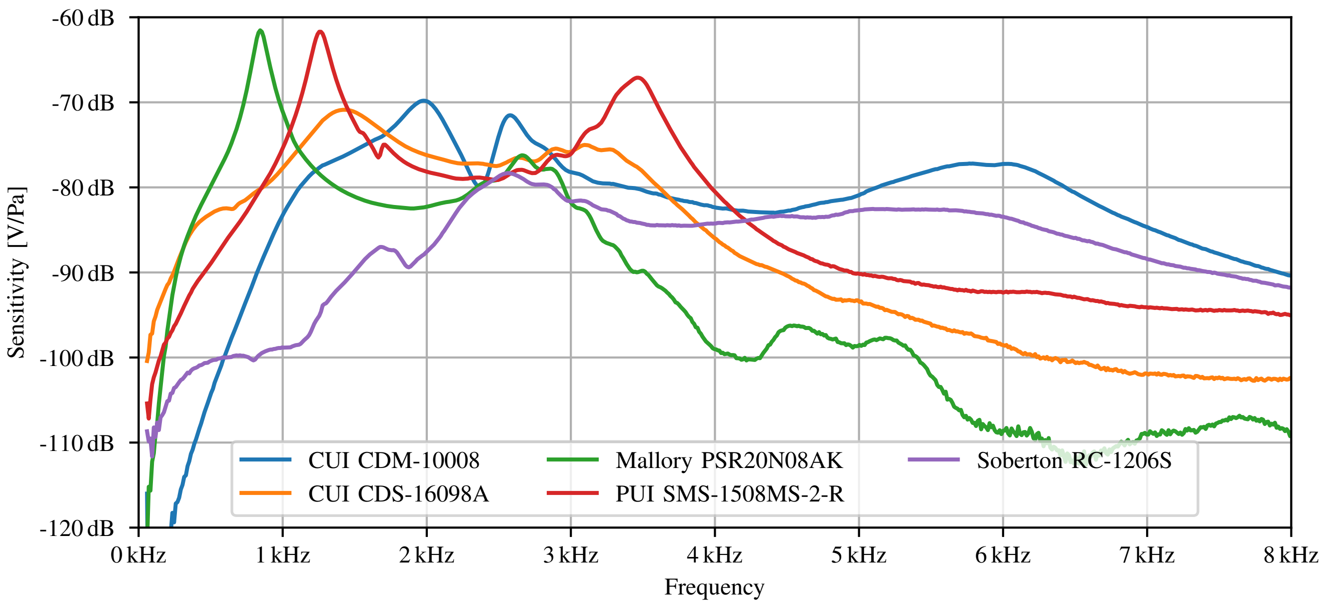
A. Hardware

Figure 6b shows a sensitivity of about $-75\,dB\,V/Pa$ for our prototype probes in the relevant frequency regions. We want to detect TEOAEs, which have sound pressures of about $-5\,dB$ to $20\,dB\,SPL$. Assuming a sound pressure of $10\,dB\,SPL$, which is $-84\,dB\,Pa$, we can expect a signal strength of about $-159\,dB\,V$. The used *NI PXI-4461* sound card has an idle noise of $-115\,dB\,V_{rms}$ at the optimal settings. Thus the signal strength has to be raised, without increasing the noise level at the same rate. We chose to built a $50\,dB$ amplifier based on the *Analog Semiconductor SSM2019*. This integrated circuit (IC) is a self-contained audio preamplifier with very low noise.

The signal levels for the click generation (stimulus) are easier to handle. An analog output of the sound card was used. However the output is low impedance and cannot be switched to high impedance during a measurement. If the input and output would be connected in parallel to the prototype probe speaker, the recorded signal strength would decrease even more. To remedy that, we chose to increase the impedance of the analog output, with a series resistor. The dynamic range is sufficient to drive the speaker, however higher drive



(a) Speaker sensitivity measured in ear simulator.



(b) Recording sensitivity measured in a custom calibrator.

Fig. 6: Sensitivity the prototype probes, when driven as speakers and recorded from in microphone mode.

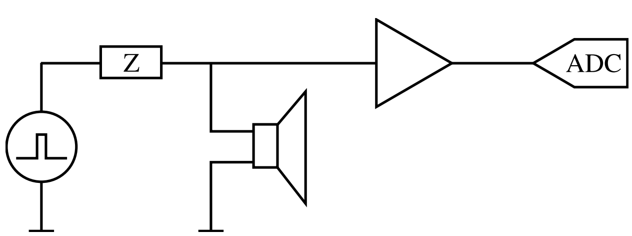


Fig. 7: Schematic of the measurement setup.

amplitudes of the analog output come with higher noise levels. An impedance of $1\,k\Omega$ was chosen as compromise between reduced signal level and introduced noise. Figure 7 shows the circuit, with the analog output of the sound card as click source on the left and the analog input on the right.

To reduce the number of connections, reduce noise and increase reliability of our measurements, the electronic circuit was implemented on a custom PCB. Figure 8 shows resulting device. The amplifier is powered by an external battery to further reduce noise. The prototype probes can be directly connected to the device with short leads using a spring clamp terminal block. The incoming stimulus signal as well as the amplified output signal are connected to the sound card with BNC connectors. The performance of the amplifier setup was verified similar to the prototype probes, with a linear chirp and different impedance resistors. The device was found to be linear and flat in frequency response.

For all following recordings, besides the anti-alias filter of

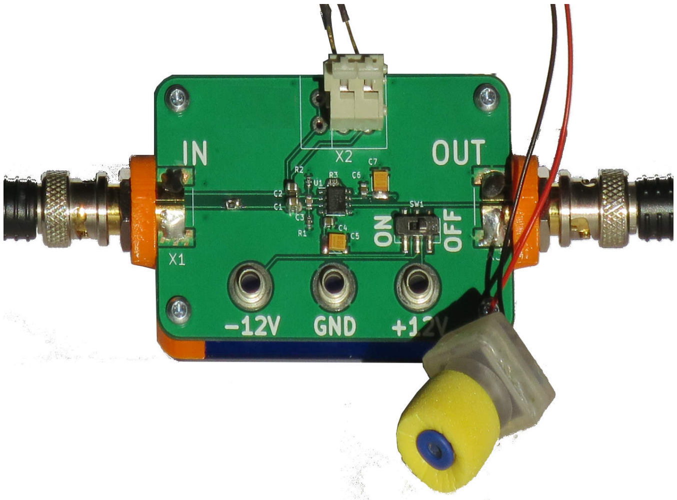


Fig. 8: Photograph of the measurement setup with the custom printed circuit board (PCB).

the sound card, a digital filter was used. This finite impulse response (FIR) band pass filter was configured to block frequencies below $500\,Hz$ and above $5\,kHz$.

B. Recording evaluation

During the measurement of TEOAEs we need to separate the linear from the non-linear components of the recordings: After a click is emitted into the ear canal, one can observe multiple reflections in the recordings, for example the reflections inside the ear canal from the ear drum. These linear reflections typically drown out the much weaker OAEs. However, the OAEs originate from a non-linear process in the inner ear. Therefore a specific pulse pattern can be used, to separate linear reflections from the non-linear OAEs. In our following measurements we used the protocol described by Kempt et al. [10]. In this protocol three clicks of equal amplitude are emitted and the responses are recorded for each click. A fourth click with inverted polarity and three times the amplitude is emitted afterwards. By averaging all four responses of this click sequence, the linear components can be eliminated and the TEOAE response remains. The click has a duration of $100\,\mu s$ and the recording window after each click lasts typically $20\,ms$. The duration of one click sequence is therefore $80\,ms$.

Since the TEOAE signal is so minuscule, a single recording of one click sequence is usually not sufficient to determine the presence of an OAE. Assuming random noise on the measurement, the noise floor in the recording is lowered by averaging multiple click sequences. Usually the measurement is continued, until a timeout is reached or an OAE is found in the recording.

To distinguish between the signal and the noise in the recording, the click sequences are summed and averaged in two independent buffers a and b. Or put differently: The first and all other odd numbered click sequences are averaged into buffer a and even numbered click sequences are averaged into buffer b. These buffers can now be compared to each other. The evaluation window in our measurements is $5\,ms$ to $13\,ms$. The signal value is defined as the sum of both buffers and calculating the RMS value in this window:

$$Signal = RMS\left(\frac{a+b}{2}\right)$$

Whereas the noise value is the difference of both buffers and again calculating the RMS value:

$$Noise = RMS\left(\frac{a-b}{2}\right)$$

Expressing both calculated values in dB allows for an easy comparison. The difference of both logarithmic values is the signal to noise ratio (SNR). The SNR represents the relative level of the OAE in our recording, thus eliminating the need for absolute calibration of our measurement system in terms of SPL. A SNR of $6\,dB$ is considered sufficient for the presence of an OAE.

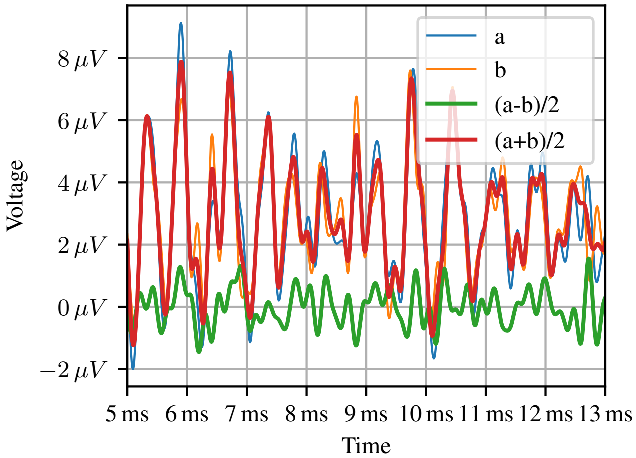
Another criterion used, is to correlate the a and b buffer. If the correlation is high, both buffers are very similar to each other and thus the measurement is considered stable.

TABLE II: Experimental results data overview.

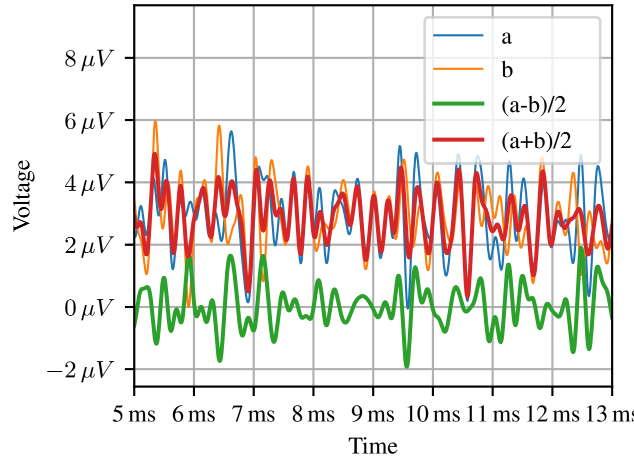
DUT	Signal dBV	Noise dBV	SNR dB	Correlation
CUI CDS-16098A	-113	-123	†10	0.83
	-115	-122	7	0.66
	-116	-121	5	0.51
	-111	-118	7	0.69
	-111	-119	8	0.70
	-111	-119	8	0.73
	-108	-120	12	0.90
	-109	-122	13	0.90
Mallory PSR20N08AK	-117	-121	4	0.41
	-117	-121	4	0.44
	-112	-119	7	0.70
	-113	-118	5	0.59
	-110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

VII. Experimental Results

To verify, that the proposed probe design can measure TEOAEs, a small study was conducted. The measurements were done on four normal hearing adults (one measurement per ear) with the two selected probes, *CUI CDS-16098A* and *Mallory PSR20N08AK*. Normal hearing was established, by measuring each ear with a commercial OAE screening device. The measurements were executed with a fixed length of 1000 click sequences each, rather than stopping when a SNR threshold is reached. One subject could not be measured with the *Mallory PSR20N08AK* probe, due to its size in the auricle. Table II shows the results. The recordings of the marked rows (†) can be seen in Figure 9. Figure 9a shows an example recording with an OAE response present. In this particular measurement, the recording reached a SNR of $6\,dB$ after 400



(a) TEOAE present at $10\,dB$ SNR.



(b) TEOAE absent in passive ear simulator.

Fig. 9: Example TEOAE recording from the results.

pulses. So the measurement would have taken $23\,s$, if it was stopped after reaching the threshold.

Of 14 measurements in ears with externally established normal hearing, our measurements resulted in a "pass" ($SNR \geq 6$) in 10 cases and "refer" in four after the full measurement time. The required criterion could have been reached with more averages. However, if a normal TEOAE probe would have been used, these measurements would have take mere seconds.

To verify that we would not detect a signal when no OAE is present, each prototype probe was tested in the *AEC 304* ear simulator, with the same settings. Figure 9b shows the resulting recording. The low SNR and correlation values indicate the correct behavior of our prototype probes and measurements.

VIII. Concluding Remarks

In this paper we proposed a novel simplified TEOAE probe, which only needs one transducer instead of two. We designed and assembled five prototype probes, based around different commercially available speakers. All probes were characterized with standard measurement equipment and our custom built probe calibrator. Two of the selected probes were used to show the feasibility of our idea in an actual OAE measurement.

However, these results should only be considered as the foundation for developing a full prototype ready for manufacturing. Based on these existing early prototypes, further optimizations can be done. Especially systematic improvement of the acoustical characteristics are necessary, which are largely dependent on the mechanical properties.

For these measurements we used high quality measurement equipment. However we intent to follow up with a cost effective solution for adapting the signal to either a smartphone or a standalone solution.

Another prospect would be the usage of in-ear headphones. They are set up almost exactly the same as our probes, however so far we found their acoustic characteristics lacking for this application. We expect high benefits of this route, since in-ear headphones are readily available at a very low-cost.

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