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Swept - Tone Evoked Otoacoustic Emissions: Stimulus Calibration and Equalization

Todor Mihajloski
University of Miami, t.mihajloski@umiami.edu

UNIVERSITY OF MIAMI

SWEPT – TONE EVOKED OTOACOUSTIC EMISSIONS: STIMULUS CALIBRATION AND EQUALIZATION

By

Todor Mihajloski

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Approved:

Özcan Özdamar, Ph.D. Professor of Biomedical Engineering	Terri A. Scandura, Ph.D. Dean of the Graduate School
Christopher L. Bennett, Ph.D. Department of Anesthesiology	Jorge Bohorquez, Ph.D. Assistant Professor of Professional Practice, Biomedical Engineering

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Otoacoustic Emissions (OAE) are minute acoustic responses originating from the cochlea as a result of an external acoustic stimulus and are recorded using a sensitive microphone placed in the ear canal. OAEs are acquired by synchronous stimulation with an acoustic click or tone burst and recording of the post-stimulus responses. This method of acquiring OAEs is known as transient evoked otoacoustic emissions (TEAOE) and is commonly used in clinics as a screening method for hearing and cochlear functionality in infants. Recently, a novel method of acquiring OAEs utilizing a swept-tone, or chirp, as a stimulus was developed. This method used a deconvolution process to compress the swept tone response into an impulse or click-like response.

Because the human ear does not hear all frequencies (pitches) at equal loudness the swept-tone stimulus was equalized in amplitude with respect to frequency. This equalized stimulus will be perceived by the ear as equally loud in all frequencies. In this study a new hearing level equalized stimulus was designed and the OAE responses were analyzed and compared to conventional click evoked OAEs. The equalized swept-tone stimulus evoked greater magnitude OAE responses when compared to the conventional methods. It was also able to evoke responses in subjects that had little TEOAEs which might fail conventional hearing screening.

ACKNOWLEDGEMENTS

I would like extend my gratitude to my mentor Dr. Özdamar for his time, commitment, and advice on this thesis. Dr. Bennett for the guidance through the swept-tone method and code and Dr. Bohorquez for his help in signal analysis and processing.

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LIST OF ABBREVIATIONS

µs	Micro Second
dB	Decibels
dBSPL	Decibel Sound Pressure Level
DNL(R)	Derived Nonlinear Response
DPOAE	Distortion Product Otoacoustic Emissions
FFT	Fast Fourier Transform
HL	Hearing Level
HLeqs	Equalized Hearing Level Swept-Tone Transient Otoacoustic Emissions
Hz	Hertz
LTI	Linear Time-Invariant
mPa	Millipascal
MR	Meatal Responses
ms	Millisecond
OAE	Otoacoustic Emissions
RMS	Root Mean Square
SFOAE	Single Frequency Otoacoustic Emissions
SNR	Signal to Noise Ratio
SOAE	Spontaneous Otoacoustic Emissions
SPL	Sound Pressure Level
sTEOAE	Swept-Tone Transient Evoked Otoacoustic Emissions
TEOAE	Transient Evoked Otoacoustic Emissions

Chapter 1 Introduction and Background

1.1 The Ear, Anatomy and Physiology

Sound perceived by humans can be described as the phenomenon of rapid compression and rarefaction of a gas, in this case air. The human ear is a sensory organ that is capable of converting these air pressure fluctuations to electrical impulses that travel via the auditory nerve to the brain. The ear and the entire process of hearing can be separated into three sections or stages (Figure 1.1.1).

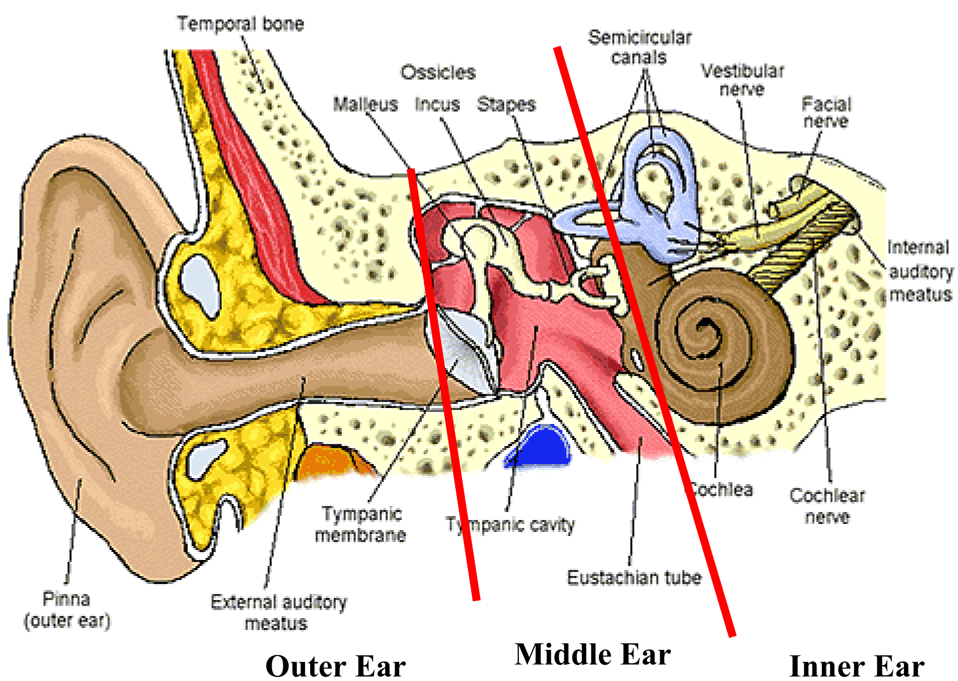


Figure 1.1.1 – Anatomical cross section of the ear, showing the three stages of hearing.

Modified from http://earinfectionsymptomsinadults.com/

The first stage is the outer ear. As the name implies it is the most external part of the ear consisting of the pinna, ear canal (meatus), and the surface of the ear drum. The outer ear captures sound waves propagating through air, focuses them into the ear canal, and delivers them to the ear drum. The next stage is the middle ear. Here the sound is transferred from the outer ear to the cochlea. The middle ear is an air filled cavity behind the ear drum and consists of three ear bones or ossicles: malleus, incus, and stapes. The ossicles connect the ear drum to the oval window of the cochlea. These bones are responsible for acoustic impedance matching, because the incoming sound travels through air and needs to be transmitted in the liquid within the cochlea. Without the ossicles, the sound media difference will causes acoustic reflections forcing the incoming sound to be reflected instead of propagating inside the cochlea.

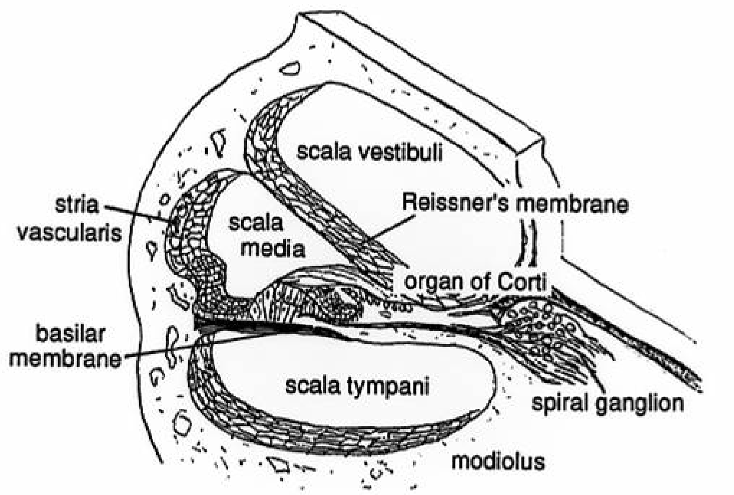


Figure 1.1.2 – Cross–section of the cochlea.

Source:
http://www.d.umn.edu/~jfitzake/Lectures/UndergradPharmacy/SensoryPhysiology/Audition/CochleaStructure.html

The last stage takes place in the inner ear, inside the cochlea. The cochlea is a fluid filled, snail shaped organ responsible for the actual conversion of the mechanical pressure waves into electrical impulses. The movement of the last ossicle, the stapes, is relayed to the oval window of the cochlea. This movement causes pressure imbalance in the cochlea, more specifically the scala tympani and scala vestibuli (Figure 1.1.2). The fluid movement inside the cochlea makes ripples on the Reisner's and the basilar membrane.

The movement of the basilar membrane causes deformations of the organ of Corti and forces the tectoral membrane to move back and forth. The movement of the tectoral membrane is sensed by a specialized kind of sensory cells called inner hair cells that have hair like projections attached, in the organ of Corti (Figure 1.1.3) and convert the membrane movement into electrical impulses. These impulses then are sent via the auditory nerve to the brain, which then interprets into sound.

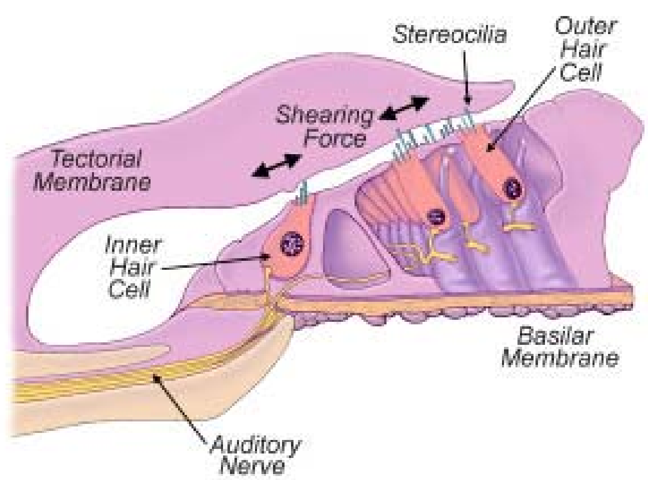


Figure 1.1.3 – The Organ of Corti, showing the membrane arrangement and the inner and outer hair cells.

Source: http://oghalailab.stanford.edu/hearing_haircell.html

Another set of specialized cells are the outer hair cells. They have the opposite role than the inner hair cells. They are stimulated by the auditory nerve causing the hair like projections to change in length. The main purpose of these cells is to change the compliance of certain sections of the tectoral membranes. By doing this some sound frequencies are amplified and some are attenuated. This is known as the cochlear filter sharpening, which is primarily used when people are trying to listen to a conversation or some sound of interest in a noisy environment.

1.2 Otoacoustic Emissions

The movement caused by the outer hair cells can lead to an unstable feedback causing oscillations on the tectoral and the basilar membrane causing movement in the cochlear fluid. Since the cochlea is a closed system the movement of the fluid gets relayed back to the oval window. The movement of the oval window gets relayed through the ossicles to the tympanic membrane. The movement of the tympanic membrane causes air pressure fluctuations, or sound.

These sounds are minute in amplitude and almost impossible to hear and they are also known as Otoacoustic Emissions (OAEs). They were first discovered by David Kemp in 1978 (Kemp, 1978). Ever since their first discovery, the methods and ways of acquiring OAEs have evolved greatly and now they are an essential part of the clinical toolkit for auditory examinations.

OAEs originate from two sources, reflection and distortion (Figure 1.2.1). One of the sources can be attributed to the reflections from the cochlear irregularities and these are independent of the stimulus but dependent of the mechanical and physical properties of the cochlea, more specifically the basilar membrane. The second type of sources unlike the first is dependent on the stimulus frequency and intensity. They primarily appear at high stimulus input levels and are related to the distortions caused by the stimulus along the basilar membrane.

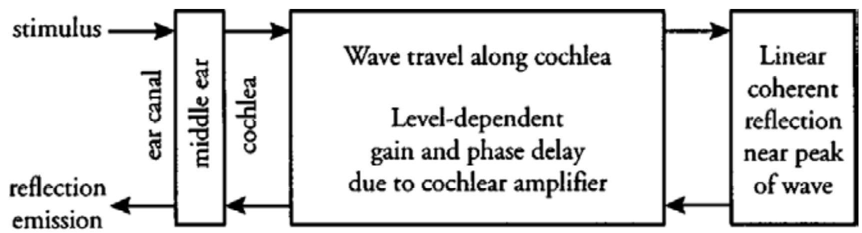


Figure 1.2.1 – Generators of OAE. Simplified model of where OAEs originate from, showing a simple linear reflection segment and the nonlinear responses due to nonlinear sources. From Shera and Guinan, 1999).

There are two primary types of OAEs: spontaneous (SOAE) and evoked (EOAE). SOAEs, as the name implies occur spontaneously without any external stimulation (Probst et al., 1991). They have a relatively small prevalence when compared to EOAEs, usually 52% of females and 30% of males will have them (Prieve et al., 1996), which makes them somewhat unreliable and unpredictable. EOAEs are OAEs responding to an external stimulus, there are several subtypes that depend on different evoking methods. Most common are the two tone distortion-product (DPOAE), single tone stimulus frequency (SFOAE), and transient evoked (TEOAE) Otoacoustic emissions.

TEOAEs generators can be compared to the SFOAEs (Shera and Guinan Jr. 2003; Kalluri and Shera 2007). Using SFOAE the time delay between the stimulus and the response can be used to determine the group delay for multiple frequencies. These delays can be compared to the TEOAE responses at low to moderate intensity levels for frequencies between 500 – 4000Hz. These group delays are caused by the cochlear tonotopy and forward/backward wave propagation. This can be explained by the coherent reflection filtering theory (Shera and Zweig, 1993; Talmadge et al., 1998).

1.3 Application and Significance

Early detection of hearing problems is essential for the proper development of speech and cognitive skills. Typically in clinics OAE tests are performed on newborns to determine the functional state of the conduction mechanisms and the cochlea (Bray and Kemp., 1987). OAE test can also be used as a quick test to determine if any hearing loss has occurred due to noise, ototoxic drug treatment side effects, or hereditary diseases. Also OAEs can be used to test for damage of the outer hair cells in cases with noise induced sensorineural hearing loss (Bray and Kemp, 1987).

1.4 TEOAE Acquisition and Analysis

Typically TEOAEs are recorded using a microphone placed in the ear canal and are evoked using a short acoustic click, presented to the ear using a speaker, also placed in the ear canal. This method makes it possible to track the OAE responses over time and see how they vary in frequency and amplitude. OAE responses are difficult to pick up because they are small in amplitude, typically smaller than 20dBSPL and because of the noise in the system. In order to obtain significant responses and eliminate noise, multiple recordings are performed lasting about 25ms, said recordings are called sweeps.

Typically 1024 sweeps are acquired and averaged together; this reduces the random background noise and brings out the actual OAE responses in the recording.

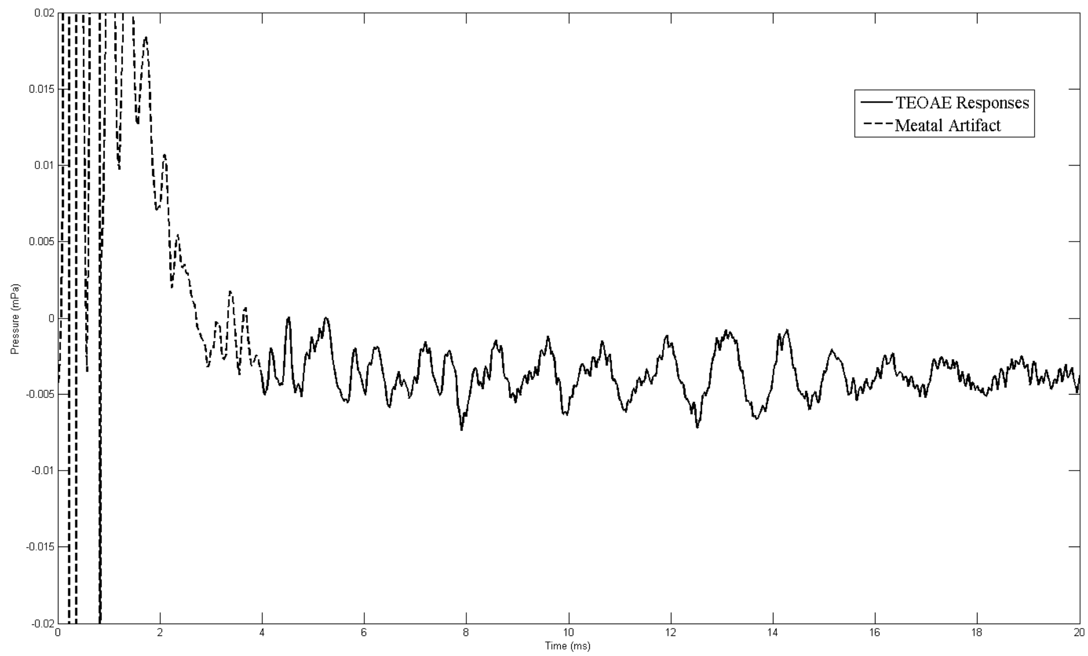


Figure 1.4.1 – Standard click TEOAE acquired at 75 dBSPL. The first 4ms of the recording are considered to be the meatal artifact (dotted line), from 4ms to the end are the OAE responses (solid line).

The recorded responses, in addition to the OAE responses, contain the meatal responses (MR), which is an acoustic artifact in the ear canal due to the stimulus and the closed cavity (Figure 1.4.1). One way of removing the MR is by grouping the sweeps in sets of four. The stimuli of the first three sweeps are sent to the ear at the original intensity and polarity. The stimulus of the fourth sweep is inverted and three times in amplitude relative to the previous three. The MR is a linear response that depends mainly on the stimulus. As previously mentioned the OAE responses are primarily non linear. By averaging the four sweeps together and simple addition the linear MR will cancel out leaving only the nonlinear OAE responses. This process is called derived non-linear responses (DNLR) acquisition (Ravazzani et al., 1996 and Grandori, 1993) (Figure 1.4.2).

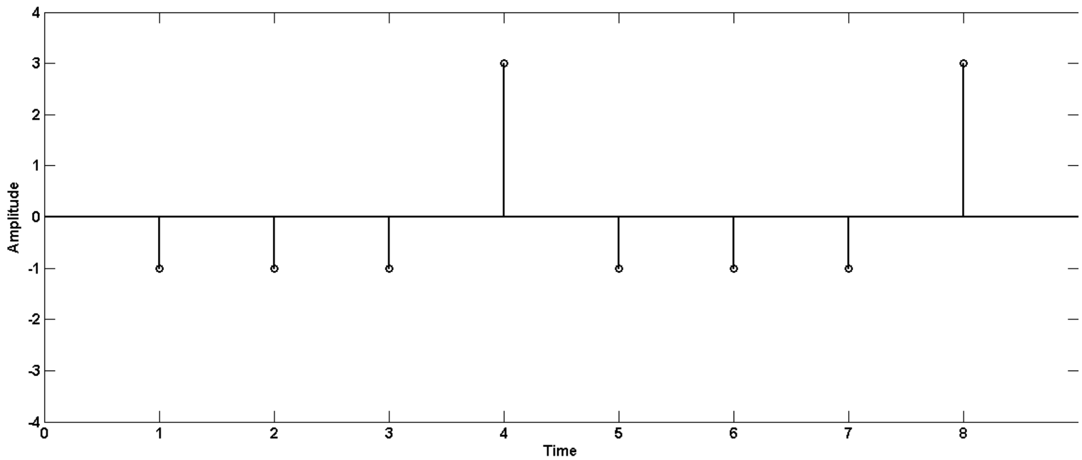


Figure 1.4.2 – Derived Nonlinear Responses (DNLR). Two sets containing 4 stimuli each. The first three stimuli are with the original intensity and negative polarity and the fourth is three times larger in amplitude with reversed polarity.

1.5 New TEOAE Acquisition Methods

Recently a novel way of evoking, recording, and obtaining OAEs was developed where a long, relative to the 100µs click, sound stimulus is utilized, called swept-tone TEOAE or sTEOAE. The stimulus is made by logarithmically sweeping a sinusoid across a predetermined frequency range or simply it can be explained as a chirp lasting for 100ms. The stimulus goes through a time reversal, where the beginning becomes the end and vice versa and an amplitude modulation over time to generate an inverse of that stimulus which will be later used for a deconvolution process. The stimulus is designed so it produces a narrow frequency range at any particular point in time, which allows for stimulation of individual, or a small number, of hair cells. On the other hand the broad band click stimulus that stimulates a large number of hair cells at the same time. The

OAEs are recorded in the same manner as the standard TEOAE method, the only difference being the use of the chirp stimulus instead of the click stimulus (Appendix 1).

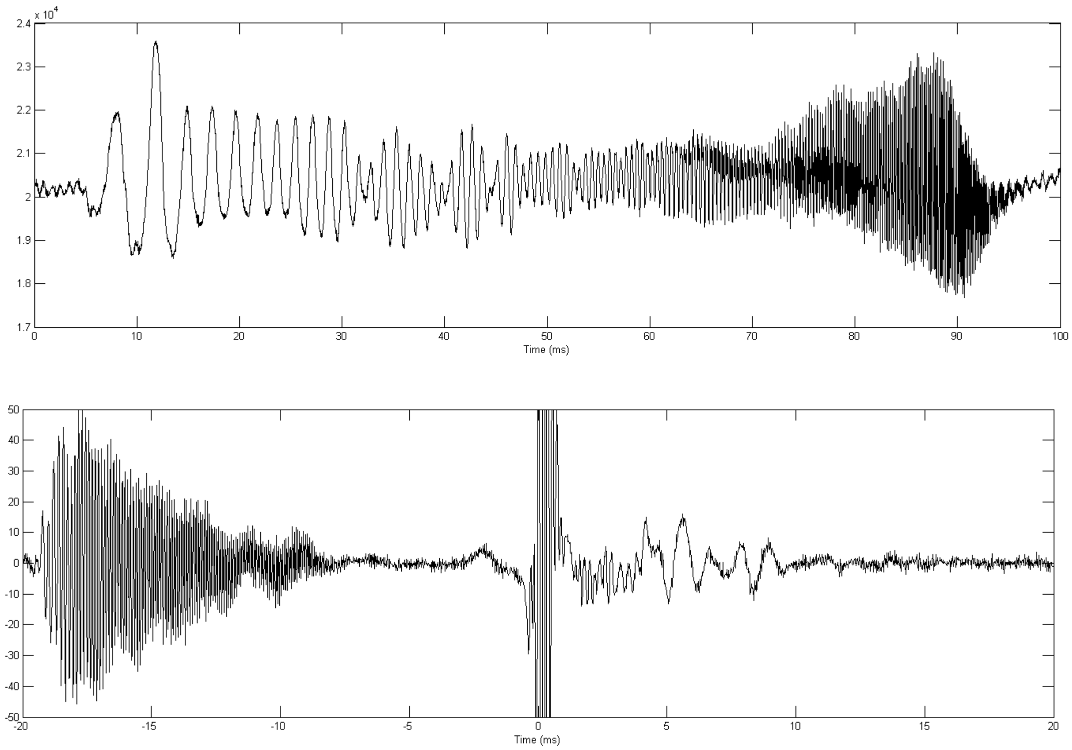


Figure 1.5.1 – Swept-Tone TEOAE deconvolution process. Unprocessed recording coming directly from the microphone (top). After deconvolution the recording (bottom) is compressed to a single impulse response at time 0, with the 1st order OAE responses to the right of the impulse response (t>0), and the 2nd order responses to the left.

The OAEs are extracted from the recordings using a deconvolution process that utilizes the previously mentioned inverse stimulus. The deconvolution process compresses the stimulus and the MR into an impulse response that resembles a click in the middle of the recording. This puts the 1st order, linear OAE, responses to the right of the impulse responses, and the nonlinear responses to the left. Using simple windowing the linear OAE responses can be analyzed in the same manner as the standard click responses (Figure 1.5.1) (Appendix 1).

This new method of acquiring swept tone OAEs (sTEOAE) is advantageous over the click (Bennett and Ozdamar, 2010). The swept tone stimulus allows for frequency and bandwidth manipulations, amplitude modulation, and frequency and time correlation. These advantages can be explored individually in order to produce a stimulus that will be able evoke OAEs much faster and with better signal to noise ratios when compared to the standard methods.

1.6 Hearing Level

The human ear behaves as a transducer that converts sound into electrical impulses. Like most transducers the ear does not have a flat frequency response, meaning that it hears some frequencies better and some worse. Because of this the human hearing level (HL) contours (Figure 1.6.1) were introduced in the ISO226:2003 as a fixed frame of reference that can be used for clinical and research purposes.

The unit PHON is used represents the sound pressure values needed to have the same loudness for all pitches. The 0 PHON values represent the minimum hearing threshold for and average human ear. This behavior can be attributed to the overall shape and mechanical properties of the ear.

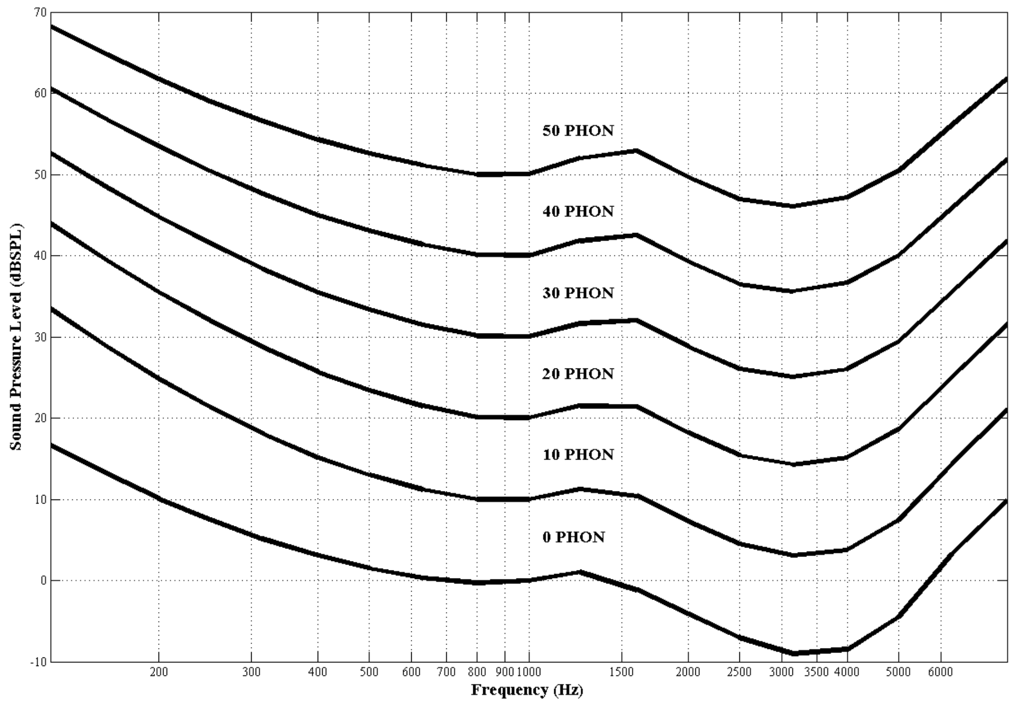


Figure 1.6.1 – ISO226:2003 Standard for human hearing levels. 0 PHON represents the minimum hearing threshold level for an average human.

1.7 Study Overview and Goals

Most of the probes used to send the stimulus to the ear do not have a flat frequency response, meaning that for constant input voltage the probe sound output, with respect to frequency, will vary in amplitude. This study will focus on the calibration of the stimulus for the probe frequency responses and compensation for the human hearing levels.

The frequency response of the probe will be obtained by using a calibrated microphone to measure the output sound pressure levels for a pre determined set of frequencies. The HL values will be recorded for the same set of frequencies. The calibration values and the HL values will be added together to produce a new equalization contour. This contour will then be converted from frequency to time domain which then will be applied to the stimulus as an amplitude envelope.

The OAE responses will be analyzed at different stimulus intensities in order to determine their behavior. The new equalized stimulus will also be compared to the standard clinical TEOAE method for acquiring OAEs.

The new equalized swept tone should be able to evoke OAE responses with improved signal to noise ratios, greater amplitudes, and evoke responses with low stimulus intensities that are close to the hearing threshold.

Chapter 2 Methods and Materials

2.1 Instrumentation

Existing medical equipment for recording OAE responses is limited only to a couple types of stimuli, click and pure tones, a relatively short recording window, and typically with 16 bit per sample resolution. The stimulus used for the sTEOAE method is 100 ms in duration and changes its frequency with time (Bennett and Ozdamar, 2010b). For this reason a customized device was used, developed by Bennett and Ozdamar, that allowed the use of a preloaded custom stimulus and recording time up to 1s.

The device used was an Analog Devices ADSP-21369 SHARC EZ-KIT Lite Evaluation Kit based on the ADSP – 21369 Digital Signal Processing (DSP) core and a SHARC® Processor. The system was set to generate and record sounds with 24bit resolution at 48000 samples per second. The 24bit resolution is a key component of the swept-tone method because the OAEs are embedded in the MR. The MR is greater in amplitude than the OAEs and it will be impossible to extract them with smaller bit resolution because at lower intensities they will be smaller than the least significant bit value.

Custom software was developed using Matlab® to control the DSP via RS-232 serial port. The software would send the stimulus that was going to be used, the intensity including DNL, number of sweeps, additional acquisition information, and the command to start recording. The DSP then would acquire and average the responses in real-time and send them back to the computer as raw recordings for further post processing. After receiving the recordings the Matlab® software performs the deconvolution process that extracts the OAE responses from the recordings and performs simple band-pass filtering to clean up the recordings from unwanted noise.

The probe used to send the stimulus and record the responses from the ear was an Etymotic Research (Elk Grove Village, IL) ER-10D OAE Probe. The ER-10D probe has an ear tip that has two speakers and one microphone. The digital to analog converter on the DSP was only capable of producing 86dBSPL, Appendix 2, with the ER-10D probe. Due to the DNL the maximum recording sound level was 70dBSPL, so a small inverting amplifier with gain of 20dB was added to the system to bring the maximum output to 106dBSPL. The microphone coming from the probe was directly connected to the analog to digital converter on the DSP without any amplification.

Additional modifications of the existing system were made to improve the rate at which new stimuli were uploaded to the system. In the original system design the stimulus was hardcoded in the program memory. The reason for this was the slow transfer protocol that required several minutes to load a new stimulus. Each sample of the stimulus consists of 24bits or 2^{24} (16,777,216) possible data points. The value of each sample was sent to the system as 8bit ASCII characters, ranging from 1 to 9 characters depending on the value. To improve the transfer rate each 24bit value was segmented into three 8 bit values that were sent to the system, which assembled them back into one 24bit value. This reduced the transfer time to several seconds for a 100ms stimulus (4800 samples). This gives the luxury of loading several stimuli during one testing session, with a short down time.

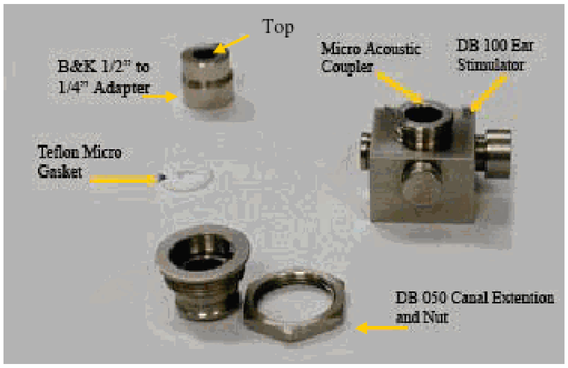
2.2 Stimulus calibration

For the hearing level (HL) equalization process the standard ISO 226:2003 normal equal loudness level contours were used from which a set of SPL to HL values were obtained (Table 2.2.1). In addition to the HL compensation values a set of calibration values were obtained to account for the frequency response of the transducers used in the ER-10D OAE probe. The expected OAE responses ranged up to 5000Hz, so a slight roll off in amplitude was added at very high frequencies, 6000 and 8000Hz.

Frequency (Hz)	250	500	750	1000	1500	2000	3000	4000	6000	8000
SPL to HL (dB)	28	22	19	17	16	20	16	13	0	0
SPL calibration values (dB)	11	9	4	6	1	3	-2	-9	17	0
Total (dB)	39	31	23	23	17	23	14	4	17	0

Table 2.2.1 – HL compensation, probe calibration values, and the total dB correction for each frequency.

The calibration values were obtained by an acoustic calibration process by coupling the ER-10D OAE with a Zwislocki acoustic coupler (Figure 2.2.1a and 2.2.1b) to a Bruel & Kjaer Type 4136 - ¼” Condenser microphone connected to a Bruel & Kjaer Model 2690 Conditioning Amplifier (Figure 2.2.2). Individual calibration values were obtained for the same frequencies as in (Table 2.2.1) by playing pure tone sounds at a certain intensity and recording the actual SPL values using an IHS USB system (Figure 2.2.2).

a) 

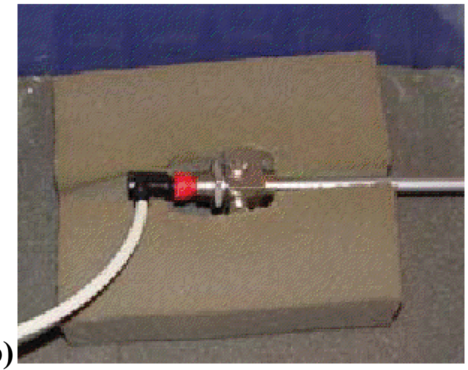
b) 

Figure 2.2.1 - Courtesy of Intelligent Hearing Systems (IHS) .
a) Components of a Zwislocki coupler.
b) ER-10D OAE Probe coupled to a B&K calibration microphone with a Zwislocki coupler.

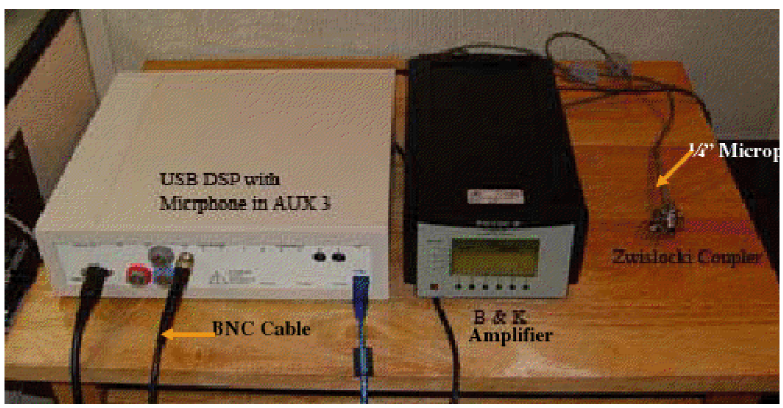


Figure 2.2.2 – Calibration setup, consisting of an IHS USB System, a B&K microphone conditioning amplifier, and a B&K calibration microphone with a Zwislocki coupler. Courtesy of Intelligent Hearing Systems (IHS)

Applying the correction values to the swept tone makes it acoustically flat in SPL levels, but not in HL. The HL equalization was done by adding the HL values and the correction values for each frequency and applying them to the swept-tone stimulus by varying the amplitude at a given frequency. Using the new correction values a new frequency contour was made using cubic interpolation (Figure 2.2.3). The temporal location of individual frequencies can be determined using Equation 2.2.1, which gives the sample at which a particular frequency can be found.

$$n(f) = N\frac{\log\left(\frac{f}{f_1}\right)}{\log\left(\frac{f_2}{f_1}\right)} \qquad \textbf{Equation 2.2.1}$$

The new frequency contour was adjusted to fit the sample-time, locations on the swept tone. This produces a new contour that has the same number of samples, time points, as the original swept tone stimulus. The dB values were normalized and by multiplying them with the swept-tone stimulus a new stimulus is made that has the same frequency distribution over time but varies in amplitude (Figure 2.2.4).

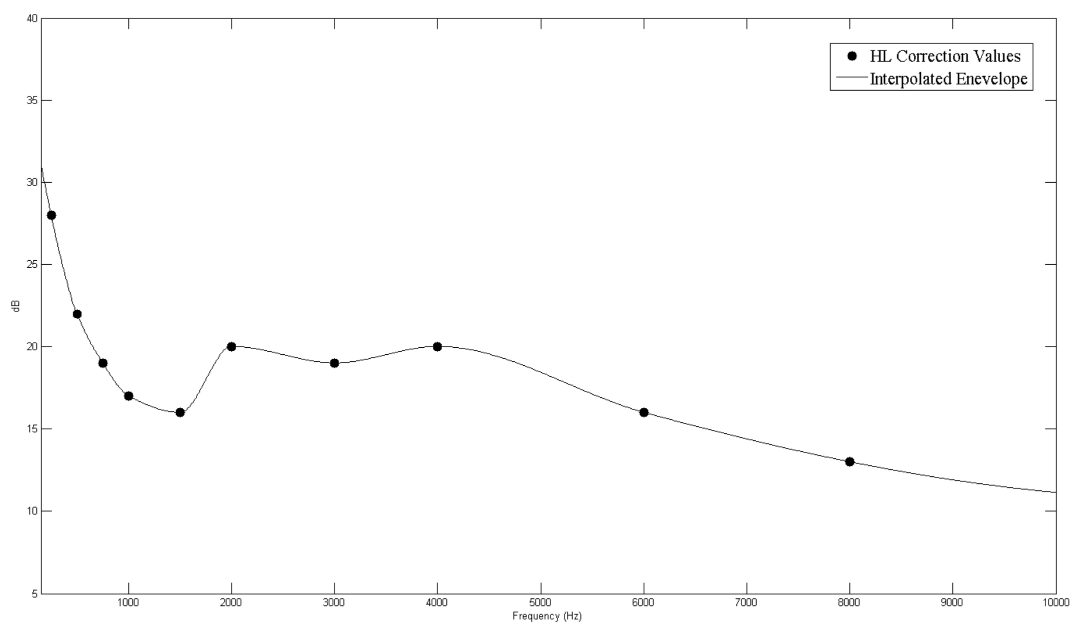


Figure 2.2.3 – Individual dBHL values and the envelope created with cubic interpolation, fitted with respect to frequency.

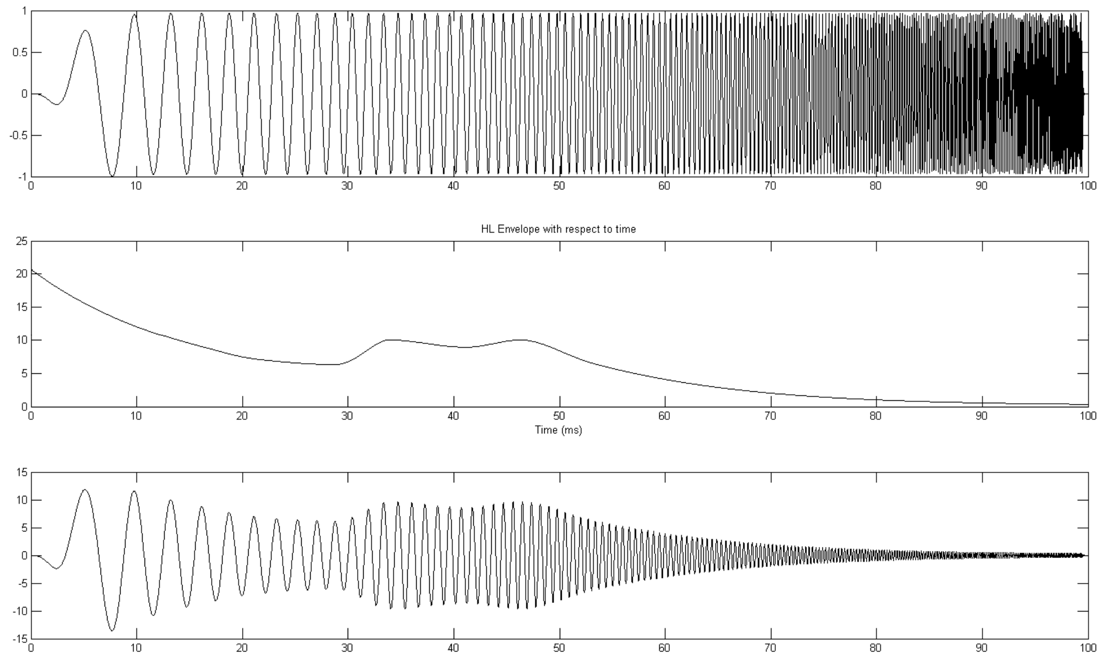


Figure 2.2.4 – Swept – Tone equalization process. The original swept – tone (top), the HL envelope with normalized values (middle), and the final product of the two, the equalized swept – tone (bottom).

2.3 Procedures and Protocol

The recordings were performed in a single session with the subjects sitting in a soundproof booth shielded from electromagnetic interference. All of the subjects were tested to determine the presence of OAEs using clinical equipment and standards. This was done using IHS USB System and SmartTrOAE software with a 100μs click at intensity of 75 dBSPL, acquired at a rate of 19.3 clicks per second for 1024 sweep (averages). A subset of 3 subjects was selected for additional recordings with the following intensities: 75, 65, 55, 45, and 35.

The swept tone stimulus used for the recordings was a 100ms sweeping across 300-9000Hz repeated at a rate of 7.9 per second. OAEs from both ears were recorded at intensities of 55, 45, 35, 25, 15, and in some subjects 5 dBHL. The averaging was done using 512 sweeps per intensity.

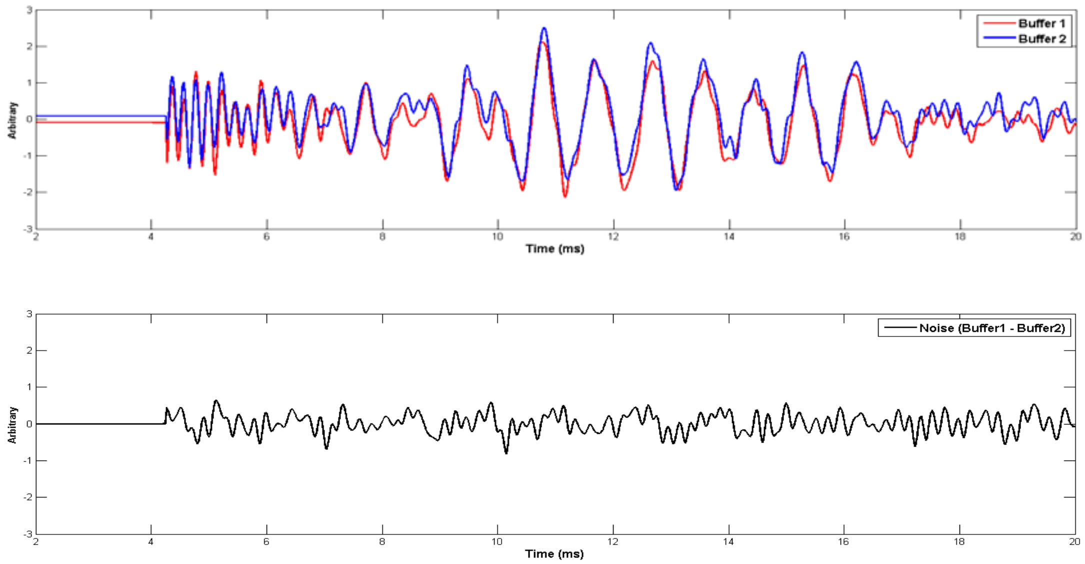


Figure 2.3.1 – Split buffer display (top) showing the first buffer in red and the second buffer in blue, with a slight offset for easier visual inspection. Noise shown in the bottom is extracted from the top recordings by subtracting the two.

The sweeps were separated into two buffers, for even and odd numbered sweeps, producing two averaged buffers containing one half of the total number of sweeps. The fourth sweep, DNL, even though even, was distributed between the two buffers to ensure proper MR removal in both. With the split buffer method it is possible to extract the noise by mathematically subtracting the two and get the clean signal by mathematically summing the two buffers (Figure 2.3.1). This is beneficial later in the analysis in determining the validity and the SNR of the OAE responses.

2.4 Post-processing and Analysis

The post processing and analysis of the recordings was also done using custom made software in Matlab® (Figure 2.4.1). After receiving the raw data from the DSP system it was formatted as a swept tone OAE recording and was stored in a file containing the two raw buffers, information about the type of recording, the inverse stimulus, calibration parameters, subject name, and other technical parameters regarding the recording.

The first step of the processing is the convolution of the raw buffers with the inverse stimulus, even though performed using convolution the actual process is called deconvolution. This will compress the recorded waveform in to a single impulse response halfway through the recording. As seen in Figure 2.4.1, the deconvolved response is composed of two parts marked in the middle by the impulse responses of the system.

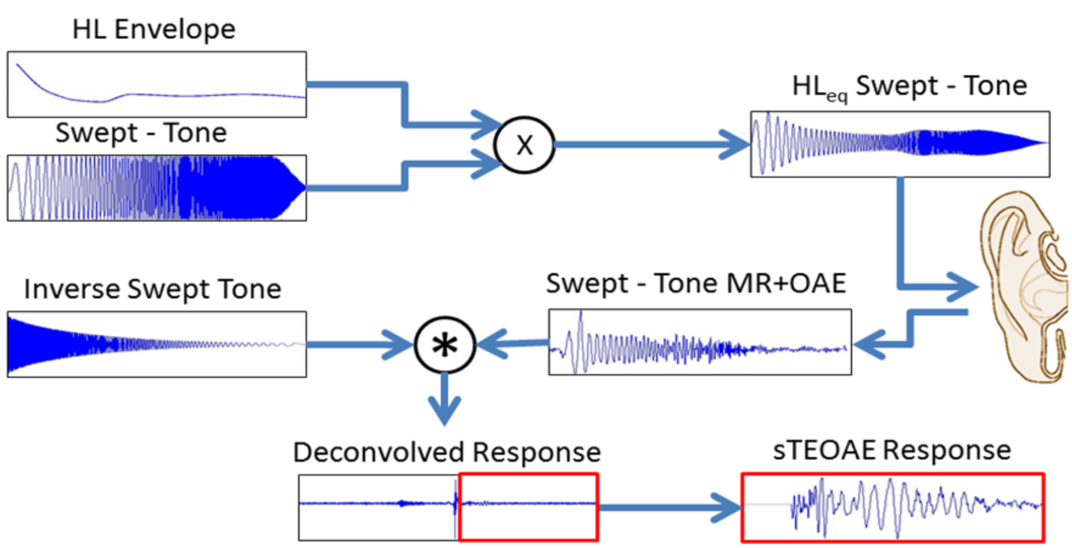


Figure 2.4.1 – Visualization of the HLeqs method, showing the stimulus enveloping, stimulation of the ear, recording, deconvolution, and windowing to obtain the final swept-tone OAE responses.

Right from the impulse response are the OAEs and left are the nonlinear responses (Appendix 1). Following the deconvolution the recordings are filtered for 250-5000Hz, this step is necessary to remove very high and very low frequency noise including the (Direct Current) DC offset.

Since we are only interested in the linear, OAE, responses the information on the left of the impulse response is discarded producing a recording that is one half of the original. The new recording is further clipped up to 4ms, starting from the impulse response, to eliminate the stimulus artifact or MR. At this point in the processing there are two filtered OAE recordings. The two recordings in the buffers are then summed to produce the final OAE response and subtracted from each other to produce the noise in the recordings. The two buffers are plotted together. This is an important step because it helps to determine the validity and quality of the OAE responses, if the plots of the two buffers align it signifies a strong OAE response otherwise it is considered to be noise (Figure 2.4.2). Additionally the spectrum of the summed signal and the noise is obtained using Fast Fourier Transforms (FFT) and are plotted together for visual inspection of the signal and noise levels of the OAE responses. From the spectra the band pass signal to noise ratios (SNRs) (Appendix 2) are calculated for 500, 1000, 1500, 2000, 3000, and 4000Hz frequency bands as described in Table 2.4.1, these will be referred to as “narrow band SNRs”.

Frequency (Hz)	500	1000	1500	2000	3000	4000
Band Pass (Hz)	250-750	750-1250	1250-1750	1750-2500	2500-3500	3500-4500

Table 2.4.1 – Frequency bands used for "narrow band" calculations.

An SNR value greater than zero signifies that signal is greater in amplitude than the noise, zero SNR means that the signal has the same amplitude as the noise, and negative SNR means that the noise is greater than the signal. In addition to the band SNR values, the total SNR value of the signal between 500Hz and 5000Hz was calculated (Appendix B), this value will be referred to as "total SNR". These representations of the OAE responses make it possible for visual and analytical analysis, and evaluate the quality of OAEs in the recordings.

The sound pressure levels in mPa for the signal and noise were calculated for each subject at different stimulus intensities. The mean and standard deviation were calculated from all subjects. The standard error was calculated by dividing the standard deviation by the mean and adding 1 and was plot. The mean and the standard error from mPa were converted into dBSPL (Appendix 2). Additionally, the SNRs were calculated from the dBSPL values. The means with the standard error of the SNRs, signal, and noise for both total and narrow band analysis were plotted together. The narrow band values were plotted as a function of frequency and the total values were plotted as a function of stimulus intensity.

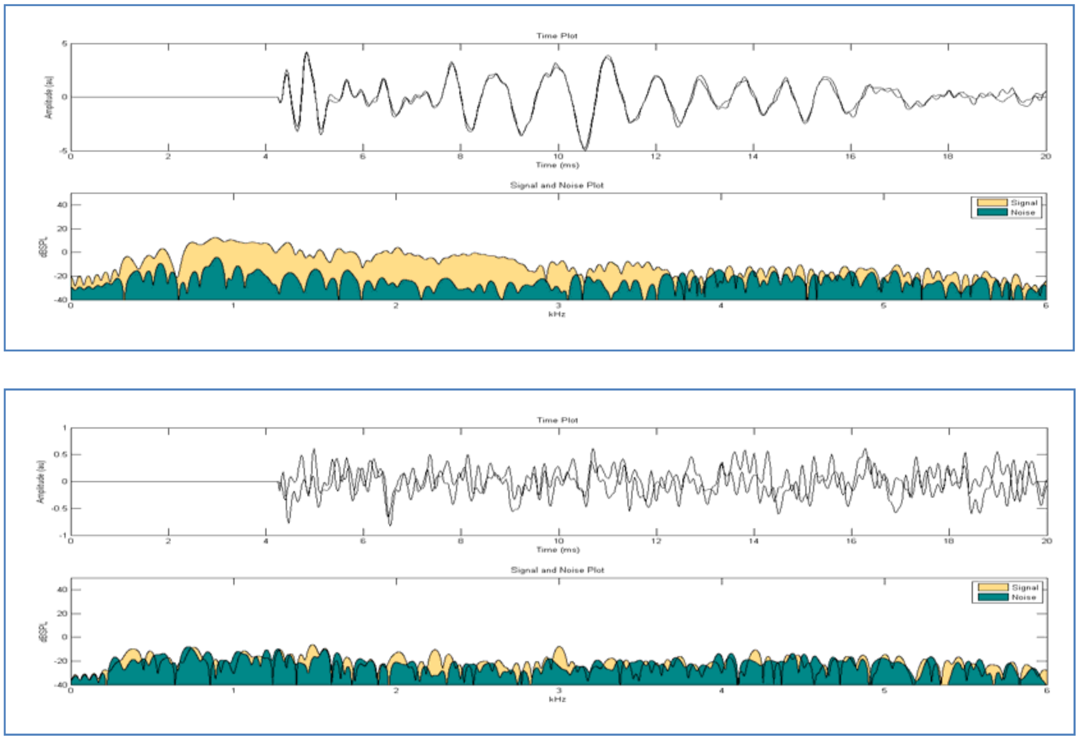


Figure 2.4.2 – Software representation of the OAE responses, showing the two buffers, time plots, and the spectrum. Top two plots, OAE responses with minimal noise from a single subject, visible buffer overlap and a signal spectrum above the noise floor. Bottom two plots, noisy recordings, attributed to the lack of OAEs, visible buffer mismatch in the time plot and the signal is not above the noise floor.

Chapter 3 Results

All of the subjects included in the following studies had normal hearing on both ears, below 30dBHL, and did not exhibit any kind of hearing impairments or losses. Two of the subjects (males) did not meet the clinical criteria for passing OAE responses at 75dBSPL (DNL) with 100μs click stimulus. One of the subjects (female) had abnormally large OAE responses on both ears. The recordings were performed accordingly with IRB protocols and regulations for responsible human research conduct and all subjects signed a written consent that explained the protocol in detail. The figures below show the mean values and their standard error, if included, of all of the recorded ears in each study.

3.1 HLeqs: Signal, Noise, and Intensity Characteristics

For the HLeqs analysis the OAE responses of 11 subjects, 22 ears, were recorded. With the exception of two, all of the subjects exhibited normal OAE responses and satisfied the clinical passing conditions. This study primarily focuses on the behavior of the HLeqs responses using the HL swept tone with respect to response frequency and stimulus intensity.

The band SNRs for each intensity were analyzed with respect to the OAE response frequencies as shown in Figure 3.1.1. From the plot it can be observed that at higher stimulus intensities, 55 and 45 dBHL, the low frequency responses ranging from 500Hz to 1500Hz are elevated relative to the high frequency responses ranging from 1500Hz to 3000Hz. There is no discrepancy between the responses at 45 and 55 dBHL for 500, 1000, and 1500 Hz frequency bands. With the decrease of stimulus intensity the low and high frequencies tend to equalize, except for the 4000Hz band which stays relatively low for all stimulus intensities. Another observation that can be made regarding the 4000Hz band is that at 55dBHL stimulus intensity, the SNR is very close to 0dB, then at 45dBHL the SNR gets elevated to around 4dB and decreases down to 0dB as the stimulus intensity decreases.

HLeqs TEOAE – Narrow Band SNR

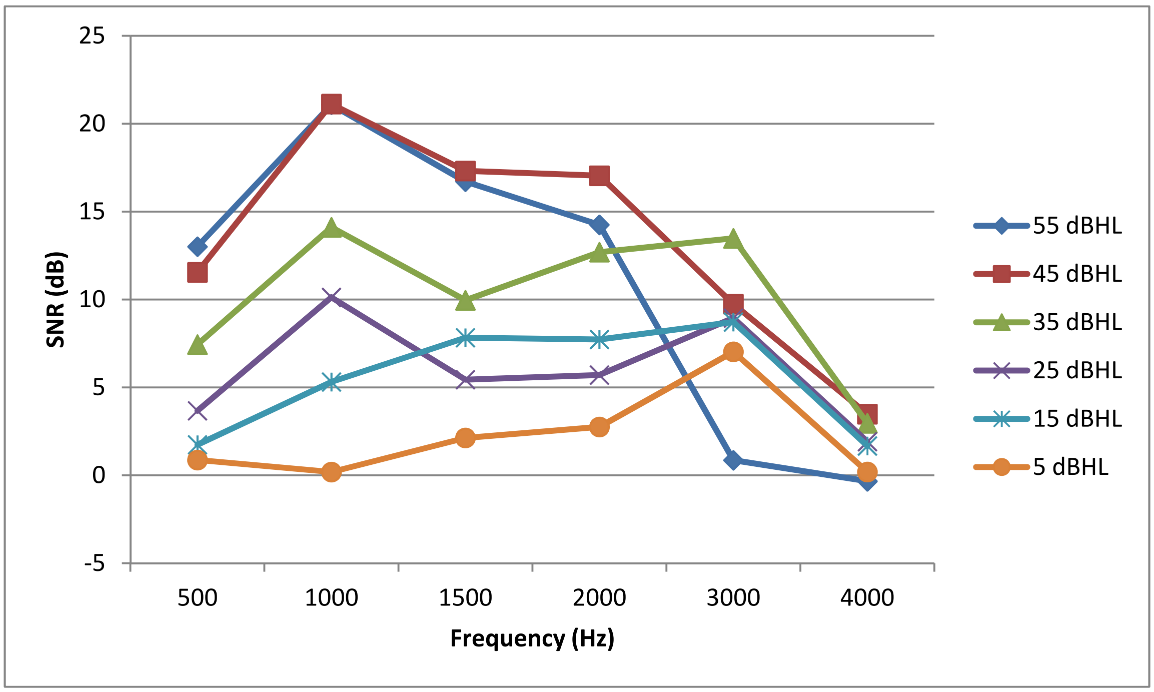


Figure 3.1.1 – HLeqs TEOAE – mean of narrow band SNR as a function of response frequency for different stimulus intensities. Showing response discrepancy between low stimulus intensity, up to 45 dBHL. Additionally a lack of discrepancy can be seen between 45 and 55 dBHL and a high frequency roll off at 55dBHL and tapering in the SNR at 4000Hz for all stimulus intensities.

The total SNR as seen in Figure 3.1.2 shows a linear increase, from 2 to 15 dB with respect to the stimulus intensity, 5 to 45 dBHL. At 55 dBHL stimulus intensity the SNR tapers of down to 14dB.

Individual plots of the SPL signal and noise levels were made to show the actual amplitudes for each frequency band, Figures 3.1.3 and 3.1.4. In addition to the individual

SPL levels the total signal SPL was computed and plotted with respect to intensity, Figure 3.1.5.

HLeqs TEOAE – Total SNR

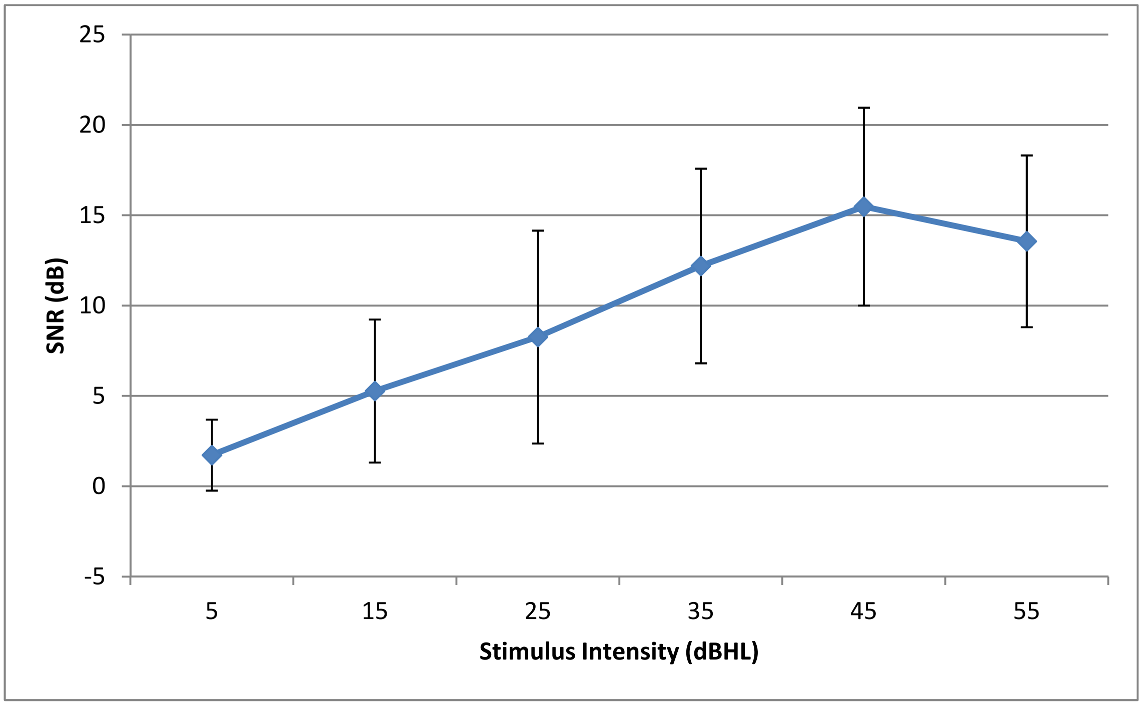


Figure 3.1.2 – HLeqs TEOAE – mean of total SNR from 500Hz to 5000Hz as a function of stimulus intensity, showing a linear rise of the SNR relative to the stimulus intensity from 5 to 45 dBHL and a slight roll off at 55dBHL.

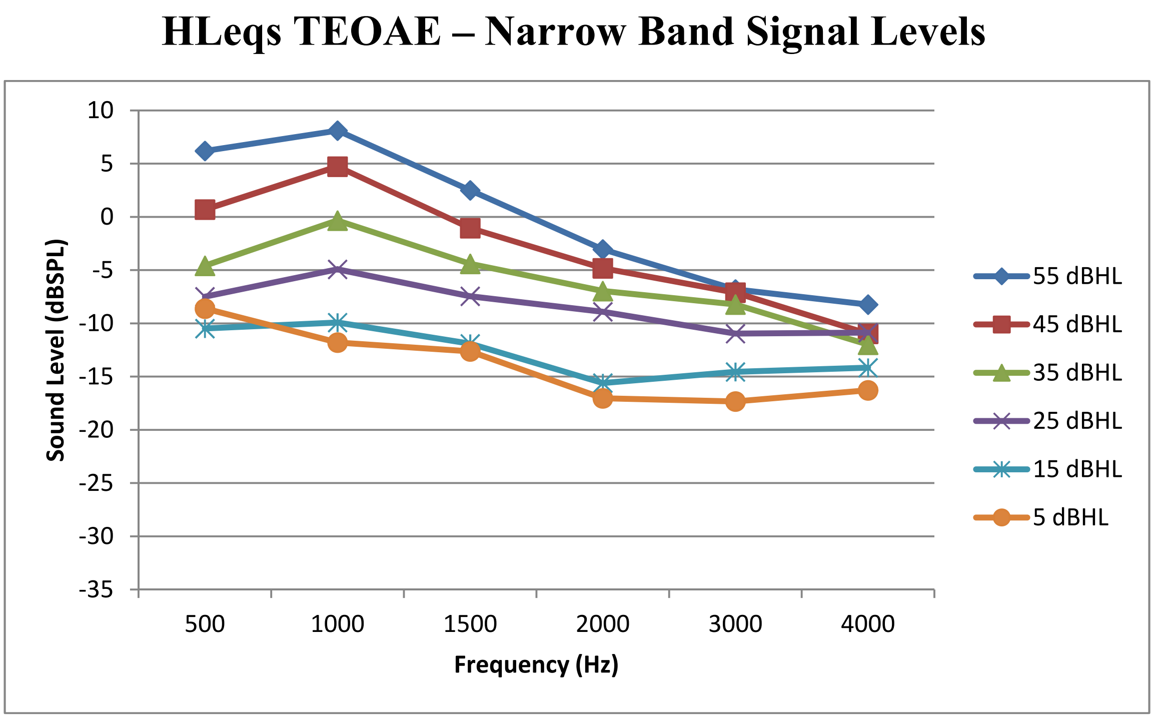


Figure 3.1.3 – HLeqs TEOAE – OAE response narrow band signal levels as a function of frequency for different stimulus intensities, showing a steady increase of signal levels with increasing stimulus intensity from 5 to 55 dBHL. Additionally it can be seen that the signals decrease in amplitude as the frequency increases.

The signal levels in Figure 3.1.3 show the actual amplitudes of the OAE responses for a select group of frequencies for all intensities. The response signals for all frequency bands show a steady decrease with respect to stimulus intensity from 55 to 25 dBHL. Lower stimulus intensities, 15 and 5 dBHL, show a small dependence to the stimulus intensity. A general trend of decreasing signal levels with increasing frequency can be observed, especially at high stimulus intensities, 45 and 55 dBHL.

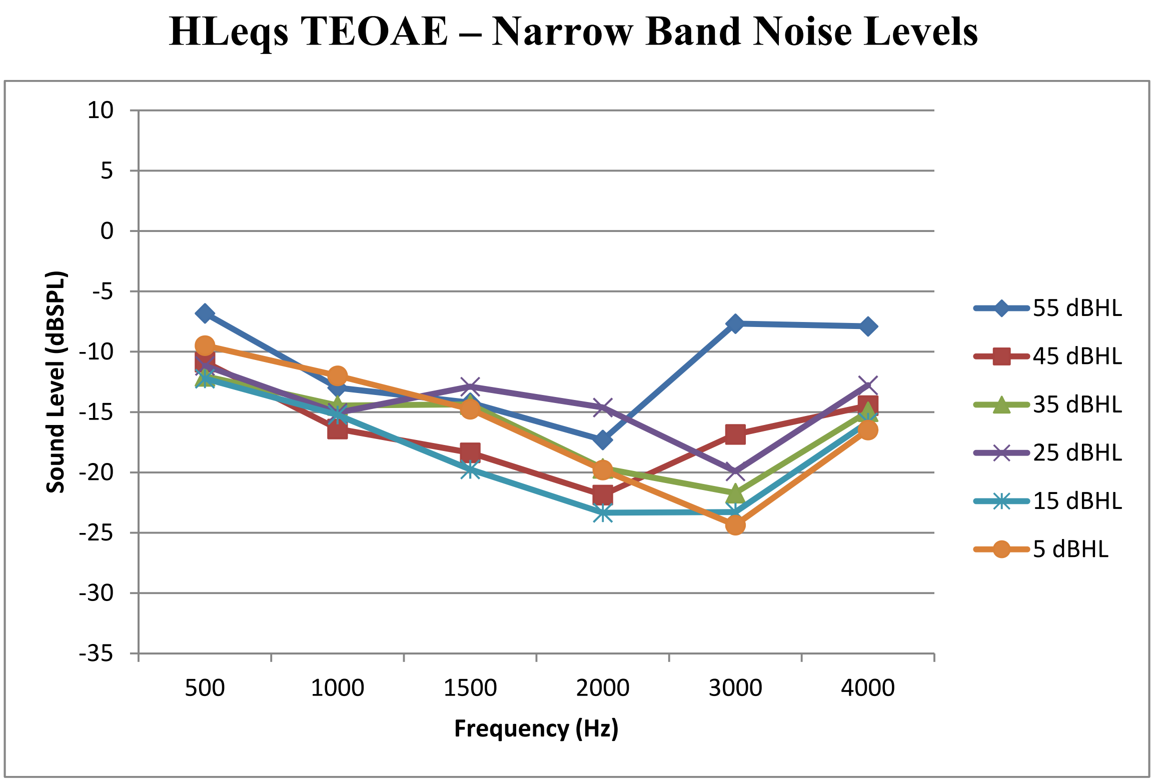


Figure 3.1.4 – HLeqs TEOAE – Narrow band noise levels in dBSPL for each intensity as a function of frequency showing small changes with respect to stimulus intensity, except for 3000 and 4000 Hz where the noise increases at 55 dBHL compared to lower intensities.

The mean noise levels computed for narrow frequency bands are plotted in Figure 3.1.4. As observed the noise floor from 500 to 2000Hz, does not change appreciably with intensity, but at 3000 and 4000Hz the noise floor decreases with decreasing stimulus intensity. From the total levels plotted in Figure 3.1.5 it can be seen that the signal decrease in amplitude as the stimulus intensity decreases. The noise levels, however, stay around -15 dBSPL and only increase to about -10 dBSPL at 55dBHL stimulus intensity.

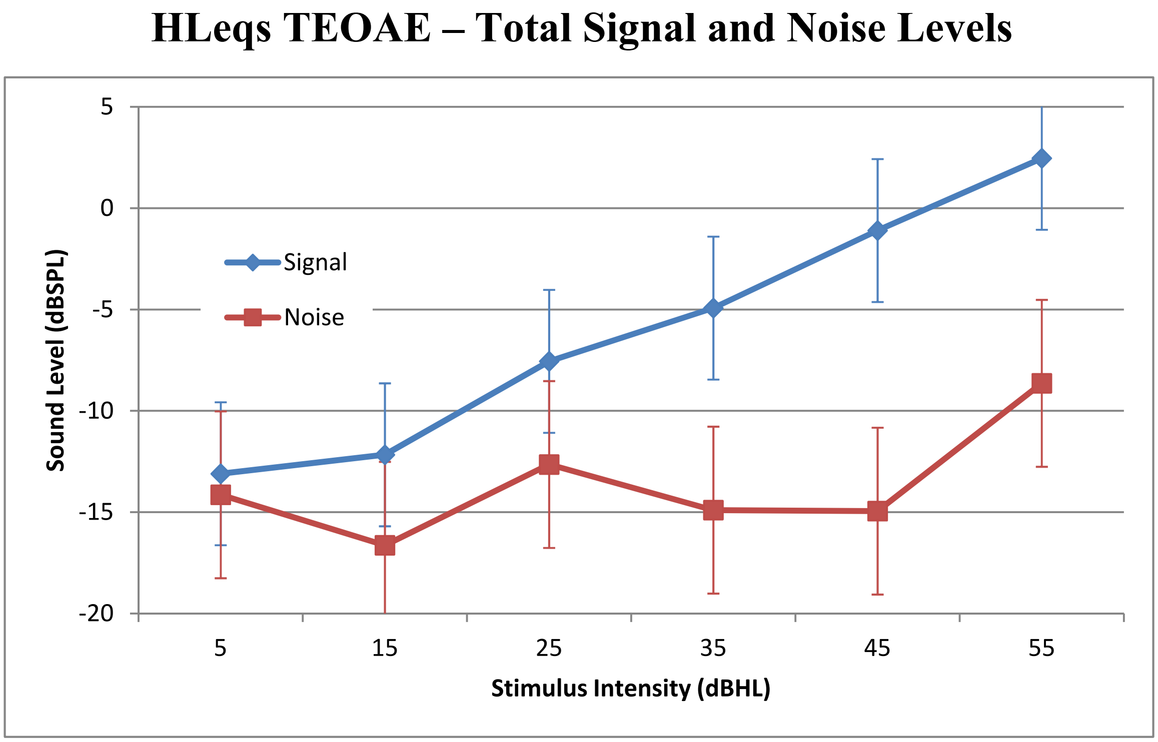


Figure 3.1.5 – HLeqs TEOAE – Total signal and noise levels in dBSPL with as a function of stimulus intensity showing a steady increase of the signal levels with increasing stimulus intensity. The noise remains steady, around 15 dBSPL, up to 45 dBHL then it rises at 55 dBHL stimulus intensity.

3.2 HLeqs and Click TEOAE: Comparison

To compare the HLeqs with the standard click TEOAEs, a set of three subjects (six ears) with normal hearing and OAE responses, were recorded with different stimulus intensities. The HLeqs was done using stimulus intensity measured in dBHL and click TEOAE was done using dBSPL, correlation between the two was made by adding the maximum HL value in Table 2.2.1 to the dBHL value. The maximum, 28dB, HL value is at 250 Hz, which can be rounded up to 30 dB, since the stimulus intensity intervals are

5dB and expressed in Equation 3.2.1, which converts dBHL values to dBSPL. The same plotting procedures were followed as in the previous section.

$$dBSPL = 30dB + dBHL \qquad \textbf{Equation 3.2.1}$$

The total SNRs computed for both methods are shown in Figure 3.2.1. AS observed both methods produced monotonically increasing SNRs with increasing stimulus intensity. The primary difference was the overall shift up of the swept tone SNR compared to click, meaning that HLeqs exhibited better OAE than the click method.

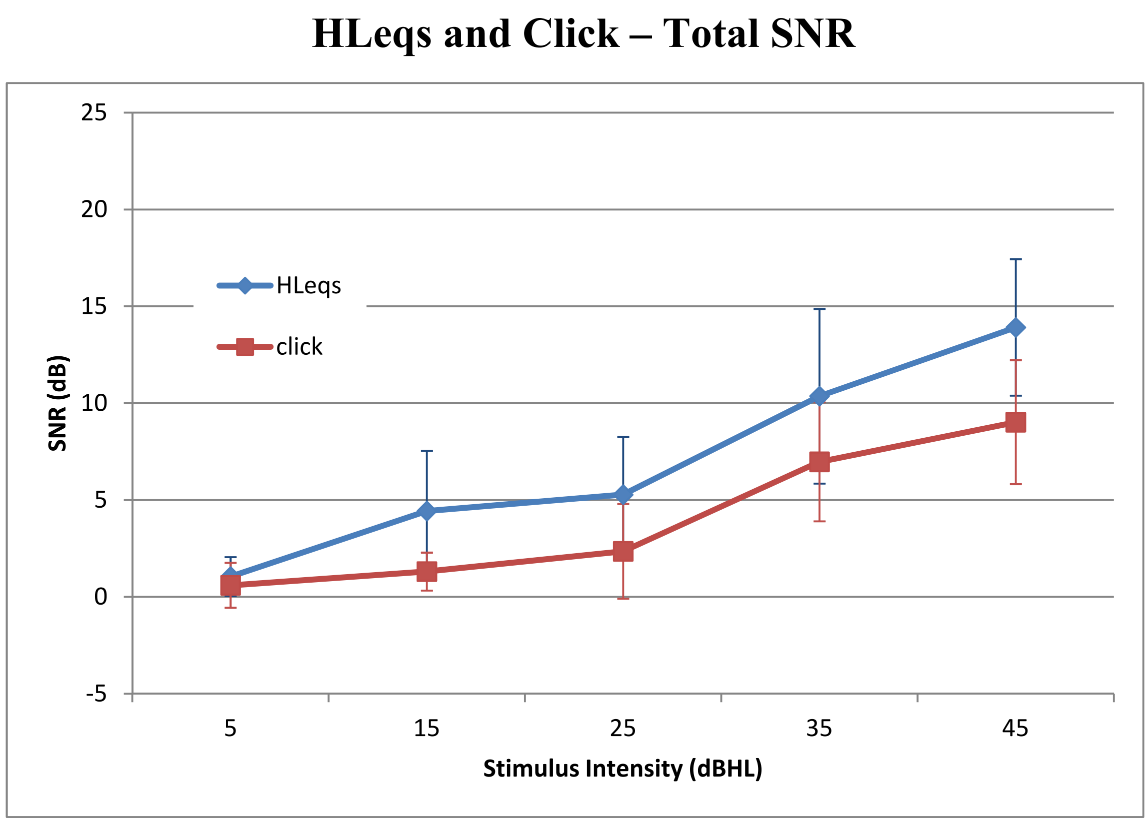


Figure 3.2.1 – HLeqs and Click TEOAE – Total SNR as a function of stimulus intensity. Both methods show similar behavior between 15 and 45 dBHL. The HLeqs has higher SNR than Click by about 4 dB. HLeqs and Click are close to 0 dB at 5 dBHL.

The band SNRs shown in Figure 3.2.2, display a detailed picture about the responses obtained by both methods. The first observation is that both methods exhibit a dip of SNR in the 4000Hz band. Next HLeqs method produces higher SNRs for the remaining frequencies relative to the click method, especially at low intensities, 25, 15, and 5 dBHL.

The signal SPL levels for both methods shown in Figure 3.2.3, exhibit the same property with increasing stimulus intensity. In general click method has lower amplitudes, when compared to HLeqs. The responses obtained with click produce an overall trend of decreasing amplitude OAEs as the stimulus intensity is lowered. Both methods show a decrease in signal levels with increasing band frequency.

The noise levels plotted in Figure 3.2.4 show very little change with stimulus intensity, with HLeqs displaying more variability than those of clicks. The overall noise maximum for click is -10 dB and minimum is -35 dBSPL. For HLeqs the maximum is around -10 dBSPL and the minimum is -30 dBSPL. Both methods show a decrease in noise levels with increasing band frequency.

The mean and the standard error of the total signal and noise levels are plotted in Figure 3.2.5 for both methods as a function of stimulus intensity. The signal levels increase with increasing stimulus intensity for both methods. HLeqs, however, has higher amplitudes relative to click by 6dB. As observed all measurements show higher variability at low intensities. As the stimulus intensity increases variability tends to decrease especially for OAE signal.

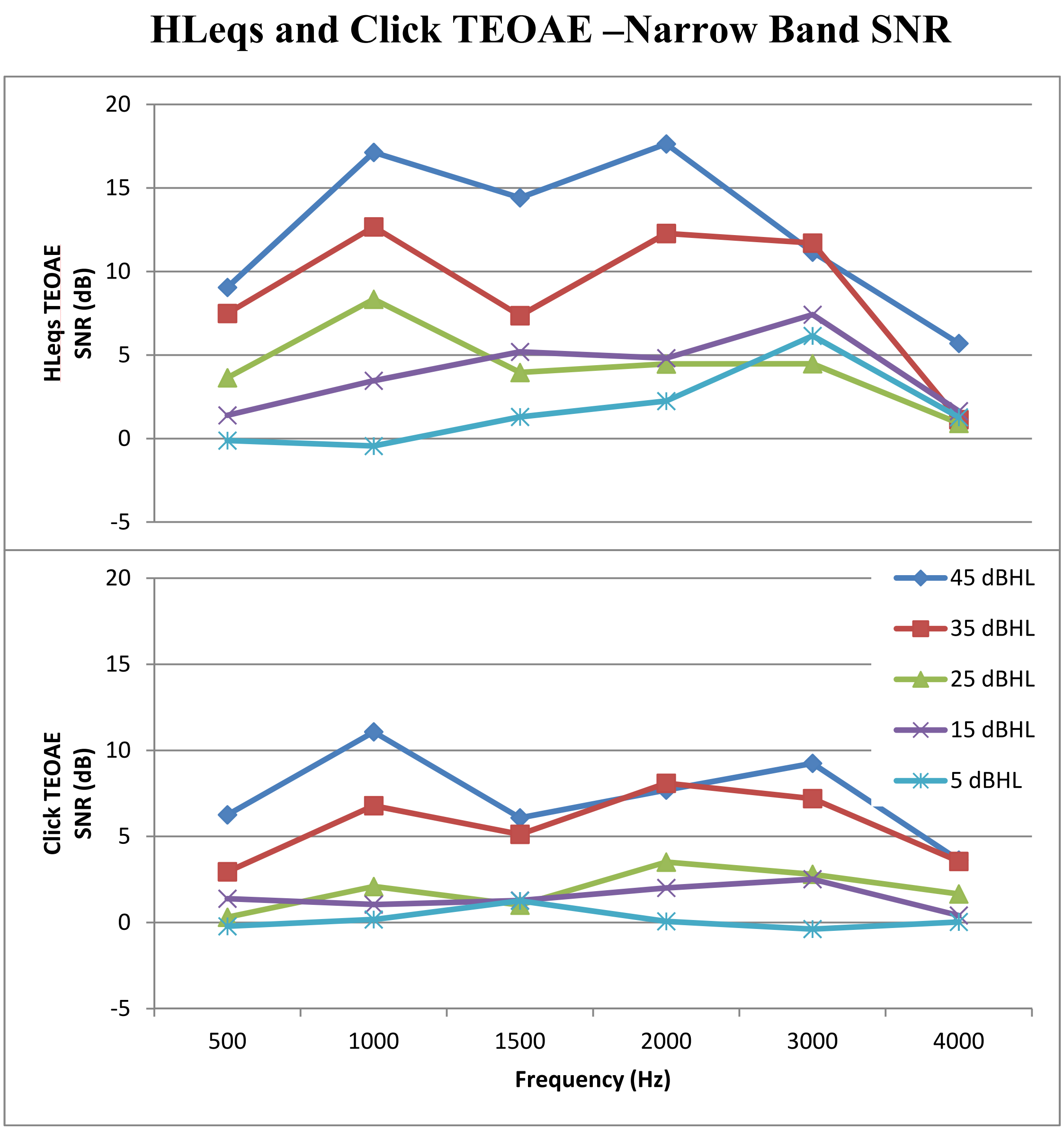


Figure 3.2.2 – HLeqs and Click TEOAE – Band SNR levels in dB with respect to frequency for the given stimulus intensities. The band SNR of the HLeqs (top) show discrepancy throughout all stimulus intensities for most frequency bands. The band SNR for Click (bottom) shows discrepancy at 45, 35, and 25 dBHL, but at lower intensities the SNRs are close to each other. Similar behavior between the two methods can be seen at 1500Hz at 45 and 35 dBHL. At 4000Hz there is a decrease in amplitude for all stimulus intensities.

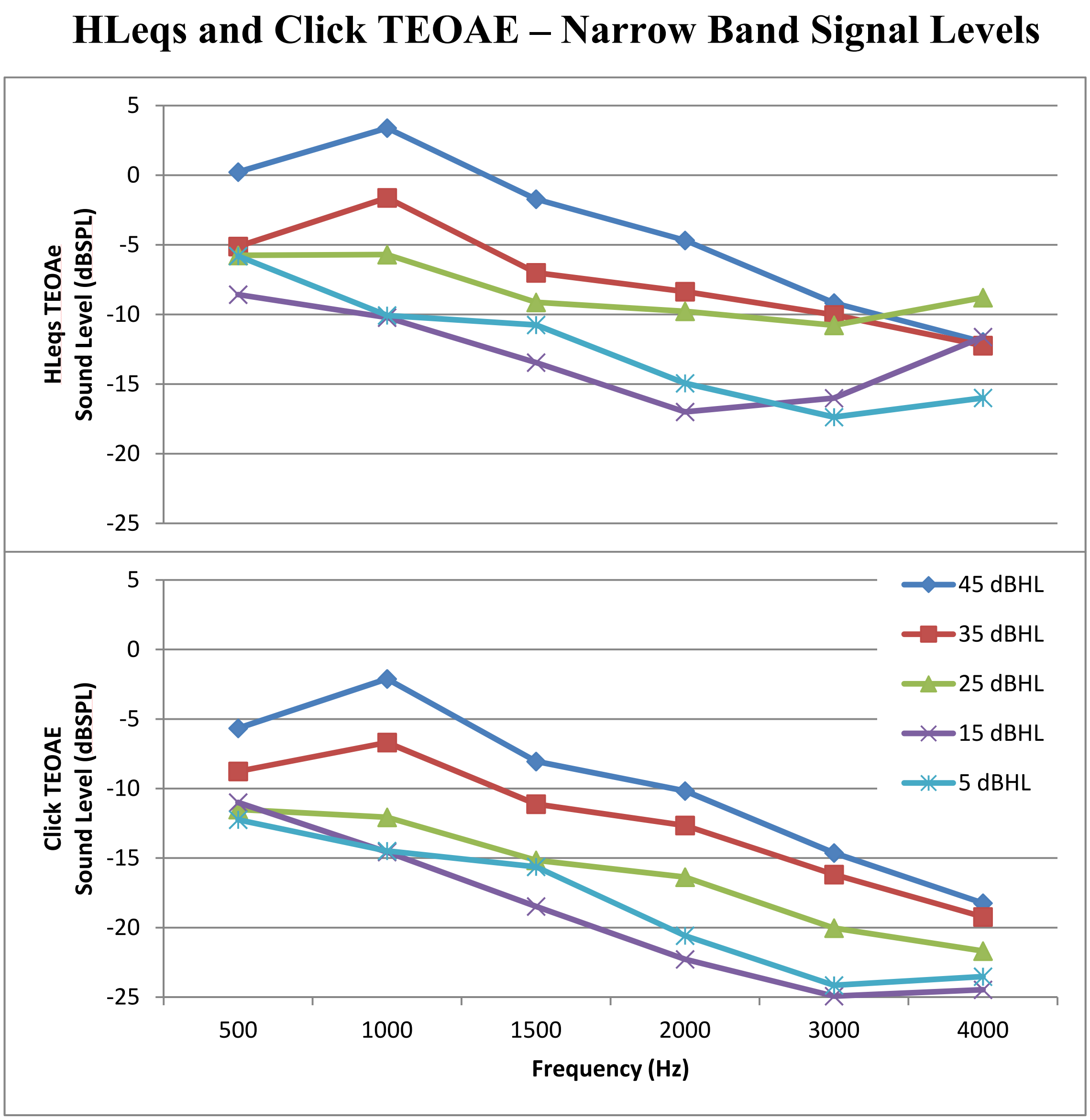


Figure 3.2.3 – HLeqs (top) and click (bottom) TEOAE – Signal levels in dBSPL for each intensity with respect to frequency. Both show amplitude discrepancy down to 15 dBHL. HLeqs in general has higher amplitudes relative to click.

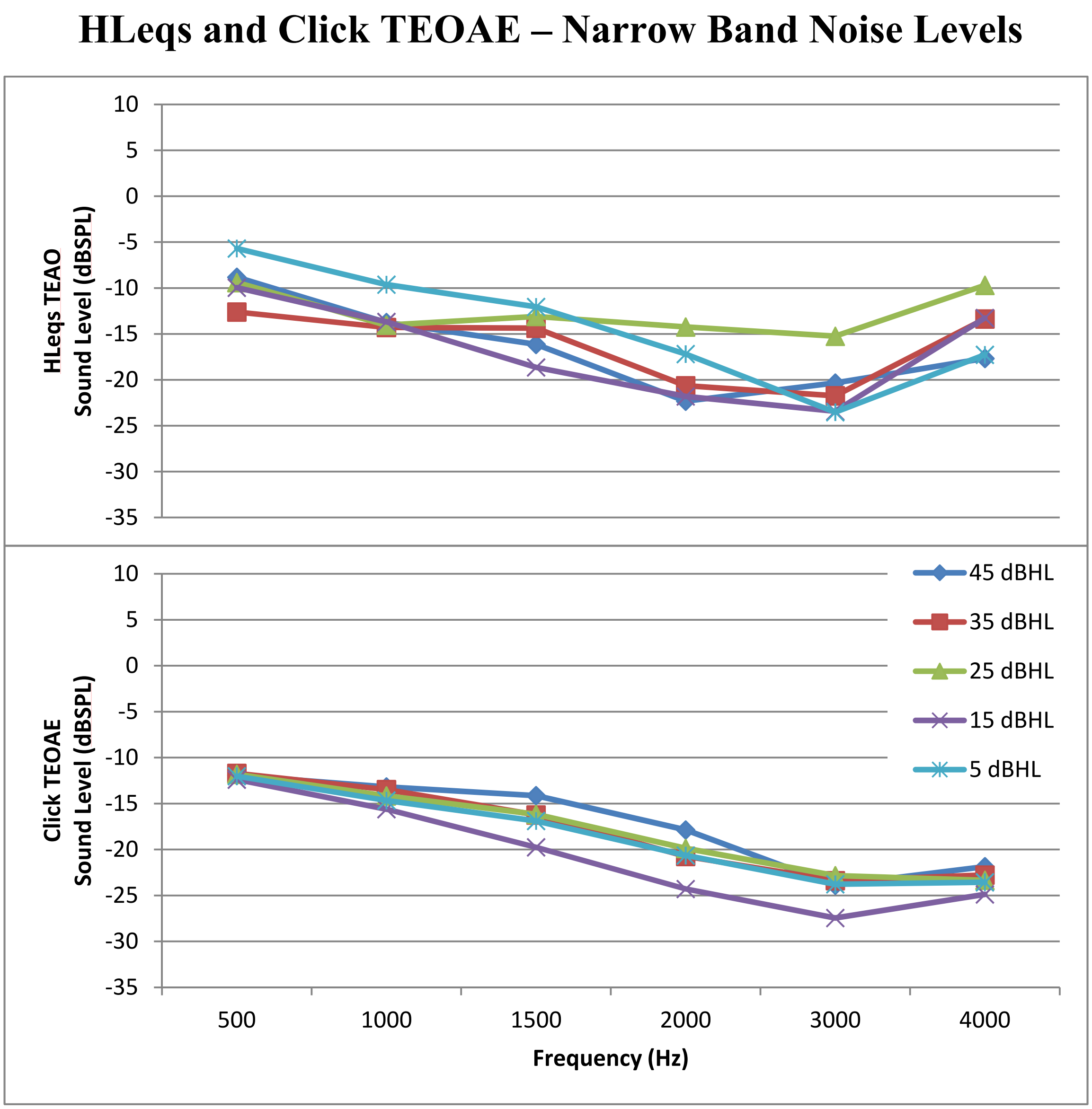


Figure 3.2.4 – HLeqs and Click TEOAE – Noise levels in dBSPL for each intensity with respect to frequency. The HLeqs noise levels (top) show minor dependence to the stimulus intensity. The Click noise levels (bottom) show almost no dependence to stimulus intensity. The Click noise levels are smaller in amplitude relative to the HLeqs noise levels. Both show dependence to response frequency. Both show a decrease in amplitude with increasing band frequency.

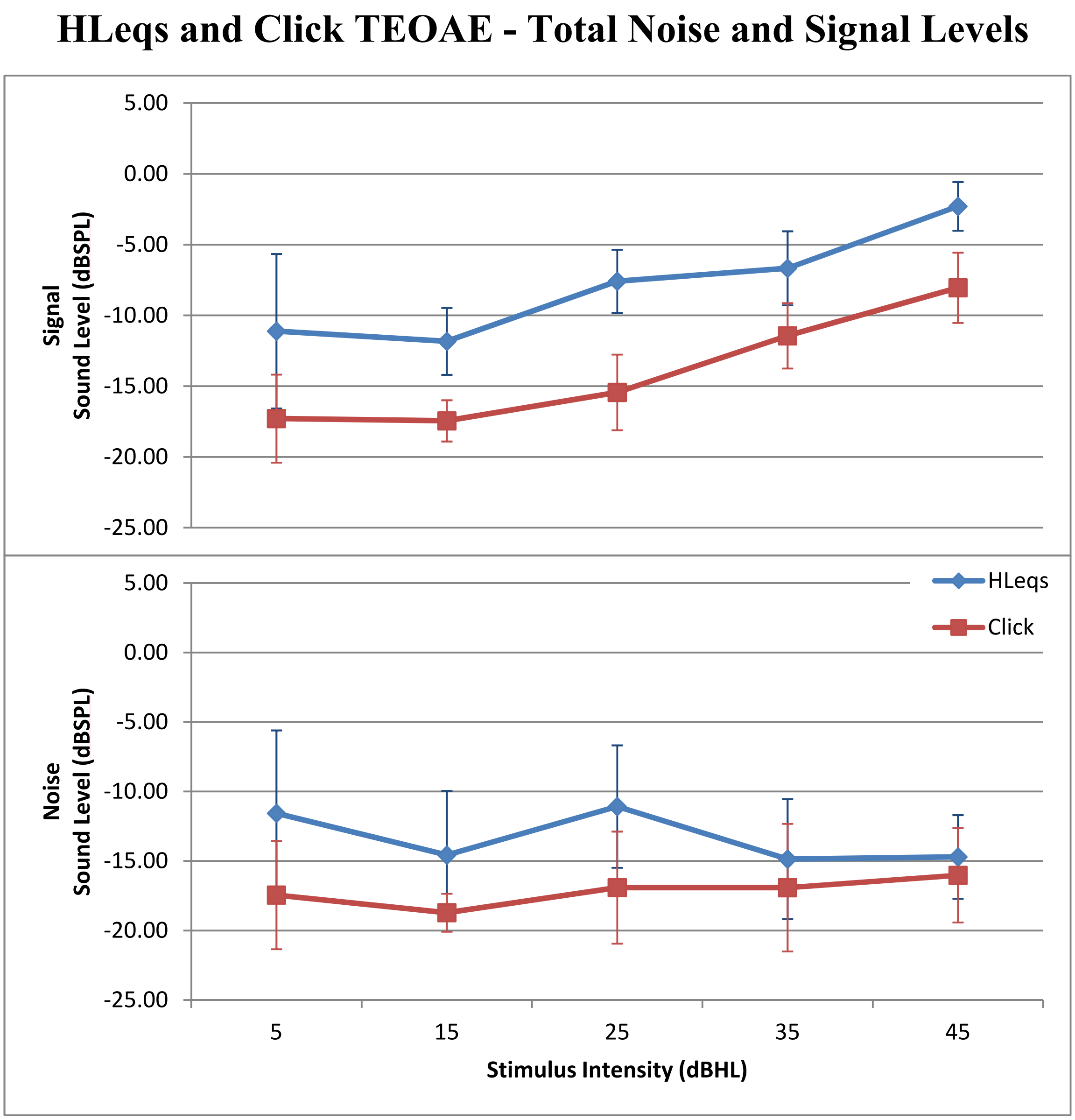


Figure 3.2.5 – HLeqs and Click TEOAE – Total signal and noise levels with respect to stimulus intensity. The signal levels (top) for HLeqs are larger in amplitude than Click. Both have a similar increase in amplitude with increasing stimulus intensity. The noise levels (bottom) for Click are lower relative to HLeqs. Both methods show almost no dependence to the stimulus intensity.

3.3 Special Cases

Two subjects that exhibited poor click TEOAE had a separate set of analysis to compare their HLeqs responses to their click TEOAE responses. The same set of analysis as before was performed. The band SNRs, Figures 3.3.1, show a significant improvement of the swept tone method over the click method at 45dBHL stimulus intensity.

HLeqs and Click – Narrow Band SNR (Special Cases)

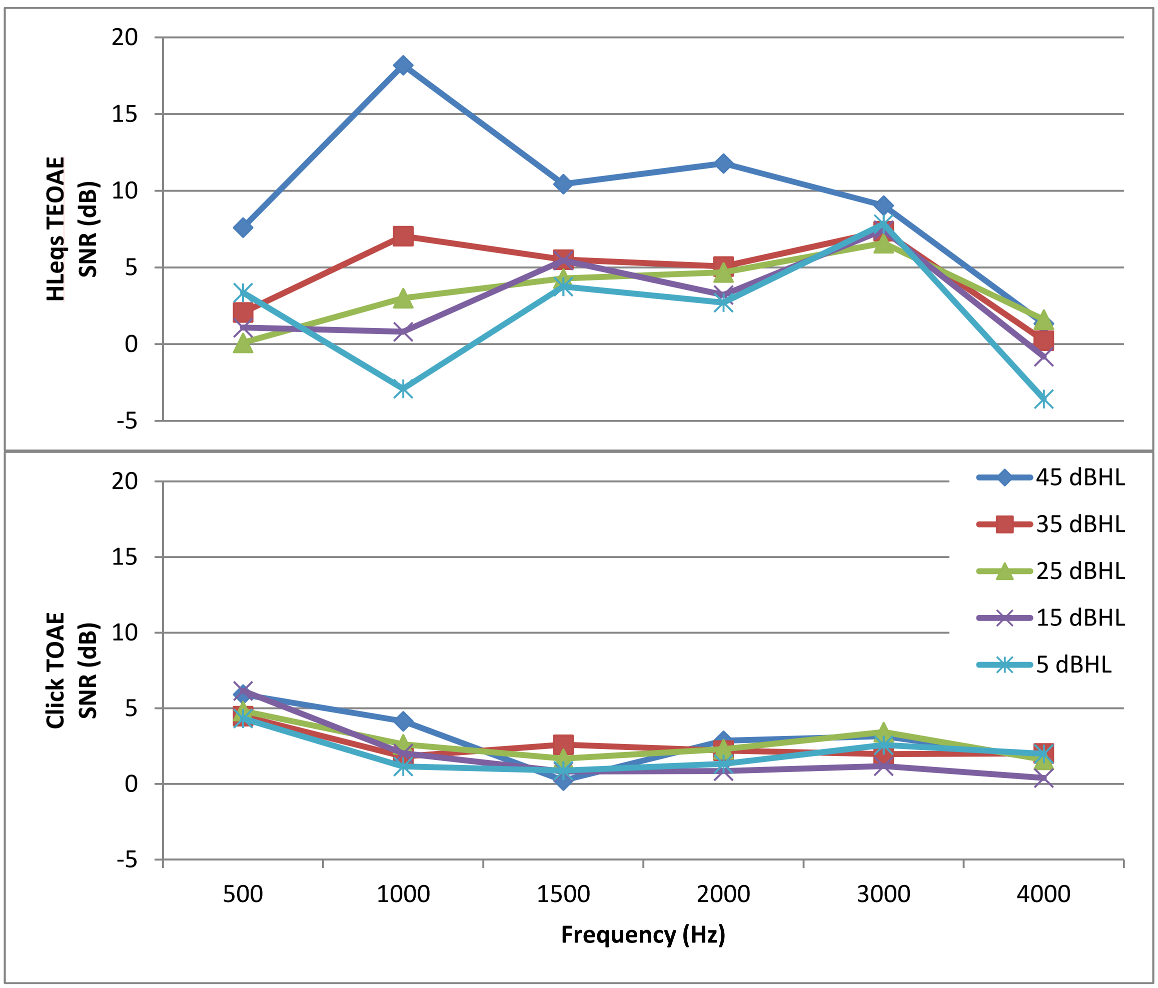


Figure 3.3.1 – Narrow band SNR for HLeqs and Click TEOAE (Subjects with no detectable OAE responses). The HLeqs SNR levels (top) show discrepancy between the response SNR 500-2000 Hz, between 45 and 35 dBHL. Lack of discrepancy at lower stimulus intensities. Some discrepancy can be seen at 1000Hz for all stimulus intensities. Click SNR levels (bottom) show no discrepancy between any of the stimulus intensities.

With the decrease of the stimulus intensity the SNRs HLeqs decrease drastically while the click SNRs stay relatively consistent. The total SNR, Figure 3.3.2, shows a similar behavior where at 45 dBHL stimulus intensity the SNR for the swept tone method is around 12 dB and click is around 3dB.

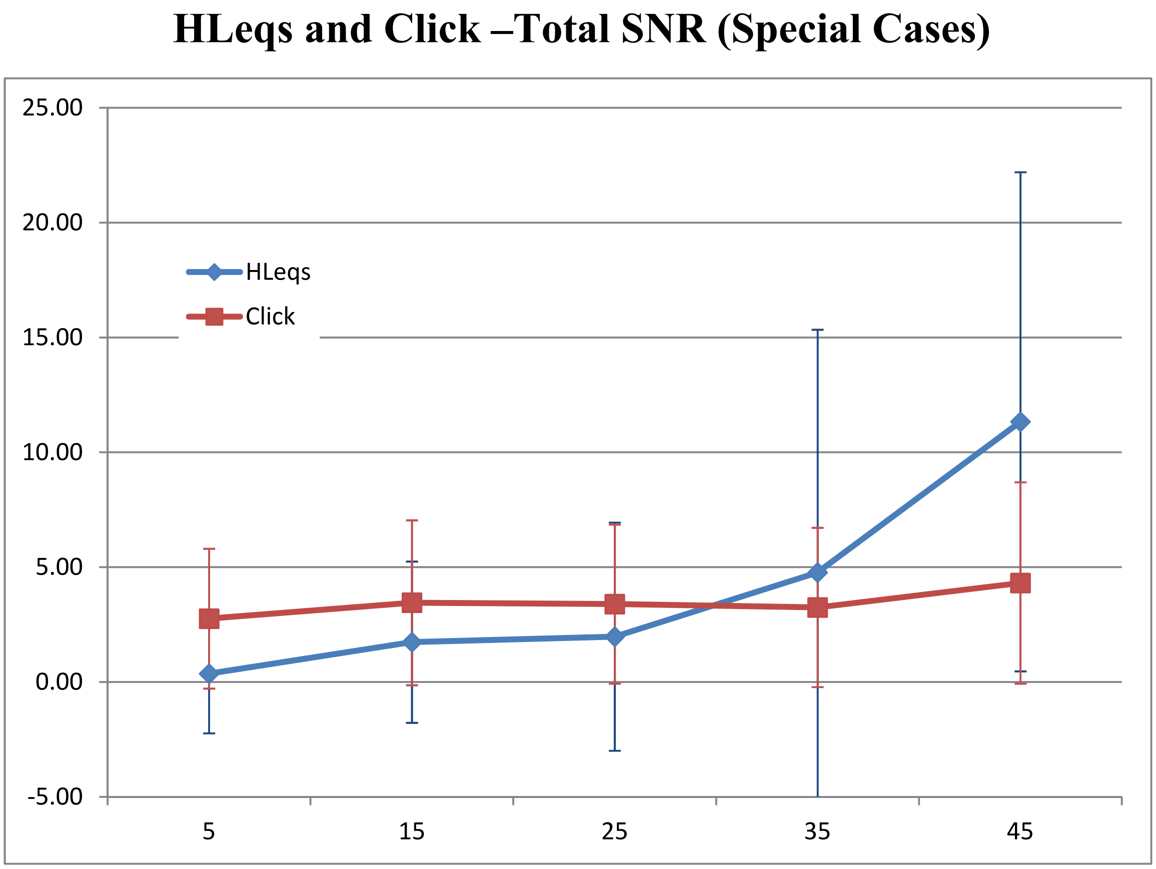


Figure 3.3.2 – HLeqs and Click TEOAE – total SNR with respect to stimulus intensity (Subjects with no detectable OAE responses). The SNR levels for Click (red) are relatively constant across all stimulus intensities. The SNR levels for HLeqs show dependence to the stimulus intensity between 25 and 45 dBHL, the SNR levels increase with increasing stimulus intensity.

The band signal levels in dBSPL for click and swept tone, Figures 3.3.3, show an increase in the overall amplitude of the swept tone over the click method. Additionally, there is more discrepancy between the responses at 45 and 35 dBHL for HLeqs and there is no discrepancy between any of the click responses.

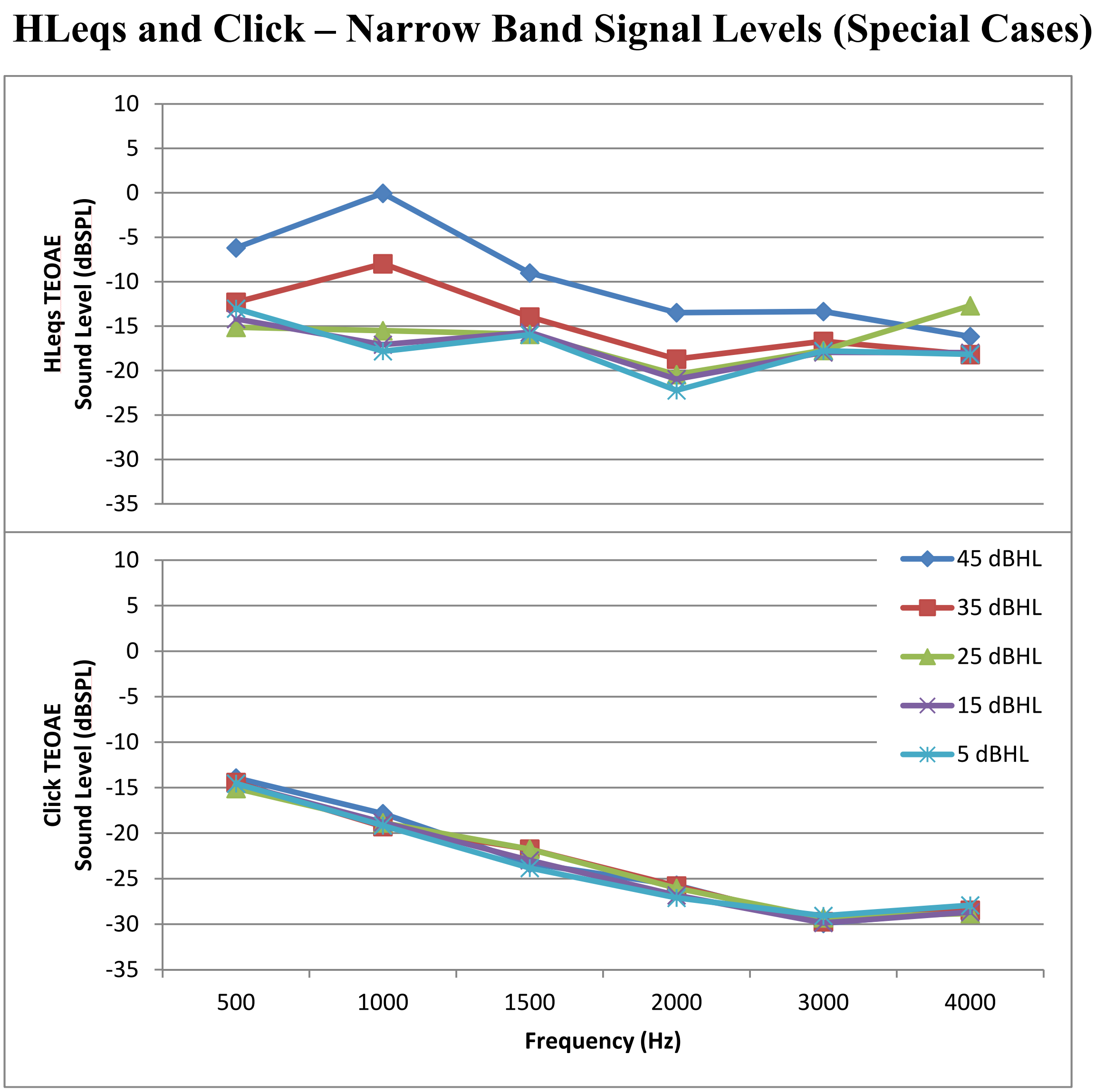


Figure 3.3.3 - Signal levels for HLeqs (top) and Click (bottom) TEOAE (Subjects with no detectable OAE responses showing dependence and discrepancy of the HLeqs signal levels for 25 to 45 dBHL stimulus intensity. Click shows no dependence to stimulus intensity.

The band noise levels Figures 3.3.4, exhibit higher noise amplitudes for HLeqs relative to click. Both methods show dependence to the band frequencies. The noise levels decrease in intensity up to 3000Hz and then start to increase. Additionally the noise levels do not show any dependence to the stimulus intensity.

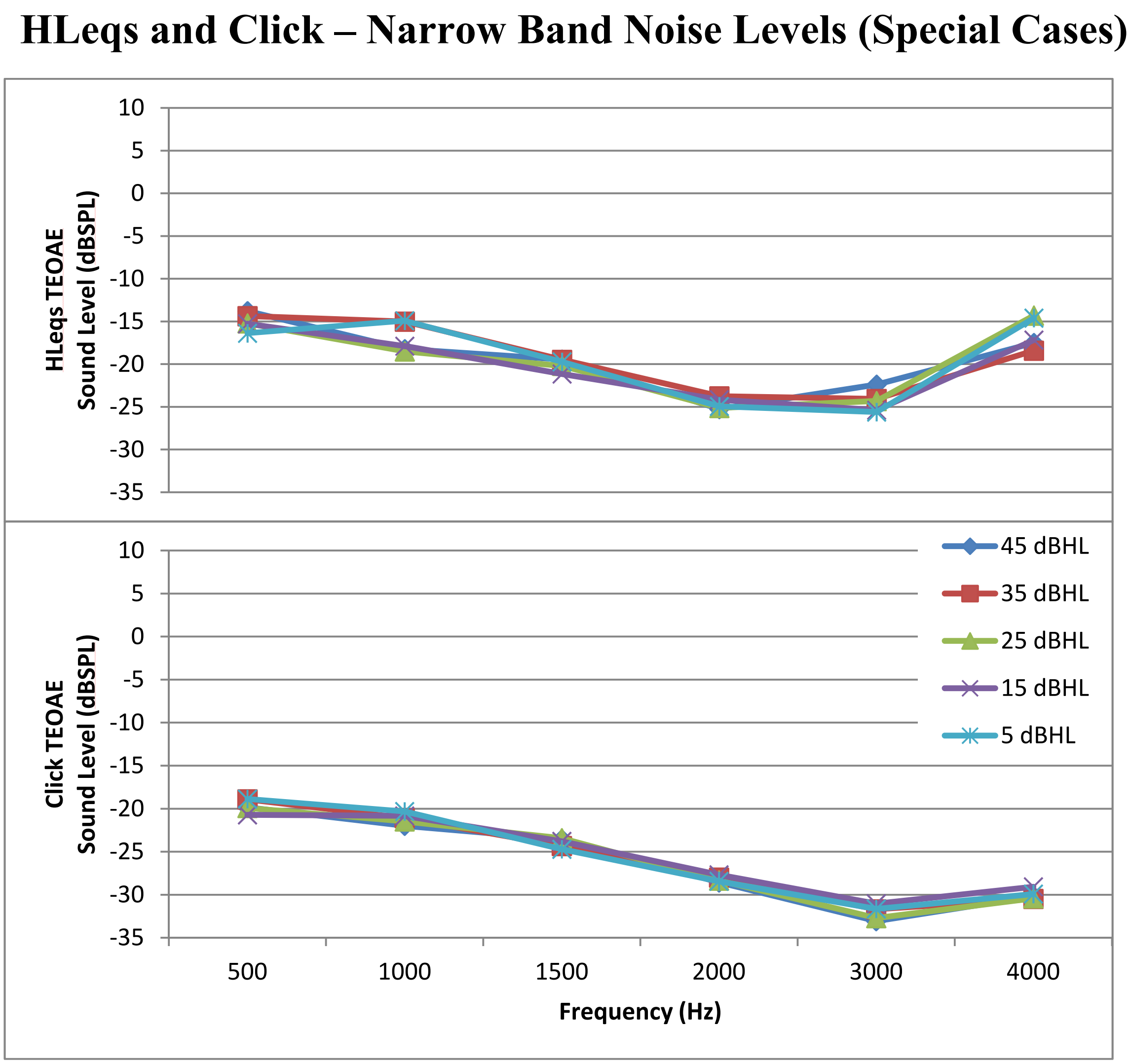


Figure 3.3.4 - Signal levels for HLeqs (top) and Click (bottom) TEOAE (Subjects with no detectable OAE responses). Both methods show independence to the stimulus intensity. HLeqs has higher noise levels when compared to Click.

The total signal and noise levels for both methods, Figures 3.3.5, show an improvement in the signal amplitude levels of the swept tone method over the click method. However, there is an increase of the amplitudes of the noise floor of the swept tone relative to the click method.

HLeqs and Click – Total Signal and Noise Levels (Special Cases)

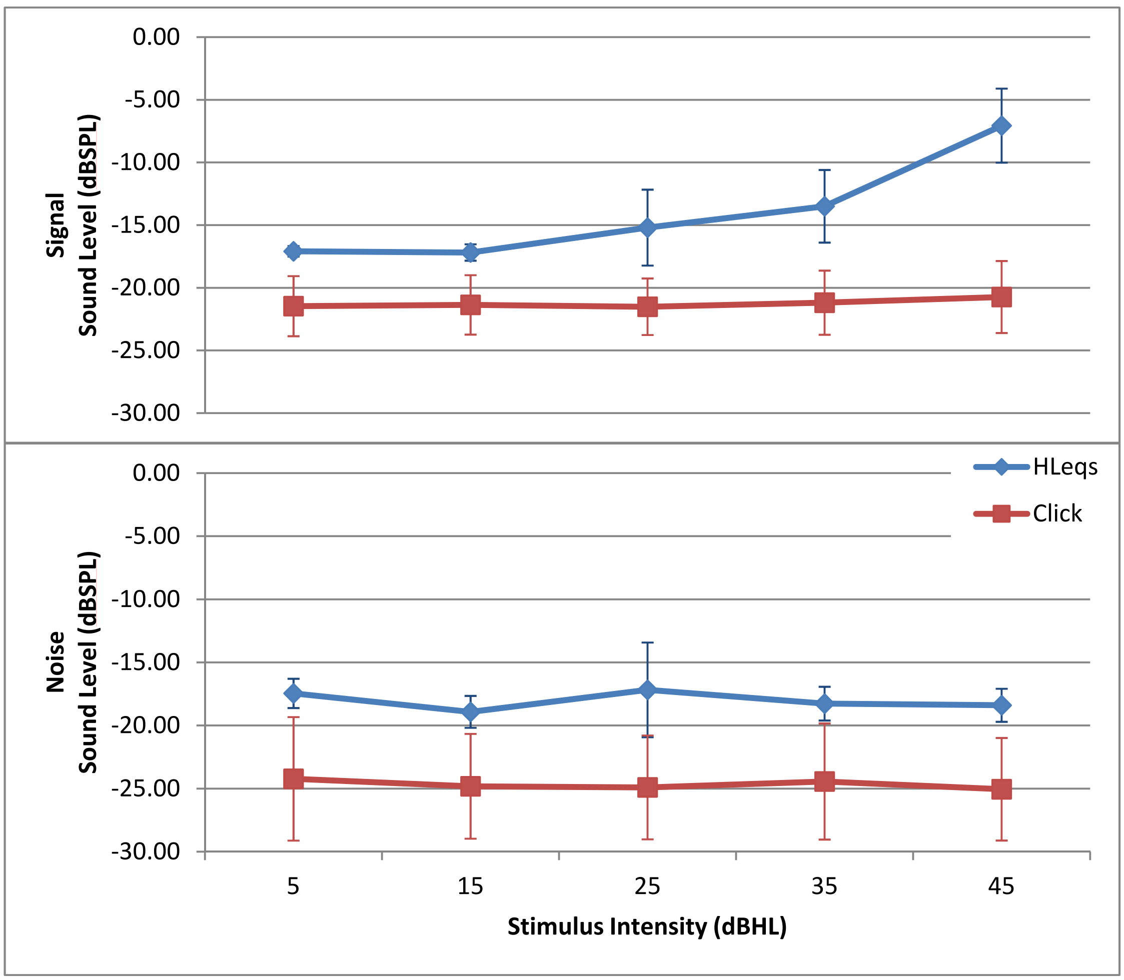


Figure 3.3.5 - Total signal (top) and noise (bottom) levels for HLeqs (red) and Click (blue) TEOAE (Subjects with no detectable OAE responses). The HLeqs signal levels increase with increasing stimulus intensity, Click levels remain constant. The noise levels in the Click recordings are about 7dB lower than HLeqs. Both methods show independence of noise to the stimulus intensity.

Chapter 4 Discussion and Summary

4.1 Signal, Noise, and SNR Analysis of Hearing Level Equalized OAEs

This study focused on the characteristics and morphology of the OAE responses acquired with the hearing level equalized swept-tone method. The band and total signal, noise, SNR values were measured with respect to different stimulus intensities, and compared with the click evoked OAEs.

The general observation regarding the OAE response signal levels is that they decrease steadily with stimulus intensities from 55 down to 15 dBHL and level off between 15 and 5 dBHL (Figure 3.1.5). The response behavior at low stimulus intensities may be explained by the hearing threshold level or the minimum threshold for evoked OAEs (Bonfils et al., 1988). This is also backed by lack of discrepancy in the responses signal levels between 15 and 5 dBHL (Figure 3.1.3).

The noise levels between 5 and 45 dBHL oscillated between -15 dBSPL (±3dB), except at 55 dBHL where it goes up to -9 dBSPL (Figure 3.1.4). The noise levels are expected to be independent of the stimulus intensity, which is observed between 5 and 45 dBHL. The reason for this behavior of the noise is that is dependent on the acquisition system. The band noise levels for 3000 and 4000Hz at 55 dBHL are also elevated when compared to lower intensities. Additionally in Figure 3.1.2 for 55 dBHL the total SNR deviates from the behavior observed at lower intensities. The possible explanation for the 55dBHL irregularity may be explained by the resonance of the ear canal or wave locking due to the stimulus (Bennett and Ozdamar, 2009).

The signal levels at 4000Hz show little discrepancy relative to the lower frequencies (Figure 3.1.3) and similar behavior can be seen in the band SNR at 4000Hz (Figure 3.1.1). This irregularity at high frequencies may result from the noise shaping caused by the convolution with the inverse swept tone, which shifts the noise to high frequencies (Bennett and Ozdamar, 2009).

Another possible explanation for the 4000Hz behavior is the 4ms windowing used to remove the residual MR. The high frequency responses appear first after the stimulus, so the windowing also removes the high frequency responses (Shera and Zweig, 1993; Talmadge et al., 1998).

With the possible exception of 4000Hz frequency and 55dBHL stimulus intensity, the study showed a dependence of the OAE response signal levels to the stimulus intensity, while the noise levels had no dependence. The OAE response signals increased in amplitude with increasing stimulus intensity. Even though the noise did not exhibit dependence to the stimulus intensity it exhibited dependence to the response frequency.

4.2 Comparison of HLeqs and Click TEOAE

When comparing the two methods it is important to note that the click duration is only 100μs and the swept tone is 100ms, the click is a broad band stimulus that stimulates the entire cochlea at once and the swept tone has a controlled bandwidth and stimulates a narrow frequency range at one point in time. Also, click recordings do not need to be deconvolved while swept tone recordings do in order to extract the actual OAE responses.

The HLeqs is capable of evoking OAE responses that are greater in amplitude than the responses from click TEOAE. Looking at the 45 dBHL response (Figure 3.2.3) for both methods, it can be established that for the entire frequency range the swept tone amplitudes are greater than the click amplitudes. Additionally looking at the lower intensities the swept tone is still capable of evoking OAE responses with greater amplitudes. The same can be confirmed in Figure 3.2.5, by observing the total signal levels.

The band noise levels are relatively similar in amplitude in both methods for frequencies between 500 Hz and 2000 Hz, Figure 3.2.4. Difference between the two can be seen in Figure 3.2.5 where the noise floor for click remains constant and between -20 and -25 dBSPL and for swept tone it varies between -15 and -20 dBSPL.

The band SNRs shown in Figure 3.2.1, point to the difference of the signal to the noise floor. At 45 dBHL, the SNR of the swept tone OAE responses are by 6 dB greater when compared to click (Figure 3.2.1), this means that even though noisier the swept tone is still capable of obtaining better SNR than click, because it evokes greater OAE responses.

The case studies also confirm the improvement of the quality of the OAE responses acquired by the HLeqs method. The main point of interest is Figure 3.3.5, where a significant difference between the signal amplitudes can be seen between the two methods. HLeqs at 55 dBHL is capable of evoking a signal of around -6 dBSPL while the click method is only capable of evoking a -24 dBSPL signal. Further on, the minimum signal level for the swept tone is around -17 dBSPL and for click it is around -26 dBSPL.

Major improvement can be seen at high stimulus intensity, 45 dBHL, in Figure 3.3.2 where there is a drastic difference of the total SNR of 11dB.

4.3 Summary, Study Limitations, and Future Improvements

The swept-tone method has been shown to acquire OAEs with better SNR than click with only half the number of sweeps (Bennett and Ozdamar 2010a). In order to be able to acquire swept-tone OAEs a new acquisition system was developed by Bennett and Ozdamar (2009). This system was an Analog Devices® ADSP 21369 EzKit Development board. In addition to the hardware Matlab® software was also developed to make the connection between the DSP and the user.

This study focused on the improvement of the swept-tone method by equalizing the swept-tone stimulus in such a way that it stimulates every segment of the cochlea with equal intensity or loudness. This was done by performing probe calibration and hearing level equalization of the stimulus. The calibration made the output of the probe equal in amplitude for all frequencies. This step alone will produce a swept-tone with a flat acoustic amplitude envelope at the output of the probe. The hearing level equalization will produce a stimulus that will compensate for the irregularities of the ear and the cochlea.

The new hearing equalized swept-tone method (HLeqs) was tested in 22 ears with normal hearing, with audiograms below 30dB HL, with different stimulus intensities. From these recordings it was possible to examine the OAE responses evoked by the HLeqs and get a picture of how they behave, with respect to stimulus intensity and response frequency.

Additionally two subsets of 6 and 4 ears were recorded for clinical click TEOAE at different stimulus intensities, which corresponded to the set of intensities used for HLeqs. The set of 6 ears had normal audiograms and clinically acceptable click OAE responses. The set of 4 ears had normal audiograms and hearing, showed no deficiencies in hearing or speech, but did not have clinically acceptable click OAEs. From these recordings it was established that the HLeqs method was able to produce OAE responses with better SNRs than the click method. Also, the levels of the HLeqs OAE responses were greater in amplitude than the ones of click. The only drawback of the HLeqs method were the higher noise levels relative to click. Additionally, the HLeqs method was able to extract acceptable OAE responses from the subset of 4 ears that did not exhibit clinically acceptable OAE responses, thus making it advantageous over click in such cases.

Even though the HLeqs showed to be advantageous over click, more analysis needs to be conducted in order to provide acceptable evidence. Statistical analysis in this study was not possible due to the small sample size. Additionally the two methods were recorded using two different acquisition devices with different specifications, acquisition parameters, and noise floors.

Further improvement can be made to the system noise levels. The click recordings were done using a clinically approved device while the swept tone recordings were done using custom made hardware that had some advantages in resolution and acquisition rates but it was disadvantageous in providing a low noise environment. All of the analysis showed that the clinical system had lower noise levels than the prototype system used for the swept tone. One possibility is to modify the clinical equipment and make it capable of acquiring swept-tone OEAs. A second possibility is to make changes to the existing

Analog Devices ® DSP system to reduce the overall system noise. A third possibility is to design and build a new system that will have the noise levels of the clinical equipment, or better, and be able to record both click and swept-tone OAEs.

Some HLeqs showed some hearing threshold – like behavior, meaning that at low intensities, around the threshold levels the SNR of the OAE responses were crossing the 0 dB line. It might be possible to make a correlation between where the OAE responses become insignificant and where the hearing level of the subject is. This can also be done by designing a new stimulus equalization contour that will allow for HL threshold detection via OAEs.

This method only explores the amplitude modulation of the swept tone stimulus. Another study can be done that will vary the duration of the stimulus and the time that is spent at each frequency. A longer stimulus will be able to spend more time at one frequency and maybe evoke even stronger OAE responses. One way of looking at this is the number of peaks the sinusoid will have at a given frequency before switching to the next. More peaks gives more time to the cochlea to adjust to the new frequency and respond.

Appendix

1. Swept – Tone Transient Evoked Otoacoustic Emissions

OAEs consist of both nonlinear and linear responses. There are several ways of modeling OAEs: Hammerstein system, Wiener system, or a hybrid of the two Wiener-Hammerstein system. The Hammerstein system is modeled as a nonlinear system and a linear time-invariant (LTI) (Figure A1.1). However, the swept-tone method of evoking and analyzing OAEs only works for a Hammerstein system.

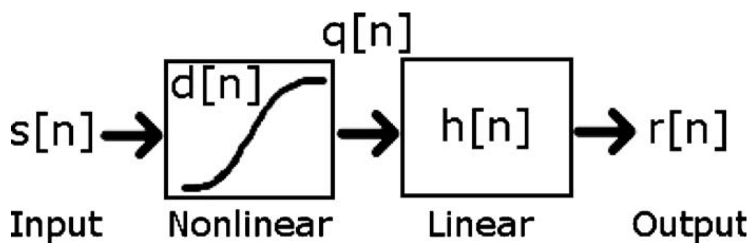


Figure A1.1 – Hammerstein model. From Bennett & Ozdamar 2010b)

The swept tone, s[n], for evoking OAEs was generated according to Equation A1.1 (Bennett and Ozdamar, 2010b). Where f_1 is the starting and f_2 is the ending frequency of the stimulus, T is the duration of the stimulus, and f_s is the sampling frequency.

$$s[n] = \left[\left(\frac{2\pi f_1 T}{\log\left(\frac{f_2}{f_1}\right)}\right) \cdot \left(\left(\frac{f_2}{f_1}\right)^{\frac{n}{f_s T}} - 1\right)\right] \qquad \textbf{Equation A1.1}$$

The inverse swept $s^{-1}[n]$ tone is generated by performing complex division of the stimulus in the frequency domain, 1/S(f). The inverse swept tone also has amplitude envelop with a slope of -10 dB per decade which is applied after the complex division and conversion back to time domain.

Swept tone OAEs are acquired by sending the stimulus, s[n], to the ear and recording the responses, r[n], simultaneously. The recorded response is the result of the convolution of s[n] with the nonlinear responses d[n] and the LTI h[n] of the Hammerstein model to produce the final output r[n] (Figure A1.1).

In order to extract the linear responses h[n] the recorded responses r[n] is deconvolved using the inverse swept $s^{-1}[n]$, $h[n] = r[n] * s^{-1}[n]$ (Figure A1.2) (Bennett and Ozdamar, 2010 a,b).

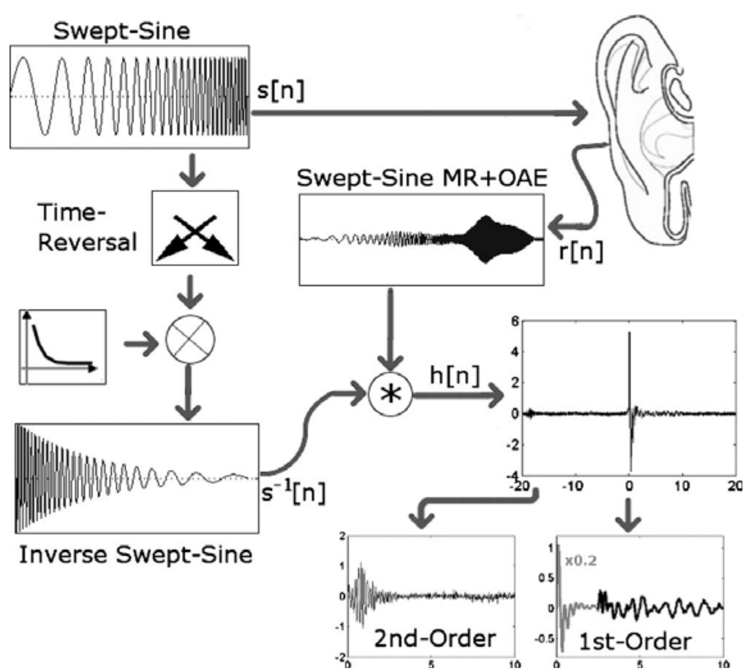


Figure A1.2 – Swept tone OAE acquisition and deconvolution process from Bennett and Ozdamar 2010

2. Sound and Acoustics, Background and Theory

Sound perceived by humans can be explained as rapid fluctuation of air pressure. Humans, on average, can hear within the range from 20Hz to 20000Hz. A unit of pressure is the equivalent value as a unit of force divided by a unit of area. The unit of pressure is the Pascal (Pa).

The ideal pure tone sound, shown in Figure A2.1, consists of a single frequency and can be mathematically described as a continuous sinusoid wave. A 1000Hz pure tone sound will have 1000 air compressions and rarefactions and will cross the zero point 2000 times in one second.

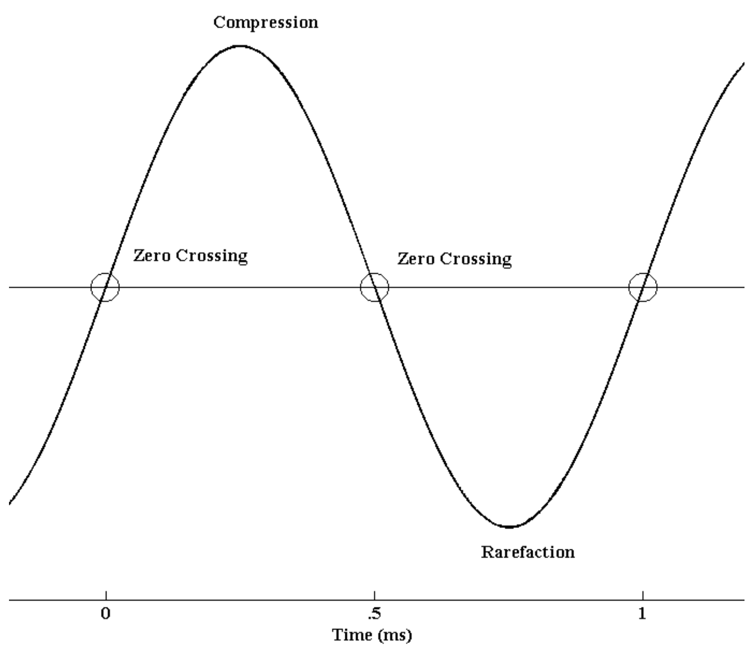


Figure A2.1 – 1 kHz sine wave, with labeled zero crossings, compression and rarefaction stages.

The minimum pressure fluctuation that humans can hear at 1000Hz is 20μPa, root mean square (RMS) (Equation A2.1), where x_n are the digitized values of the measured signal and n is the total number of points measured.

$$RMS = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)} \qquad \textbf{Equation A2.1}$$

Decibel (dB) is a logarithmic representation of two quantities, A and B, where quantity B is a predetermined reference and quantity A is the measured or desired value (Equation A2.2). Decibels are commonly used in acoustics and engineering for calculation amplification and attenuation. Positive dB values mean amplification or A is greater than B, 0 dB means A is equal to B, and negative dB means A is smaller than B.

$$Decibels = 10 * Log_{10}\left(\frac{A}{B}\right)^2 dB \ = 20 * Log_{10}\left(\frac{A}{B}\right) dB \qquad \textbf{Equation A 2.2}$$

When acquiring information or signals from a system it is normal for it to be contaminated with noise. The quality of the signal and the recording can be determined by the signal to noise ratio (SNR). SNR is also calculated in dB (Equation A2.2), however in this case the value of A will be the magnitude signal and B will be the magnitude of the noise. In acoustics commonly the RMS values of the signal and noise of a recording are used for SNR calculations. Ideally, the value of the SNR should be as low as possible below zero.

The magnitude of sound waves is usually quantified as sound pressure level (SPL) or dBSPL. SPL is calculated in dB with Equation A2.2. In this case A is the RMS value of the recorded or desired sound pressure (*Prms)* and B is the reference pressure (*Pref)*. The previously mentioned 20µPa threshold level for humans is the reference value used for calculating dBSPL (Equation A2.3).

$$SPL = 10 * Log_{10}\left(\frac{P_{rms}}{P_{ref}}\right)^2 = 20 * Log_{10}\left(\frac{P_{rms}}{20\mu\mathrm{Pa}}\right) dB \qquad \textbf{Equation A2.3}$$

Detailed explanation of the previous can be found in “Engineering acoustic an introduction to noise control” by Moser (2009) and “Principles of Vibration and Sound” by Rossing and Fletcher (1995).

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