AALBORG UNIVERSITY

MASTER THESIS

Assessment of crossed auditory paths using Distortion-Product Otoacoustic Emissions

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A thesis submitted in fulfilment of the requirements for the degree of Master programme in Acoustics

in

Acoustics
Electronics Systems

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Declaration of Authorship

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Abstract

Engineering and Science
Electronics Systems

Master programme in Acoustics

Assessment of crossed auditory paths using Distortion-Product Otoacoustic Emissions

by Pablo CERVANTES FRUCTUOSO

Middle Ear and Medial Olive-cochlear reflex can be activated by means of contralateral stimulation in humans. Their activation produces a change in DPOAE amplitude that can be measured at the entrance of the ear canal. Since both reflexes are activated at the same time, assessment of one of the two reflexes isolated using OAEs becomes a difficult task. 15 normal-hearing subjects have participated in the experiment performed in the present study. Since MEM reflex shows an adaptation behavior to sound exposure, long contralateral stimulation (60 seconds) is used for separation of MEM and MOC reflex. DPOAE is elicited during 80 seconds (10 seconds of pre and post exposure each one) monitored during the whole measurement. DPOAE frequencies studied are 520, 1000, 2000, 30000, 4000 and 5040 Hz. CAS used is white noise with bandwidth [300 - 3000] Hz. Pre and post exposure levels are used as reference values for the calculation of DPOAE amplitude shifts originated by the activation of the ear reflexes. Adaptation on DPOAE amplitude shift is observed for all subjects in at least 1 frequency. Maximum DPOAE amplitude shift attributable to MOC reflex is 2.38 dB for 1000 Hz. Maximum DPOAE amplitude shift (at CAS onset) is 3.28 dB at 1000 Hz.

Reading Guide

The Thesis documentation is divided into the following three parts:

- **Report:** is the main documentation for the thesis and is chronologically composed. To understand the thesis it is recommended to read this part. The report is divided into several smaller sections. A problem formulation section where the problem is described. Analysis part where theory and practical issues are discussed and analyzed. An implementation section where the development of experiments performed are explained and finally a conclusion.
- **Appendices:** include further and deeper information about the thesis. However the appendices are not mandatory for the thesis understanding. Raw data, measurements and other information of low importance are placed in this part.
- **DVD:** includes Matlab codes, pictures, etc. Documentes which have very low importance for thesis understanding or data not printable. The DVD also contains the report and the appendices in pdf format.

References of used material are written in squared brackets with author and surname and year of publication. The same is applicable for webpages but only the page name is in the brackets. A total list of references is available in section Bibliography

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Dedicated to my parents…

Chapter 1

Introduction

1.1 Introduction

Otoacoustic emissions (OAEs) are signals generating in the cochlea, and its study has become of a big importance in medical assessment, since they could be measured for first time in 1978 by David T. Kemp.

The aim of the present project is to study the possibility of the use of Distortion Product Otoacoustic Emissions (DPOAEs) for the measurement of the medial olivocochlear effect (MOC) and the middle ear muscle reflex (MEM).

These two reflexes are of a big importance in the assessment of clinical hearing state. Extended research can be found in the use of DPOAEs for the measurement of MOC reflex but few can be found for MEM reflex assessment. Thus, an investigation of an entire procedure for the measurement of MEM and MOC reflexes will be developed.

An experiment will be carried out on normal-hearing people with the aim of measuring the two different reflexes mentioned before which will be completed with an analysis of the data obtained.

As it has been mentioned at the beginning of this section, OAEs will be the main topic of the work in this project. For the better understanding of what they are and how they originate, firstly an overview of the main aspects of the auditory system will be introduced for a deeper development in certain aspects that are of a big consideration for a better understanding of OAEs.

1.2 Problem Formulation

Medial olivocochlear reflex (MOC) and middle ear muscle reflex (MEM) are important mechanisms in the hearing process. Both reflexes are part of protection mechanisms against loud sounds and MOC reflex is also believed to play an important role in the detection of sounds in noisy environments. Although they share similar functions, the underlying mechanisms involved in the activation of both reflexes are different.

Nowadays, MOC reflex can be measured using OAEs, observing the effect of its activation on amplitude and phase of OAEs response. Since MEM reflex can be activated by the same stimulus which is used for MOC reflex elicitation, care has to be taken when reflex SPL elicitor is chosen for the study of MOC reflex. One way of overcome this problem is the use of low elicitor stimuli levels, but it has been prooved that little stapedius muscle contractions are difficult to measure, arising the uncertainty of MEM reflex presence, thus, clinical hearing assessment derived from MOC measurements is limited. Therefore, to enable MOC measurements as a useful clinical tool for hearing assessment, accurate quantification of MEM reflex's influence on MOC measurements is required.

Chapter 2

Analysis and Theory

2.1 Introduction

OAEs are acoustic signals originated in the cochlea. The reason for them to originate and the how they reach the outer ear for us to be able to record them hides behind the explanation of how our hearing process is developed from a single sound event in the environment, to a sound event in our brain.

Following, an overview of our auditory system is presented. The reading of this chapter is highly recommended if the reader is not familiar with anatomy and physiology of the ear and hearing process, on the other hand, this chapter can be skipped if the reader has experience and is familiar with the topic.

The present chapter is based on [Gelfand, 2010a, Fuchs, 2010, Lustig, 2010, Rosowski, 2010].

2.2 Auditory System

The auditory system (AS) is the sensory system related with hearing. It consists of every element in our body which has an effect on the sound perception. The main role of the AS is the conversion of sound from the environment to bioelectrical signals that can be interpreted by the brain. AS can be divided into three different parts.

Middle ear: it consists of the minute bones responsible for the transmission of eardrum vibrations to the inner ear. These bones are placed in a air-filled cavity between the external ear and the inner ear. Muscles, tendons, and other tissues located in this cavity are also considered a part of the middle ear.

Inner ear: Cochlea.

2.2.1 External ear

The external ear consists of the head, torso, pinna, concha, ear canal and eardrum. Its function is to carry the sound from the environment to the eardrum in order to set it into motion (vibration of the eardrum).

The pinna is the visible part of the ear. Its shape facilitate the reception of the sound from certain directions carrying the sound to the concha which is the entrance of the ear canal, thus, because of its direction-dependent influence on the sound, it has an important role in source localization.

The ear canal is a slightly S-shaped tube of about 9 mm high by 6.5 mm wide and 2.5 - 3.5 cm long. It usually contains wax and sebaceous for protection against microbes.

The tympanic membrane or eardrum, is a flexible, thin membrane located at the end of the ear canal, which make contact with the tiny bones located at the middle ear.

2.2.2 Middle Ear

The middle ear is the cavity that is behind the tympanic membrane. Once the sound pressure is carried by the external ear to the eardrum, this pressure will make the tympanic membrane to vibrate. This vibration is conducted to the cochlea by three small bones, which are jointed forming a chain.

The three bones are the smallest bones in the body and are called, *malleus incus* and *stapes*. These three minute bones have the function of effective transmission of the motion energy of the eardrum to the cochlea. The cochlea is filled up with a liquid substance with mechanical characteristics very similar to water and if we compare it with the air, we can say that this fluid is almost uncompressible.

Obviously, in the energy path from the eardrum to the cochlea, there is a big change of the characteristic impedance of the media, which will lead to losses and thus to an inefficient energetic transmission. But it turns out that this transmission of energy is highly efficient. The main function of the ossicles chain is to work as an impedance matching between the external ear and the inner ear.

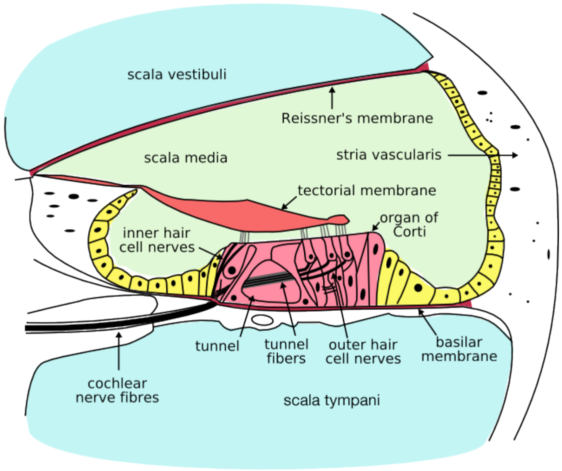

Figure 2.1: Drawing of a cross-sectional view of the cochlea and its components. [Wikipedia, 2013a].

2.2.3 Inner ear

The inner ear is the cochlea. The cochlea is the organ responsible of the conversion of the vibrations of the eardrum into neural response. The cochlea is a complex coil-shaped organ that is divided into three cavities. These cavities are *scala vestibule, scala tympani* and *scala media*. The cochlea presents two openings covered with two flexible membranes in its surface of big importance in the hearing process. These membranes are the oval window, giving access to the *scala vestibule* and the round window, giving access to the *scala tympani*, see figure 2.2.

In the *scala media*, lying beneath the scala media, is the Organ of Corti. The organ of Corti lyes on the basilar membrane (BM). The organ of Corti has supporting cells and the hair cells. Within the *scala media* is the tectorial membrane, which is mechanically connected to the hair cells.

Scala vestibule and *scala tympanni* are connected through the apical part of the BM, the helicotrema. These cavities are filled with a low potassium and high sodium aqueous substance called perylimph. The *scala media* is filled with a high potassium and low sodium aqueous substance called endolymph, leading to an electrical voltage difference between the basal surface of the hair cells and their apical surfaces called *Endocochlear Potential* (EP).

2.2.3.1 Basilar Membrane (BM)

The basilar membrane is a structure located under the organ of Corti between the scala tympani and the *scala media*. It is extended along the cochlear spiral and it is excited by the motion of the cochlear fluids caused by the motion transmitted by the middle ear. Basilar membrane is stiff and narrow at its base and it progressively becomes wider and more flexible along the cochlea.

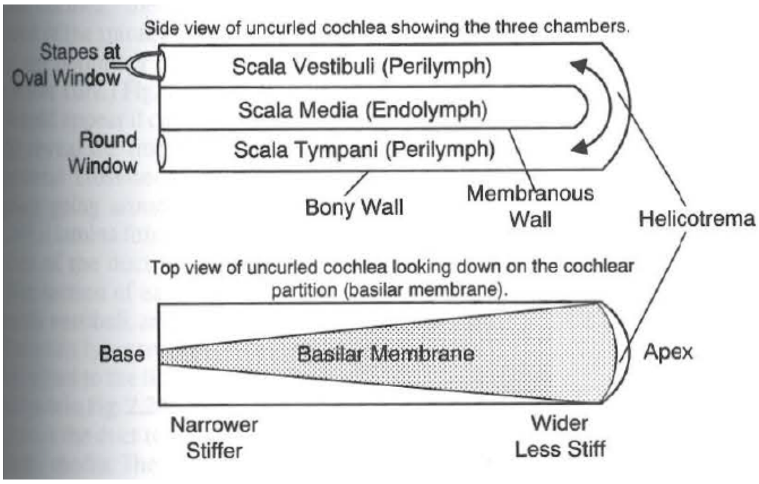

Figure 2.2: Scheme of basic structure of Cochlea. Openings in the cochlea, cochlear cavities and basilar membrane. Picture extracted from[Gelfand, 2010a]

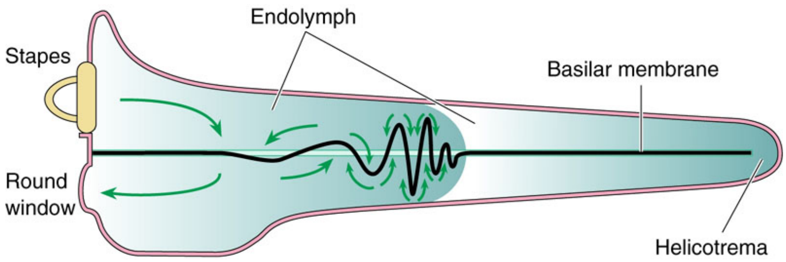

Figure 2.3: Basilar membrane motion. The travelling wave. Picture extracted from [Pedersen, 2012].

Its elasticity is uniform along the cochlea and it is fixed along its sides. Motions of the fluids will excite the membrane creating a wave called the travelling wave, see figure 2.3

2.2.3.2 The Travelling Wave

The travelling wave theory was proposed by Bekesy in 1960. It aims to explain how the frequency content of a sound is coded by the cochlea taking advantage of the vibration of the basilar membrane. As it is mentioned before, the basilar membrane is stiffer at its base and more flexible at its apex and this change is produced in a progressive way. Because of this, sound reaching the cochlea creates a wave that always moves from the base to the apex as it is illustrated in figure 2.3.

As it can be seen in figure 2.3, the amplitude (displacement of the basilar membrane in vertical direction in figure 2.4) characteristics of the wave can be described as following:

- The amplitude of the wave is increasing gradually up until a peak is reached in a certain location of the basilar membrane.

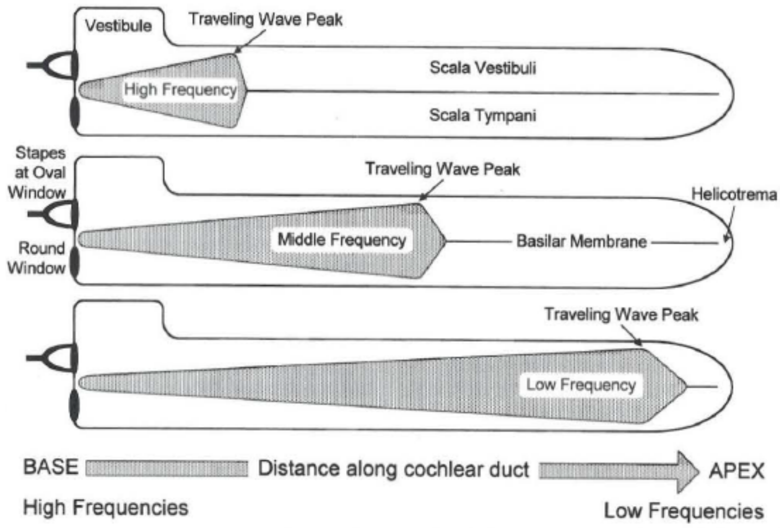

Figure 2.4: Frequency content location in the basilar membrane. Pictured extracted from [Gelfand, 2010a].

- After the peak is reached, the amplitude of the wave decreases very quickly very fast.

The location of the basilar membrane where the peak is reached depends on the frequency of the sound. Therefore, the basilar membrane has the ability of "transforming" frequency information in spatial (location) information, this characteristic is called *tonotopic organization*. Because of mechanical properties of the basilar membrane, high frequency content will create displacements of the basilar membrane at its base, and low frequency content will do it at its apex, see figure 2.4.

The travelling wave will cause the movement of the reticular membrane and the tectorial membrane relative to one another.

2.2.3.3 Hair cells

Hair cells are mechanosensory cells placed on the organ of Corti. The organ of Corti contains other kind of non-sensory cells which help to stiff the cochlear partition. Hair cells present in their apical surface microscopic haired-structures called stereocilia and they are connected between them through small filaments called tip-links.

The hair cells are divided into two different groups and their names come from their position with respect the organ of Corti, although they present more differences between them than their location.

- **Outer Hair Cells (OHCs):** they are arranged in 3 to 5 rows in humans. There are about 12,000 of them with 140 stereocilia each one. They're joint to the tectorial membrane.

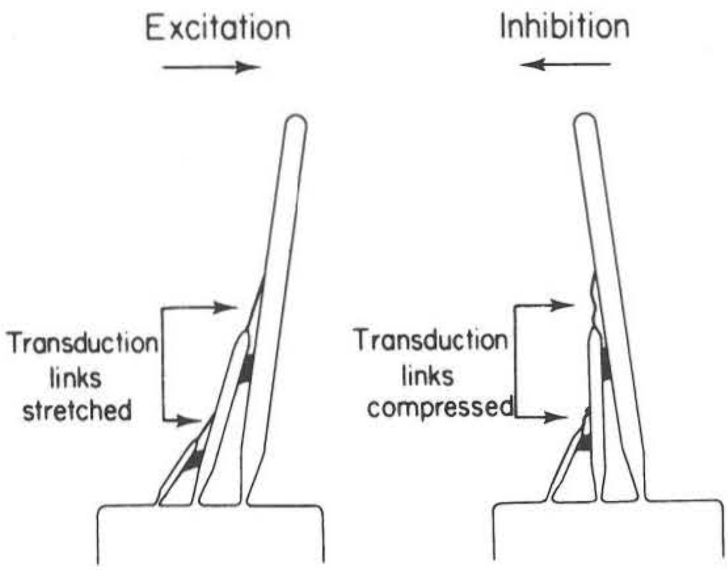

Figure 2.5: Connection between stereocilia through tip-links mechanism. Pictured extracted from [Gelfand, 2010a]

Tectorial membrane motion (produced by the travelling wave see section 2.2.3.2) causes displacement of the OHCs, [Moore, 2012].

- **Innerr Hair Cells (IHCs):**: they are arranged in one row with around 3,500 IHCs with 40 stereocilia each one. They are not connected directly to the tectorial membrane but indirectly through fluid viscosity, [Fuchs, 2010].

Hair cells are activated when their stereocilia are bent in one direction causing the opening of a pore at the top of each stereocilia, which permits the flow of potassium ions through the hair cell, activating it (excitation). If the stereocilia are bent in the opposite direction, tip-links will close the pore, inhibiting the hair cell (inhibition). This process is how the hair cells transform mechanical motion into electro-mechanical response which will be transmitted to the auditory neurons connected to the hair cells. In figure 2.5 we can see in detail how this mechanism works.

2.2.3.4 Hair cell Innervation and function and Auditory pathways

Hair cells are connected to the auditory nervous system. The innervation of the cochlea is made by efferent and afferent neurons.

Efferent neurons provide a communication channel from auditory nervous system to the cochlea, whereas afferent neurons provide communication in the opposite direction, this is from cochlea to auditory nervous system.

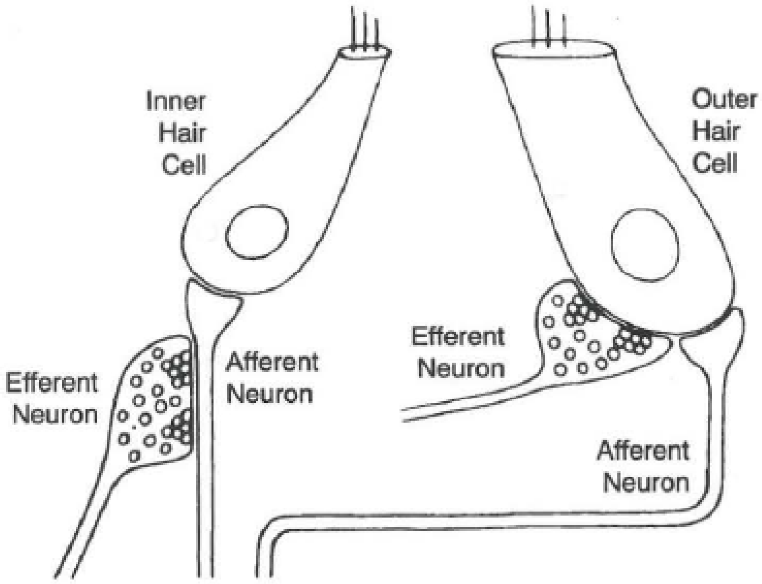

Figure 2.6: Efferent and afferent neurons synapse with OHCs and IHCS. As it can be seen efferent neurons act directly on OHCs and indirectly through the afferent neuron associated on the IHCs. Picture extracted from [Gelfand, 2010a].

Efferent communication is made via the olivocochlear bundle (OCB) which is a series of pathways from the superior olivary complex (SOC).

SOC is a collection of brainstem nuclei that plays an important role in the auditory pathways. It is divided into three different primary nuclei:

- **Medial Superior Olive (MSO):** it is thought to help in source localization in the horizontal plane (azimuth). It is the largest nucleus, and it contains around 150,500 neurons. One of its principal functions is detection of different time arrivals of a sound to the two ears, [Wikipedia, 2013b].
- **Lateral Superior Olive (LSO)**: as the MSO, its main function involves source localization but in this case, LSO detects different sound intensities between sound arrivals to the two ears at the same time, [Wikipedia, 2013b].
- **Medial nucleus of the trapezoid body (MNTB):** it plays an important role in the interaural intensity differences. Principal cells of MNTB receive their input from the contralateral cochlear nucleus, [Wikipedia, 2013b, C. Kopp-Scheinpflug, 2008]

Approximately, 1,600 efferent neurons enter the temporal bone from the OCB, and then separate to enter the cochlea ending up in the hair cells. Most of the efferent neurons synapse with OHCs, whereas afferent neurons synapse with IHCs, see figure 2.6.

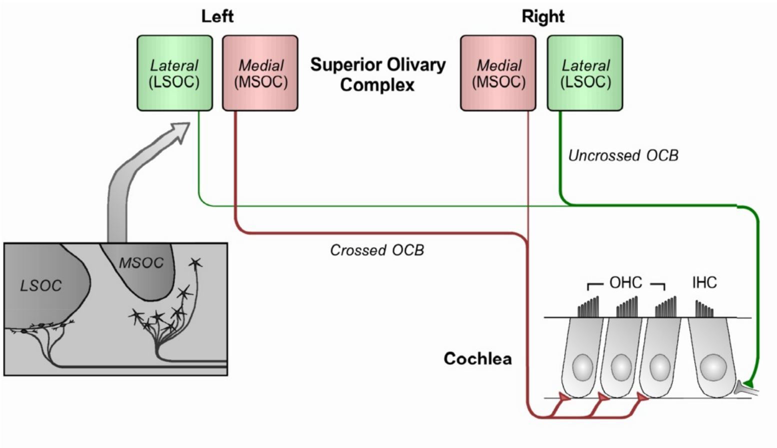

Figure 2.7: scheme of auditory pathways from SOC to the cochlea. Green lines represent LOCs fibers and red lines represent MOCs fibers. Right cochlea example. Picture extracted from [Wikipedia, 2012].

OHCs are connected to medial olivo-cochlear efferent neurons (MOCs) and the activation of these fibers inhibits basilar membrane response to low level sounds. These fibers originate in the medial part of the SOC (on both sides) and project to the cochlea through the vestibular nerve, [John J. Guinan, 2006].

Another kind of efferent neurons exists, lateral olivo-cochlear neurons (LOCs). These fibers originate mainly in the ipsilateral part of the brain (for the right cochlea on the right part and vice versa) and innervate nerve fibers under IHCs. It is important to mention that both kind of fibers project collaterals into the cochlear nucleus and to brainstem vestibular nuclei (right part of brain to left cochlear nucleus and vice versa) [John J. Guinan, 2006], see figure 2.7.

2.2.3.5 The Cochlear Amplifier

IHCs send information when they're enough excited by the movement of the cochlear partitions (concretely relative movement of the tectorial membrane with the reticular lamina) to higher auditory levels.

OHCs are able to return mechanical energy to the cochlea. This process depends on the neural signals received by OHCs through the OCB. OHCs are able to respond to electrical signals changing their shapes either increasing their lengths or decreasing it around a resting length. This ability is called electromotility [Brownell, 1990].

This OHCs ability helps increasing the displacement of the basilar membrane, amplifying the signal received by the IHCs. Due to the tonotopic organization of the location of OHCs on the organ of Corti, the motion of OHCs is frequency dependent, meaning that not all OHCs of the organ of Corti will move at the same time but just those ones located in the right frequency place of the Organ of Corti. This will help to concentrate the amplification into a small range of frequencies leading to a sharp peak on the travelling wave.

Therefore there is a mechanical-electrical-mechanical feedback loop between IHCs and OHCs which helps us to distinguish small frequency differences, this is *frequency discrimination*, and increases our hearing sensitivity.

This energetic process is also believed to be the origin of OAEs.

Chapter 3

Otoacoustic Emissions (OAEs)

3.1 Introduction

Following, an overview of OAEs generation is carried out. The reading of this chapter is highly recommended if the reader is not familiar with otoacoustic emissions, on the other hand, this chapter can be skipped if the reader has experience and is familiar with the topic.

Cochlear amplification system is the way that the inner ear has for re-gain the energy lost by viscous damping. Researchers believe that this mechanism injects more energy than just the energy which has been lost in the propagation of the travelling wave. A small part of this energy comes back to the eardrum and creates OAEs. An *auditory response* is defined as a detectable electrical or mechanical signal originated in the cochlea due to a stimulation. An auditory response is a leakage of energy from the energetic processes involved in the hearing activity.

Otoacostic emissions are sounds created by vibrations of the eardrum and which are a direct byproduct of the hearing process [Kemp, 2010]. In the hearing process, vibrations travel from the eardrum to the cochlea while in the production of OAEs, vibrations travel in the opposite direction, from the cochlea to the eardrum, making it to vibrate and therefore originating sound that can be recorded at the entrance of the ear canal.

OAEs generally can arise in two different ways:

- evoked, or stimulated OAEs
- internal self-stimulated; spontaneous OAEs

3.2 Spontaneous Otoacoustic Emissions (SOAEs)

They consist of single pure tones continuously emitted by the ear. They are result of an accidental feedback loop, where vibrations of OHCs are sent to the middle ear and these are reflected again to the cochlea exciting the same OHCs.

These emissions will just occur if the reflected signal at the eardrum is at least equally strong than the original signal. The clinical use of SOAEs is not very extended because not all healthy ears present this kind of emissions.

3.3 Stimulated Otoacoustis Emissions

The majority of OAEs measurements are done using a stimulus for the generation of OAE. Different methods can be used to obtain OAE measurements, but it is worth to mention that depending on the method used, different components of the OAE will be measured.

Following a description of different methods for the measurement of evoked OAEs will be presented

3.3.1 Transient Evoked Otoacoustic Emmissions (TEOAEs)

This method consists of stimulating OAEs with click stimuli. Theyre widely used in newborn hearing screening.

Normally TEOAEs are measured immediately after the presentation of the stimulus over a period of time of about 20 ms, where the pressure fluctuations created by the eardrum after the stimulation are recorded.

Normally peak amplitudes of around 80 dB and 90 dB SPL are used for the click stimulus. The response wave from is usually 100 times smaller and much more complex than the stimulus waveform. Intersubject variability is very large, from 5 up to 35 dB, but the response of an ear is very stable over years. Therefore they are useful for hearing health evolution over time.

Tone bursts can also be used for the measurement of TEOAEs, but over a limited frequency range. The frequency range of TEOAEs will be similar to that of the stimulus.

TEOAEs are frequency specific and frequency place specific. Since the cochlea is tonotopic organized, the waveform of TEOAE in a certain frequency is highly related with the hair cell activity in the place of the cochlea where this frequency is processed. This is very clinically useful because any damage in a specific part of the organ of Corti will be reflected in a reduction of intensity of TEOAE frequency-place related level.

An effect on TEOAEs can be seen when another stimulus is presented to the other ear (the one that is not tested), contralateral stimulus, activating MOC reflex, see 4.3.

3.3.2 Stimulus Frequency Otoacoustic Emissions (SFOAEs)

If a single tone is used for the evocation of the otoacoustic emission, a single tone will be obtained as a response. One of the biggest drawbacks of this OAE's component is the separation of the cochlear emission from the stimulus used in its elicitation, being mor difficult the extraction of the OAE response from the measurement of the sound pressure level in the subject's ear canal.

This is usually overcome calculating the delay of the emission and response.

3.3.3 Distortion Product Otoacoustic Emissions (DPOAEs)

DPOAEs are emissions created by distortion vibrations generated but OHCs. These distortions are generated because of the non-linearity response of the cochlea when it is excited by a pair of tones called *primary tones* and noted as f_1 and f_2.

This non-linearity of the cochlea is easy to prove when two tones are applied to the ear at the same time. As it can be seen in figure **??**, the amplitude of the travelling wave is increasing progressively up until reach a certain peak. After the peak is reached the amplitude decays quickly. This makes low frequency content to mask easier high frequencies than opposite, due to the fast decay of travelling wave amplitude in the lower frequency region with respect the peak. Therefore, if two tones with different frequency are presented simultaneously, their respective travelling wave's peaks will overlap. Of course this will depend on the frequency difference. When this happens, if the lower frequency is strong enough in level, it will make the higher frequency wave peak smaller and wider.

Let's say that we two primary tones of frequencies f_1 and f_2, where f_2 is higher in frequency. If the ratio between f_2 and f_1 is smaller than 1.3, intensities of both travelling waves will affect each other's leading to a decrease in intensity of both travelling waves[Kemp, 2010]. Therefore any OAE produced by these travelling waves will be reduced in intensity, which is called two-tone OAE supression.

OHC's response contains new frequency components, called intermodulation distortions. These intermodulations distrotions are a mechanical process, and it can be predicted. Therefore, we

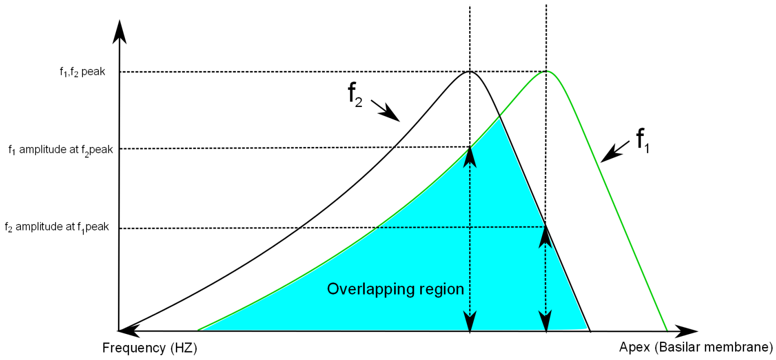

Figure 3.1: Schematic representation of basilar membrane displacement when it's excited by two tones with close frequencies. As it can be seen, basilar membrane displacement due to f_1 will contribute to the basilar displacement created by f_2 much more than f_2 BM's displacement to BM's displacement created by f_1 excitation

can predict, which "new" frequencies are going to be added to the OAE response, knowing the frequencies f_1 and f_2. This is one of the biggest advantages of DPOAE.

Intermodulation products occur at frequency spaces of $f_2 - f_1$ above and below the original frequencies, and they can be predicted by the equation 3.1

$$f_{DP} = f_1 + N \cdot (f_2 - f_1) \tag{3.1}$$

Where N $\in \mathbb{Z}$

In humans, DPOAE component $2f_1$-f_2, also called *cubic* component, is the most significant in terms of cochlear health assessment [Kemp, 2010] and the higher in amplitude in humans [Thomas Jannsen, 2005].

3.3.3.1 Optimal frequency relation f_1/f_2

If we consider frequencies f_1 and f_2 travelling through the basilar membrane, and these frequencies are close enough, there will be a region on the basilar membrane with displacement overlapping. Since f_2 is located in a more basal place than f_1, when the travelling wave of f_2 reaches its peak, part of the displacement of the basilar membrane due to f_1 will contribute to a higher displacement in f_2 basilar membrane location, see figure 3.1.

Experimentally, it has been prooved that higher DPOAE's amplitudes are not generated with smaller ratios f_2/f_1 even though the conditions seems to be optimal, but there is a ratio between f_1 and f_2 where the spatial distribution of distortion products is optimal for their travelling back to the middle ear. According to [A., 2000], this ratio has been proved to be around 1.2 for cubic DPOAE component $2f_1 - f_2$.

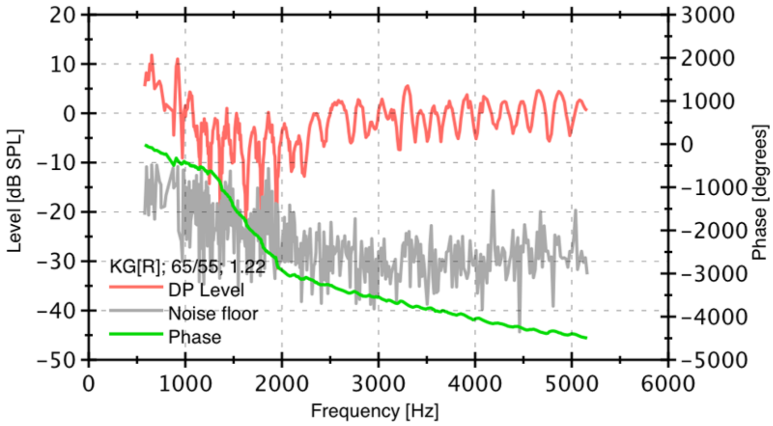

Figure 3.2: Example of DPOAE where fine structure can be seen (peaks and deeps in DPOAE response). Plot exctrated from [fin, 2013]

3.3.4 DPOAE sources

Recent studies support the idea of that two different sources are involved in the generation of DPOAE. One component is, as mentioned before, created by intermodulation, and other one is originated by a reflection [George Zweig, 1995].

The distortion product (DP) energy originated by intermodulation, can travel along the basilar membrane as if an external sound with frequency equal to that of DP would have reached the inner ear. A part of this energy travels back directly to the middle ear, meanwhile, other part of the energy will travel apically (suppossing a distortion product with lower frequency than f_1 and f_2, for instance $2f_1 - f_2$) to the DP specific frequency location at the basilar membrane, and can be reflected back due to inhomogenities on the basilar membrane. Therefore two signals with the same frequency content will add together at the signal recorded in the ear canal. As one of them has travelled along the basilar membrane to its frequency specific place, these two signals can have different phases and add in a destructive way.

This phenomenon arises constructive and destructive interference between the two sources, leading to what it is called DPOAE fine structure, see figure 3.2.

3.3.4.1 Optimal frequency relation l_1/l_2

Many researchers have studied the optimal relation between SPL levels of primary tones in terms of obtaining the biggest DPOAE amplitude.

Optimal relation l_1/l_2 is described by the equation 3.2 proposed by [Boege P., 1999].

$$l_1 = 0.4 \cdot l_2 + 39 \tag{3.2}$$

Where l_1 and l_2 are in dB units

In general, most of the studies made on this topic point out that DPOAE amplitude level is mainly dependent on the level of primary tone f_1, l_1. According to [M. L. Whitehead, 1995b], when $l_1 \geq 75$ dB, mean DPOAE's amplitude decreases when level of the primary tone f_2 is presented below the level of f_1. However, mean DPOAE's amplitude increases when $l_1 = 65$ dB, and l_2 is presented at a level below l_1.

In the study carried out by [R. Hauser, 1991], maximum DPOAE amplitude was measured for a difference l_1 - l_2 of 10 dB.

In [M. L. Whitehead, 1995a], a study of DPOAE amplitude depending on values of primary levels can be found. In this study equation 3.3 to describe the optimal relation between primary tones SPL level with a frequency ratio $f_2/f_1 \in [1.2, 1.3]$ is proposed.

$$l_1 = 0.5 \cdot l_2 + 42.5 \tag{3.3}$$

Where l_1 and l_2 are in dB units

3.3.4.2 Measurement of DPOAE

DPOAE measurements are done using a probe which seals the ear canal, which allows to maximize sound pressure level in emission (no energy leakage) and avoid contamination due to external noise.

Primary tones are presented via two independent loudspeakers in order to avoid possible harmonic distortion created by the transducers and be confused with DPOAE. Probe provides a microphone for signal recording at the ear canal.

Due to relative DPOAE low-levels (5 - 10 dB in mature normal-hearing people according to [Kemp, 2010]), especial attention should be paid to noise floor present in DPOAE measurements.

Signal to Noise ratio Contamination due to different sources is inevitable. External noise, noise from subject's movement, breathing, swallowing, are normal noise sources in DPOAE measurements. Therefore, attention should be paid to the subject's comfort and possible noise sources in the room where measurements are done. A good fitting of the probe is very important for reliability on the measurement (sound pressure level emission and signal recording). Synchronized average between measurements or large measurement times decreases noise from an stochastic point of view (if we assume that noise is uniformly distributed).

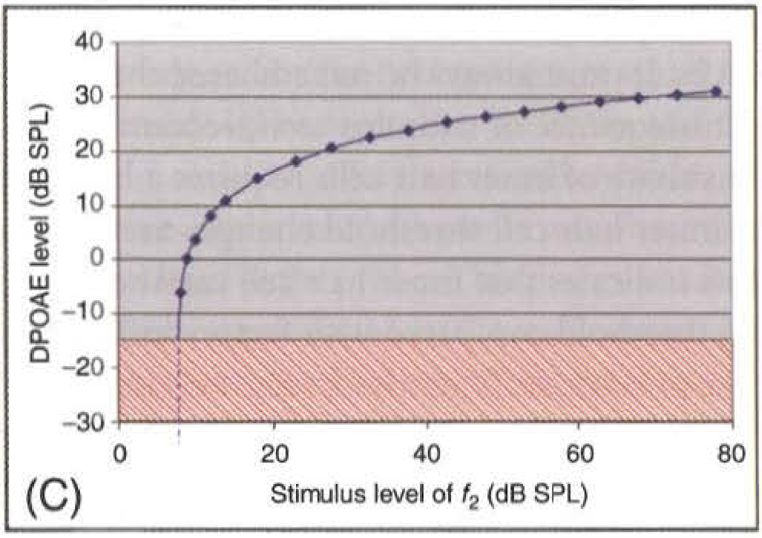

Figure 3.3: DPOAEs amplitude levels as a function of f_2 with a fixed ration between f_2 and f_1 fixed at 1.2. Red zone represent the noise floor of the measurement device. No information about the exact ratio and level of f1 is given. Picture extracted from [Kemp, 2010]

Once care has been taken in order to avoid noise as much as possible, noise estimation should be done. This is normally done by averaging the sound pressure level of frequencies around DPOAE frequency.

No specific information about frequency range taken into account in noise estimation is found. However, most of the research literature uses an average of sound pressure level in a frequency range of about (100 - 200) Hz around DPOAE frequency, [M. L. Whitehead, 1995a, Sun, 2008a, S. Chéry-Croze and Collet, 1993]

Signal-to-noise ratio of about 6 dB is generally accepted for OAEs measurements [Kemp, 2010]. In figure 3.3, we can see DPOAE's amplitude level function of f_2 frequency with ratio between f_2 and f_1 fixed at 1.2.

Chapter 4

Ear Reflexes

4.1 Introduction

An ear reflex is an involuntary mechanism which is activated by an acoustic stimulus. In the present project, two different reflexes are studied. These reflexes are the Middle Ear Muscle reflex (MEM reflex) and Medial Olivo-Cochlear reflex (MOC).

4.2 Middle ear muscle reflex (MEM)

MEM reflex, also called *Acoustic reflex* or *Stapedius reflex*, was described by Borg in 1973. It is observed in mammals and it consists in the involuntary contraction of the middle ears muscles, concretely *stapedius* and *tensor tympani* muscles.

This contraction produces an increase of the middle ear's immitance which leads to a reduction in sound transmission from environment to cochlea.

Abnormal MEM reflex behavior can reveal possible hearing damage, its study is widely used as a clinical tool for hearing assessment.

4.2.1 MEM reflex activation and pathway

MEM reflex is mainly activated by high acoustic stimuli levels. When an acoustic stimulus reaches one ear, this one, travels through the outer, and middle ear to the inner ear where it excites cochlear partitions as well as IHCs and OHCs, see sections 2.2.3.4 and 2.2.3.3. The activation of the reflex involves afferent and efferent pathways from the ventral cochlear nucleus (in one ear) to the superior olivary complex (SOC) on both sides of the brainstem, see section

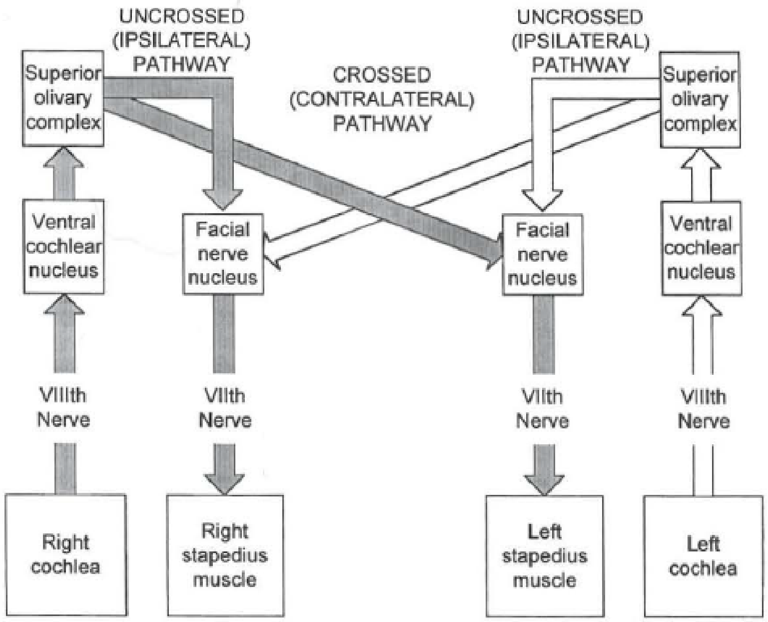

Figure 4.1: Auditory pathway of MEM reflex activation, scheme extracted from [Gelfand, 2010b].

2.2.3.4. Then, right and left SOCs send efferent information to the facial nerve nuclei on their respective sides [Gelfand, 2010b]. Therefore, one of the most important characteristics of the MEM reflex is that it can activated at both ears through the stimulation of one ear.

When the activation of the reflex is done presenting the stimulus at the same ear where the reflex is measured, the stimulation is called *ipsilateral acoustic stimulation* and the acoustic reflex measured is referred as *ipsilateral acoustic reflex*. On the other hand, if the stimulus is presented at the opposite ear where the reflex is measured, the stimulation is called *contralateral acoustic stimulation (CAS)* and the acoustic reflex measured is referred as *contralateral acoustic reflex*.

An scheme of the pathways of ipsilateral and contralateral MEM reflex activation can be seen in figure 4.1.

4.2.2 Measurement of MEM reflex

MEM reflex is usually assessed measuring immitance changes of the middle ear. The procedure consists of acoustic stimulation of one ear and measurement of the middle ear's immitance at the same ear where the stimulus is presented (ipsilateral technique), or at the opposite ear (contralateral technique). In both cases, the ear where the acoustic stimulus is presented is considered as the "test ear" [Gelfand, 2010b].

There are two main MEM reflex tests.

4.2.2.1 MEM reflex threshold

MEM reflex threshold also called Acoustic Reflex Threshold (ART) is defined as the lowest level of a stimulus that causes a measurable change in acoustic ear's immitance [Gelfand, 2010b]. It is normally measured by observing the changes in admittance in one ear when different intensity level stimuli are presented. Normal types of stimulus used by clinicians are pure tones at 500, 1000 and 2000 Hz, using 5 dB steps. In broadband noise (BBN) case, steps in intensity level are of about 1-2 dB [Gelfand, 2010b].

	CAS				
	Pure tone (Hz)				**Broad Band Noise**
	500	**1000**	**2000**	**4000**	
Mean	84.6	85.9	84.4	89.8	66.3
Standard Deviation	6.3	5.2	5.7	8.9	8.8

Table 4.1: ART values for contralateral stimulation of MEM reflex. Values are presented in dB HL and extracted from [Gelfand, 2010b].

As it can be seen in table 4.1, broadband noise is much more efficient in terms of MEM reflex elicitation, meaning that less stimulus intensity is needed for reflex activation. Values 10 dBs above ART are usually used for the activation of MEM reflex [Gelfand, 2010b].

4.2.2.2 MEM reflex adaptation

One of the characteristics of the MEM reflex is that during long stimulation time, it shows an adaptation to the stimulus, and the muscles involved in the reflex start to relax, decreasing its effect on the ear's admittance.

MEM reflex adaptation is normally assessed monitoring the ear's immitance while stimulation is presented to the test ear. Contralateral and ipsilateral techniques are possible for CAS presentation and the test is considered "postive" (normal response), if the ear's immitance returns to at least the 50% of its maximum within 10 seconds of CAS presentation, [Gelfand, 2010b].

4.2.3 MEM reflex Time Course

The contraction of the stapedius muscle occurs within a range from 25 ms for high stimuli levels, and 100 ms for stimuli close to ART levels, see [Møller, 2005]. As it has been mentioned before, one of the main characteristics of the MEM reflex is its adaptation to a certain stimulation within a certain time of exposure.

MEM reflex adaptation (MEMRA) time is defined as the stimulation time needed for the complete extinction of MEM reflex.

MEMRA depends on the health state of the auditory system, and on the physical characteristics of the stimulus used for its activation. These characteristics are:

- **Frequency dependency**: behavior of MEM reflex adaptation depending on the frequency content of the CAS.
- **Intensity level dependency**: behavior of MEM reflex adaptation depending on the intensity level of the CAS.
- **Time dependency**: behavior of MEM reflex adaptation depending on the duration of the CAS.

As can it be seen in figure 4.2 and according to [Richard H. Wilson, 1978], MEMRA time is directly proportional to the intensity level of the CAS and inversely proportional to the frequency content of the stimulus. Therefore, if a low frequency tone is used for the elicitation of the reflex, the adaptation time will increase considerably. The same rationale can be applied for high levels of stimulus.

An interesting observation from figure 4.2 is that maximum values of MEM reflex are measured for broadband noise as CAS and no complete adaptation was measured using this kind of stimulus. However, the lowest level tested was 96 dB SPL, which is a considerable high level, and taking into consideration that MEMRA time is directly proportional to the stimulus intensity level, the use of a lower level than those tested in [Richard H. Wilson, 1978] should lead to shorter MEMRA times.

4.2.4 MEM reflex function. Clinical use

MEM reflex has been shown as a control system regulating the level input of sounds to the cochlea. As it has been mentioned, it increases the impedance of the middle ear, thereby, reducing the sound amplitude reaching the tympanic membrane. Its effect can be seen mostly for low frequencies (below 0.8 KHz). Due to the latency of the activation of MEM reflex (time needed by the stapedius muscle for contraction), MEM reflex does not affect fast amplitude changes in the sound (below 25 ms) [Møller, 2005].

In [Xiao Dong Pangm, 1997], control stapedius muscle contraction was induced in anesthetized cats, and measurments of the effect of the contractions on the masking of single auditory nerve fibers and on the reduction of sound intensity in the middle ear transmission were done, suggesting that activation of MEM reflex helps reducing masking of high frequencies by low frequency sounds.

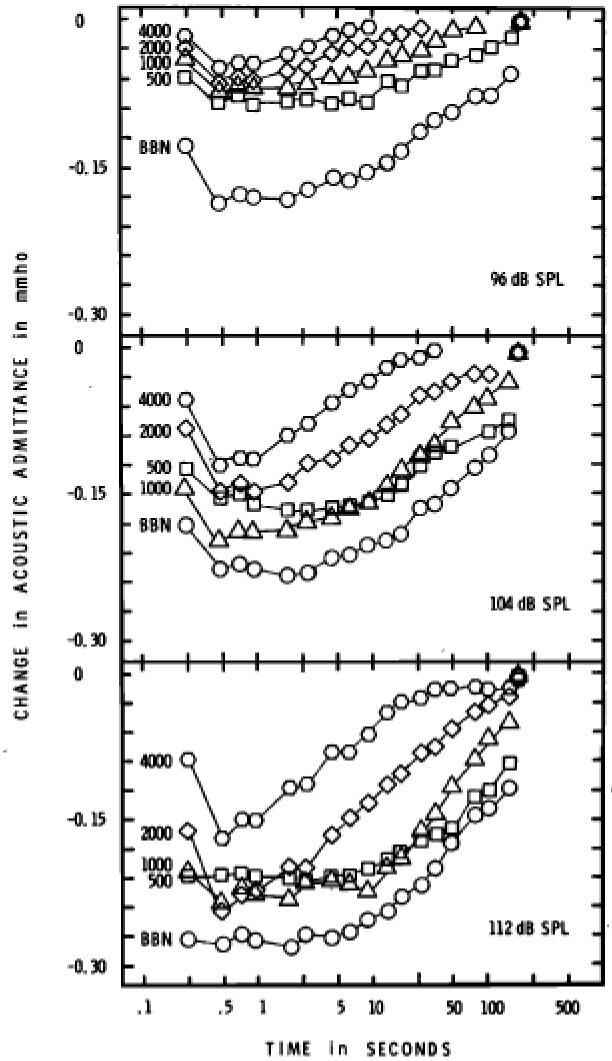

Figure 4.2: Adpatation times for MEM reflex. Y-axis represents the change in one ears admittance when CAS was presented to the opposite ear. The value at the right-top of each figure represents the value of the ears admittance measured 30 seconds after stimulus offset measured as a base-line value. [Richard H. Wilson, 1978]

MEM reflex measurement is a valuable test for hearing assessment. Due to its activation pathway, it can help to distinguish between hearing loss due to cochlear damage and that produced by auditory nerve damage. For isntance, a patient with hearing loss with normal MEM reflex activity may have cochlear damage, whereas a patient with hearing loss with high ART may have some kind of auditory nerve damage. MEM reflex is also used in middle-ear disorders detection [Møller, 2005].

4.2.5 DPOAE and MEM reflex

Since MEM reflex activation produces an increase on the impedance of the middle ear, descreasing the sound intensity reaching the cochlea from a sound event in the enviroment, this increase of the middle ear's impedance also produces a change in the OAE's amplitude measured at the ear canal [John J. Guinan, 2006].

Although, MEM reflex activation has a big effect on OAE's, few investigation has been done in the assessment of this reflex using OAE measurement. Examples can be found in [Thomas Venet], where a system for the MEM reflex assessment using DPOAE measurement and contralateral acoustic stimulation using broadband noise is developed.

However, most of the research in the assessment of ear reflexes using OAE measurements has focused on other ear reflex (MOC reflex), and effort has been made in order to isolate MOC reflex effect on OAE measurments using low level reflex elicitors avoiding MEM reflex activation.

4.3 Medial olivocochlear reflex (MOC)

MOC reflex activation inhibits basilar membrane responses to low level sounds [John J. Guinan, 2006]. This means a decrease in the cochlear amplifier mechanism (see section **??**. This inhibition is done through MOC efferents, which end on OHCs and are able to change OHC's action on the motion of the basilar membrane causing changes in OAEs.

4.3.1 MOC reflex activation and pathway

When a sound reaches the cochlea, the auditory nerve fibers are excited. These fibers innervate reflex neurons in the cochlear nucleus. Neurons' axons cross the brainstem and innervate MOC neurons at the contralateral side of it. Contralateral neurons project into the ipsilateral ear through the crossed olivocochlear bundle (OCB). For the contralateral MOC refflex, auditory nerve fibers excited by a sound, innervate neurons in the contralateral cochlear nucleus. Neuron's axons cross the brainstem and innervate MOC neurons located at the ipsilateral side of the brainstem. This neurons project into the ipsilateral ear through the uncrossed olivocochlear bundlde (UOCB) citepGuinan2006. An scheme extracted from [John J. Guinan, 2006], of the MOC auditory pathway can be seen in figure 4.3.

Different types of stimuli have been used by several researchers in order to activate MOC reflex.

Regarding frequency content, pure tones and different broad-band noises are used to evoke MOC reflex. Broadband noise stimuli are effective and strong activators of MOC activity [Shawn S. Goodman, 2006].

Regarding intensity levels, the biggest shifts in OAE's amplitudes due to MOC activity are seen for low level of stimulation, which is expected due to the non-linearity behavior of the cochlear amplifier mechanism [John J. Guinan, 2006].

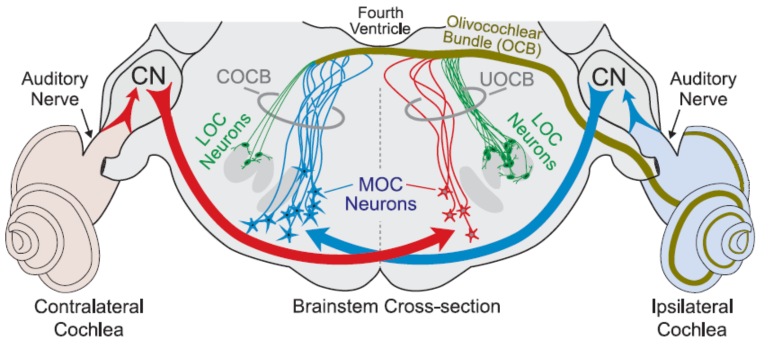

Figure 4.3: MOC reflex pathway. The picture shows the pathway for MOC ipsilateral reflex activation of the right ear. Picture extracted from [John J. Guinan, 2006]

4.3.2 Measurement of MOC reflex

MOC reflex has been measured observing the auditory nerve firing rate in response to sound stmilulation, or electrical stimulation of MOC fibers. As it can be seen in figure 4.3 MOC reflex in one ear, can be elicitepd by stimulation of the ipsilateral ear (test ear) or the contralateral ear.

Ipsilateral MOC reflex in animals is from 2 to 3 times stronger than contralateral MOC reflex. In most of the mammals, there are from 2 to 3 times crossed MOC fibers than uncrossed, and as it has been mentioned in section 4.3.1, crossed fibers are responsible for the ipsilateral moc reflex activation. However, similar ispsilateral and contralateral MOC effects have been measured, suggesting the existance of similar amount of crossed and uncrossed fibers in humans.

4.3.2.1 MOC reflex measurement and OAEs

In humans, MOC reflex has been measured with OAEs tests, measuring the supression of OAE's amplitude or phase shifts in OAEs in presence of a stimulus, the stimulus can be presented at the contralateral ear for measuring the contralateral MOC reflex or at the ipsilateral ear for the measurement of the ipsilateral MOC reflex.

SFOAEs have been used for the quantification of MOC reflex in [Guinan J. J., 2003], but most of the studies where MOC effects have been studied using OAEs, DPOAEs and TEOAEs are the most common OAE components used, maybe because their relative easiest way of measuring (SFOAEs are more difficult to extract because stimulation and response have the same frequency see section 3.3.2).

The biggest drawback in the use of TEOAEs for MOC quantification, is the use of clicks or tone pips for the evocation of TEOAEs. They have been proved as powerful MOC reflex elicitors, therefore, if contralateral stimulation is used for MOC reflex activation, effects on TEOAEs can be difficult to be attributable to only the contralateral MOC reflex [John J. Guinan, 2006].

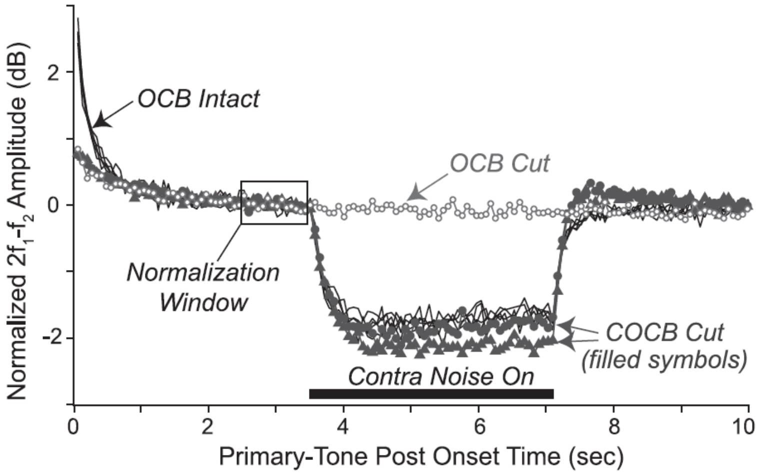

Figure 4.4: Example of MOC reflex effect on DPOAE measurement due to contralateral noise stimulation. Picture extracted from [John J. Guinan, 2006]

DPOAEs have been used for the measurement and quantification of MOC reflex in several studies [Sun, 2008a, M.C. Liberman, 1996, A. Moulin, 1993, Carolina Abdala, 2008]. One of the biggest drawbacks in the quantification of the MOC reflex in DPOAEs is that its effect can result into a decrease or an enhacement of DPOAE's amplitude.

As it has been mentioned in section 3.3.4, DPOAEs have two different sources. One of them (the distortion component), is directly related with the OHCs non-linear activity. When MOC reflex is activated, OHC's response changes, therefore the component of DPOAE which OHCs activy are responsible for, will also change. As we know, interference between the two different DPOAE sources is responsible for the fine structure seen in DPOAE measurements, thus, if one component of DPOAE is changed due to MOC activity, destructive interference between these two DPOAE components in a certain frequency can dissapear, leading to an enhacement in DPOAE amplitude when MOC reflex is activated.

A measurement of MOC reflex effect on DPOAE using contralateral stimulation can be seen in figure 4.4. The figure has been extracted from [John J. Guinan, 2006]. It's worth to mention that figure 4.4 reflects a measurement done in cats, where DPOAE measurements were done before and after cutting efferents.

Since MEM reflex can be activated through ipsilateral and contralateral stimulation (see section 4.2.1), its activation will be reflected on OAE's response, making difficult the accurate quantification of MOC reflex effect. Some studies overcome this problem measuring ARTs in each subject for the election of CAS SPL, keeping this level below ART to ensure no MEM reflex activation. However, typical measurement devices for MEM reflex are not sensitive enough for detecting little contractions of the stapedius muscle [John J. Guinan, 2006].

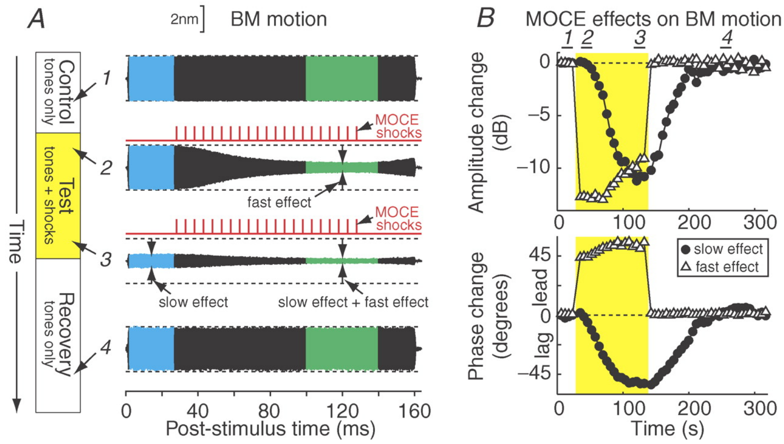

Figure 4.5: Measurement of Basilar Membrane motion amplitude, where slow and fast effects on the BM's motion can be seen. Post-stimulus BM's motion amplitude measurements can be seen on the left part of the figure. As it can be seen at the begginning of period 3 a considerable reduction of the amplitude un the BM's motion can be seen (before MOC shocks are presented) which reveals a BM's adaptation to the stimulation. Fast effect can be seen in the reduction of the BM's motion around 100 ms after the onset of MOC shocks. Picture extracted from [N. P. Cooper, 2006]

Since activation of MEM reflex will change the ear canal impedance, taking advantage of the bigger sensitivity of the equipments used in OAEs measurements, one way to overcome with this problem, or at least to determine if there is activation of MEM reflex, is to observe for changes in the stimulus used for OAEs evocation, [John J. Guinan, 2006].

4.3.3 MOC reflex Time course

Two MOC effects have been suggested regarding its time course in [N. P. Cooper, 2006]. Fast MOC effect has an onset and offset times around 100 ms [N. P. Cooper, 2006, Guinan J. J., 2006], whereas slow effect has onset and offset times around 10 seconds [N. P. Cooper, 2006]. In figure 4.5, extracted from [N. P. Cooper, 2006] shows the different MOC reflex effects on the basilar membrane. The experiment was done using a 35 dB SPL tone burst centered at the BM's center frequency of 19 KHz.

Measurements of the BM's amplitude were done, before and during the presentation of the tone burst. As it can be seen in figure 4.5, where dark lines with full circles represents measurements before the presentation and dark lines with empty triangles represents measurements done during CAS presentation, the measurements before the presentation of a tone burst show a certain effect accumulation, while observing the measurements done during the presentation of the burst tone, we can see a fast decay on the amplitude of BM's motion.

In [Guinan J. J., 2006], MOC reflex time course was studied with different wide-band noise contralateral elicitors, not finding a consistent effect on MOC time course due to elicitor level.

There are no many studies about MOC reflex adaptation. In [Brown, 2001], MOC adaptation was investigated for 10 seconds stimulation, and concluded that MOC response adaptation is minimal with that of auditory nerve fibers.

4.3.4 MOC reflex function. Clinical use.

Different functions have been attributed to MOC reflex. Following some of them are mentioned, however it's worth to mention that, by now functional roles of this reflex are just hypothesis, so care should be taken when these functions are considered.

- **Protecion against sound overexposure:** Studies in animals have revealed a protection role of the MOC reflex. Different studies have studied differences in temporal and permanent temporal shifts before and after sound overexposures. In [Sharon G. Kujawa, 1997], made an study where OC-bundle was cut in a group of animals meanwhile other group kept OC-bundle intact. Btoh groups were exposed to large acoustic overexposures. Results revealed less hearing damage in those animals with OC-bundle intact.
- **Detection and discrimination of transient sounds in noisy enviroment (MOC unmasking):** Since MOC reflex inhibits the cochlear amplifier mechanism, this will lead to a reduction of the hearing sensitivity and a reduction in the response to a certain noise, avoiding auditory fatigue. If auditory fatigue is produced, IHCs will run out of supply of neural transmitter and they will become incapable of responding to sound stimulation. Therefore, with MOC reflex activation inducing no auditory fatigue, IHCs are able to response to high level transient sounds, see [John J. Guinan, 2006].

Since MOC reflex role in hearing activity is still a matter of investigation and discussion, clinical use of MOC reflex is limited to the assessment of auditory pathways and more research on the role of MOC reflex in hearing is needed fot the consolidation of MOC reflex assessment as an important clinical test.

Chapter 5

Pilot Test

5.1 Introduction

An experiment is carried out for the study of the possible separation of MOC and MEM reflex effects taking advantage of the adaptation characteristic of the MEM reflex.

The experiment consists in the measurement of Distortion product otoacoustic emissions (DPOAEs) at one ear while MOC and MEM reflex are elicited by contralateral stimulation. DPOAEs will be monitored cointinuosly in each measurement.

The aim of the pilot experiment is to study the most suitable stimuli characteristics in order to carry out the separation between MOC and MEM reflexes effects on DPOAE response.

The experiment is carried out in the the standard stereo listening room at Aalborg University (Listening room).

5.2 Hypothesis

MEM and MOC reflexes share part of the afferent pathway from cochlea to higher levels of auditory system in the brainstem. These relfexes are activated through different efferent pathways. These efferent pathways connect with both ears, making possible the activation of both reflexes at the ipsilateral ear when an eliciting stimulus is presented at the contralateral ear (Contralateral Acoustic Stimulus CAS) [Gelfand, 2010b, John J. Guinan, 2006], see figure 5.1. When this technique is used for activation of MEM and MOC reflexes, they are referred as contralateral MEM and MOC reflexes.

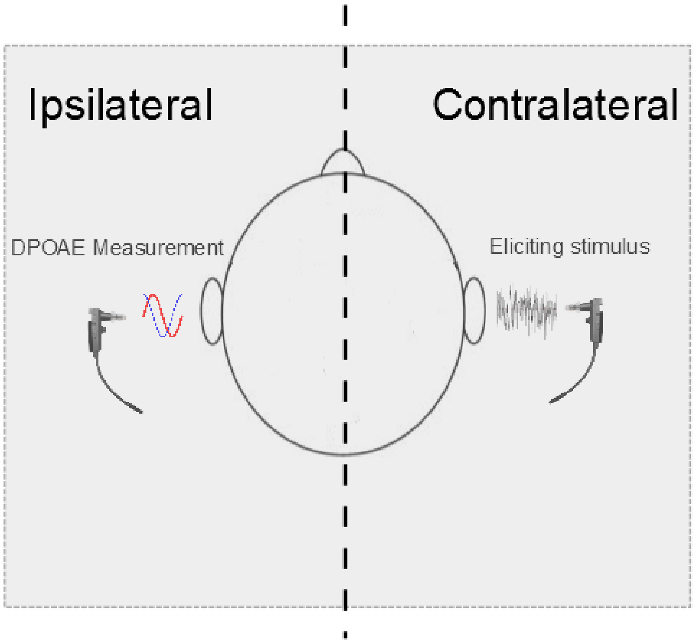

Figure 5.1: DPOAEs measurement at the ipsilateral ear, while a CAS is presented at the contralateral ear

MOC and MEM reflexes have influence on DPOAE amplitude behavior. One important characteristic of the MEM reflex is that, during stimulation, it shows an adaptation to the reflex elicitor, decreasing its effect on middle ear's impedance as well as its effect on the transmission of OAEs.

Taking advantage of this particular characteristic, if MEM reflex effect disappears, the only reflex involved in the contralateral stimulation effect on DPOAE will be the MOC reflex. Therefore, a quantification of MOC reflex effect without contamination from MEM reflex is possible. A drawing of the hypothetical DPOAE amplitude behavior along measurement designed for this pilot test can be seen in figure 5.2.

5.3 Measurement Scheme

DPOAE measurement in this experiment can be seen in figure 5.2. As it can be seen, the measurement is divided in 5 different time intervals for the better explanation of the expected behavior of the DPOAE amplitude along a measurement.

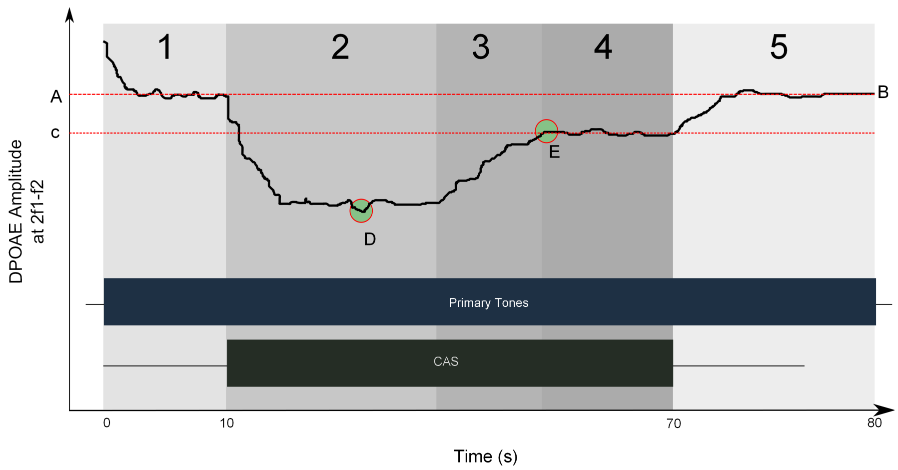

Figure 5.2: Example of hypothetical measurement. In the figure 5 different stages of the measurement in time can be distinguished. These stages will be explained in 5.3.1. Points A, B and C, D represent DPOAE amplitude values calculated in certain stages of the measurement. E point represents the point of DPOAE amplitude stabilization. The meaning of these points is convered in 5.3.1 and in 5.8.1.

5.3.1 Measurement time intervals

5.3.1.1 Time interval 1

Interval 1 covers 10 seconds. Here, measurement of DPOAE is done in order to get a reference value of DPOAE amplitude of the test subject.

Base-line value of DPOAEs at the test ear will be measured before the presentation of the CAS. This value will be calculated as an average of DPOAE amplitude registered within this time interval (point A in figure 5.2).

5.3.1.2 Time interval 2

Interval 2 covers from the onset of the CAS, which will be at second 10 of the measurement, until the onset of the MEM reflex adaptation.

A fast decrease in DPOAE amplitude is expected when contralateral stimulation starts, due to the suppression effect on DPOAE produced by MEM reflex [John J. Guinan, 2006]. As it has been mentioned in section 4.3.2.1, MOC reflex can have either an increasing or a decreasing effect on DPOAE amplitude.

At this interval, MOC and MEM reflexes will contribute to the total effect on DPOAE amplitude, reaching the maximum reduction in DPOAE amplitude, point D in figure 5.2.

After the fast decay of the DPOAE amplitude, response at this interval is expected to be stable, due to a constant MOC and MEM reflex effect. An average will be computed on the DPOAE amplitude at this stage (point C in figure 5.2).

5.3.1.3 Time interval 3

Interval 3 starts with the onset of the MEM reflex adaptation. This is expected to start around 2 or 3 seconds after the onset of the CAS according to results obtained in [Richard H. Wilson, 1978].

At this interval, MOC and MEM reflex will contribute to the suppression effect on DPOAE amplitude, but MEM reflex effect is expected to wear off progressively. Therefore a continuous increase in DPOAE amplitude is expected during this time interval.

5.3.1.4 Time interval 4

Interval 4 starts when total adaptation of MEM reflex is reached. Due to limitations in the study made by H. Wilson in [Richard H. Wilson, 1978], where the minimum level used for eliciting MEM reflex is 96 dB SPL (which is discarded for its use in the present study), duration of this period remains uncertain, and possible changes regarding time duration of stimulation will be considered depending on test results.

A steady state of DPOAE amplitude is expected to be reached at this stage, where MEM reflex effect on DPOAE amplitude suppression will be minimum. Thus, MOC reflex effect will be the only contribution to the DPOAE amplitude supression at this interval.

An average value on DPOAE amplitude at this time interval (point C in figure 5.2), will be computed in order to be able to compare it with the base-line value B (see section 5.3.1.5).

5.3.1.5 Time interval 5

This interval will start within the end of the elicitor stimulus. This is at the second 70 of the whole measurement.

A total recovery of DPOAE amplitude is expected at this time interval, returning to the base-line value shown in time interval 1. An average value on DPOAE amplitude at this time interval (point B in figure 5.2).

5.4 DPOAE Elicitor Stimuli

A pair of primary tones is used for eliciting DPOAE in the present study are. Two main signal characteristics are to be taken into account for the election of the primary tones. The first characteristic is the frequency relation between them and the second characteristic, is the relation between their intensity levels.

5.4.1 Frequency and Intensity relation between f_1 and f_1

Two different constraints define frequencies of primary tones:

- Ratio f_2/f_1: from [Kemp, 2010], optimal ratio for obtain maximum DPOAE amplitude is 1.2.
- $2f_1$-f_2 DPOAE component: cubic $2f_1$-f_2 DPOAE component is the largest one in human beings. Research on DPOAE is focused mainly at mid-high frequency. For the present test, DPOAE frequency is set to 1000 Hz.

Therefore, $f_2/f_1 = 1500/1250$ Hz and $f_2 = 1500$ Hz.

Regarding primaries SPL, following considerations for the sound pressure levels is depicted:

- DPOAE amplitude generally increases as the primary levels increases [Kemp, 2010].
- DPOAE amplitude shows a bigger dependency on level of primary f_1, l_1 [M. L. Whitehead, 1995b], where a change on mean DPOAE amplitude is seen for $l_1 \geq 75$ dB, and level of primary f_2, l_2 is kept below l_1, showing a decrease in the mean DPOAE amplitude as l_1 increases. However, mean DPOAE amplitude increases when $l_1 = 65$ dB, and l_2 is presented at a level below l_1, see [M. L. Whitehead, 1995b].
- According to [M. L. Whitehead, 1995a], figure 5.3 shows mean DPOAE amplitude as a function of l_1 and l_2 , with primaries ($f_2/f_2 = 1529/1263.6$ Hz) very close to the ones chosen for the present test. Equation 3.3 suggested in [M. L. Whitehead, 1995a] to generate maximum DPOAE amplitude is used for the calculation of the primary tones SPL.
- Ideally, primary tones SPL should not evoke ipsilateral MOC or MEM reflex, therefore sound pressure levels will be kept as low as possible.

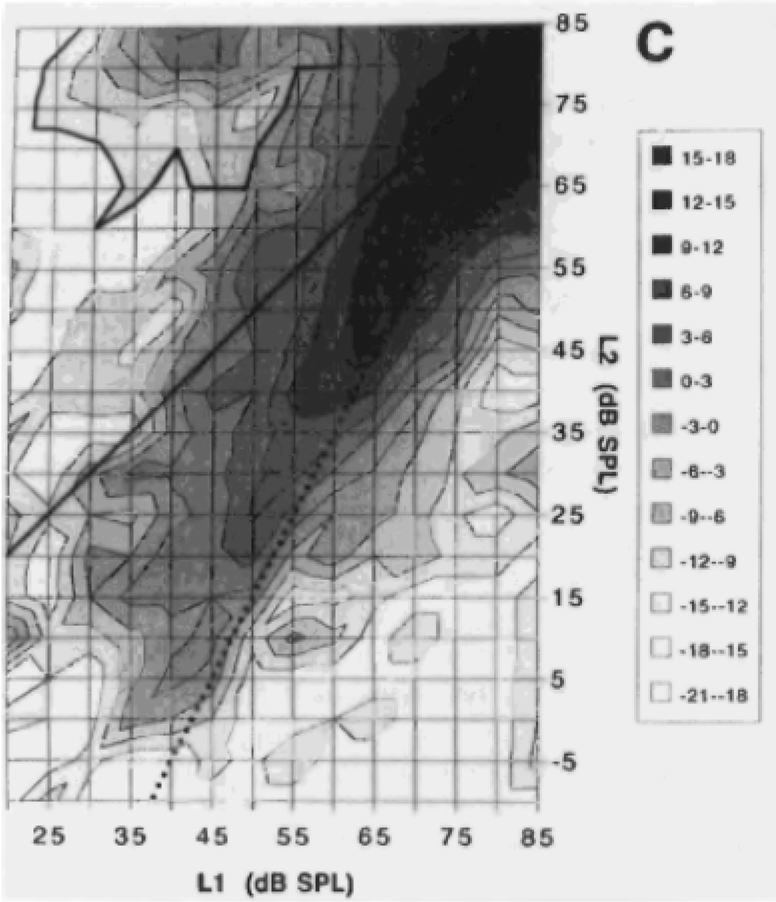

Figure 5.3: DPOAE amplitude levels as a function of f_1 and f_2. f_1 and f_2 are mean geometric frequencies of 1.39 KHz, with a ratio of $f_2/f_1 = 1.21$. This makes a primary tone f_1 of 1263.6 Hz and a primary tone f_2 of 1529 Hz. Dotted dark line is defined by equation 3.3. Picture extracted from [M. L. Whitehead, 1995a]

Taking into account these considerations, it seems reasonable to set a maximum of 65 dB for primary tone l_1, as a tradeoff between large DPOAE amplitude and minimum ipsilateral evocation of MOC or MEM reflex.

In order to explore what are the different features and characteristics of the stimulus that can affect to the study of MEM and MOC reflex, different levels of primary tones will be studied.

5.4.2 Primary tones election

In table 5.1 characteristics of primary tones f_1 and f_2 can be seen.

Primary	f1	f2
Frequency (Hz)	1250	1500
	65	55
SPL (dB)	65	45
	60	35
Duration (s)	80	80

Table 5.1: Primary tones f_1 and f_2 characteristics

As it can be seen pair of values $l_1/l_2 = 65/55$ dB SPL does not fulfill equation 3.3, but it has been proposed as an optimal relation in [Michael P. Gorga, 1996], for the best separation between normal and impaired ears, being widely used in clinical DPOAE measurements, thus it is of high interest the the study these primary tones pressure levels in the present test.

5.5 Contralateral Acoustic Stimulus

Contralateral acoustic stimulus (CAS), is defined as the stimulus used for the elicitation of MOC and MEM reflexes. Frequency content and intensity level of the CAS for the present test is chosen based of the following criteria.

1. **MOC reflex elicitation:** The stimulus should be able to elicit MOC reflex maximum as possible.
2. **MEM reflex elicitation:** The stimulus should be able to elicit MEM reflex.
3. **MEM reflex adaptation time:** The stimulus should provide the shortest time possible for the adaptation of MEM reflex.
4. **Interaural attenuation:** The level of the CAS should be low enough to avoid sound transmission between ears via bone and air conduction.

First 3 points have been discussed in chapter 4. Interaural attenuation is covered following.

5.5.1 Interaural attenuation

Sound transmission from the ear where CAS is presented to the test ear can ruin and contaminate DPOAE measurements from MOC and MEM reflexes are assessed. Therefore when contralateral stimulation paradigm is used, special care must be taken in the possible sound transmission through bone and air conduction.

Two possible headphones are taken into consideration for CAS presentation, supra-aural headphones telephonics TDH-39P and insert earphone Ear-Tone ER 3A.

According to [Munro and Agnew, 1999], interaural attenuation for Etymotic ER-3A and TDH-39P is studied in the frequency range (0.25 - 8 KHz). 18 subjects participated in this study, all of them presented no hearing in one ear. IA was calculated as «the difference the good-ear and the poor-ear not masked air conduction threshold for a given audiometric frequency and earphone». Results pointed out larger IA values for insert earphone ER-3A depend on the depth of insertion of the earphone. For deep insertion IA of ER-3A was measured 15-20 dB greater than IA for telephonics TDH-39P.

Sklare and Denenberg found minimum IA values for insert earphones (concretely ER-3A) of 70 to 75 dB for frequencies up to 1 KHz and 50 to 65 dB below 1 KHz [Gelfand, 2010c].

Taking into account these values, it seems reasonable to consider the most restrictive value, IA value of 65 dB.

5.5.2 Contralateral Acoustic Stimulation (CAS) election

Following, a summary of the factors and charactiristics of CAS taken into account for its election is done:

- **Type:** Broadband stimulus are strong activators of both reflexes, whereas single pure tones are less efficient for eliciting MEM reflex. Since one of the aims of the present test is to study the influence of different signals characteristics on the ear reflexes activation, two widely types of broad band noise used in acoustics field is used, this is white noise and pink noise.

  White noise has equal energy along frequency, meanwhile pink noise has equal energy per frequency octave, which will lead to a bigger excitation in low frequencies in comparison with white noise. Since MEM reflex is stronger activated by low frequency content, it is interesting to study differences between white and pink noise when they are used as CAS.

- **Bandwidth:** Since earphone ER-3A is used for CAS presentation, its frequency response is measured and it is shown in section 5.6. As it can be seen in figure 5.6, ER-3A transducer presents a roll-off starting over 5000 Hz. Compensation for frequency response of the transducer is considered as well as filtering CAS with the response of the transducer. However if compensation for frequency response is made, the transducer will be forced to act in a frequency range, where naturally its reponse is poorer. This can introduce harmonic distortion and increases the risk of a sound pressure overexposure to the subject, due to the high gain applied in the poorer frequency range. Therefore a filtering from 50 to 6000 Hz is chosen for the CAS presentation. Following the same rationale than with the type of broadband noise, it's interesting to study possible differences in the ear reflexes activation due to the frequency content of CAS. Therefore, another CAS with frequency range (300 - 3000 Hz) is chosen. This frequency range is chosen as a trade-off between broadband noise advantages in ear reflexes activation and significant difference between the frequency range of (50 - 6000 Hz).

- **Intensity Level:** MEM reflex threshold (ART) is the largest restriction in the election of the intensity level. Although stimulus level for MEM reflex tests is usually 10 dB above the ART, a quantity equivalent to ART's standard deviation is chosen for being above the ART, this is 8.8 dB, see table 4.1. Since Interaural attenuation (IA) is about 65 dB,it seems reasonable to set an additional CAS SPL in order to study the possible contamination of DPOAE amplitude due to the contralateral elicting stimulus presentation. A value corresponding to half of the ART's standard deviation is add to the mean ART mean threshold is chosen. Therefore two different pressure levels of CAS, 75.5 and 71.7 dB SPL is chosen as a tradeoff between optimal requirements for MOC activity elicitation, MEM reflex activation and minimum sound transmission between ears.

- **Duration:** MEM reflex adaptation times is the bigger limitation in the election of the duration of the CAS. Although normal MEM reflex adaptation tests are made with elicitor signals of 10 seconds of duration, these tests look for an adaptation of the 50 % with respect the maximum MEM reflex effect on the middle ear's admittance. Taking into account section 4.2.3, 60 seconds of duration should be enough for complete MEM reflex adaptation. However, especial attention should be paid on the results of the pilot test and checking for a reasonable steady state in interval 4 to ensure total adaptation of MEM reflex should be done.

Regarding the different requirements for the CAS that have been discussed before, the characteristics of the CAS are depicted in table 5.2

CAS			
Type	BW (Hz)	SPL (dB)	Duration (s)
White Noise	50 - 6000	75.5	60
	300 - 3000	71.7	
Pink Noise	50 - 6000	75.5	

Table 5.2: Contralateral acoustic stimulus characteristics

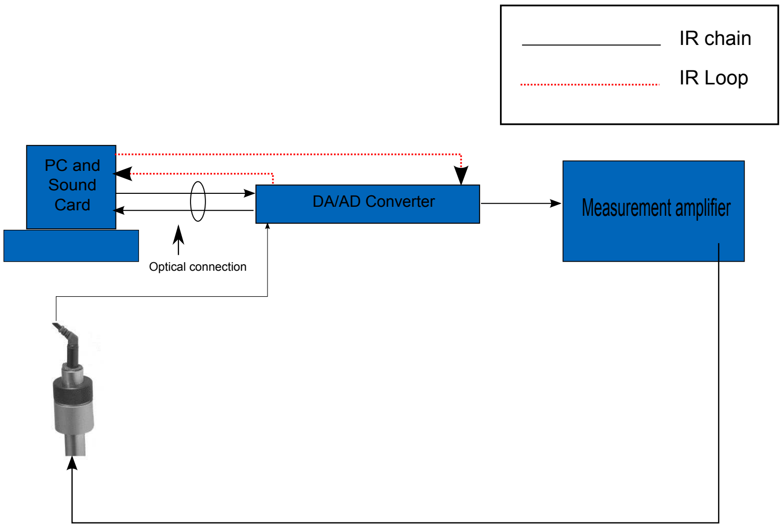

Figure 5.4: General scheme for calibration of the measurement system. Black lines describe the measurement chain. Red dotted lines, describe the measurment of the $\mathrm{IR}_{PC \leftrightarrow AD/DA}$.

5.6 Equipment and Calibration

In order to control the SPL levels presented to the subject, measurement chain should be calibrated. The equipment for the calibration of the measurement chain can be seen in table 5.3.

Equipment used for calibration.		
Equipment	Type	Serial Number
Ear simulator	B&K 4157	08157-00
Ear simulator	B&K 4153	07631-00
Measuring amplifier	B&K 2636	08717-00
Sine/Noise generator	B&K 1049	08718-00
Electronic Voltmeter	B&K 2409	06677-00
A/D D/A converter	RME ADI 8 DS	33966-00
Calibrator	B&K 4230	08155-00
Sound Card	RME Digi 96/8 PST	-
DPOAE Probe Driver-Preamp	Etymotic ER-10C	75584-00
Ear Probe	Etymotic ER-10C	75584-00
Earphones	Etymotic EAR TONE-3A	-
Headphones	Telephonics TDH -39 P	-

Table 5.3: Equipment used in the measurement chain calibration

A general scheme for the calibration can be seen in figure 5.4. Following the procedure for the calibration is described:

5.6.1 Procedure

For the calibration of the measurement chain and the control of the SPL delivered to the subject's eardrum, an ear simulator is used for this purpose. An artificial ear simulates the average volume of a human ear as well as the average acoustic impedance of a human ear. For the calibration of the transducers used in the pilot test, two different ear simulators are used. Both ear simulators conform to IEC 711 and ANSI S3.25/1979 (ASA39/1979) standards. These standards define frequency response and phase response of an average human ear.

Calibrator B&K type 4230 is coupled to the ear simulator and signal from the calibrator is recorded using *Matlab* software and *playrec* function. The root mean squared (rms) of the signal is calculated and used as conversion factor from digital units (DU) to pascals units,$Conv_{pa \leftarrow DU}$. It's worth to mention that gains in all measurement chain (measuring amplifier, AD/DA converter, Input sound card) are set at the beggining of the calibration procedure, and not changed at any moment of the calibration procedure.

Ear simulator B&K 4157 is used for the calibration of earphones ER-3A and ear probe ER-10C. An especial ear mould for simulating the external ear, DB 2012, is used. For the coupling between earphone and ear simulator, especial eartips Etymotic ER-10C 14B are used. The eartip will be fitted with its top at the perpendicular plane of the ear canal axis at the tip of the ear mould.

Ear simulator B&k 4153 with especial adaptor ring DB-0843 is used for the calibration of headphone Telephonics TDH-39 P. This headphone is type supra-aural and cannot be fitted into the ear simulator 4157. A force of 5 N is applied to the headphone for clamping the headphone to the ear simulator.

In order to measure the Impulse Response of the measurement chain (IR_{chain}), a logarithmic sweep is generated using function chirp in *Matlab* software. The length of the sweep is 10 seconds. Then, since the latency of the system is about 48 ms (see section **??**) this signal is padd with zeros (0.1s) in order to cover the latency of the system. A fade-in and fade-out of 100 ms is applied to the measuring sweep. The signal is played through *playrec* function, adjusting its amplitude to the maximum without clipping at the input of the AD/DA converter. The response is recorded using *playrec* function. The impulse response is obtained by:

$$IR_{chain\,\frac{DU}{DU}} = \Re\left\{\mathcal{F}^{-1}\left\{\frac{\mathcal{F}\left\{Sweep_{output}\right\}}{\mathcal{F}\left\{Sweep_{input}\right\}}\right\}\right\} \tag{5.1}$$

First, the impulse response of the loop-back indicated in figure 5.4 is measured, in order to check the frequency response of the elctrical part of the measurement chain. The response in

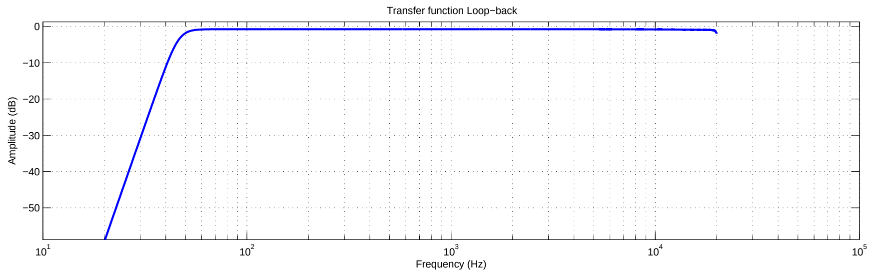

Figure 5.5: Measured transfer function of loop-back indicated in figure 5.4.

frequency of this part can be seen in figure 5.5. As it can be seen, frequency response is flat in the frequency range (20-20,000 Hz).

This process is repeated three times for the same transducer, so that 3 Impulse responses are obtained. The three impulse responses are averaged in time, in order to reduce possible noise in the recordings [Swen Müller]. A visual inspection of the fourier transform of $IR_{chain\,\frac{DU}{DU}}$ reveals noise in high frequency, up to 20 KHz. Although this noise is not hearable, a band-pass butterworth filter is applied to $IR_{chain\,\frac{DU}{DU}}$. The butterworth filter applied is calculated using the function *design* with stop frequencies at 20 and 20,000 Hz.

Since we are interested in the IR from DU to pascals, in order to be able to control the sound pressure delivered to the eardrum (in the measurement chain the ear simulator), $IR_{chain\,\frac{DU}{DU}}$ is converted to $IR_{chain\,\frac{DU}{PA}}$ using the conversion term measured with the calibrator tone.

$$IR_{\vec{chain}\,\frac{DU}{PA}} = \frac{IR_{\vec{chain}\,\frac{DU}{DU}}}{Conv_{pa\leftarrow DU}} \tag{5.2}$$

Impulse responses computed are used in the functions programmed in *Matlab* for the generation of the stimuli used in the pilot test. Transfer functions measured can be seen in figure 5.6.

Once the calibration is done stimuli SPL generated by functions programmed are checked in the ear simulator B&K 4157. In table 5.4 SPL values measured can been seen. It's worth to mention that only values used in the pilot test are checked. Two measurements are done for each stimulus.

During validation tests before carrying out the pilot test, variance in the latency of the system was observed, therefore a control signal was used for the calculation of the latency in each measurement. The control signal consists of a pulse located wich is sent through the system from D/A converter to input A/D converter. The latency is calculated from the control signal recorded, and used for cutting the signal recorded at the subject's ear canal. Results can be seen in appendix G

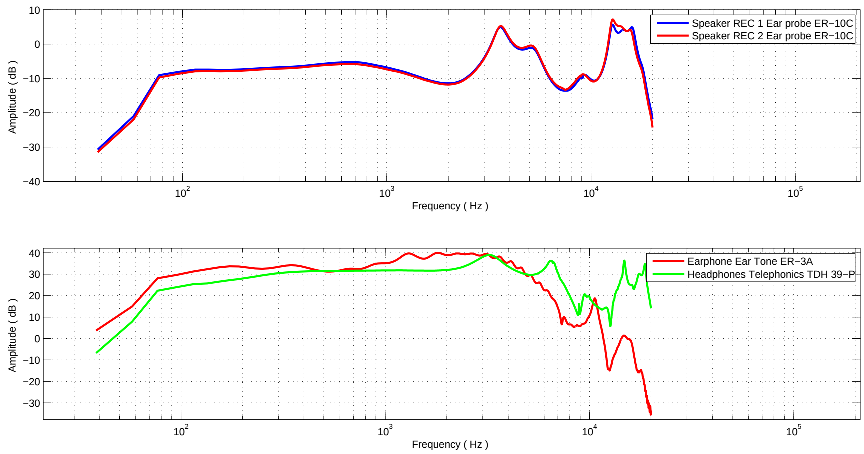

Figure 5.6: Transfer functions $\mathcal{F}\left\{IR_{chain\,\frac{DU}{PA}}\right\}$.

Stimulus	SPL (dB)	
	Theoretical	Measured
CAS $WN_{50-6000}$		75.07
CAS $PN_{50-6000}$	75.5	74.78
CAS $WN_{300-3000}$		76.22
CAS $WN_{300-3000}$	71.7	72.97
f_1	65	64.45
	60	59.30
f_2	55	54.21
	45	44.98
	35	36.86

Table 5.4: SPL values of stimuli used in Pilot test measured in ear simulator B&K 4157

5.7 Pilot Test. Measurements and Scenarios

The main aim of the pilot test is to explore different possibilities regarding physical properties of stimuli used for DPOAE evocation and reflex elicitation. Therefore different scenarios are chosen to carry out. Each scenario consists of a description of the physical properties of stimuli used in one measurement. Two measurements of DPOAE amplitude will be carried out for each *scenario* and each subject.

5.7.1 Pilot Test Scenarios

12 different scenarios are set for the present pilot test. Characteristics of the 12 different scenarios can be seen in table 5.5

Scenario	Primary tones SPL level		CAS	
	f1 1250 Hz	f2 1500 Hz	Type Broad-band noise	SPL dB
Scenario 1	65	55	$WN_{50-6000}$	75.5
Scenario 2	65	45	$WN_{50-6000}$	
Scenario 3	60	35	$WN_{50-6000}$	
Scenario 4	65	55	$PN_{50-6000}$	
Scenario 5	65	45	$PN_{50-6000}$	
Scenario 6	60	35	$PN_{50-6000}$	
Scenario 7	65	55	$WN_{300-3000}$	
Scenario 8	65	45	$WN_{300-3000}$	
Scenario 9	60	35	$WN_{300-3000}$	
Scenario 10	65	55	$WN_{300-3000}$	71.7
Scenario 11	65	45	$WN_{300-3000}$	
Scenario 12	60	35	$WN_{300-3000}$	

Table 5.5: Stimuli characteristics for the pilot experiment. Note: WN: White noise and PN: Pink noise. Subindex represents bandwidth in Hz

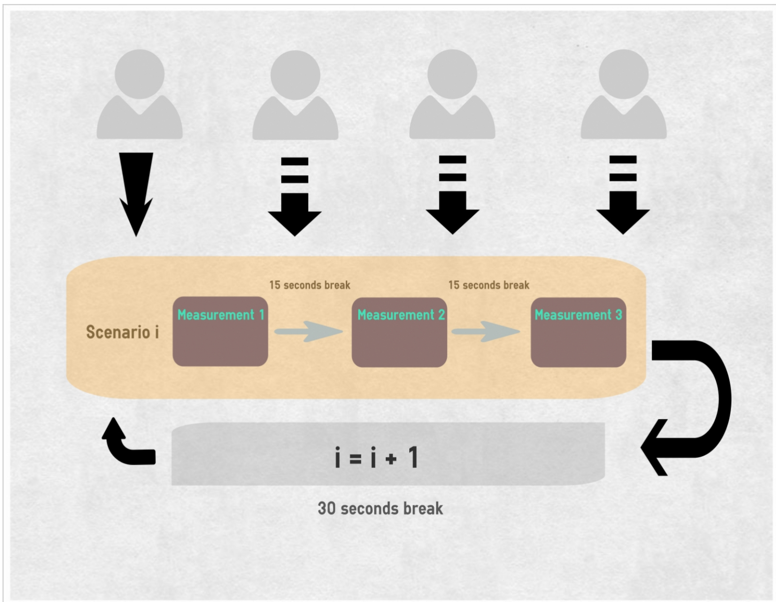

Figure 5.7: Scheme of measurements in pilot test.

5.7.2 Measurements and DPOAE time course extraction

For each scenario 3 measurements will be done. These 3 measurements are joined in just one presentation to the subject. Between each measurement there is a break of 15 seconds and between scenarios the break lasts 30 seconds. A general scheme of the pilot test can be seen in figure 5.7

In one measurement, primary tones are presented during 80 seconds and CAS is presented during 60 seconds. Primary tones present a fade-in and fade out of 20 ms. 0.1 s is added to the entire measurement in order to cover the latency of the measurement system. After 10 seconds of the onset of the primary tones CAS stimulus is presented over 60 seconds. CAS presents a fade-in and fade-out of 20 ms. After the offset of the CAS primary tones will continue over 10 seconds, see figure 5.2. A recording of the sound pressure level at the ear canal over 80 seconds of the measurement will be done at 48000 Hz sampling rate.

Ear probe ER-10C is used for the presentation of the primary tones and the recording at the ipsilateral ear. CAS is presented through ER-3A earphones.

Each block of 3 measurements, is extracted from the recording taking into account the latency of the measurement system, see section **??**. A high pass filter is applied with cut-off frequency at 300 Hz is applied to the whole measurement. Then a rectangular window of 100 ms (4800 samples at 48 KHz sampling rate) with no overlapping is applied to each of the repetitions. Fast fourier transform (FFT) is applied to each window and DPOAE amplitude and noise amplitude es calculated from the FFT.

Regarding noise estimation, an average of 6 bins around DPOAE frequency bin (6 bin frequencies to both sides of the DPOAE frequency bin) is averaged. Since the time window applied is of 100 ms, and sampling frequency 48 Khz, frequency resolution of FFT is 10 Hz. The equivalent rectangular bandwidth (ERB) of the auditory filter with center frequency at DPOAE frequency (1000 Hz) can be calculated with equation 5.3 given in [Moore, 2012], resulting 130.91 Hz. Half of the ERB calculated is approximately 60 Hz, then six bins are taken into account at both sides of DPOAE bin, resulting 12 bins in total for noise estimation.

$$ERB = 24.7\,(4.3F + 1) \tag{5.3}$$

Where F is given in KHz.

A general scheme of the extraction of the DPOAE time course for one scenario is shown in figure 5.8.

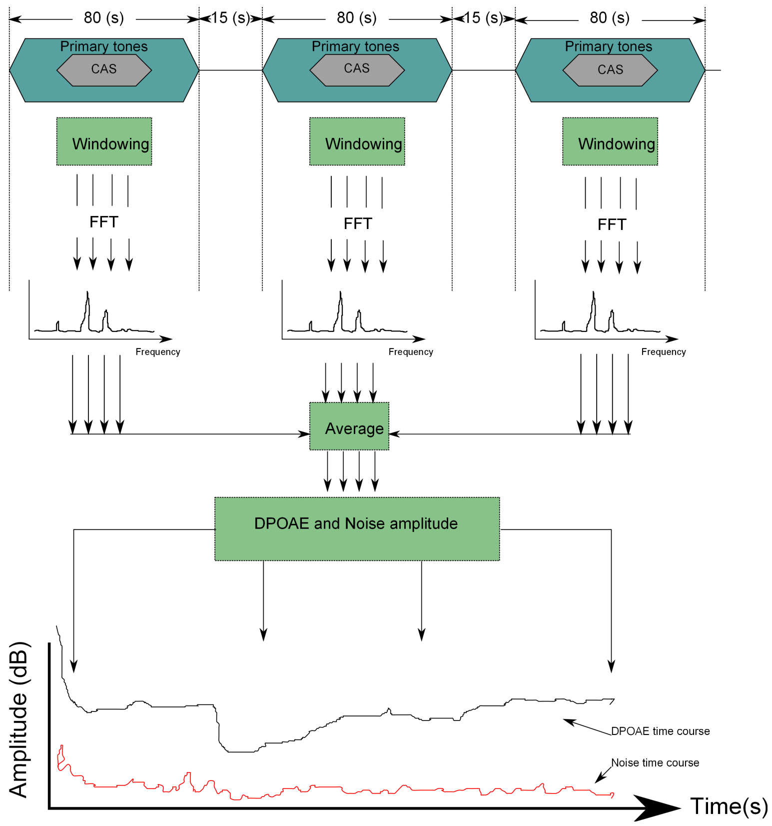

Figure 5.8: Extraction of DPOAE time course for one scenario

For each subject a total of 36 measurements will be done. Subject is able to stop the measurement or to have a larger break between blocks of measurements.

5.8 Analysis of results

4 subjects participate in the pilot test, 12 scenarios with different characteristics regarding SPL levels of primary tones for evoking DPOAE and CAS SPL level and frequency content are studied. Due to time limitations no hearing test (audiometry or tympanomery) is carried out in the pilot test.

Results of the pilot test are analyzed in order to explore the best stimuli features that can be used for ear reflexes separation.

First, an analysis of each subject is done and then, an analysis taking into account the response of all subjects is made.

A real measurement is shown in figure 5.9. As it can be seen, DPOAE amplitude shows a shift due to contralateral stimulation. First, DPOAE amplitude shows a variation around a certain value, which depends on primary tones SPL and subject, this value is noted as "A" in figure

5.2. Then DPOAE amplitudes shows a fast amplitude shift when CAS is turned on, reaching its minimum value (maximum effect of MEM and MOC reflexes). This maximum value it is noted as "D" in figure 5.2. Then an adaptation of the subject's DPOAE amplitude is observed reaching an stabilization period in some cases. When this stabilization period is reached, a point of stabilization noted as "E" in figure 5.2 is calculated. When CAS is turned off, a fast increase in DPOAE amplitude is observed, turning back to its base line value. This last base line value is noted as B in figure 5.2.

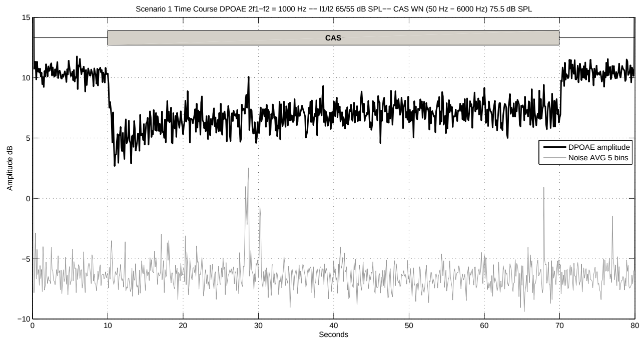

Figure 5.9: Example of a real measurement. Grey textbox represents the onset and offset of CAS. SPL level of CAS is not represented by the location of the textbox, and its SPL is indicated above the plot.

It's worth to mention that interval 2 explained in section 5.3.1 differs from the behavior seen in real measurements. In a real measurement time interval 2 consists of a fast decay until DPOAE amplitude reaches its minimum and no stabilization of DPOAE amplitude is seen in this time interval.

As it can be seen in figure 5.9, DPOAE time course present big variance along the measurement and can be seen for all subjects, see appendices A, B, C and D. Due to this variance and to ease the localization of the stabilization point E and visualization of adaptation tendency, the measurement is divided into three main parts. These parts are:

1. From measurement start to CAS onset (0-10 s). Time interval 1
2. From CAS onset to CAS offset (10-70 s). Time interval 1, 2, 3 and 4
3. From CAS offset to the end of the measurement (70 - 80 s). Time interval 5.

For part number 1 and 3 a one-degree polynomial is fitted and a second-degree polynomial curve is fitted to the part 3. The curves are calculated using least squares method using matlab function polyfit in the data obtained in the pilot test. An example of curve fitting can be seen in figure 5.10

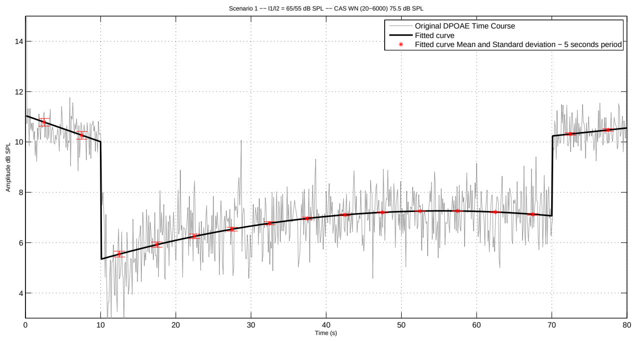

Figure 5.10: Fitted 2nd degree polynomial curve example. Mean and standard deviation of the fitted curve each 5 seconds period is plotted.

Once the curves are calculated, a general tendency of DPOAE amplitude over time can be seen for all subjects in all scenarios. In order to calculate the stabilization point E, the first order derivative of the fitted curve in the measurement part number 2 of the measurement is calculated. Local maxima will be the point of the curve where its derivative is equal to 0, (assuming for all measurements an ascendent tendency).

5.8.1 Parameters Calculated

Although parameters calculated are explained in section 5.3.1, following a short description of each parameter and its notation in the present study is reviewed. It's worth to mention that these parameters are described according to the hypothesis described in 5.2.

- **A:** Base line value calculated as the average of DPOAE amplitude in time interval 1 (0-10 s). This term is expressed in dB SPL.
- **B:** Base line value calculated as the average of DPOAE amplitude in time interval 5 (70-80 s). This term is expressed in dB SPL.
- **C:** Average DPOAE amplitude in time interval 4. This term is expressed in dB SPL.
- **D:** Minimum DPOAE amplitude reached when CAS is turned on. This term is expressed in dB SPL.
- **E:** Stabilization point. Point where the first derivative of the fitted curve is equal to 0. This term is expressed in seconds.
- **A - D:** DPOAE amplitude shift from base line value A to minimum DPOAE amplitude.
- **B - C:** DPOAE amplitude shift from base line value B to average DPOAE amplitude in time interval 4. MOC reflex is the only reflex involved according to the hypothesis described in 5.2. This term is expressed in dB SPL.

- **C - D:** Differece between average DPOAE amplitude in time interval 4 and minimum DPOAE amplitude after CAS onset. This term is expressed in dB SPL.
- **C - Noise Avg:** Signal-to-noise ratio (SNR) in time interval 4. From now on it will be noted as SNR. This term is expressed in dB SPL.

Once the main parameters are defined, analysis of results obtained in the measurements can be done.

5.8.2 Intrasubject Analysis

5.8.2.1 Subject 1

Results for subject 1 can be seen in table 5.6. All values are expressed in dB units, except stabilization point E which is expressed in seconds. Figures of measurements on subject 1 can be seen in appendix A as well as and other data with less importance or too large for its presentation in the main report.

Subject 1												
Scenario	**A**	**B**	**A - B**	**E** (seconds)	**C**	**STD (C)**	**B - C**	**D**	**A - D**	**C - D**	**Noise Avg**	**SNR (C - Noise Avg)**
1	10.38	10.39	0.01	55.50	7.21	0.84	3.18	2.68	7.70	4.54	-6.30	13.51
2	4.74	4.85	0.11	52.30	1.00	1.84	3.86	-7.20	11.94	8.19	-6.34	7.34
3	-0.76	-0.67	0.09	50.10	-4.27	2.58	3.60	-13.13	12.37	8.86	-6.09	1.82
4	11.56	11.62	0.07	58.80	8.95	0.81	2.67	4.65	6.91	4.31	-5.57	14.52
5	6.20	6.00	0.20	66.10	2.43	1.42	3.57	-3.94	10.14	6.37	-5.78	8.21
6	0.52	0.86	0.34	69.80	-3.39	2.02	4.25	-10.47	10.99	7.08	-5.48	2.09
7	11.33	11.76	0.43	53.40	9.02	0.68	2.74	4.54	6.79	4.48	-5.17	14.19
8	6.88	6.62	0.26	49.10	2.97	1.60	3.65	-3.03	9.91	6.01	-5.06	8.03
9	0.93	1.70	0.77	10.10	-2.18	3.21	3.88	-14.54	15.47	12.36	-4.07	1.89
10	12.25	12.18	0.07	56.10	9.67	0.73	2.51	6.33	5.92	3.34	-5.80	15.47
11	6.24	6.60	0.36	65.70	3.27	1.26	3.33	-6.90	13.14	10.17	-5.52	8.79
12	1.64	1.80	0.17	70.00	0.28	-	1.53	-11.78	13.42	12.06	-5.12	5.40

Table 5.6: Results of Subject 1. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

As it can be seen in table 5.6, scenarios with $l_1/l_2 = 65/35$ dB do not present enough SNR (less than 6 dB difference between C and Noise Avg). Thus, scenarios with these levels are left out from the analysis. As it has been mentioned before all measurements can be seen in appendix A. Measurements for scenarios with $l_1/l_2 = 65/55$ and $65/45$ can be seen in figure 5.11.In figure 5.12, most important parameters calculated can be seen graphically.

Base line values A and B do not present big difference between them. Largest DPOAE values are seen in Scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB.

Scenario 12 does not present stabilization within the 60 seconds of CAS presentation.

Shift $A - D$ is larger for scenarios with $l_1/l_2 = 65/45$ dB. Regarding CAS type, for $l_1/l_2 = 65/55$ dB larger shift $A - D$ is for scenario 1. However for $l_1/l_2 = 65/45$ the largest shift $A - D$ is seen for Scenario 11.

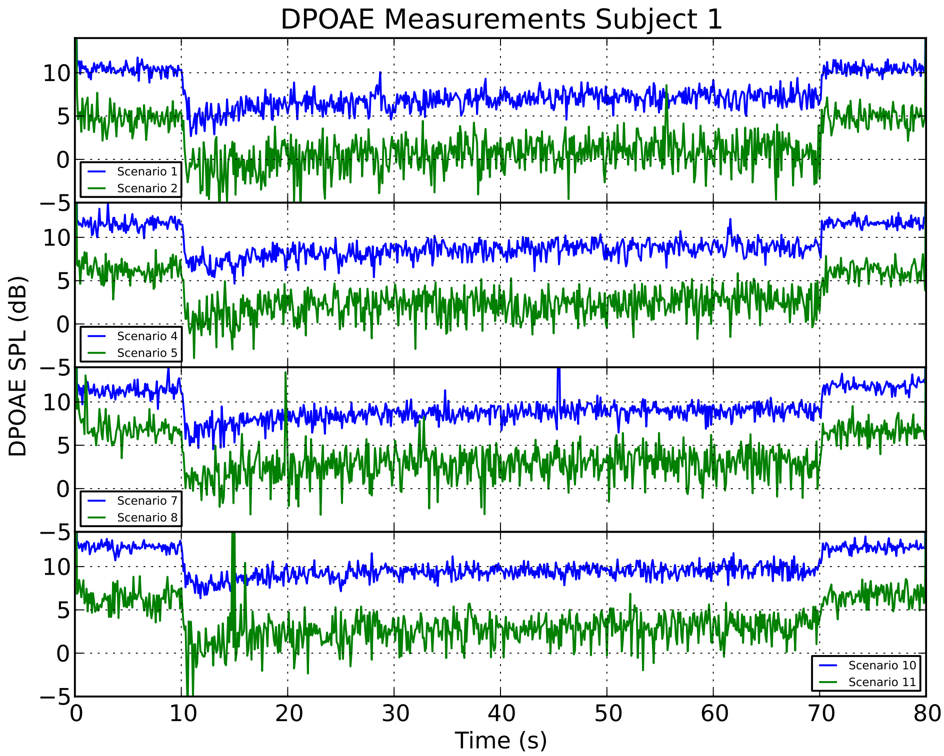

Figure 5.11: Subject 1 measurements for secenarios with $l_1/l_2 = 65/55$ and $65/45$ dB.

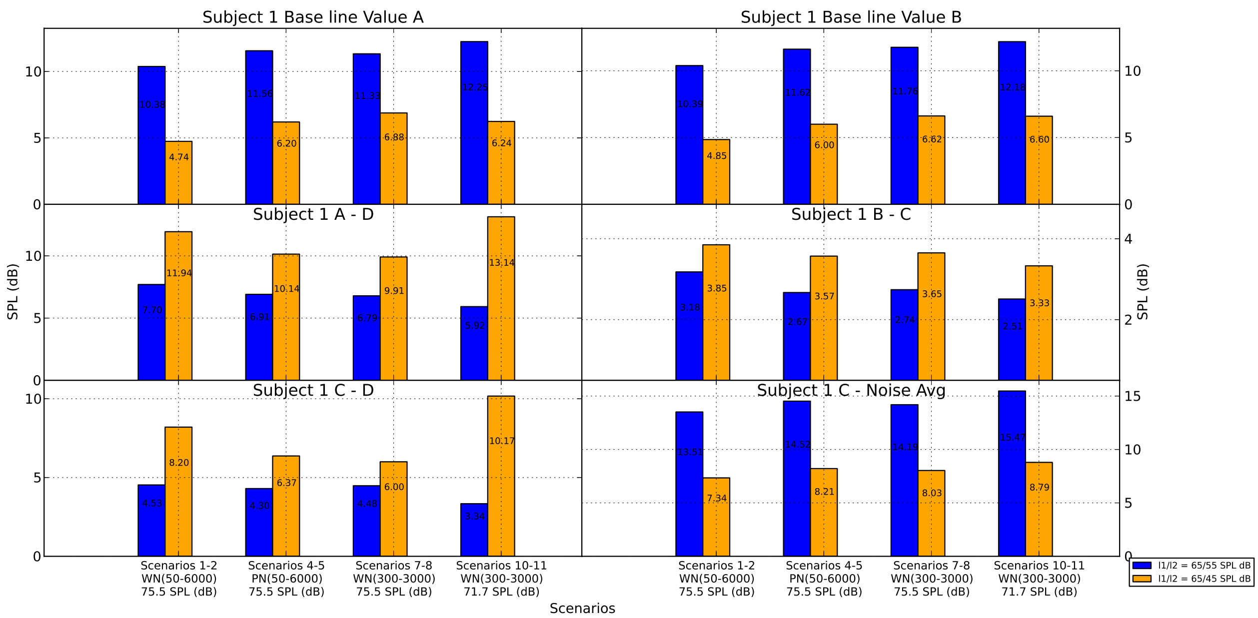

Figure 5.12: Data calculated from Subject 1

Shift $B - C$ don't present big differences regarding CAS type used. However it seems to be more sensitive to SPL levels of primary tones used. These shift is larger for scenarios with $l_1/l_2 = 65/45$ dB.

Shift $C - D$ is larger for scenarios with $l_1/l_2 = 65/45$ dB. Regarding CAS type, largest differences in this shift are seen for scenario 11. For scenarios $l_1/l_2 = 65/55$ dB CAS type seems not to have big influence on this difference, except for scenario 10.

SNR is larger for scenarios where $l_1/l_2 = 65/55$ dB. For scenarios with primary tones SPL $l_1/l_2 = 65/45$ dB, SNR is smaller but still larger than 6 dB difference. For $l_1/l_2 = 65/35$ dB SNR becomes smaller not reaching 6 dB difference at any scenario.

5.8.2.2 Subject 2

Results for subject 2 can be seen in table 5.7. All values are expressed in dB units, except stabilization point E which is expressed in seconds. Figures of measurements on subject 2 can be seen in appendix B as well as and other data with less importance or too large for its presentation in the main report.

Subject 2												
Scenario	**A**	**B**	**A - B**	**E** (seconds)	**C**	**STD (C)**	**B - C**	**D**	**A - D**	**C - D**	**Noise Avg**	**SNR (C - Noise Avg)**
1	8.57	9.36	-0.79	70.00	6.00	-	3.36	-1.52	10.09	7.52	-4.92	10.92
2	1.72	2.23	-0.51	64.70	0.23	2.13	1.99	-6.14	7.85	6.37	-4.99	5.22
3	-0.68	-0.01	-0.67	59.60	-2.88	2.98	2.87	-12.77	12.09	9.90	-4.94	2.06
4	9.71	10.23	-0.52	52.90	8.18	0.84	2.06	2.70	7.01	5.47	-5.22	13.40
5	1.90	2.09	-0.18	70.00	0.09	-	2.00	-6.11	8.01	6.19	-5.68	5.76
6	-1.01	-0.45	-0.56	49.30	-2.76	2.81	2.31	-10.47	11.31	9.56	-5.57	2.82
7	9.94	10.34	-0.40	53.60	8.22	0.89	2.12	4.67	5.27	3.55	-5.33	13.55
8	1.91	2.78	-0.87	60.40	0.44	2.06	2.34	-6.76	8.67	7.20	-5.29	5.73
9	-1.03	0.44	-1.47	49.90	-2.84	2.68	3.28	-13.07	12.03	10.23	-5.33	2.49
10	9.57	9.92	-0.35	56.10	8.02	0.90	1.90	4.16	5.41	3.86	-5.40	13.42
11	1.88	2.53	-0.65	70.00	3.62	-	-1.09	-9.51	11.38	13.13	-5.06	8.69
12	0.29	0.15	0.14	70.00	0.52	-	-0.37	-14.38	14.67	14.89	-5.19	5.71

Table 5.7: Results of Subject 2. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

As it can be seen in table 5.7, scenarios with $l_1/l_2 = 65/35$ dB do not present enough SNR (less than 6 dB difference between C and Noise Avg). Thus, scenarios with these levels are left out from the analysis. As it has been mentioned before all measurements can be seen in appendix B. Measurements for scenarios with $l_1/l_2 = 65/55$ and $65/45$ can be seen in figure 5.13.In figure 5.14, most important parameters calculated can be seen graphically.

As it can be seen in table 5.7 base line values A and B are much larger for scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB. Differences between base line values A and B are small and they are about 0.5 dB. It is worth to mention that base line value B is always bigger than base line value A.

Scenarios 1, 5, 11 and 12 seem not to present DPOAE shift adaptation, according to the fitted curve. As it can be seen in all scenarios where there is no DPOAE shift adaptation, the standard

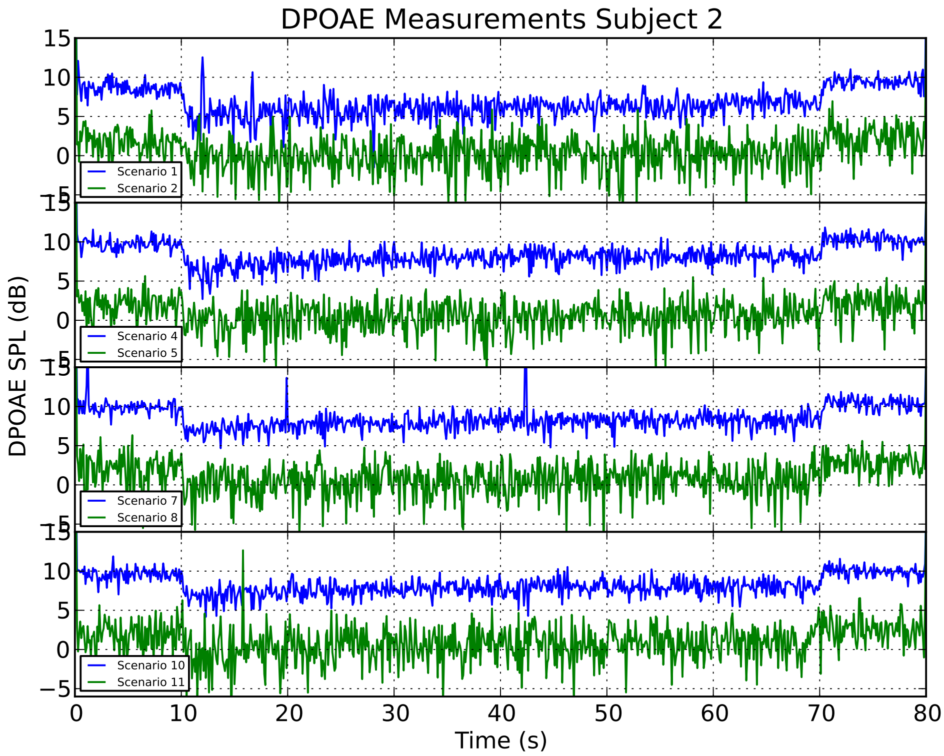

Figure 5.13: Subject 2 measurements for secenarios with $l_1/l_2 = 65/55$ and $65/45$

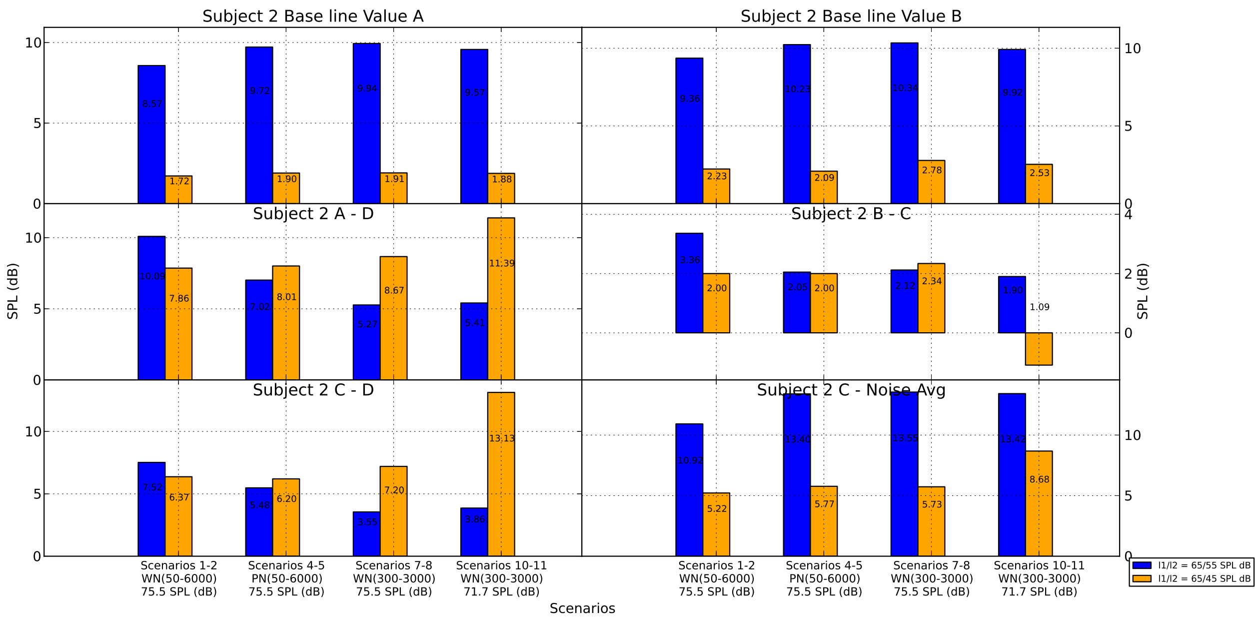

Figure 5.14: Data calculated from Subject 2

deviation in the last 10 seconds of the fitted curve is very small which can point out an adaptation but when the first derivative of the fitted curve is calculated exact value of 0 is not reached. The standard deviation in DPOAE amplitude in the last ten seconds (two periods of 5 seconds) in scenarios 1, 5, 11 and 12 are very similar to that observed in the whole measurement. Mean and standard deviations calculated in periods of 5 seconds of the measurement and the fitted curve can be seen in tables B.1, B.2, B.3 and B.4 in appendix B.

Shift $A - D$ is larger for scenarios with $l_1/l_2 = 65/45$ dB except for scenarios 1 and 2. Regarding CAS type, for $l_1/l_2 = 65/55$ dB largest shift $A - D$ is for scenario 1. However for $l_1/l_2 = 65/45$ the largest shift $A - D$ is seen for Scenario 11. As it can be seen in figure 5.14, larger shifts $A - D$ are seen as scenario number decreases for $l_1/l_2 = 65/55$ and the opposite can be seen for scenarios with $l_1/l_2 = 65/45$ dB.

Shift $B - C$ don't present big differences regarding CAS type or primary tones SPL used except for scenario 1 and scenario 11. It's worth to mention that for scenario 11 shift $B - C$ is negative, however if we see this scenario measurement in figure 5.13 we can see that value B is larger than C. This is due to no shift adaptation of DPOAE amplitude in this scenario, and value of C is taken as value of DPOAE amplitude at second 70.

Shifts between $C - D$ are larger for scenarios with $l_1/l_2 = 65/45$ dB except for scenarios 1 and 2. Regarding CAS type, different influence can be seen depending on the primary tones SPL. The largest difference $C - D$ is seen for scenario 11.

Only Scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB and scenario 11 using $l_1/l_2 = 65/45$ dB fulfills with a difference between C and Noise Avg larger than 6 dB. However, it's worth to mention that all scenarios with $l_1/l_2 = 65/45$ present a difference between C and Noise Avg very close to 6 dB. Scenarios with $l_1/l_2 = 60/35$ dB present small SNR.

5.8.2.3 Subject 3

Results for subject 3 can be seen in table 5.8. All values are expressed in dB units, except stabilization point E which is expressed in seconds. Figures of measurements on subject 3 can be seen in appendix C as well as and other data with less importance or too large for its presentation in the main report.

As it can be seen in table 5.8, scenarios with $l_1/l_2 = 65/35$ dB do not present enough SNR (less than 6 dB difference between C and Noise Avg). Thus, scenarios with these levels are left out from the analysis. As it has been mentioned before all measurements can be seen in appendix C. Measurements for scenarios with $l_1/l_2 = 65/55$ and $65/45$ can be seen in figure 5.15.In figure 5.16, most important parameters calculated can be seen graphically.

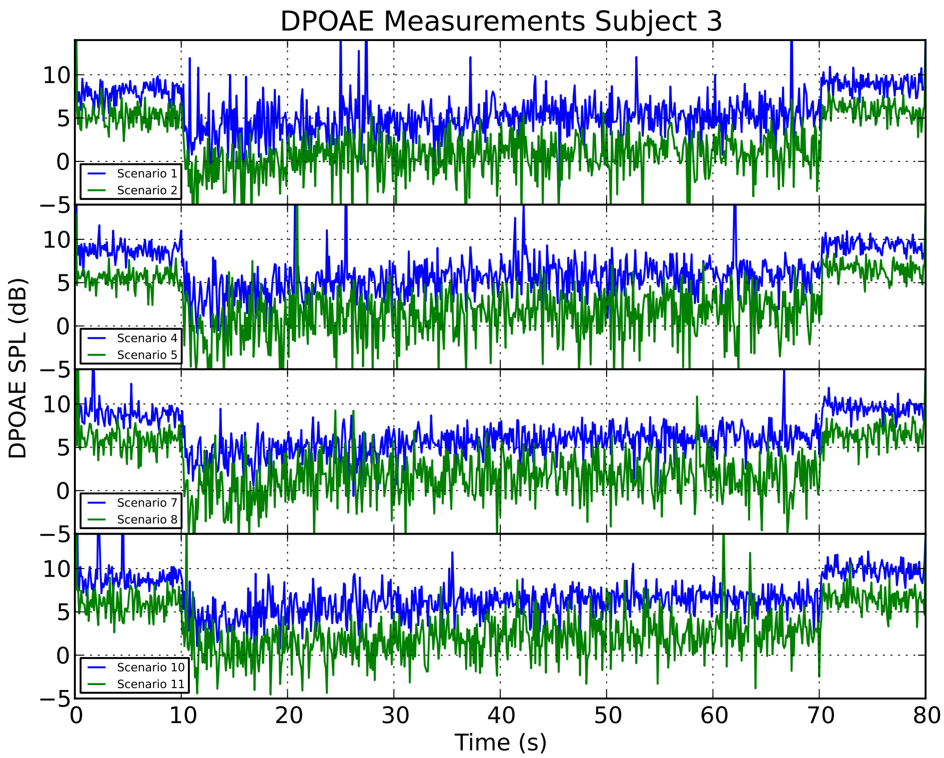

Figure 5.15: Subject 3 measurements for secenarios with $l_1/l_2 = 65/55$ and $65/45$

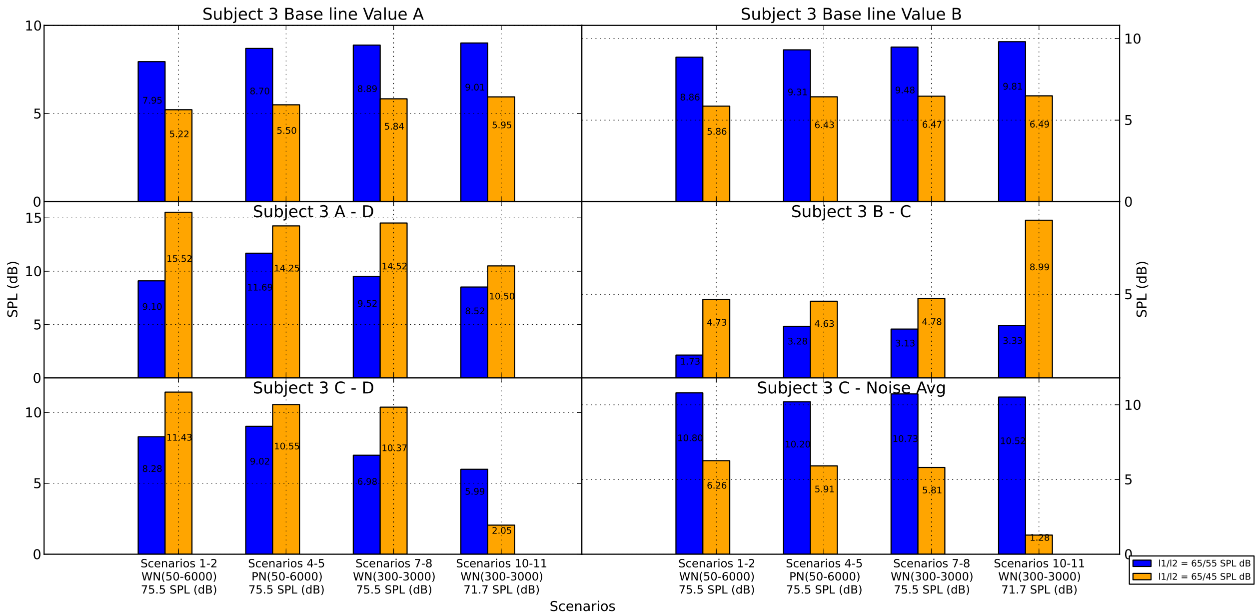

Figure 5.16: Data calculated from Subject 3

						Subject 3						
Scenario	**A**	**B**	**A - B**	**E** (seconds)	**C**	**STD (C)**	**B - C**	**D**	**A - D**	**C - D**	**Noise Avg**	**SNR(C - Noise Avg)**
1	7.95	8.86	-0.91	70.00	7.13	-	1.73	-1.15	9.10	8.28	-3.67	10.80
2	5.22	5.86	-0.64	59.00	1.13	2.02	4.73	-10.30	15.51	11.43	-5.13	6.26
3	-0.14	0.80	-0.94	42.50	-4.10	3.59	4.91	-18.29	18.15	14.19	-4.87	0.77
4	8.70	9.31	-0.62	54.10	6.03	1.84	3.28	-2.99	11.69	9.02	-4.17	10.20
5	5.50	6.43	-0.94	59.50	1.80	2.50	4.63	-8.75	14.25	10.55	-4.11	5.91
6	0.41	1.30	-0.90	37.90	-3.10	3.29	4.40	-15.98	16.39	12.89	-3.77	0.68
7	8.89	9.48	-0.59	64.80	6.35	1.63	3.14	-0.63	9.52	6.97	-4.38	10.73
8	5.84	6.47	-0.62	47.30	1.69	2.32	4.78	-8.68	14.52	10.36	-4.12	5.81
9	0.01	2.00	-1.99	36.90	-3.03	3.50	5.02	-13.59	13.60	10.57	-4.02	1.00
10	9.01	9.81	-0.80	55.60	6.48	1.16	3.33	0.49	8.52	5.99	-4.04	10.52
11	5.95	6.49	-0.54	70.00	-2.50	-	8.98	-4.55	10.50	2.06	-3.78	1.28
12	0.52	1.72	-1.20	70.00	-4.21	-	5.93	-10.26	10.78	6.04	-3.55	-0.66

Table 5.8: Results of Subject 3. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

DPOAE amplitude is larger for scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB. Differences between base line values A and B are around 1 dB, base line values B larger than A values.

There's no DPOAE amplitude shift adaptation in scenarios 1, 11 ans 12. As it can be seen in all scenarios where there is no adaptation, the standard deviation in the last 10 seconds of the fitted curve is very small which can point out an adaptation but when the first derivative of the fitted curve is calculated exact value of 0 is not reached. The standard deviation in DPOAE amplitude in the last ten seconds (two periods of 5 seconds) in scenarios 1, 5, 11 and 12 are very simmilar to that observed in the whole measurement. Mean and standard deviations calculated in periods of 5 seconds of the measurement and the fitted curve can be seen in tables C.1, C.2, C.3 and C.4 in appendix C.

Shift $A - D$ is larger for scenarios with $l_1/l_2 = 65/45$ dB. Largest difference is seen for scenario 2. Regarding CAS type, there are no big differences for scenarios with $l_1/l_2 = 65/55$ dB except fo scenario 3. For $l_1/l_2)65/45$ dB CAS type has no big influence except for scenario 11.

Shift $B - C$ don't present big differences between scenarios with $l_1/l_2 = 65/55$ dB and $65/45$ dB, except for scenarios 1 ans 11, which are scenarios where no DPOAE amplitude adaptation is reached.

Shifts $C - D$ are larger for scenarios with $l_1/l_2 = 65/45$ dB. Regarding CAS type,for scenarios with $l_1/l_2 = 65/55$ dB,largest shift $C - D$ is seen for scenario 4 while for l_1/l_2 largest difference $C - D$ is seen for secnario 2 in which other CAS type from scenario 4 is used.

All scenarios with $l_1/l_2 = 65/55$ dB, have C at least 6 dB over Noise Avg. For scenarios with $l_1/l_2 = 65/45$ dB, although SNR is smaller than 6 dB, except for scenario 2 which is larger, this difference is very close to 6 dB.

5.8.2.4 Subject 4

Results for subject 4 can be seen in table 5.9. All values are expressed in dB units, except stabilization point E which is expressed in seconds. Figures of measurements on subject 4 can be seen in appendix D as well as and other data with less importance or too large for its presentation in the main report.

Subject 4												
Scenario	**A**	**B**	**A - B**	**E** (seconds)	**C**	**STD (C)**	**B - C**	**D**	**A - D**	**C - D**	**Noise Avg**	**SNR (C - Noise Avg)**
1	4.48	5.45	-0.97	10.10	2.98	1.46	2.47	-0.49	4.98	3.48	-5.64	8.62
2	3.99	3.66	0.33	56.20	2.94	1.39	0.72	-3.74	7.73	6.68	-6.42	9.36
3	1.83	2.55	-0.72	68.30	-0.61	1.40	3.16	-8.92	10.74	8.31	-6.26	5.65
4	4.64	4.55	0.09	70.00	4.27	-	0.27	-2.63	7.27	6.91	-6.22	10.50
5	4.05	3.69	0.37	70.00	2.57	-	1.12	-5.30	9.35	7.87	-5.46	8.03
6	1.07	2.11	-1.04	55.70	-0.97	2.21	3.09	-7.94	9.01	6.97	-6.18	5.21
7	4.77	4.92	-0.15	55.30	3.18	1.44	1.74	-1.90	6.67	5.08	-6.11	9.30
8	4.19	3.65	0.53	50.20	2.95	1.40	0.70	-2.68	6.87	5.63	-5.94	8.89
9	2.31	2.98	-0.66	10.10	-0.68	2.15	3.66	-6.54	8.85	5.86	-5.65	4.97
10	4.72	5.03	-0.31	10.10	3.60	1.99	1.43	-1.51	6.23	5.11	-5.39	8.99
11	3.96	3.95	0.01	10.10	2.94	1.71	1.01	-2.19	6.15	5.13	-5.43	8.37
12	3.56	3.95	-0.38	70.00	2.35	-	1.60	-9.37	12.93	11.72	-5.78	8.12

Table 5.9: Results of Subject 4. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

As it can be seen in table 5.9, scenarios with $l_1/l_2 = 65/35$ dB do not present enough SNR (less than 6 dB difference between C and Noise Avg). Thus, scenarios with these levels are left out from the analysis. As it has been mentioned before all measurements can be seen in appendix D. Measurements for scenarios with $l_1/l_2 = 65/55$ and $65/45$ can be seen in figure 5.17.In figure 5.18, most important parameters calculated can be seen graphically.

Subject 4 is the subject who presents lower DPOAE amplitude in scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB. Except for scenario 12, DPOAE amplitude in scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB and $65/45$ dB are very similar. For $l_1/l_2 = 60/35$ dB, DPOAE amplitude is even lower.

It seems no to be adaptation on DPOAE amplitude shift for scenarios 4 and 5 and 12.

Differences between base line values A and B are about 0.4 dB and 60 % of times B is larger than A.

As it can be seen in all scenarios where there is no adaptation, the standard deviation in the last 10 seconds of the fitted curve is very small which can point out an adaptation but when the first derivative of the fitted curve is calculated exact value of 0 is not reached. The standard deviation in DPOAE amplitude in the last ten seconds (two periods of 5 seconds) in scenarios 4, 5 and 12 are very simmilar to that observed in the whole measurement. Mean and standard deviations calculated in periods of 5 seconds of the measurement and the fitted curve can be seen in tables D.1, D.2, D.3 and D.4 in appendix D.

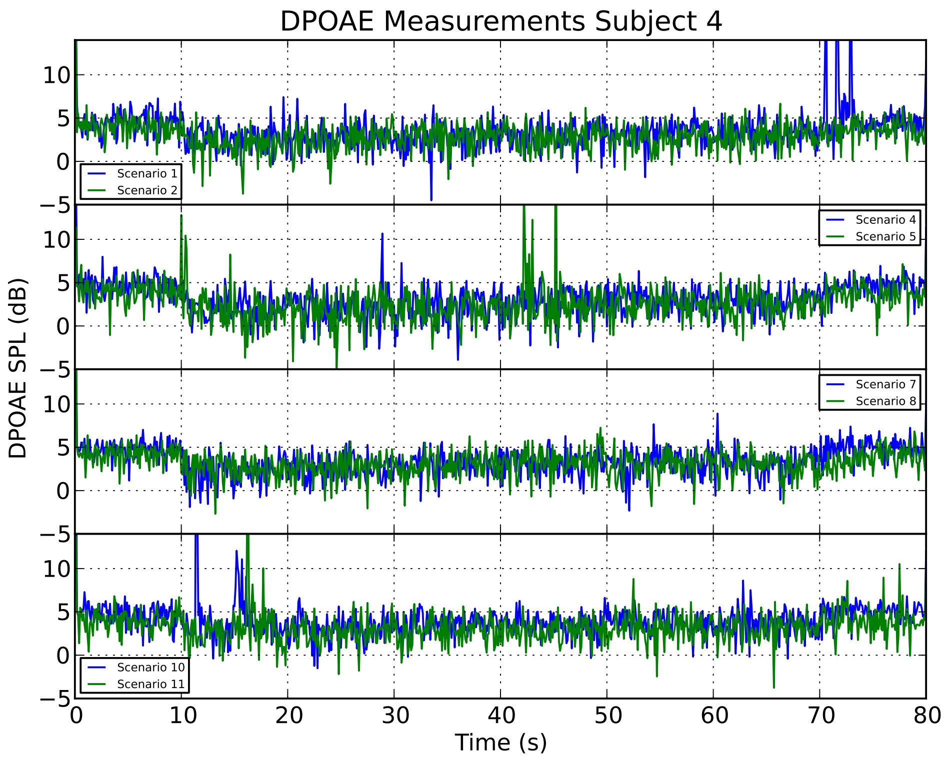

Figure 5.17: Subject 4 measurements for secenarios with $l_1/l_2 = 65/55$ and $65/45$

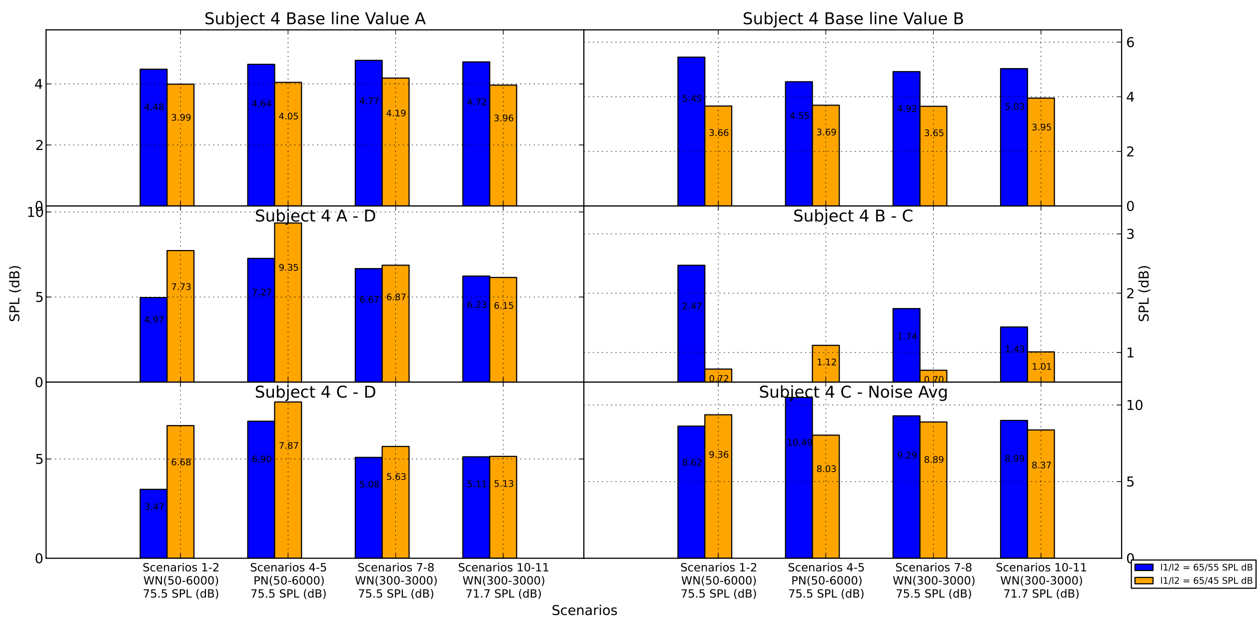

Figure 5.18: Data calculated from Subject 4

Shift $A - D$ is larger for scenarios with $l_1/l_2 = 65/45$ dB except for scenarios 10-11. Largest difference is seen for scenario 5. Regarding CAS type, biggest shift $A-D$ is seen for $PN_{50-6000}$ at 75.5 SPL dB.

Shift $B - C$ is larger for scenarios with $l_1/l_2 = 65/55$ dB except for scenarios 4-5. Largest shift is seen for scenario 1. It's weorth to mention that shifts $B - C$ except for scenario 1 are around 1 dB or less.

Shifts between $C - D$ are larger for scenarios with $l_1/l_2 = 65/45$ dB. Largest shift is seen for scenario 5.

All scenarios fulfills with a SNR larger than 6 dB except for scenarios 3, 6 and 9. Primary tones SPL in these scenarios are $l_1/l_2 = 60/35$ dB. It's worth to mention that SNR in scenarios 3 and 6 is very close to 6 dB. However it's worth to mention that these is due to the little DPOAE amplitude shifts observed when CAS is turned on.

5.8.3 Intersubjects Analysis

In general, larger values of DPOAE amplitude are found for scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB, reaching at least 6 dB of SNR.

Regarding scenarios with primary tones SPL $l_1/l_2 = 60/35$ dB, just one scenario in one subject present a difference between DPOAE amplitude and Noise Avg amplitude larger than 6 dB. In the rest of the measurements with these primary tones SPL much this difference is much smaller than 6 dB.

Therefore, scenarios with primary tones SPL $l_1/l_2 = 60/35$ dB can be discarded for further investigations due to their small SNR.

Since the aim of the pilot test is to study the most suitable stimuli characteristics for the possible separation of MEM and MOC reflex effect on the DPOAE amplitude time course, which is observed in the DPOAE amplitude shifts $A - D$, $B - C$ and $C - D$, it seems reasonable to study across subjects. SNR ($C - NoiseAvg$) is also considered in the present analysis.

In figure 5.19, DPOAE amplitude shifts $A - D$, $B - C$, and $C - D$ can be seen as well as differences $C - NoiseAvg$. All data in figure 5.19 is calculated as the average between subjects 1,2,3 and 4.

5.8.4 Conclusion

Since measured DPOAE shifts are observed when CAS is turned on, we can conclude that at least one of the two reflexes is involved in these shifts. The larger the shifts, the more accurate

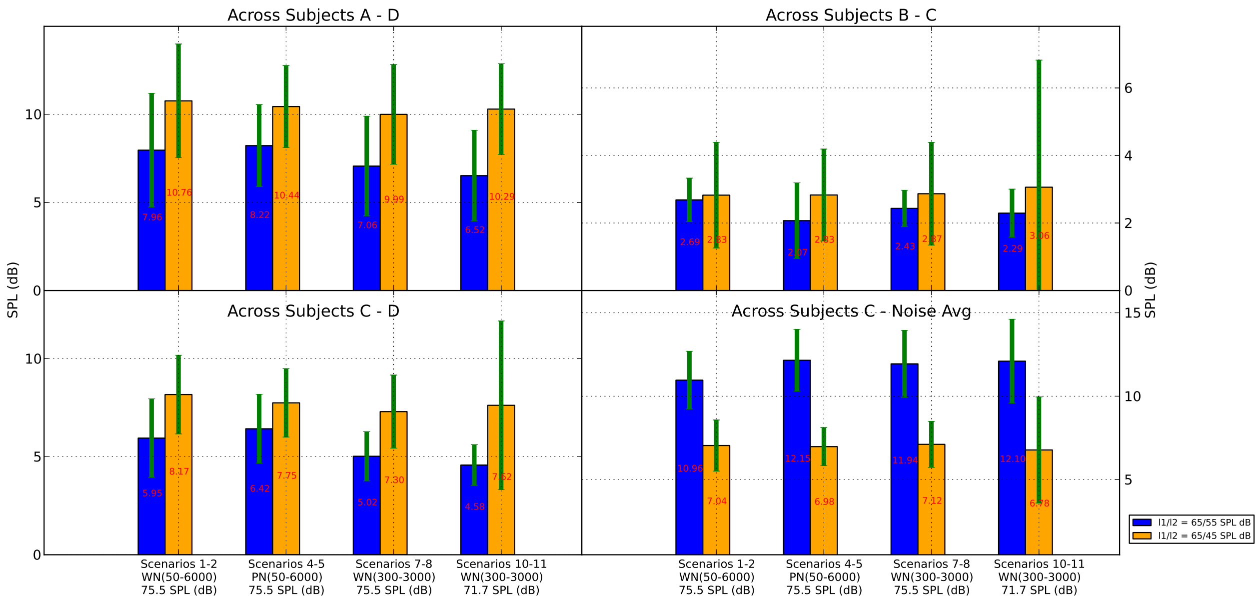

Figure 5.19: $A - D$, $B - C$, $C - D$, and $C - NoiseAvg$, calculated across subjects. Numeric value is indicated in red. Standard deviations of the parameter calculated for each scenario is plotted with a green vertical line

is the assessment of the reflexes therefore criteria to choose the scenario for the finar test is explained following.

1. SNR should be larger than 6 dB.
2. All subjects must present adaptation on DPOAE amplitude shift within 60 seconds of CAS presentation.
3. Scenarios should present the largest values of shifts $(A - D)$ and $(B - C)$ as possible.

Scenarios with primary tones SPL $l_1/l_2 = 60/35$ dB are discarded due to their small SNR.

Since shift $(B - C)$ is more sensitive to become so small that no signicance difference can be seen, it seems reasonable to observe more carefully to this parameter.

At first sight we can see in figure 5.19, scenario with largest value of shift $B - C$ is scenario 11. However subjects 2 and 3 do not present adaptation on DPOAE amplitude shift within 60 seconds of CAS presentation.

The second scenario with largest $B - C$ value is scenario 8 which consists of white noise with (300-300 Hz) bandwidth and 75.5 dB SPL as CAS with primary tones SPL $l_1/l_2 = 65/45$ dB. All subjects present adaptation within CAS presentation in this scenario having an average difference $B - C$ value of 2.87 dB as an average across subjects.

Shift $A - D$ is 9.99 dB. Shift $C - D$ is 7.30 dB. The standard deviation in DPOAE amplitude in time interval 4 is 1.85 dB, and SNR is 7.12 dB. Therefore this scenario seems to fulfills with the criteria mentioned before, and it is proposed for its use in the final test.

Third scenario with largest shift $B - C$ is scenario 5 which consists of pink noise with (50-6000 Hz) bandwidth and 75.5 dB SPL as CAS with primary tones SPL $l_1/l_2 = 65/45$ dB. However subject 2 and subject 4 do not present adaptation on DPOAE amplitude shift within 60 seconds of CAS presentation.

Fourth scenario with largest shift $B - C$ is scenario 2 which consists of white noise with (50-6000 Hz) bandwidth and 75.5 dB SPL as CAS with primary tones SPL $l_1/l_2 = 65/45$ dB. All subjects present adaptation on DPOAE amplitude shift within CAS presentation in this scenario, having a shift $B - C$ of 2.82 dB as an average across subjects.

Shift $A - D$ is 11.03 dB. Shift $C - D$ is 8.17 dB. The standard deviation in DPOAE amplitude in time interval 4 is 1.84 dB, and SNR is 7.04 dB. Therefore this scenario seems to fulfills with the criteria mentioned before, and it is proposed for its use in the final test.

Since all scenarios mentioned before present primary tones SPL of $l_1/l_2 = 65/45$ dB, scenarios with primary tones SPL $l_1/l_2 = 65/55$ dB are also considered, due to their less variance in DPOAE amplitude time course, and their relative big SNR.

Scenario 1 which consists of white noise with (50 - 6000 Hz) bandwidth as CAS and l1/l2 = 65/55 dB, present the biggest shift $B - C$. However, if we see tables 5.7 and 5.8, we can see that for subjects 2 and 3, there is no adaptation on DPOAE amplitude shift , therefore it seems reasonable not to take into account this scenario.

Scenario 7 which consists of white noise with (300-3000 Hz) bandwidth and 75.5 dB SPL as CAS with primary tones SPL $l_1/l_2 = 65/55$ dB. All subjects present adaptation on DPOAE amplitude shift within CAS presentation in this scenario having a shift $B - C$ of 2.43 dB as an average across subjects.

Shift $A - D$ is 7.10 dB. Shift $C - D$ is 5.02 dB. The standard deviation in DPOAE amplitude in time interval 4 is 1.16 dB and SNR is 11.94 dB. Therefore this scenario seems to fulfills with the criteria mentioned before, and it is proposed for its use in the final test.

Scenario 10 which consists of white noise with (50-6000 Hz) bandwidth and 75.5 dB SPL as CAS with primary tones SPL $l_1/l_2 = 65/55$ dB. All subjects present adaptation on DPOAE amplitude shift within CAS presentation in this scenario having a shift $B - C$ of 2.29 dB as an average across subjects.

Shift $A - D$ is 5.98 dB. Shift $C - D$ is 4.58 dB. The standard deviation in DPOAE amplitude in time interval 4 is 1.19 dB and SNR is 12.10 dB. Therefore this scenario fulfills with the criteria mentioned before, and it is proposed for its use in the final test.

Scenario 4 do not present adaptation on DPOAE amplitude shift for subject 4.

Therefore scenarios proposed for final test are 2, 7 8 and 10. Their characteristics can be seen in table 5.10

Scenario	Primary tones SPL level		CAS	
	f1 SPL	f2 SPL	Type Broad-band noise	SPL dB
Scenario 2	65	45	$WN_{50-6000}$	
Scenario 7	65	55	$WN_{300-3000}$	75.5
Scenario 8	65	45	$WN_{300-3000}$	
Scenario 10	65	55	$WN_{300-3000}$	71.7

Table 5.10: Stimuli characteristics of scenarios proposed for final test. Note: WN: White noise. Subindex represents bandwidth in Hz

Chapter 6

Final Test

6.1 Introduction

After the pilot test done in chapter 5, scenarios which with best results in terms of SNR in tables 5.6, 5.7, 5.8, 5.9) and shift (B - C) in tables 5.6, 5.7, 5.8, 5.9) are selected for the study of MEM and MOC reflexes assessment are chosen and used in a final test, where the study will be expanded to other frequencies.

6.2 Methodology

6.2.1 Scenarios for the final test

Regarding election of the "best" scenario for its use in the final test, one of the biggest drawbacks in the pilot test expressed by the subjects is the large duration of the measurements. It's worth to mention that pilot test in one subject takes around 55 minutes. Since DPOAE measurements are very sensitive to noise produced by subject's movements, breathing, swallowing, subjects were told to try to avoid these noises while measurements were running. Although breaks were taken into account, subjects manifested that duration of the experiment was too large.

Since duration of DPOAE measurements is the same in the final test, just one set of primary levels and one type of CAS are chosen for the final test. This scenario correponds to where the maximum MOC induced DPOAE shift $(B - C)$ is observed in the pilot test. The scenario corresponds to number 8 in the pilot test and its characteristics can be seen in table 5.10

As it is mentioned before, the test is desired to be expanded to other frequencies. Distortion product frequencies are chosen so that primary tones used for their elicitation are represented exactly by one bin of the 10-Hz resolution FFT analysis. The following distortion product frequencies are used in the final test: 520, 1000, 2000, 3000 and 5040 Hz.

Each set of distortion product frequency and primary tones is noted as a different scenario. These scenarios are described in table 6.1.

Scenario	Distortion Product frequency $2f_1 - f_2$ (Hz)	Primary Tones f_1/f_2 (Hz)	Primary tones SPL l_1/l_2 (dB)	CAS type and Bandwidth (Hz)
1	520	650 / 780	65 / 45	$\mathrm{WN}_{300-3000}$
2	1000	1250 / 1500		
3	2000	2500 / 3000		
4	3000	3750 / 4500		
5	4000	5000 / 6000		
6	5040	6300 / 7560		

Table 6.1: DPOAE frequencies and primary tones frequencies proposed for the final test. $f_2/f_1 = 1.2$. WN: White noise. Subindex represents bandwidth in Hz

6.2.2 Equipment, Calibration and Procedure

Equipment, calibration, DPOAE extraction and noise estimation are carried out as in pilot test and can be seen section 5.6.1 except for curve fitting. Parameters calculated are the same than in chapter 5 and they can be seen in 5.8.1 except for D and determination of stabilization point E.

Regarding calibration, primary tones SPLs for each scenario are checked in ear simulator B&K 4157. Measurements can be seen in table 6.2.

Primary tone	Frequency (Hz)	SPL (dB)
f_1	650	63.78
	1250	63.88
	2500	64.50
	3750	65.04
	5000	64.76
	6300	63.62
f_2	780	43.98
	1500	44.25
	3000	44.52
	4500	45.72
	6000	43.58
	7560	44.59

Table 6.2: SPL values of primary tones at different frequencies measured in ear simulator B&K 4157.

Regarding parameter D, due to the effect of the noise floor to DPOAE amplitude response seen at pilot test, this point is now calculated from the fitted curve instead from the raw DPOAE amplitude response.

Following, steps for the determination of fitting curve and stabilization point determination are described.

6.2.2.1 Curve fitting and Stabilization point determination

By looking at the results obtained in the pilot test, by visual inspection of the measurements it is observed that adaptation of the measurement occurs before than what it was calculated according to the procedure explained in section 5.8.

1. An exponential curve is fitted on DPOAE reponse within time intervals 2, 3 and 4 of DPOAE measurement, see section 5.3.1. Use of exponential curve fitting for DPOAE adaptation time course have been used in previous studies [D.O. Kim, 2001]. In the present study *Matlab* curve fitting toolbox have been used for this purpose, using a 2 terms exponential equation and non-linear least squares method. Good of fitness described by the root mean square error (rmse) for each subject and scenario can be seen in appendix F.
2. Difference between minimum and maximum value of fitted curve is calculated.
3. 10% of this difference is calculated and substracted from the mean value of the DPOAE time course in the time period (60-70 s), defining the threshold to establish the stabilization point.
4. First value of the curve which reaches this point is considered as the stabilization point of the DPOAE response when CAS is presented.
5. If this value is reached after second 60, stabilization point is set to second 60.

6.2.3 Subjects

A total of 15 subjects participated in the experiment. All the subjects underwent 3 different tests before been selected for the experiment.

6.2.3.1 Hearing assessment before experiment

The present section is mainly based in [Arlinger, 2010]. Tests performed are:

Pure tone Air-conduction audiometry It consists of the determination of hearing thresholds when stimuli are pure tones presented monoaurally. Pure tones of standardised frequencies in the range of [125 - 8000] Hz, in octave bands, are presented. Equipment fulfills with ISO 389 (1985). The test is carried out in room B5-102, listening cabin A of Aalborg University and standard [ANSI S3.21] is used for the measurements. Practically, in clinical audiometries, hearing thresholds are defined as the level which the subject responds three times in repeated series presenting the stimulus in an ascending way. The series of repetitions should be repeated at most 5 times.

All subjects exhibited lower hearing thresholds than 20 dB HL for all frequencies in the range of [125 - 8000] Hz.

Tympanometry 226-Hz tymaponemtry to ensure normal tympanic response is carried out using *Interacoustics AT235* audiometer which complies with standard (IEC 1027, 1991). A tympanometry test, consists of the measurement of the middle ear immitance when air pressure is changed into the ear canal. Middle ear pressure at maximum compliance (maximum eardrum mobility) using a tone of 226 Hz is considered normal when the line of symmetry of the bell-shaped curve measured is located at ± 25 daPa for adults.

According to [Gelfand, 2010b], for abnormal tympanometry consideration, low cutoff value for negative peak pressures of middle ear in tympanometry is set to -100 daPa. No information for high positive peak pressures is found. The limits of the static admittance measured in the tymapnogram is set to a maximum of 1.66 mmhos and a minimum of 0.37 mmhos.

All subjects exhibited normal tympanometries according the criteria mentioned before.

DPOAE Amplitude Level Pre-test The aim of this pre-test is to ensure enough SNR in at least 3 DPOAE frequencies of those used in the final test. It consists in a short version of the final test, where DPOAE SPL for each frequency is measured using the same primary tones which are used in the final test. In this pre-test no CAS is presented to the opposite ear.

Primary levels l_1 and l_2 are checked on each subject to ensure no big variation from levels shown in table 6.2 and a good fitting in the ear canal. If pre-test is positive final test is performed.

6.3 Analysis and Results

6.3.1 Analysis

The analysis is divided into two parts. First part consists in an intra-subject analysis, where measurements will be analyzed per subject and second part consists of inter-subject analysis.

6.3.1.1 Intra-subject Analysis

Due to the number of subjects, numeric data for each subject regarding parameters calculated are shown in appendix F. An analysis of measurements on each subject is performed and general types of DPOAE time course behaviors are described following.

As it is mentioned before, an exponential curve is fitted to the DPOAE time course during CAS presentation and a stabilization point is determined for each measurement. Observing measurements of all subjects, bad fitting and wrong stabilization point determination are observed. Measurements where this is observed seems to show certain patterns that are described following. In figure 6.1, fitting curves for all subjects can be seen. Note that curve fittings are normalized to 0 dB, where the reference value is base line value A for each subject and scenario. Good of fitness defined calculated as the Root Mean Square Error (RMSE) for each fitting curve can be seen in table 6.3.

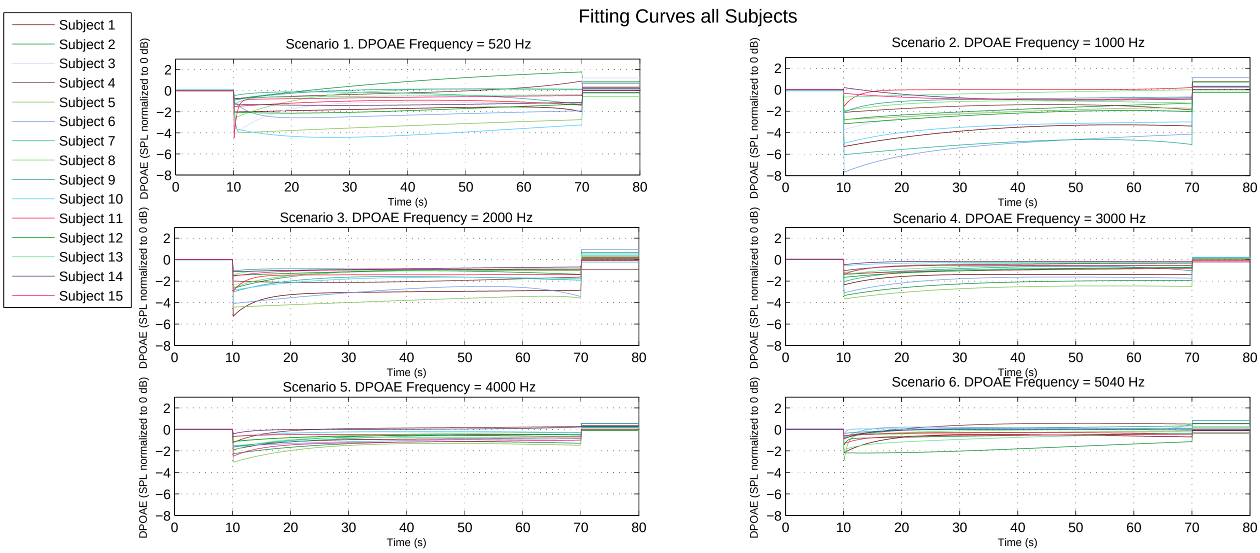

Figure 6.1: Fitting Curves per subject and Scenario. All curves are normalized to 0 dB SPL taking as a reference base line value A

RMSE fitting curve															
Scenario	Subject														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.74	3.42	2.53	2.50	1.35	3.10	3.41	3.85	3.06	2.63	2.81	2.67	3.14	1.56	2.72
2	2.07	2.04	1.53	0.77	0.87	3.73	2.61	1.09	2.23	1.20	2.91	1.53	3.05	2.08	1.58
3	1.72	2.23	0.57	1.03	0.77	2.96	1.72	1.31	2.34	1.95	2.45	1.76	1.03	0.56	0.42
4	0.39	0.69	0.22	0.50	0.63	0.78	0.44	0.35	1.00	0.45	1.00	0.46	0.20	0.42	0.41
5	0.31	0.83	0.21	0.85	1.53	1.14	0.40	0.44	0.86	0.36	0.30	0.33	0.86	0.68	0.26
6	1.24	1.29	0.32	1.00	2.85	2.28	0.68	0.81	1.04	0.30	0.52	0.69	1.19	1.90	0.72

Table 6.3: Good of fitness Root Mean Square Error of fitting curves per subject and scenario

As it can be seen, error in fitting is smaller as DPOAE frequency increases. This is due to the variability on DPOAE amplitude time course observed which is smaller as the frequency increases.

In figure 6.2, a good fitting and stabilization point determination is calculated. This type of measurement is usually seen for high DPOAE levels and a clear DPOAE amplitude shift $A - D$, although it is seen for low DPOAE levels.

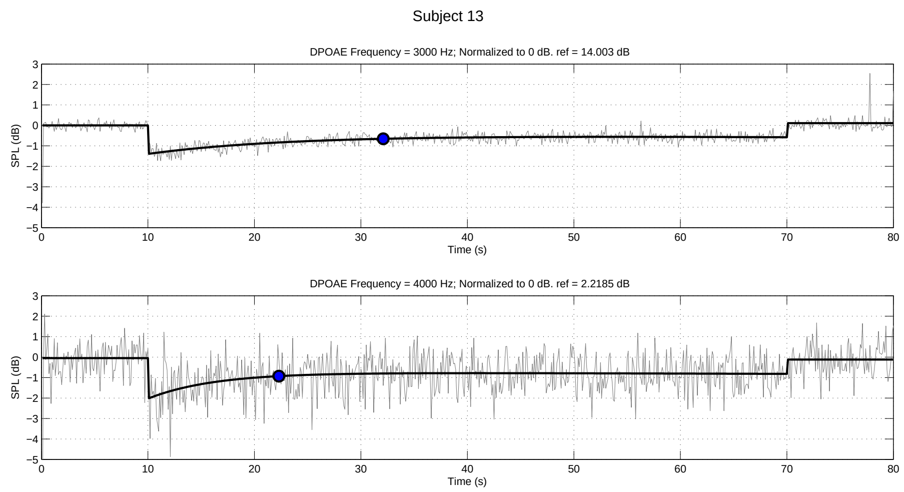

Figure 6.2: Example of good fitting and good stabilization point determintation. Subject 13 Scenario 4. Measurements normalized to 0 dB. Reference base line value A.

In figure 6.3 we can observe four measurements with good fitting but wrong stabilization point determintation. As it can be seen, fitting of first two plots (top part of figure) show a constant increase, but visually we can see how this increase is not significant and DPOAE level get stable before determination. At the bottom part of the figure other two measurements present the same problem but caused by another reason. As we can see, visually there is no difference (or this difference is very small) between DPOAE aplitude shift ($A - D$) and DPOAE amplitude shift ($B - C$). This can be due to non-activation of MEM reflex at that specific measurement, or if this occurs in high frequency, it can be due to low effect of MEM contractions to DPOAE amplitude, however for considering this cause, the same behavior should be maintained for the higher frequencies tested.

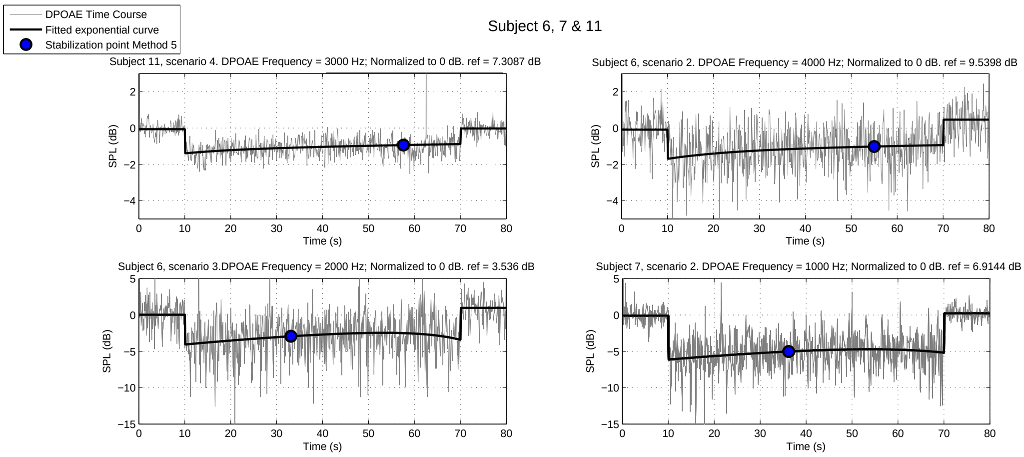

Figure 6.3: Example of good fitting but wrong stabilization point determination. Measurements normalized to 0 dB. Reference base line value A.

In figure 6.4 we can observe measurements with bad fitting and wrong stabilization point determination. First two plots (top part of the figure) are two measuerements with SNR (C - Noise Avg) larger than 6 dB. No DPOAE amplitude shift is seen during the whole measurement. It's worth to mention that all subjects present DPOAE amplitude shift ($A - D$ and $B - C$) in at least one frequency. Since contralateral earphone was not removed at any moment of the measurements on any subject, if this behavior is seen at any scenario before scenario 6 and DPOAE amplitude shift is observed in later scenarios, this behavior can be due to non-activation of ear reflexes at one specific frequency. However, if this behavior is observed just in the last scenario on any subject, the behavior can be due to a change in the fitting of the contralateral earphone. It's worth to mention that no visual change in the fitting of the contralateral earphone was observed for any subject, however, the lack of a method to check the fitting of it, arises uncertainty on the fitting and approximated SPL level at the contralateral ear.

Plots at the bottom part of the figure show very noisy measurements with $C - NoiseAvg$ smaller than 6 dB. DPOAE levels at these measurements are usually close or below 0 dB SPL or noise SPL is high. If swallowings or sudden movements are present they ar easily distinguished in this kind of measurements, for instance it can be seen in 6.4 (top left), around seconds 41 and 65. In fact, strong breathing or other possible biological noises (like heart beating) can be seen in noise estimation at some measurements. Examples of this can be seen in appendix F.

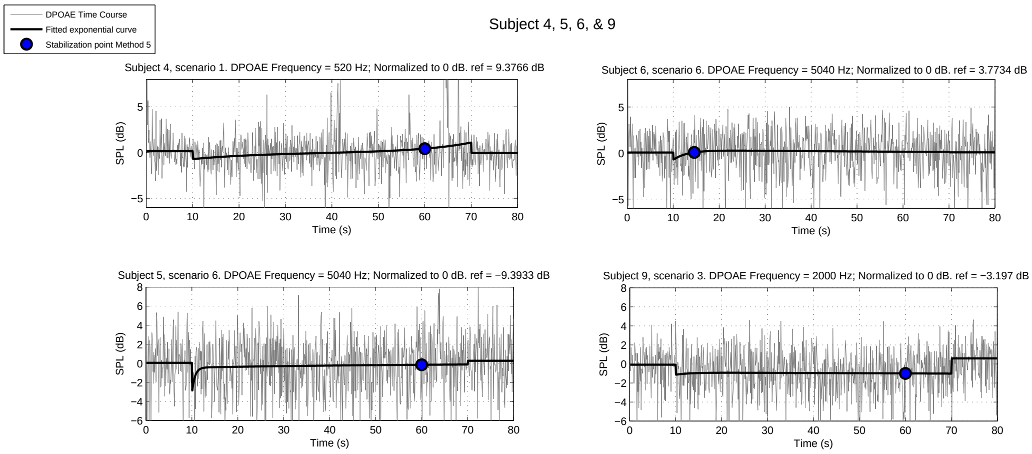

Figure 6.4: Example of bad fitting and wrong stabilization point determination. Measurements normalized to 0 dB. Reference base line value A.

Regarding intearaural attenuation, visual inspection to noise floors estimated on measuremets revealed that CAS onset has no effect on noise floor except for subject 3 and 8 in scenario 2, which show a strange response in noise floor after CAS onset. However it's worth to mention that for subject 3, this strange behavior is maintained when CAS dissapears, therefore this strange behavior can be due to other noise source. Some examples, including scneario 2 for subject 3 and 8 can be seen in figure 6.5. Rest of measurements with noise floor estimated can be seen in appendix F.

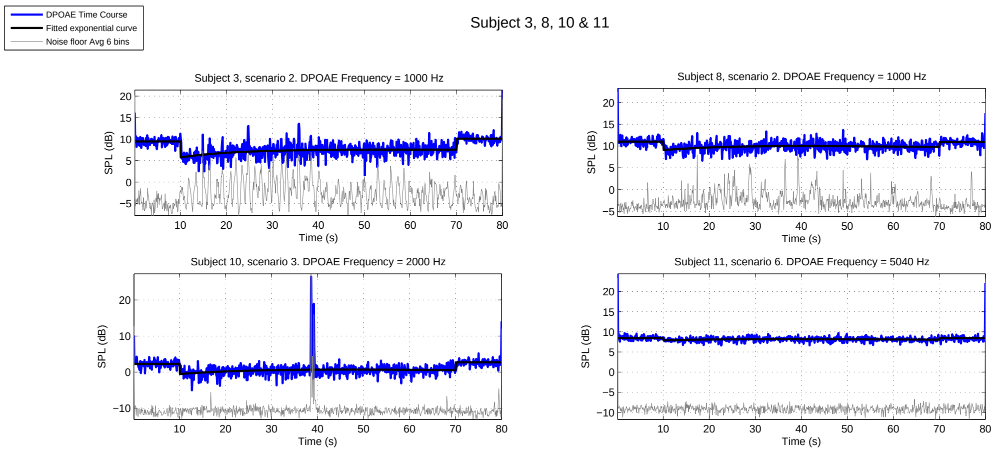

Figure 6.5: Examples of DPOAE measurements with noise floor estimated.

As it has been discussed in the present section, stabilization point determination algorithm doesn't work in all situations. Since MOC induced shift on DPOAE amplitude is calculated by $B - C$, and C is determined by the stabilization point, uncertainty exists on the calculation of this parameter, therefore, stabilization period (time interval 4) is set to the last 10 seconds of CAS presentation.

Important aim of intrasubject analysis is to determine which measurements will be taken into account for the intersubject analysis. Criteria of larger SNR ($C - NoiseAvg$) than 6 dB on the measurement is applied. This criteria is based on the generally accepted SNR for DPOAE measurements according to [Kemp, 2010]. Although this SNR is accepted for DPOAE measurement with no shift, since MOC and MEM induced shifts are desired to assess SNR is calculated as $C - NoiseAvg$.

In table 6.4 number of scenarios which present SNR larger than 6 dB across subjects can be seen. As it can be observed noise is more problematic at low frequencies, having 2 subjects out of 15 who present enough DPOAE level at 520 Hz in order to have a SNR larger than 6 dB.

Scenario	DPOAE Frequency	N. Scenarios $C - NoiseAvg > 6$dB
1	520	2
2	1000	11
3	2000	11
4	3000	15
5	4000	15
6	5040	13

Table 6.4: Number of times that each scenario present signal-to-noise ratio larger than 6 dB across subjects

6.3.1.2 Inter-subject Analysis

Following mean values across subjects of parameters for each scneario are shown. Only measurements with larger SNR (C-Noise Avg) than 6 dB has been taken into account for calculations across subjects, except for stabilization point E in which measurements where good stabilization point determination has been performed by the automatic algorithm. These measurements has been chosen by visual inspection.

Scenario	$A - B$ (dB)		E (s)		$B - C$ (dB)		$A - D$ (dB)		$C - D$ (dB)		$C - NoiseAvg$ (dB)	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
1	-0.55	0.26	22.90	0.00	2.48	1.62	2.54	1.94	0.61	0.58	9.19	0.84
2	-0.43	0.32	31.09	13.84	2.38	1.30	3.28	1.69	1.33	0.60	10.45	4.09
3	-0.16	0.23	27.42	7.98	1.59	0.99	2.47	1.37	1.04	0.67	12.97	4.12
4	-0.07	0.10	32.71	11.57	0.95	0.71	1.75	0.98	0.88	0.35	19.70	3.71
5	-0.12	0.25	32.95	11.14	0.69	0.45	1.49	0.71	0.92	0.44	18.46	5.22
6	-0.11	0.37	34.77	21.27	0.33	0.28	1.10	0.75	0.88	0.41	14.68	4.62

Table 6.5: Final test parameters. Mean and Standard deviation values across subjects. All values are expressed in SPL (dB) except parameter E which is expressed in seconds.

As it can be seen in figure 6.6 difference between base line values are always below 0 dB. This means that base line value B is always above base line value A (in average). However, difference between them is very small and decreases as DPOAE frequency increases.

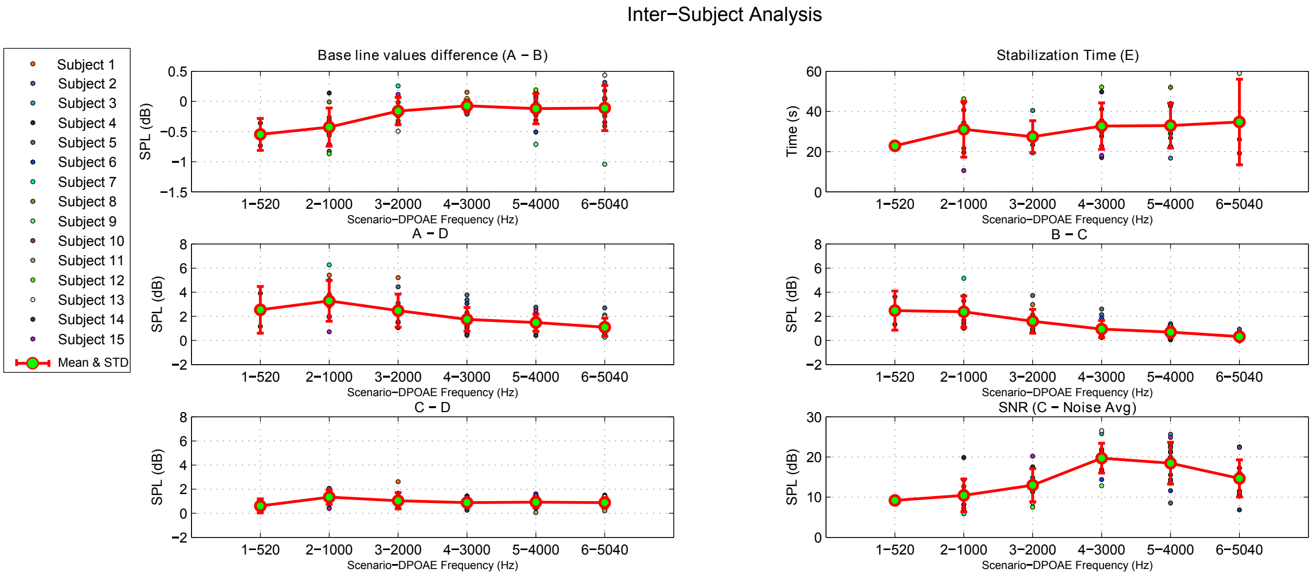

Figure 6.6: Final test parameters. Mean and Standard deviation values across subjects. Graphic representation

Measurements visually chosen for stabilization point analysis can be seen in table 6.6. As it can be seen, just one stabilization point at one measurement is well determined by the automatic algorithm explained in 6.2.2.1. As it can be seen averages stabilization points are above 20 seconds. In other words, CAS duration needed to DPOAE amplitude get stable is larger than 10 seconds. However, care should be taken when this data is considered due to the lack of measurements where a reliable stabilization point determination can be done.

Scenario	Subject Number
1	3
2	1,3,4,8,10,12,15
3	1,3,7,8,15
4	1,2,3,4,5,6,8,12,13,14,15
5	1,2,3,5,7,8,9,10,12,13,15
6	1,3,13

Table 6.6: Subjects chosen per scenario for stabilization point Inter-subject analysis

Regarding DPOAE amplitude shift $(A-D)$, as it is expected, this shift is larger for low frequency than for high frequency. For scenario 1 we can observe a lower effect than at 1 KHz, however this can be caused by the lack of subjects with high signal-to-noise ratio in this scenario.

DPOAE shift $B - C$ is around 2.4 dB for low frequency (520, 1000 Hz) and it decreases until 0.33 dB for 5040 Hz. As it can be seen, it decreases as the frequency increases.

DPOAE shift $C-D$ which reflects sole MEM induced shift, we can say that there is a significant contribution of MEM reflex to the overall effect on DPOAE amplitude, and this contribution become smaller as the frequency increases and get stable from 3000 to 5040 Hz.

In order to check if shifts $(A-D)$,$(B-C)$ and $(C-D)$ shifts are statisically significant, 3 T-tests are performed. Pools of data samples are constructed using just those subjects which at present SNR larger than 6 dB in the scenario tested. For all scenarios and type of shift, null hypothesis is rejected with a p value below significance level of 5$\%$ except scenario 1. As it can be seen in table 6.4, for scenario 1, only two subjects fulfills with the SNR criteria, therefore results for this scenario should be considered carefully.

SNR increases with frequency. Maximum SNR is obtained for DPOAE frequency at 3 KHz. As it can be seen in 6.3, values of RMSE decreases as the frequency increases, meaning that error of the fitting becomes smaller as the frequency increases. As it is mentioned in section 6.3.1.1, variability in DPOAE amplitude time course decreases as the frequency increases. In order to represent this variability, standard deviation of residuals between fit curve and POAE amplitude on stabilization period (time interval 4) per subject and scenario is calculated. Data obtained is plotted in figure 6.7 versus average SNR per scenario. It's worth noting that in this case average SNR is calculated taking into account all subjects.

Although there is a big variation between DPOAE amplitude variabilities per subject within the same scenario, a linear fit is calculated. As it can be seen, this linear fit indicates that DPOAE variability decreases as SNR in stabilization period increases. One interesting appreciation from this plot is the prediction of the SNR $(C-NoiseAvg)$ needed for having an stable DPOAE amplitude time course. Model defined by the linear fit calculated predicts a SNR $(C-NoiseAvg)$ of 21.77 dB.

A pearson's correlation is calculated between SNR and variability of DPOAE amplitude (calculated as it has been mentioned before), obtaining a correlation factor of -0.7536 and p-value smaller than 0.01.

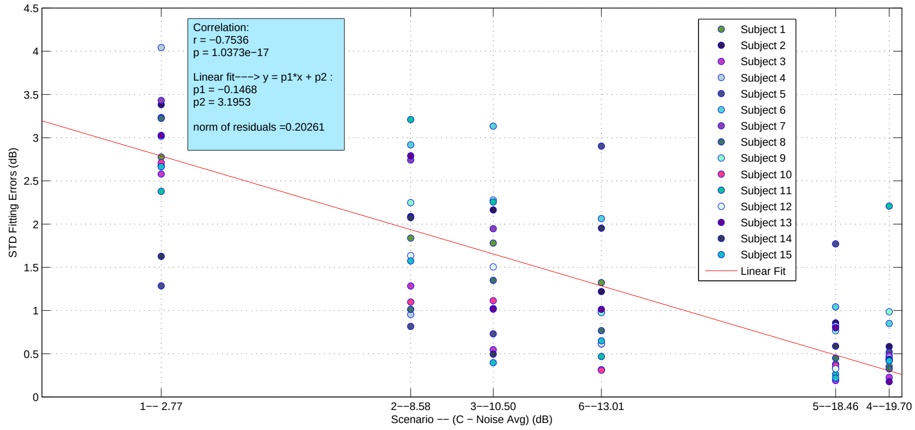

Figure 6.7: Average SNR ($C - NoiseAvg$) versus STD of errors between fitted curves and DPOAE amplitude in stabilization period. All subjects for all scenarios are taken into consid-reation. Red line depicts linear polynomial fitting. Fitting done using Least Mean Square Error method (LMSE). Pearson's correlation and linear fit details are described in textbox with blue bakground color.

6.3.2 Results

Since DPOAE amplitude shift is observed at the onset of CAS, we can conclude that ear reflexes mechanisms are activated. Since no MEM reflex threshold has been measured previously on any subject, uncertainty on the activation of MEM reflex exists. However, stabilization on DPOAE amplitude shift is observed and since reflex adaptation has been only reported for MEM reflex, this stabilization is attributable to MEM reflex relaxation. Therefore, we will refer to $(A - D)$ shift as Combined DPOAE shift (MOC + MEM), $(B - C)$ shift as MOC reflex shift and $(C - D)$ as MEM reflex shift.

Scenario	DPOAE Frequency (Hz)	DPOAE Amplitude Shifts (dB)		
		MEM + MOC	MOC	MEM
1	520	-	-	-
2	1000	3.28	2.38	1.33
3	2000	2.47	1.59	1.04
4	3000	1.75	0.95	0.88
5	4000	1.49	0.69	0.92
6	5040	1.10	0.33	0.88

Table 6.7: DPOAE amplitude shifts measured. Primary tones $f_2/f_1 = 1.2$ with $l_1/l_2 = 65/45$ SPL (dB). CAS type $WN_{300-3000Hz}$.

6.3.2.1 Result Comparison

In order to be able to compare results with other results, measurement paradigm used in the present study should be taken into account. Measurement paradigm can be summarized as follows.

In the present study contralateral MEM and MOC reflexes are assessed using long CAS and DPOAE amplitude monitoring. DPOAE is elicited by a pair of primary tones with frequency ratio $f_2/f1 = 1.2$ and SPL levels $l_1/l_2 = 65/45dB$. CAS type is white noise with bandwidth [300 - 3000] Hz and SPL 75.5 dB.

Pre and post-exposure base line values are measured as references for DPOAE amplitude shifts calculation. A two-component exponential curve is fitted to DPOAE amplitude time course when CAS is present. Induced shifts on DPOAE amplitude can be seen in table 6.7.

MOC reflex shifts are consistent with previous studies, [Carolina Abdala, 2008], where MOC reflex where measured using CAS (broadband noise at 60 SPL dB) and primary tones $l_1/l_2 = 65/55$ dB SPL and frequency ratio $f_2/f_1 = 1.22$. DPOAE frequency varied in the range of [500 - 2500] Hz, and mean DPOAE shift measured at DPOAE amplitude peaks was 2.05 dB. MEM contractions were assumed to be non activated by the CAS used.

Other study which reported similar DPOAE amplitude shifts due to MOC reflex was [A. Moulin, 1993]. Here CAS paradigm was used where CAS consisted in narrowband noise with ans ascending and descending slope of 24 dB/octave and 55 dB SPL. DPOAE frequencies were studied at 1, 2, 3 and 5 KHz, with primaries ratio $f_2/f_1 = 1.17$ and SPL $l_1/l_2 = 1$ varying from 22 to 55 dB. Maximums shifts observed were 1.37 and 1.43 for 1 and 2 KHz respectively.

MOC reflex effect on DPOAE frequencies which are not contained in CAS bandwidth is smaller than for frequencies centered at CAS bandwidth. This suggests MOC reflex frequency specifity and it is consistent with other studies that reflect certain frequency specifity such [A. Moulin, 1993]. Due to limitations of the final test performed, further study should be done in order to support this sugestion. Use of other CAS bandwidths depending on DPOAE frequency as well as increasing the resolution in DPOAE frequency range would be interesting for this purpose.

MEM reflex can be assessed using DPOAE measurements. MEM induced shift on DPOAE measurements is larger for low frequencies than for high frequencies, being as maximum 1.33 dB for scenario 2 (1000 Hz) and 0.88 dB as minimum. However no previous with DPOAE shifts values due to MEM reflex has been found.

Chapter 7

Discussion and Conclusion

7.1 Introduction

In this chapter a discussion about the results obtained in the final test is carried out. Comparison with other studies, comments on results and possible improvements and future investigations are discussed.

Due to non-significant DPOAE shifts found for scenario 1 with DPOAE frequency at 520 Hz, scenario 1 is left out for following discussion.

7.2 Discussion and Study limitations

Regarding DPOAE amplitude shift to MOC reflex, results obtained are supported by other studies where MOC induced shifts have been measured using DPOAE amplitude. However no DPOAE amplitude shifts values due to MEM reflex have been found.

In the present study a linear relation between MOC and MEM reflexes is assumed and sole MEM reflex DPOAE shift is calculated substracting MOC reflex shift to the combined DPOAE shift obtained at CAS onset, where MEM reflex, if activated, has its maximum effect. However, other possible ear reflexes (LOC) or other unknown biological mechanisms may be involved in the DPOAE amplitude shift, therefore this limitation should be taken into account when results of the present study are considered.

Further study on the relation between MEM and MOC reflexes is needed. MEM reflex can be measured by other techniques like measuring changes in earcanal admittance using the same CAS paradigm. Using this technique, stabilization times for MEM reflex can be measured and algorithm for stabilization point determination can be improved.

Since DPOAE amplitude shifts are calculated by means of fitted curves to DPOAE amplitude, variability on DPOAE amplitude arises uncertainty on the ear reflexes assessment. As it has been seen, noise has big influence on this variability (correlation of -0.7536 with $p<0.01$). This suggests that DPOAE measurements at peaks on fine structure provide more reliable ear reflex assessment. Regarding relation between MOC induced shifts and DPOAE fine structure, it's worth to mention that in other studies like [Sun, 2008b], largest DPOAE amplitude shifts were observed at frequency peaks at DPOAE fine structure which support the ear reflex assessment using DPOAE measurements at peaks on fine structure.

MOC reflex effect on DPOAE frequencies which are not contained in CAS bandwidth is smaller than for frequencies centered at CAS bandwidth. This suggests MOC reflex frequency specifity and it is consistent with other studies that reflect certain frequency specifity such [A. Moulin, 1993]. Due to limitations of the final test performed, further study should be done in order to support this sugestion. Use of other CAS bandwidths depending on DPOAE frequency as well as increasing the resolution in DPOAE frequency range would be interesting for this purpose.

Regarding stabilization time of DPOAE amplitude shift, MEM reflex activation and adaptation have been suggested to be time, frequency and intensity dependent in section 4.2.3. Since characteristics of CAS are the same in all scenarios, time of adaptation should be the same for the same subject in all scenarios, while magnitude of the DPOAE amplitude shift originated by MEM reflex would change. However, time of stabilization on DPOAE amplitude shift varies with DPOAE frequency tested. This suggests that other factors apart from the ones mentioned before, are involved in the MEM reflex adaptation and further investigation should be done on this subject.

Due to calibration method used (ear simulator), acoustic characteristics of individual ear canals are not taken into consideration, therefore uncertainty on the SPL levels of primaries and CAS delivered to the eardrum exists.

Primary SPL levels at ear-probe microphone position are checked at the pre-test performed on each subject. However, due to the transducer used for contralateral stimulation (which is not provided with a microphone), fitting of CAS transducer is evaluated visually and by subject's feedback.

7.2.1 Improvements and Practical Issues

Calibration depending on the acoustic ear canal properties for each subject, minimizing differences in SPL of stimuli delivered to the eardrum across subjects can be applied.

Correct fitting of the CAS transducer can be improved by using transducers provided with a microphone.

In order to improve SNR, a pre-test consisting in DPOAE fine structure analysis in order to be able to select frequencies with high DPOAE amplitude can be done. However care should be taken on the election of the frequencies regarding their DPOAE amplitude due to previous studies that have reported bigger DPOAE shifts at frequencies close to dips in DPOAE fine structure. Therefore a trade-off between good signal-to-noise ratio and significance MOC induced shift should be the criteria used for DPOAE frequency selection.

From a practical point of view, one of the disadvantages of the DPOAE measurement paradigm used in the present study is the duration of the measurements. Although no active participation from subjects was asked and breaks for relaxation were presented, some of the subjects manifested difficulty in avoiding swallowing or strong movements during such a long time. Therefore further investigation should be done in order to minimize the time of CAS presentation. Besides subject comfort in terms of exposure time, this will help to avoid undesired and confounding changes of DPOAE levels due to changes of middle ear impedance (strong swallowings during the breaks, yawning, etc.). Also it will help to reduce the risk of a change in the fitting of the transducers used in the measurements. Regarding subject's comfort, use of a head restraint is recommended, mainly, when long measurements are performed.

In order to reduce the time of measurement, MEM reflex thresholds can be measured previously on each subject. Using MEM reflex thresholds for CAS SPL will reduce the time of total relaxation of stapedius muscles involved in MEM reflex.

Lighting or acoustic indication of measurement starting can help to reduce undesired noise from subject's movements, swallowings etc. However, if acoustic indication is used, care should be taken to ensure no undesired pre-stimulation of the tested ear.

7.3 Conclusion

DPOAE measurements have shown high sensitivity to contralateral stimulation. DPOAE amplitude shift due to CAS presentation has been observed for all subjects in at least one DPOAE frequency tested.

This study shows the potential of DPOAE measurements as a clinical tool for auditory pathways assessment as well as study of ear reflexes behavior and their biological roles.

Results of this study suggests that MOC and MEM reflexes can be assessed by means of long DPOAE measurement and contralateral stimulation paradigm. However, as it has been mentioned in section 7.2 and 7.2.1, different uncertainties and limitations exist and further investigation should be done in order to increase the reliability on MOC and MEM reflex assessment by DPOAE measurements.

Appendix A

Pilot Test Measurements. Subject 1

Large data and figures regarding pilot test's measurements can be seen here.

A.1 Data Tables

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	4.54	4.35	2.06	4.91	4.07	0.77	4.97	4.43	2.52	5.39	4.16	3.91
5 - 10	4.71	3.88	1.81	4.65	4.18	1.57	4.82	4.24	2.27	4.43	3.94	3.40
10 - 15	2.88	2.02	-2.03	2.22	2.36	-1.88	2.13	2.63	-0.80	4.00	2.63	-0.34
15 - 20	2.66	1.87	-2.07	2.06	1.32	-1.49	2.37	2.46	-0.95	4.24	3.56	0.03
20 - 25	2.74	2.20	-1.89	2.03	1.58	-1.31	2.57	2.41	-1.01	2.89	2.47	-0.29
25 - 30	2.99	2.92	-0.94	2.20	1.98	-1.12	2.66	2.79	-0.48	3.03	2.94	-0.24
30 - 35	2.60	2.97	-0.94	2.28	1.66	-1.26	3.04	2.61	-0.92	3.64	2.72	0.14
35 - 40	2.76	2.84	-0.83	2.37	2.02	-1.35	3.01	3.27	-0.88	3.69	2.91	-0.26
40 - 45	2.91	2.76	-0.41	2.64	2.85	-1.24	3.33	3.15	-1.14	3.60	2.80	0.79
45 - 50	3.01	2.82	-0.78	2.65	2.86	-0.89	3.06	3.57	-0.35	3.40	2.93	-0.20
50 - 55	2.99	2.44	-0.60	2.92	2.60	-1.08	3.07	2.64	-0.35	3.91	3.13	0.18
55 - 60	3.56	2.85	-1.07	2.92	2.45	-0.82	3.18	3.26	-0.58	3.65	3.23	0.01
60 - 65	3.47	2.81	-0.07	2.68	2.62	-0.82	3.10	3.18	-0.64	3.70	2.86	0.34
65 - 70	3.25	3.10	-0.30	2.96	2.38	-1.25	3.24	2.71	-0.09	3.49	3.14	0.31
70 - 75	6.29	3.63	2.54	4.41	3.80	2.17	4.91	3.18	3.24	5.05	4.06	3.95
75 - 80	4.65	3.72	2.57	4.84	3.66	2.09	5.05	4.22	2.84	5.13	3.95	3.97

Table A.1: Average DPOAE's amplitude values each 5 seconds. Subject 1.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	1.82	2.65	3.36	2.35	2.71	2.85	2.08	2.97	3.41	1.87	2.77	3.07
5 - 10	0.58	1.00	2.27	0.55	0.90	2.04	0.81	0.78	2.31	0.40	1.22	1.89
10 - 15	1.35	2.30	3.15	1.17	1.97	3.18	1.34	1.60	2.82	0.94	3.61	3.03
15 - 20	0.85	1.83	2.66	0.80	1.47	2.91	0.76	2.43	4.57	0.70	1.96	2.13
20 - 25	0.88	2.16	2.91	0.85	1.39	2.73	0.78	1.83	4.38	0.66	1.61	2.72
25 - 30	1.13	1.65	2.89	0.83	1.38	2.54	0.69	1.63	3.14	0.73	1.56	2.86
30 - 35	0.82	1.64	2.53	0.83	1.66	2.70	0.78	1.89	2.73	0.60	1.40	2.50
35 - 40	0.86	1.72	2.41	0.77	1.44	3.48	0.66	1.82	2.56	0.64	1.54	1.86
40 - 45	0.71	1.36	2.10	0.82	1.47	2.60	0.75	1.30	2.26	0.54	1.07	6.96
45 - 50	0.85	1.60	2.09	0.78	1.21	2.68	1.84	1.38	2.43	0.59	1.35	2.95
50 - 55	0.82	1.42	2.79	0.82	1.34	2.43	0.74	1.76	3.20	0.67	1.72	2.44
55 - 60	0.73	2.04	3.04	0.73	1.48	2.22	0.72	1.67	2.85	0.65	1.35	5.61
60 - 65	0.86	1.70	2.31	0.99	1.40	2.63	0.63	1.56	2.58	0.73	1.34	3.95
65 - 70	0.90	1.95	2.14	0.65	1.39	2.44	0.67	1.49	3.24	0.79	1.25	3.13
70 - 75	0.76	1.11	2.08	0.72	1.02	1.80	0.73	1.12	2.09	0.56	0.94	1.63
75 - 80	1.73	2.44	3.01	1.60	2.39	2.90	1.67	2.30	2.67	1.53	2.38	2.87

Table A.2: STD DPOAE's amplitude values each 5 seconds. Subject 1.

4

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	10.78	5.24	-0.10	11.91	6.70	1.28	11.60	7.68	1.54	12.61	6.70	2.24
5 - 10	10.26	4.64	-1.03	11.53	6.10	0.15	11.34	6.58	0.80	12.17	6.20	1.45
10 - 15	5.55	-0.84	-4.61	7.34	1.31	-3.47	7.34	1.71	-2.07	8.43	1.70	-3.60
15 - 20	5.92	-0.39	-4.49	7.67	1.54	-3.38	7.75	2.06	-2.20	8.70	1.96	-3.20
20 - 25	6.25	0.00	-4.39	7.95	1.74	-3.29	8.10	2.37	-2.29	8.93	2.18	-2.83
25 - 30	6.54	0.33	-4.30	8.20	1.92	-3.21	8.41	2.62	-2.36	9.14	2.38	-2.50
30 - 35	6.77	0.59	-4.23	8.41	2.08	-3.14	8.66	2.82	-2.39	9.31	2.56	-2.21
35 - 40	6.96	0.80	-4.18	8.59	2.22	-3.08	8.85	2.96	-2.39	9.44	2.71	-1.95
40 - 45	7.11	0.95	-4.15	8.73	2.33	-3.03	8.99	3.06	-2.35	9.55	2.84	-1.72
45 - 50	7.20	1.03	-4.13	8.83	2.42	-2.98	9.08	3.10	-2.28	9.62	2.94	-1.53
50 - 55	7.25	1.06	-4.13	8.89	2.49	-2.95	9.12	3.09	-2.18	9.66	3.02	-1.38
55 - 60	7.26	1.03	-4.15	8.92	2.54	-2.92	9.10	3.03	-2.05	9.67	3.08	-1.26
60 - 65	7.21	0.93	-4.18	8.91	2.57	-2.90	9.03	2.91	-1.89	9.64	3.10	-1.17
65 - 70	7.12	0.78	-4.23	8.87	2.57	-2.90	8.91	2.75	-1.69	9.58	3.11	-1.13
70 - 75	10.32	4.85	-0.65	11.57	5.92	0.75	11.68	6.51	1.50	12.10	6.44	1.81
75 - 80	10.48	4.82	-0.77	11.67	6.15	0.95	11.89	6.74	1.85	12.26	6.77	1.79

Table A.3: Mean fitted curve values each 5 seconds. Subject 1.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	0.15	0.17	0.27	0.11	0.18	0.33	0.08	0.32	0.21	0.13	0.15	0.23
5 - 10	0.15	0.17	0.27	0.11	0.18	0.33	0.08	0.32	0.21	0.13	0.15	0.23
10 - 15	0.12	0.14	0.04	0.10	0.07	0.03	0.13	0.11	0.04	0.08	0.08	0.12
15 - 20	0.10	0.12	0.03	0.09	0.06	0.03	0.11	0.10	0.03	0.07	0.07	0.11
20 - 25	0.09	0.10	0.03	0.08	0.06	0.02	0.10	0.08	0.02	0.06	0.06	0.10
25 - 30	0.08	0.09	0.02	0.07	0.05	0.02	0.08	0.07	0.01	0.05	0.06	0.09
30 - 35	0.06	0.07	0.02	0.06	0.04	0.02	0.06	0.05	0.00	0.04	0.05	0.08
35 - 40	0.05	0.05	0.01	0.05	0.04	0.02	0.05	0.04	0.01	0.04	0.04	0.07
40 - 45	0.04	0.03	0.01	0.03	0.03	0.01	0.03	0.02	0.01	0.03	0.03	0.06
45 - 50	0.02	0.02	0.00	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.03	0.05
50 - 55	0.01	0.00	0.00	0.01	0.02	0.01	0.00	0.01	0.03	0.01	0.02	0.04
55 - 60	0.01	0.02	0.01	0.00	0.01	0.01	0.01	0.03	0.04	0.00	0.01	0.03
60 - 65	0.02	0.04	0.01	0.01	0.00	0.00	0.03	0.04	0.05	0.01	0.00	0.02
65 - 70	0.03	0.05	0.02	0.02	0.00	0.00	0.04	0.06	0.06	0.02	0.00	0.01
70 - 75	0.05	0.01	0.03	0.03	0.07	0.06	0.06	0.07	0.10	0.05	0.10	0.00
75 - 80	0.05	0.01	0.03	0.03	0.07	0.06	0.06	0.07	0.10	0.05	0.10	0.00

Table A.4: STD fitted curve values each 5 seconds. Subject 1.

A.1.1 Measurement Figures

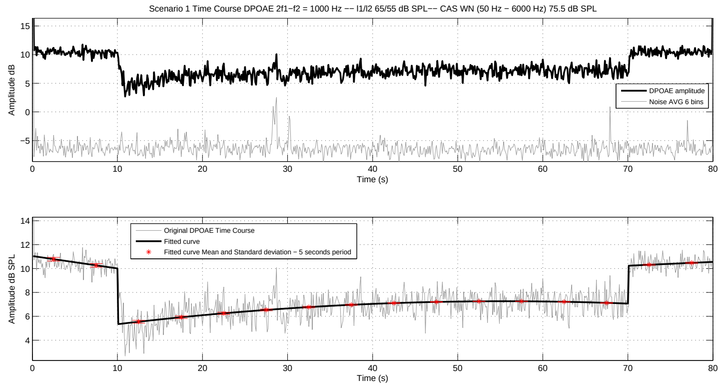

Figure A.1: Measurement subject 1, scenario 1. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

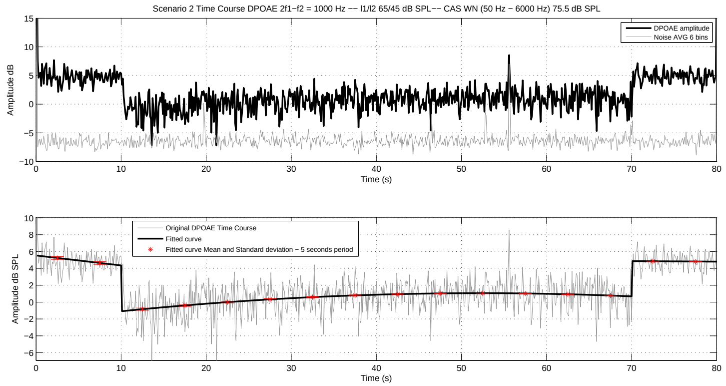

Figure A.2: Measurement subject 1, scenario 2. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

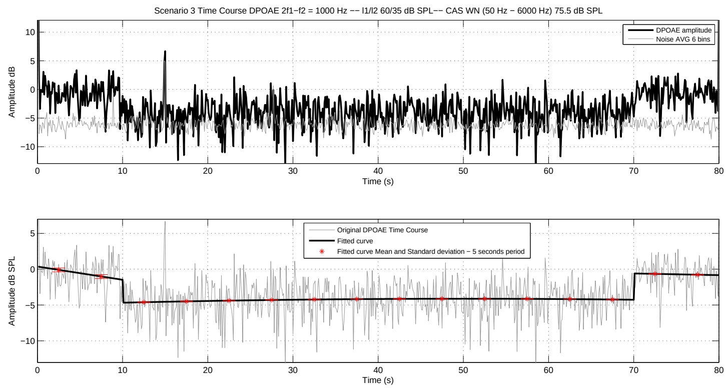

Figure A.3: Measurement subject 1, scenario 3. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

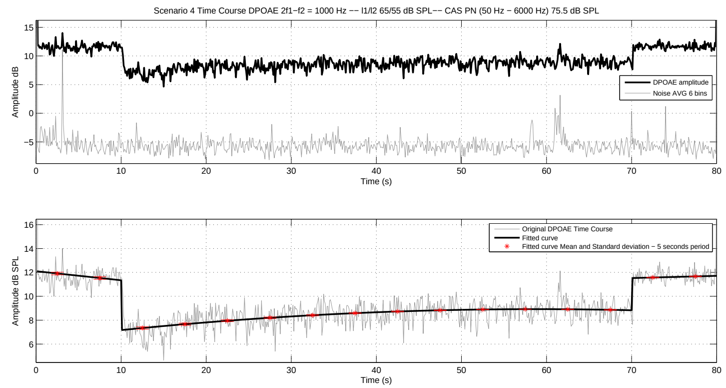

Figure A.4: Measurement subject 1, scenario 4. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

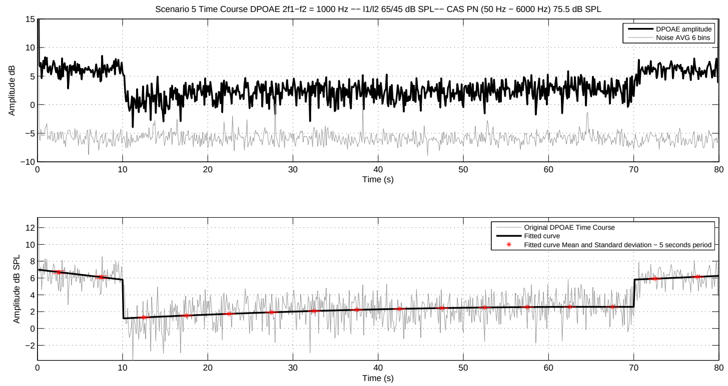

Figure A.5: Measurement subject 1, scenario 5. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

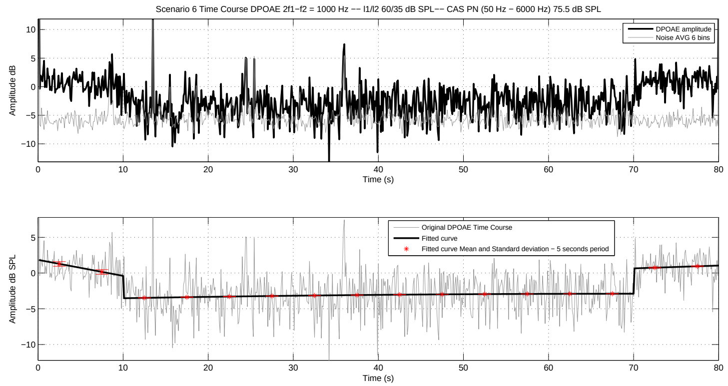

Figure A.6: Measurement subject 1, scenario 6. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

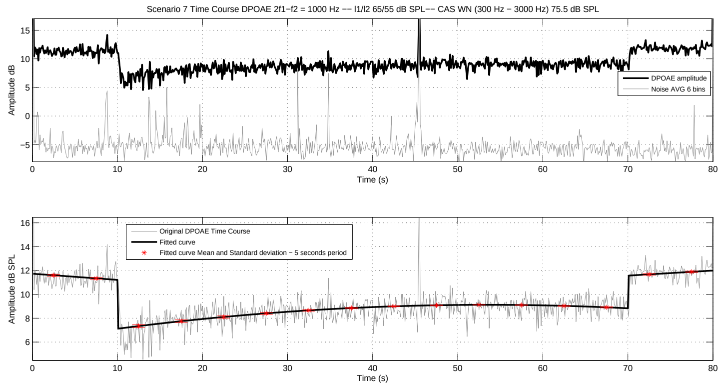

Figure A.7: Measurement subject 1, scenario 7. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

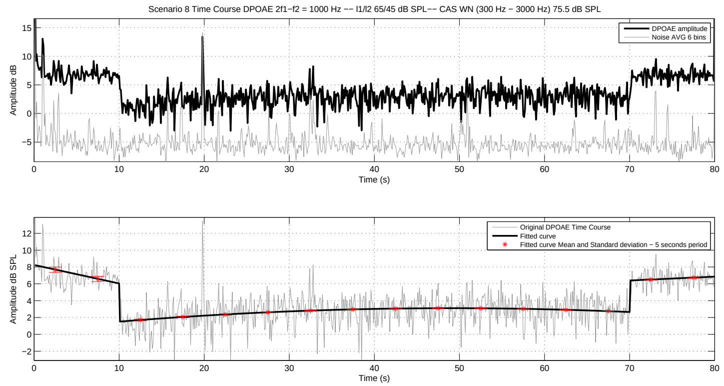

Figure A.8: Measurement subject 1, scenario 8. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

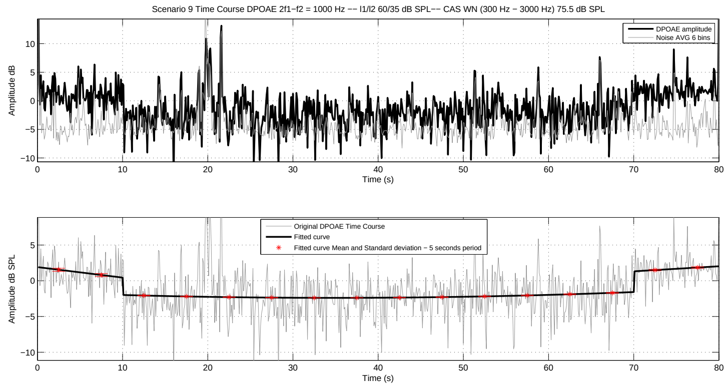

Figure A.9: Measurement subject 1, scenario 9. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

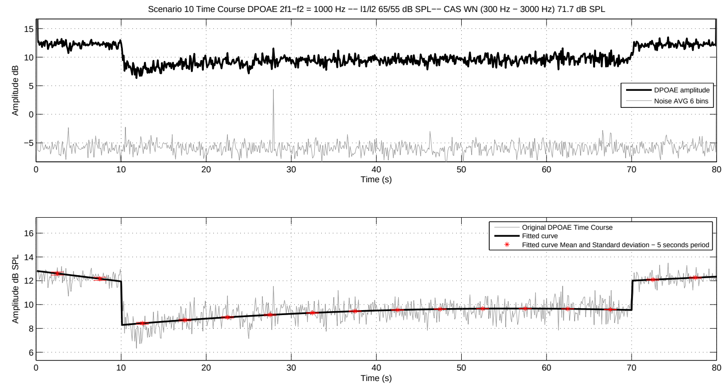

Figure A.10: Measurement subject 1, scenario 10. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

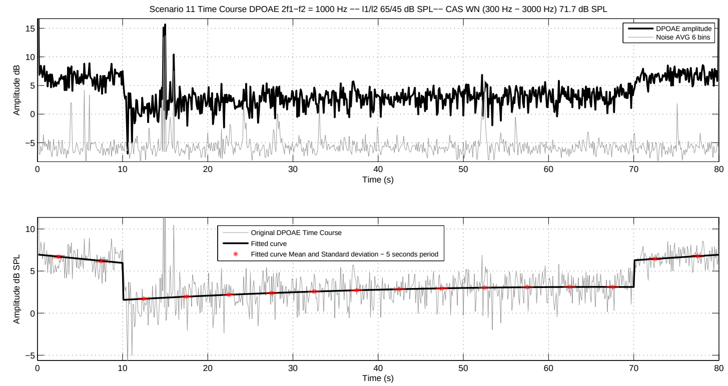

Figure A.11: Measurement subject 1, scenario 11. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

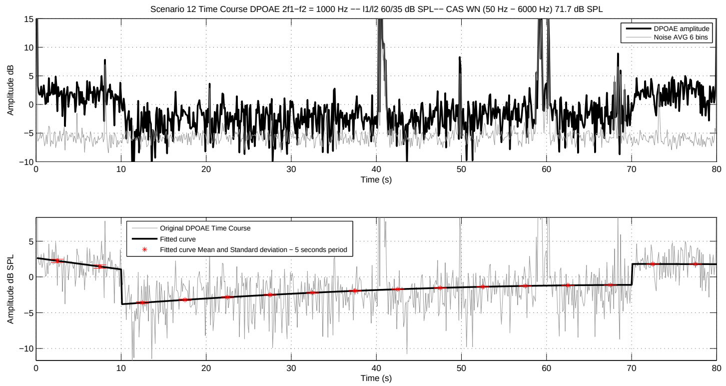

Figure A.12: Measurement subject 1, scenario 12. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

Appendix B

Pilot Test Measurements. Subject 2

Large data and figures regarding pilot test's measurements can be seen here.

B.1 Data Tables

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	9.00	2.24	0.19	9.91	2.24	-0.70	10.32	2.40	-1.21	9.77	2.07	0.13
5 - 10	8.44	1.51	-1.17	9.79	1.98	-0.83	9.85	1.80	-0.52	9.66	2.03	0.81
10 - 15	5.49	-0.09	-3.93	6.52	-0.36	-4.33	7.03	0.03	-3.67	6.93	-0.69	-3.65
15 - 20	5.26	-0.75	-3.80	7.13	0.08	-3.39	7.54	0.01	-3.93	7.11	0.20	-3.20
20 - 25	5.79	-0.25	-2.79	7.53	0.35	-3.04	7.71	0.29	-3.04	7.60	0.11	-3.31
25 - 30	5.73	-0.25	-3.36	7.84	0.23	-2.87	7.83	0.52	-2.06	7.59	0.70	-3.49
30 - 35	5.98	0.24	-3.10	7.83	0.50	-2.98	7.81	0.24	-3.19	7.75	0.33	-2.96
35 - 40	5.81	-0.09	-3.39	7.97	0.04	-3.07	8.19	0.15	-3.37	7.87	0.62	-3.08
40 - 45	6.27	0.63	-2.99	8.30	0.19	-1.67	8.35	0.47	-2.75	7.79	0.82	-2.75
45 - 50	6.08	-0.04	-2.73	8.04	0.73	-2.74	8.27	0.51	-2.59	8.12	0.10	-3.44
50 - 55	6.43	-0.26	-2.41	8.10	0.25	-3.36	8.16	0.94	-2.91	7.82	1.25	-2.40
55 - 60	6.16	0.43	-2.61	8.19	0.55	-2.64	8.33	1.05	-2.68	8.01	0.53	-2.93
60 - 65	6.78	0.02	-2.69	8.26	0.67	-2.33	8.14	0.60	-2.60	7.98	0.95	-2.16
65 - 70	6.78	0.20	-2.94	8.08	0.86	-2.74	8.25	0.37	-3.13	8.01	1.03	-3.20
70 - 75	9.34	2.18	0.65	10.34	2.25	-0.30	10.45	2.86	0.69	10.00	2.56	0.11
75 - 80	9.59	2.55	-0.52	10.22	2.24	-0.45	10.34	3.00	0.44	9.99	2.78	-0.07

Table B.1: Average DPOAE's amplitude values each 5 seconds. Subject 2.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	1.80	3.06	3.53	1.87	2.98	3.28	2.35	3.39	3.59	1.99	3.09	2.96
5 - 10	0.66	1.62	2.09	0.67	1.50	1.97	0.66	2.08	2.08	0.61	1.77	3.88
10 - 15	2.00	2.17	3.61	1.41	1.74	2.64	0.85	2.16	2.94	1.08	3.05	2.72
15 - 20	1.72	2.35	3.46	1.08	2.33	3.02	1.26	1.65	3.31	0.87	2.66	2.80
20 - 25	1.44	2.00	2.94	0.97	1.86	2.49	0.95	2.26	2.58	1.05	2.23	2.51
25 - 30	1.58	2.11	3.33	1.00	1.86	2.58	0.71	2.17	3.38	0.81	2.02	2.65
30 - 35	1.13	1.82	2.44	0.87	1.95	2.78	0.91	1.99	2.99	0.80	2.17	2.61
35 - 40	1.31	2.91	2.87	0.72	2.18	2.36	0.94	1.95	2.88	0.87	2.00	2.13
40 - 45	0.89	2.13	2.91	0.99	2.02	3.45	2.04	1.95	2.78	1.06	2.19	2.46
45 - 50	1.01	1.98	2.84	0.92	1.31	2.73	0.72	2.59	3.47	0.94	2.20	3.05
50 - 55	0.98	2.93	2.55	0.90	1.85	2.99	0.98	1.95	2.63	0.89	1.78	2.29
55 - 60	1.09	2.18	3.37	0.95	2.38	2.74	0.77	1.58	2.66	0.89	1.89	2.96
60 - 65	0.99	2.00	3.24	0.82	1.85	3.08	0.91	1.82	2.49	0.94	1.89	2.06
65 - 70	0.85	2.21	2.83	0.78	1.63	2.44	0.98	2.26	3.01	0.81	1.90	2.71
70 - 75	0.75	1.95	2.18	0.78	1.68	2.19	0.80	1.44	1.83	0.72	1.86	2.45
75 - 80	1.68	2.71	3.19	1.03	2.75	2.40	1.09	2.46	3.17	1.17	2.69	2.50

Table B.2: STD DPOAE's amplitude values each 5 seconds. Subject 2.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	8.97	2.33	0.17	10.03	2.26	-0.40	10.44	2.34	-1.05	9.89	2.22	0.74
5 - 10	8.47	1.42	-1.15	9.67	1.96	-1.13	9.73	1.87	-0.68	9.54	1.88	0.20
10 - 15	5.41	-0.39	-3.88	6.72	-0.07	-3.98	7.14	-0.06	-3.69	6.98	-0.24	-3.56
15 - 20	5.52	-0.29	-3.64	7.08	0.02	-3.61	7.41	0.08	-3.45	7.21	-0.05	-3.43
20 - 25	5.62	-0.20	-3.43	7.39	0.09	-3.29	7.64	0.21	-3.24	7.40	0.13	-3.31
25 -30	5.73	-0.11	-3.25	7.65	0.17	-3.03	7.83	0.32	-3.07	7.57	0.28	-3.20
30 - 35	5.85	-0.04	-3.09	7.86	0.25	-2.82	7.99	0.41	-2.93	7.72	0.42	-3.11
35 - 40	5.97	0.02	-2.96	8.03	0.32	-2.66	8.12	0.49	-2.83	7.83	0.55	-3.02
40 - 45	6.09	0.07	-2.85	8.15	0.39	-2.56	8.21	0.56	-2.76	7.92	0.65	-2.94
45 - 50	6.21	0.11	-2.78	8.22	0.46	-2.52	8.27	0.60	-2.72	7.98	0.74	-2.88
50 - 55	6.34	0.14	-2.72	8.25	0.52	-2.53	8.30	0.64	-2.72	8.01	0.81	-2.83
55 - 60	6.47	0.16	-2.70	8.23	0.59	-2.59	8.29	0.65	-2.76	8.02	0.86	-2.79
60 - 65	6.61	0.17	-2.70	8.16	0.65	-2.71	8.24	0.66	-2.83	8.00	0.90	-2.76
65 - 70	6.74	0.17	-2.73	8.05	0.71	-2.88	8.16	0.64	-2.93	7.95	0.91	-2.74
70 - 75	9.32	2.21	0.46	10.32	2.21	-0.21	10.41	2.82	0.59	10.02	2.54	0.15
75 - 80	9.42	2.22	-0.58	10.13	1.97	-0.85	10.26	2.75	0.27	9.80	2.44	-0.38

Table B.3: Mean fitted curve values each 5 seconds. Subject 2.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	0.15	0.26	0.38	0.10	0.09	0.21	0.20	0.14	0.11	0.10	0.10	0.16
5 - 10	0.15	0.26	0.38	0.10	0.09	0.21	0.20	0.14	0.11	0.10	0.10	0.16
10 - 15	0.03	0.03	0.07	0.11	0.02	0.12	0.08	0.04	0.08	0.07	0.06	0.04
15 - 20	0.03	0.03	0.07	0.10	0.02	0.10	0.07	0.04	0.07	0.06	0.05	0.04
20 - 25	0.03	0.03	0.06	0.08	0.02	0.08	0.06	0.03	0.06	0.05	0.05	0.03
25 -30	0.03	0.02	0.05	0.07	0.02	0.07	0.05	0.03	0.05	0.05	0.04	0.03
30 - 35	0.03	0.02	0.04	0.06	0.02	0.05	0.04	0.03	0.04	0.04	0.04	0.03
35 - 40	0.03	0.02	0.03	0.04	0.02	0.04	0.03	0.02	0.03	0.03	0.03	0.02
40 - 45	0.04	0.01	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.03	0.02
45 - 50	0.04	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.00	0.01	0.02	0.02
50 - 55	0.04	0.01	0.01	0.00	0.02	0.01	0.00	0.01	0.01	0.01	0.02	0.01
55 - 60	0.04	0.00	0.00	0.01	0.02	0.03	0.01	0.00	0.02	0.00	0.01	0.01
60 - 65	0.04	0.00	0.00	0.03	0.02	0.04	0.02	0.00	0.03	0.01	0.01	0.01
65 - 70	0.04	0.00	0.01	0.04	0.02	0.06	0.03	0.01	0.04	0.02	0.00	0.00
70 - 75	0.03	0.00	0.30	0.05	0.07	0.18	0.04	0.02	0.09	0.06	0.03	0.16
75 - 80	0.03	0.00	0.30	0.05	0.07	0.18	0.04	0.02	0.09	0.06	0.03	0.16

Table B.4: STD fitted curve values each 5 seconds. Subject 2.

B.1.1 Measurement Figures

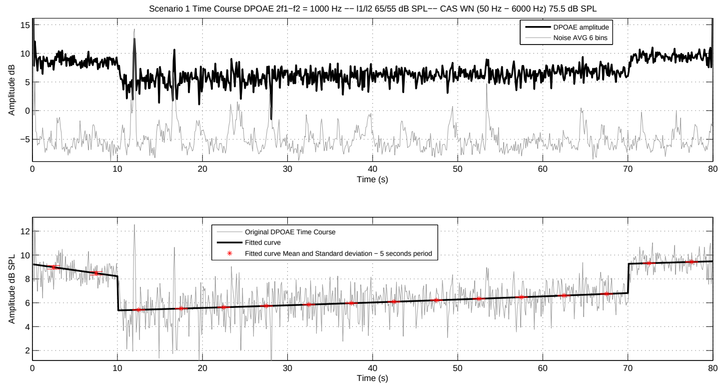

Figure B.1: Measurement subject 2, scenario 1. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

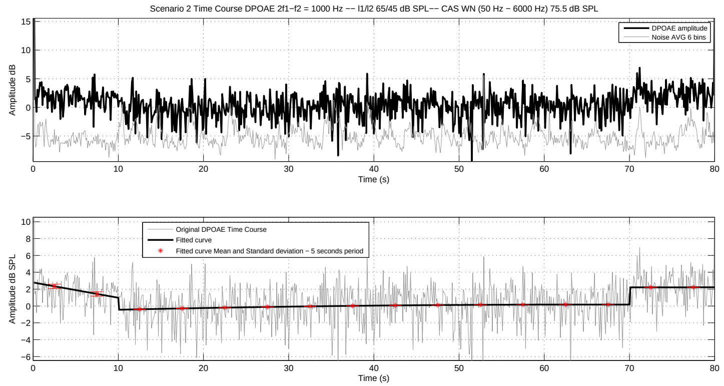

Figure B.2: Measurement subject 2, scenario 2. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

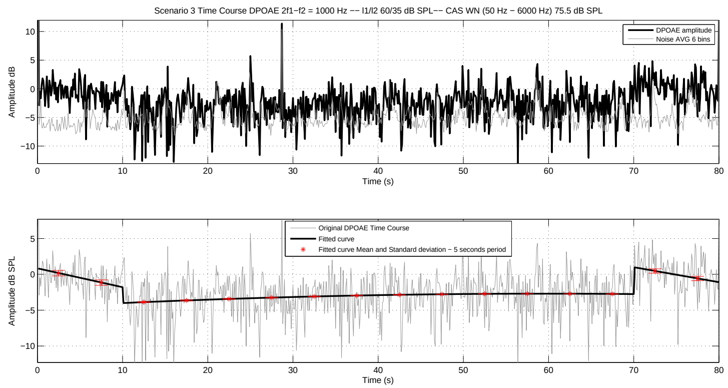

Figure B.3: Measurement subject 2, scenario 3. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

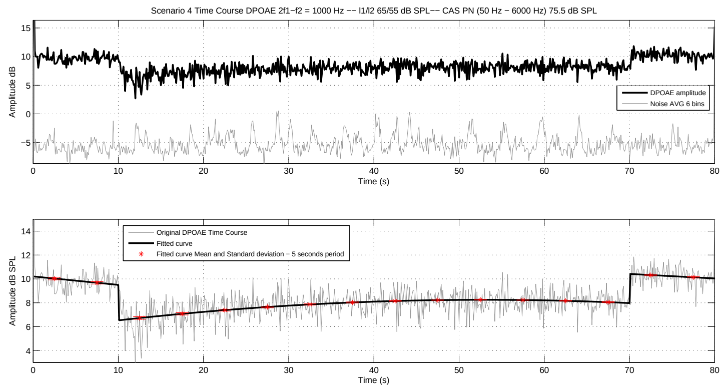

Figure B.4: Measurement subject 2, scenario 4. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

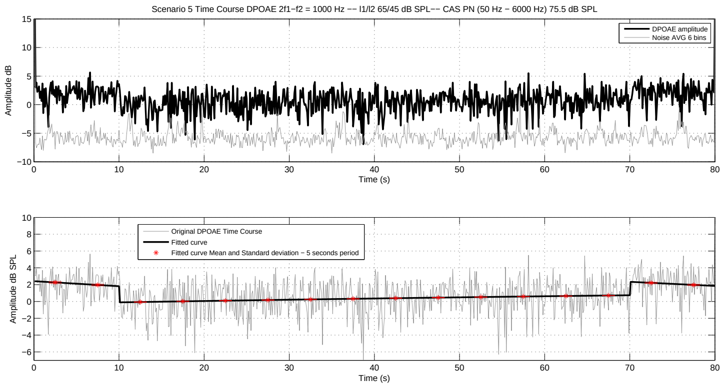

Figure B.5: Measurement subject 2, scenario 5. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

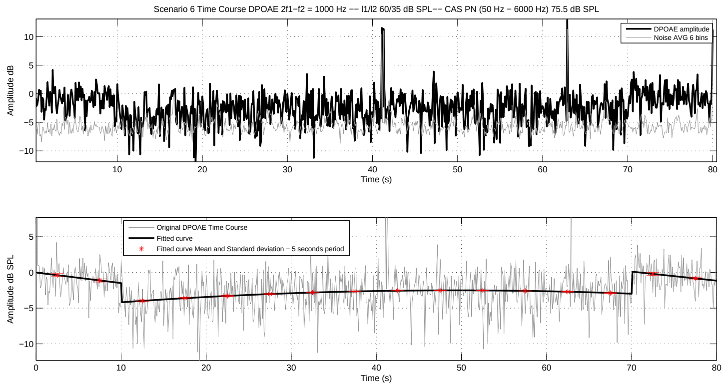

Figure B.6: Measurement subject 2, scenario 6. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

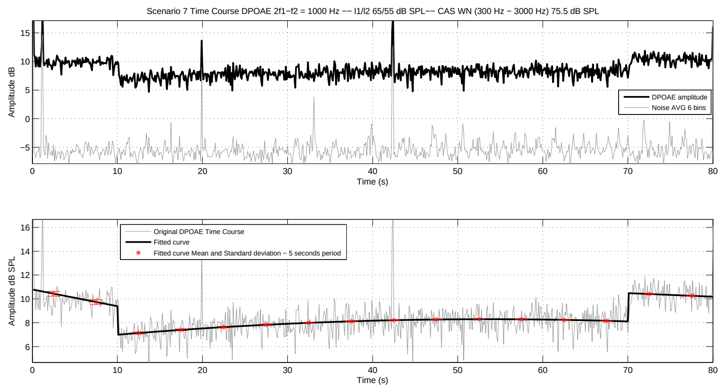

Figure B.7: Measurement subject 2, scenario 7. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

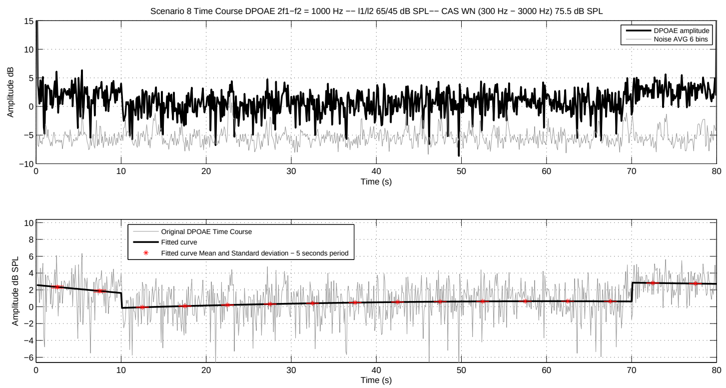

Figure B.8: Measurement subject 2, scenario 8. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

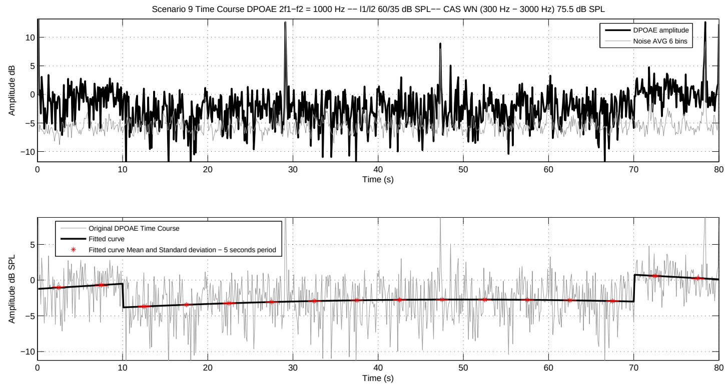

Figure B.9: Measurement subject 2, scenario 9. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

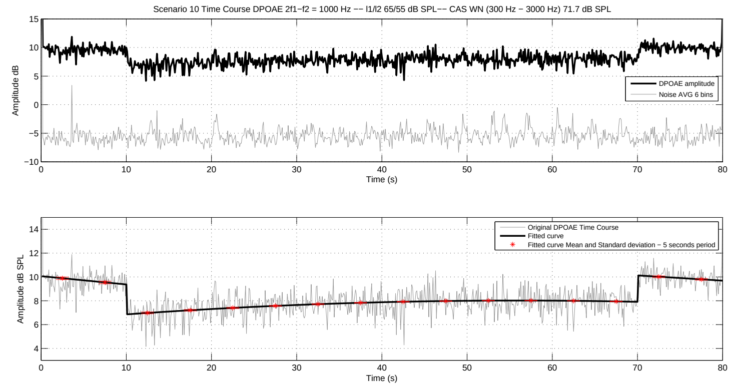

Figure B.10: Measurement subject 2, scenario 10. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

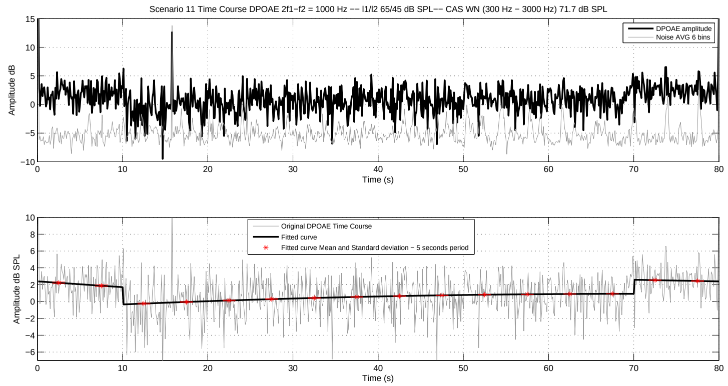

Figure B.11: Measurement subject 2, scenario 11. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

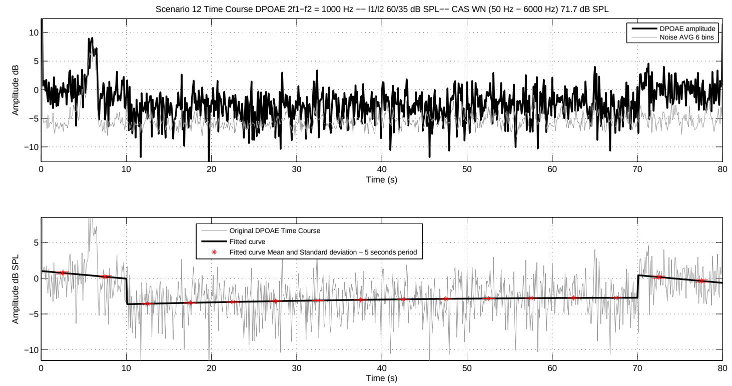

Figure B.12: Measurement subject 2, scenario 12. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

Appendix C

Pilot Test Measurements. Subject 3

Large data and figures regarding pilot test's measurements can be seen here.

C.1 Data Tables

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	7.95	5.51	-0.05	9.03	5.63	0.33	9.39	6.38	0.01	9.65	6.03	0.84
5 - 10	8.17	5.21	0.00	8.65	5.52	0.78	8.71	5.81	0.26	8.77	6.17	0.51
10 - 15	3.85	-1.07	-5.41	3.54	-0.59	-3.57	4.05	-0.16	-3.07	4.35	1.08	-3.59
15 - 20	3.96	-0.79	-4.95	4.18	0.12	-3.47	4.27	0.14	-3.23	4.93	0.65	-1.90
20 - 25	4.08	0.59	-4.20	5.22	1.55	-1.95	5.02	1.68	-3.58	5.35	0.91	-2.93
25 -30	5.14	0.76	-4.49	5.24	1.05	-3.37	4.87	1.82	-2.22	6.16	1.28	-3.29
30 - 35	4.11	0.18	-4.97	5.27	0.68	-3.68	5.53	1.29	-2.92	5.67	1.66	-2.52
35 - 40	5.09	0.53	-3.99	5.65	1.34	-3.67	5.74	1.56	-2.24	6.22	1.83	-1.29
40 - 45	5.56	0.96	-3.09	6.57	1.96	-2.13	5.81	2.14	-2.00	6.14	2.60	-2.78
45 - 50	5.11	0.83	-3.21	5.74	1.04	-2.26	5.98	1.91	-2.77	6.35	2.20	-2.57
50 - 55	5.44	0.79	-4.33	5.83	1.41	-4.13	6.10	1.60	-3.53	6.68	2.81	-2.48
55 - 60	5.10	0.98	-4.64	5.92	1.83	-3.16	6.05	2.39	-4.54	6.62	2.08	-2.48
60 - 65	5.40	1.15	-4.51	6.26	1.86	-3.54	6.20	1.06	-2.88	6.44	3.43	-2.74
65 - 70	5.89	1.28	-5.07	5.86	1.68	-3.02	6.38	1.64	-3.14	6.37	2.64	-1.70
70 - 75	8.89	5.94	1.10	9.34	6.52	1.57	9.59	6.23	3.10	9.90	6.63	1.89
75 - 80	8.97	5.89	0.75	9.32	6.48	1.10	9.46	6.90	0.86	9.76	6.45	1.45

Table C.1: Average DPOAE's amplitude values each 5 seconds. Subject 3.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	2.00	2.30	2.43	2.24	1.35	2.66	2.47	2.91	2.99	3.52	2.24	3.01
5 - 10	0.90	1.09	2.83	0.85	1.09	2.48	0.91	1.23	1.88	0.70	1.26	2.12
10 - 15	2.82	2.74	4.05	2.41	3.11	3.66	1.91	3.01	3.02	1.72	3.26	2.46
15 - 20	2.51	2.26	3.84	1.65	2.76	2.64	1.69	2.70	3.64	2.05	2.03	3.06
20 - 25	2.55	2.00	2.97	2.67	3.45	3.85	1.36	2.59	3.54	1.50	1.91	4.04
25 -30	3.31	2.69	3.50	3.01	2.79	3.13	2.06	2.67	2.53	1.78	1.84	3.02
30 - 35	1.82	1.79	3.42	1.68	2.42	3.20	1.33	2.25	3.44	1.48	2.06	3.94
35 - 40	1.75	2.52	2.84	1.47	2.35	3.16	1.30	2.39	3.70	1.56	1.95	5.09
40 - 45	1.55	2.52	4.89	2.27	2.22	3.35	1.35	1.92	4.18	1.30	2.16	2.56
45 - 50	2.00	1.97	4.00	1.64	2.46	3.33	1.15	2.06	3.66	1.44	2.36	3.48
50 - 55	1.79	2.36	2.44	1.64	2.90	3.53	1.51	2.25	2.91	1.27	2.49	4.08
55 - 60	1.59	2.28	2.97	1.70	2.63	2.49	1.42	2.53	3.99	1.04	1.68	4.88
60 - 65	1.80	1.60	2.98	2.44	2.87	3.46	1.26	1.92	2.68	1.11	3.20	3.84
65 - 70	2.55	2.39	3.01	1.34	2.22	3.24	1.67	2.45	2.82	1.28	1.79	4.15
70 - 75	1.17	1.28	2.04	0.96	1.26	2.24	0.90	1.17	2.63	0.97	1.29	2.41
75 - 80	1.26	1.62	1.81	0.93	1.48	2.69	1.09	1.64	2.63	1.06	1.64	3.01

Table C.2: STD DPOAE's amplitude values each 5 seconds. Subject 3.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	8.04	5.58	-0.05	9.04	5.68	0.65	9.48	6.47	0.19	9.57	6.21	1.10
5 - 10	8.08	5.15	0.00	8.63	5.47	0.47	8.62	5.73	0.07	8.85	5.99	0.25
10 - 15	3.78	-0.80	-5.52	3.79	-0.09	-3.28	4.03	-0.01	-3.30	4.51	0.67	-2.93
15 - 20	4.05	-0.42	-5.00	4.31	0.28	-3.20	4.43	0.53	-3.08	4.95	0.94	-2.84
20 - 25	4.30	-0.07	-4.58	4.77	0.60	-3.14	4.79	0.98	-2.91	5.34	1.20	-2.76
25 -30	4.53	0.22	-4.25	5.16	0.88	-3.09	5.11	1.36	-2.78	5.67	1.44	-2.68
30 - 35	4.74	0.48	-4.02	5.48	1.12	-3.07	5.39	1.64	-2.71	5.95	1.68	-2.60
35 - 40	4.93	0.69	-3.88	5.74	1.32	-3.06	5.64	1.85	-2.69	6.17	1.90	-2.53
40 - 45	5.10	0.85	-3.84	5.93	1.48	-3.06	5.84	1.97	-2.73	6.34	2.11	-2.46
45 - 50	5.24	0.98	-3.88	6.05	1.60	-3.09	6.00	2.01	-2.81	6.46	2.30	-2.40
50 - 55	5.37	1.06	-4.03	6.10	1.67	-3.13	6.11	1.96	-2.94	6.52	2.49	-2.34
55 - 60	5.48	1.09	-4.26	6.09	1.71	-3.19	6.19	1.83	-3.13	6.52	2.66	-2.29
60 - 65	5.56	1.08	-4.59	6.01	1.71	-3.26	6.23	1.62	-3.37	6.48	2.82	-2.24
65 - 70	5.63	1.03	-5.02	5.86	1.66	-3.36	6.23	1.32	-3.65	6.37	2.96	-2.19
70 - 75	8.87	5.94	1.04	9.32	6.47	1.42	9.55	6.32	2.69	9.84	6.54	1.82
75 - 80	8.88	5.70	0.61	9.26	6.36	1.08	9.39	6.61	1.12	9.71	6.42	1.34

Table C.3: Mean fitted curve values each 5 seconds. Subject 3.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	0.01	0.13	0.02	0.12	0.06	0.05	0.25	0.22	0.03	0.21	0.06	0.25
5 - 10	0.01	0.13	0.02	0.12	0.06	0.05	0.25	0.22	0.03	0.21	0.06	0.25
10 - 15	0.08	0.12	0.16	0.16	0.11	0.03	0.12	0.17	0.07	0.14	0.08	0.03
15 - 20	0.08	0.11	0.14	0.14	0.10	0.02	0.11	0.15	0.06	0.12	0.08	0.03
20 - 25	0.07	0.09	0.11	0.12	0.09	0.02	0.10	0.12	0.04	0.11	0.07	0.02
25 -30	0.06	0.08	0.08	0.10	0.08	0.01	0.09	0.10	0.03	0.09	0.07	0.02
30 - 35	0.06	0.07	0.05	0.08	0.06	0.01	0.08	0.07	0.01	0.07	0.07	0.02
35 - 40	0.05	0.05	0.03	0.06	0.05	0.00	0.06	0.05	0.00	0.06	0.06	0.02
40 - 45	0.05	0.04	0.00	0.05	0.04	0.00	0.05	0.02	0.02	0.04	0.06	0.02
45 - 50	0.04	0.03	0.03	0.03	0.03	0.01	0.04	0.00	0.03	0.03	0.06	0.02
50 - 55	0.03	0.02	0.06	0.01	0.02	0.01	0.03	0.03	0.05	0.01	0.05	0.02
55 - 60	0.03	0.00	0.08	0.01	0.00	0.02	0.02	0.05	0.06	0.01	0.05	0.02
60 - 65	0.02	0.01	0.11	0.03	0.01	0.02	0.01	0.07	0.08	0.02	0.04	0.01
65 - 70	0.02	0.02	0.14	0.05	0.02	0.03	0.01	0.10	0.09	0.04	0.04	0.01
70 - 75	0.00	0.07	0.12	0.02	0.03	0.10	0.05	0.09	0.46	0.04	0.03	0.14
75 - 80	0.00	0.07	0.12	0.02	0.03	0.10	0.05	0.09	0.46	0.04	0.03	0.14

Table C.4: STD fitted curve values each 5 seconds. Subject 3.

C.1.1 Measurement Figures

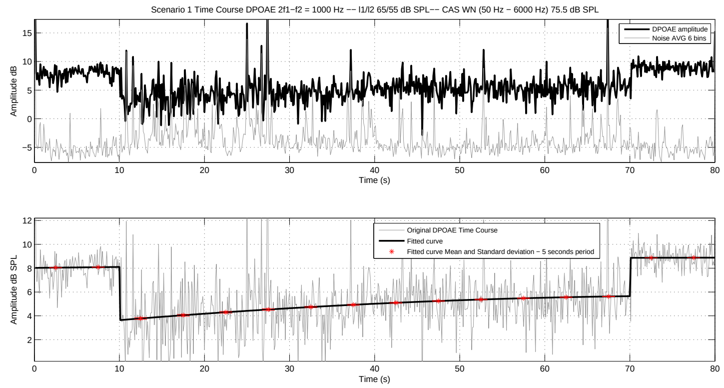

Figure C.1: Measurement subject 3, scenario 1. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

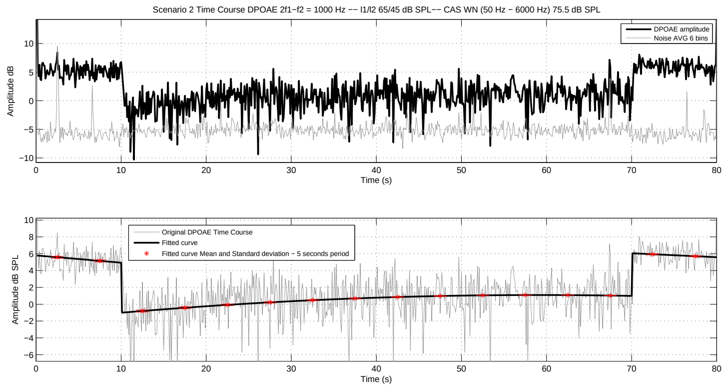

Figure C.2: Measurement subject 3, scenario 2. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

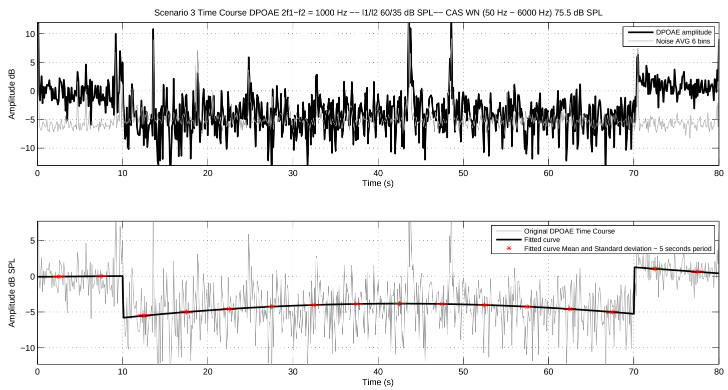

Figure C.3: Measurement subject 3, scenario 3. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

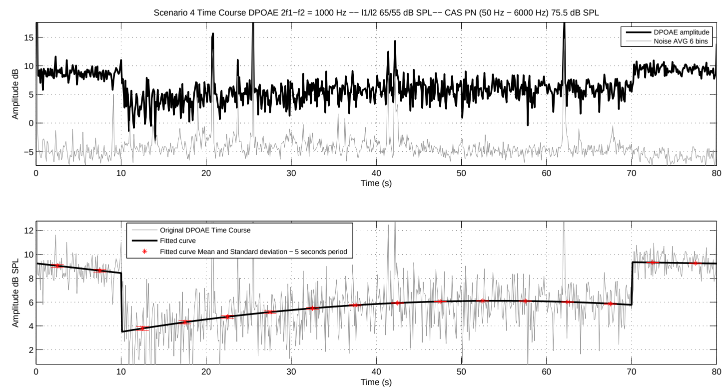

Figure C.4: Measurement subject 3, scenario 4. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

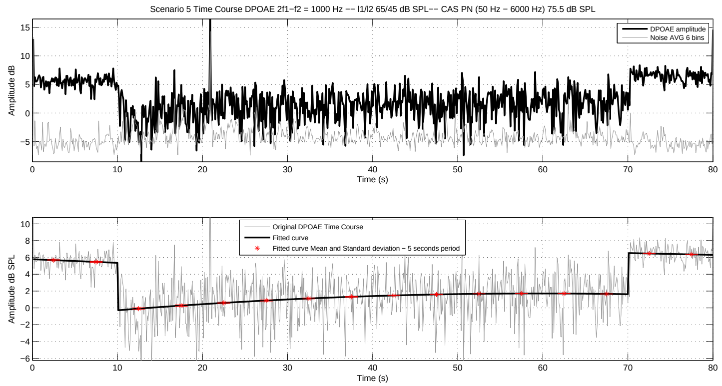

Figure C.5: Measurement subject 3, scenario 5. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

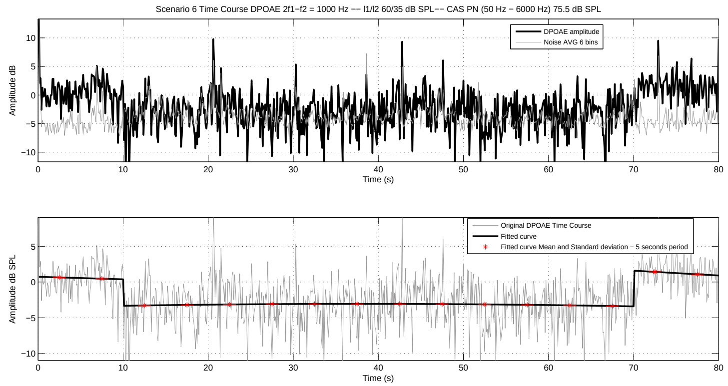

Figure C.6: Measurement subject 3, scenario 6. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

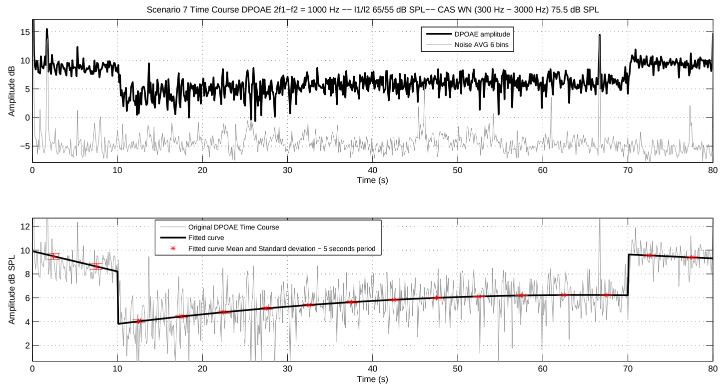

Figure C.7: Measurement subject 3, scenario 7. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

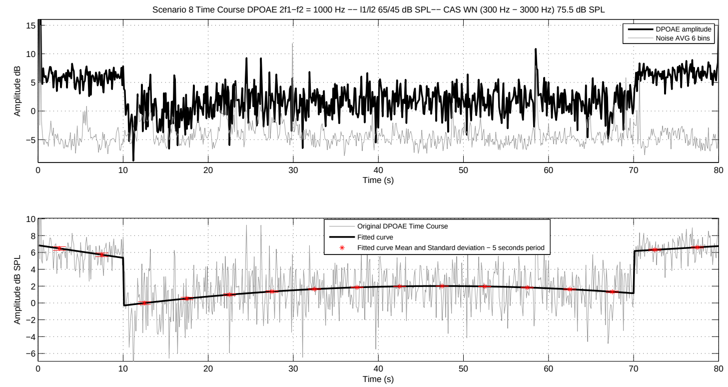

Figure C.8: Measurement subject 3, scenario 8. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

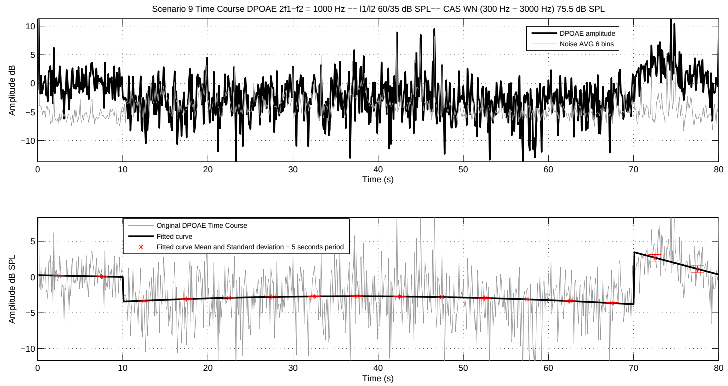

Figure C.9: Measurement subject 3, scenario 9. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

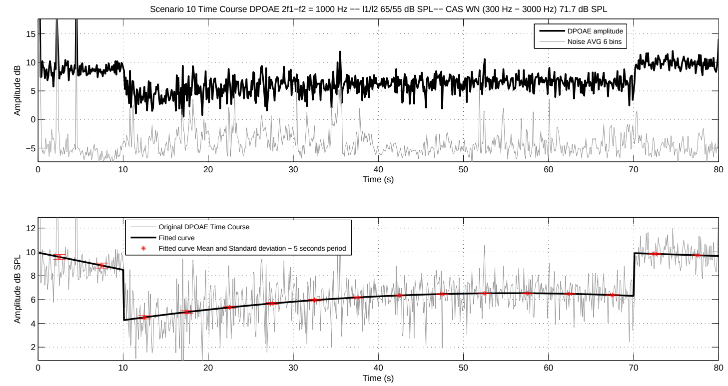

Figure C.10: Measurement subject 3, scenario 10. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

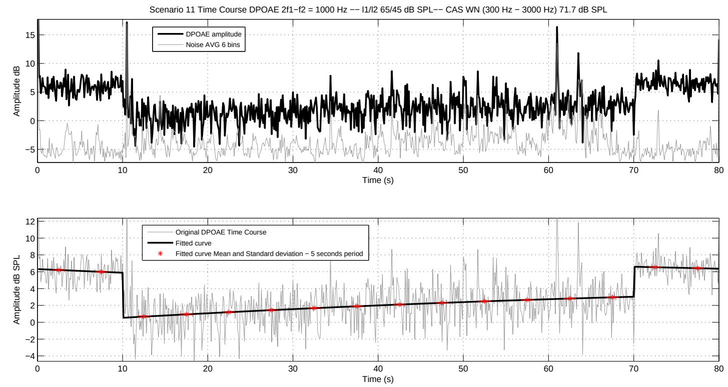

Figure C.11: Measurement subject 3, scenario 11. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

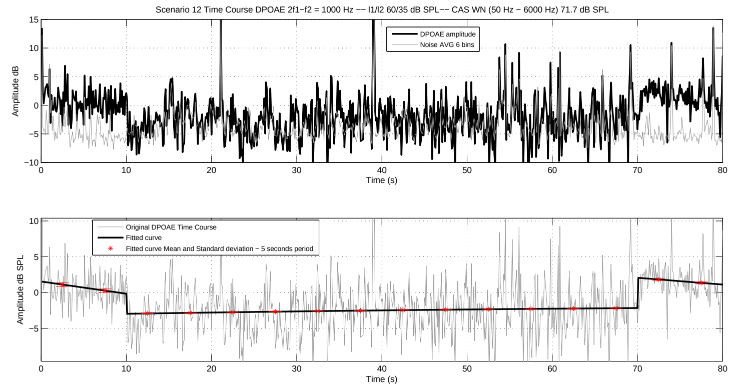

Figure C.12: Measurement subject 3, scenario 12. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

Appendix D

Pilot Test Measurements. Subject 4

Large data and figures regarding pilot test's measurements can be seen here.

D.1 Data Tables

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	4.54	4.35	2.06	4.91	4.07	0.77	4.97	4.43	2.52	5.39	4.16	3.91
5 - 10	4.71	3.88	1.81	4.65	4.18	1.57	4.82	4.24	2.27	4.43	3.94	3.40
10 - 15	2.88	2.02	-2.03	2.22	2.36	-1.88	2.13	2.63	-0.80	4.00	2.63	-0.34
15 - 20	2.66	1.87	-2.07	2.06	1.32	-1.49	2.37	2.46	-0.95	4.24	3.56	0.03
20 - 25	2.74	2.20	-1.89	2.03	1.58	-1.31	2.57	2.41	-1.01	2.89	2.47	-0.29
25 -30	2.99	2.92	-0.94	2.20	1.98	-1.12	2.66	2.79	-0.48	3.03	2.94	-0.24
30 - 35	2.60	2.97	-0.94	2.28	1.66	-1.26	3.04	2.61	-0.92	3.64	2.72	0.14
35 - 40	2.76	2.84	-0.83	2.37	2.02	-1.35	3.01	3.27	-0.88	3.69	2.91	-0.26
40 - 45	2.91	2.76	-0.41	2.64	2.85	-1.24	3.33	3.15	-1.14	3.60	2.80	0.79
45 - 50	3.01	2.82	-0.78	2.65	2.86	-0.89	3.06	3.57	-0.35	3.40	2.93	-0.20
50 - 55	2.99	2.44	-0.60	2.92	2.60	-1.08	3.07	2.64	-0.35	3.91	3.13	0.18
55 - 60	3.56	2.85	-1.07	2.92	2.45	-0.82	3.18	3.26	-0.58	3.65	3.23	0.01
60 - 65	3.47	2.81	-0.07	2.68	2.62	-0.82	3.10	3.18	-0.64	3.70	2.86	0.34
65 - 70	3.25	3.10	-0.30	2.96	2.38	-1.25	3.24	2.71	-0.09	3.49	3.14	0.31
70 - 75	6.29	3.63	2.54	4.41	3.80	2.17	4.91	3.18	3.24	5.05	4.06	3.95
75 - 80	4.65	3.72	2.57	4.84	3.66	2.09	5.05	4.22	2.84	5.13	3.95	3.97

Table D.1: Average DPOAE's amplitude values each 5 seconds. Subject 4.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	2.00	2.30	2.43	2.24	1.35	2.66	2.47	2.91	2.99	3.52	2.24	3.01
5 - 10	0.90	1.09	2.83	0.85	1.09	2.48	0.91	1.23	1.88	0.70	1.26	2.12
10 - 15	2.82	2.74	4.05	2.41	3.11	3.66	1.91	3.01	3.02	1.72	3.26	2.46
15 - 20	2.51	2.26	3.84	1.65	2.76	2.64	1.69	2.70	3.64	2.05	2.03	3.06
20 - 25	2.55	2.00	2.97	2.67	3.45	3.85	1.36	2.59	3.54	1.50	1.91	4.04
25 - 30	3.31	2.69	3.50	3.01	2.79	3.13	2.06	2.67	2.53	1.78	1.84	3.02
30 - 35	1.82	1.79	3.42	1.68	2.42	3.20	1.33	2.25	3.44	1.48	2.06	3.94
35 - 40	1.75	2.52	2.84	1.47	2.35	3.16	1.30	2.39	3.70	1.56	1.95	5.09
40 - 45	1.55	2.52	4.89	2.27	2.22	3.35	1.35	1.92	4.18	1.30	2.16	2.56
45 - 50	2.00	1.97	4.00	1.64	2.46	3.33	1.15	2.06	3.66	1.44	2.36	3.48
50 - 55	1.79	2.36	2.44	1.64	2.90	3.53	1.51	2.25	2.91	1.27	2.49	4.08
55 - 60	1.59	2.28	2.97	1.70	2.63	2.49	1.42	2.53	3.99	1.04	1.68	4.88
60 - 65	1.80	1.60	2.98	2.44	2.87	3.46	1.26	1.92	2.68	1.11	3.20	3.84
65 - 70	2.55	2.39	3.01	1.34	2.22	3.24	1.67	2.45	2.82	1.28	1.79	4.15
70 - 75	1.17	1.28	2.04	0.96	1.26	2.24	0.90	1.17	2.63	0.97	1.29	2.41
75 - 80	1.26	1.62	1.81	0.93	1.48	2.69	1.09	1.64	2.63	1.06	1.64	3.01

Table D.2: STD DPOAE's amplitude values each 5 seconds. Subject 4.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	8.04	5.58	-0.05	9.04	5.68	0.65	9.48	6.47	0.19	9.57	6.21	1.10
5 - 10	8.08	5.15	0.00	8.63	5.47	0.47	8.62	5.73	0.07	8.85	5.99	0.25
10 - 15	3.78	-0.80	-5.52	3.79	-0.09	-3.28	4.03	-0.01	-3.30	4.51	0.67	-2.93
15 - 20	4.05	-0.42	-5.00	4.31	0.28	-3.20	4.43	0.53	-3.08	4.95	0.94	-2.84
20 - 25	4.30	-0.07	-4.58	4.77	0.60	-3.14	4.79	0.98	-2.91	5.34	1.20	-2.76
25 -30	4.53	0.22	-4.25	5.16	0.88	-3.09	5.11	1.36	-2.78	5.67	1.44	-2.68
30 - 35	4.74	0.48	-4.02	5.48	1.12	-3.07	5.39	1.64	-2.71	5.95	1.68	-2.60
35 - 40	4.93	0.69	-3.88	5.74	1.32	-3.06	5.64	1.85	-2.69	6.17	1.90	-2.53
40 - 45	5.10	0.85	-3.84	5.93	1.48	-3.06	5.84	1.97	-2.73	6.34	2.11	-2.46
45 - 50	5.24	0.98	-3.88	6.05	1.60	-3.09	6.00	2.01	-2.81	6.46	2.30	-2.40
50 - 55	5.37	1.06	-4.03	6.10	1.67	-3.13	6.11	1.96	-2.94	6.52	2.49	-2.34
55 - 60	5.48	1.09	-4.26	6.09	1.71	-3.19	6.19	1.83	-3.13	6.52	2.66	-2.29
60 - 65	5.56	1.08	-4.59	6.01	1.71	-3.26	6.23	1.62	-3.37	6.48	2.82	-2.24
65 - 70	5.63	1.03	-5.02	5.86	1.66	-3.36	6.23	1.32	-3.65	6.37	2.96	-2.19
70 - 75	8.87	5.94	1.04	9.32	6.47	1.42	9.55	6.32	2.69	9.84	6.54	1.82
75 - 80	8.88	5.70	0.61	9.26	6.36	1.08	9.39	6.61	1.12	9.71	6.42	1.34

Table D.3: Mean fitted curve values each 5 seconds. Subject 4.

	Scenario											
Time (s)	1	2	3	4	5	6	7	8	9	10	11	12
0 - 5	0.01	0.13	0.02	0.12	0.06	0.05	0.25	0.22	0.03	0.21	0.06	0.25
5 - 10	0.01	0.13	0.02	0.12	0.06	0.05	0.25	0.22	0.03	0.21	0.06	0.25
10 - 15	0.08	0.12	0.16	0.16	0.11	0.03	0.12	0.17	0.07	0.14	0.08	0.03
15 - 20	0.08	0.11	0.14	0.14	0.10	0.02	0.11	0.15	0.06	0.12	0.08	0.03
20 - 25	0.07	0.09	0.11	0.12	0.09	0.02	0.10	0.12	0.04	0.11	0.07	0.02
25 -30	0.06	0.08	0.08	0.10	0.08	0.01	0.09	0.10	0.03	0.09	0.07	0.02
30 - 35	0.06	0.07	0.05	0.08	0.06	0.01	0.08	0.07	0.01	0.07	0.07	0.02
35 - 40	0.05	0.05	0.03	0.06	0.05	0.00	0.06	0.05	0.00	0.06	0.06	0.02
40 - 45	0.05	0.04	0.00	0.05	0.04	0.00	0.05	0.02	0.02	0.04	0.06	0.02
45 - 50	0.04	0.03	0.03	0.03	0.03	0.01	0.04	0.00	0.03	0.03	0.06	0.02
50 - 55	0.03	0.02	0.06	0.01	0.02	0.01	0.03	0.03	0.05	0.01	0.05	0.02
55 - 60	0.03	0.00	0.08	0.01	0.00	0.02	0.02	0.05	0.06	0.01	0.05	0.02
60 - 65	0.02	0.01	0.11	0.03	0.01	0.02	0.01	0.07	0.08	0.02	0.04	0.01
65 - 70	0.02	0.02	0.14	0.05	0.02	0.03	0.01	0.10	0.09	0.04	0.04	0.01
70 - 75	0.00	0.07	0.12	0.02	0.03	0.10	0.05	0.09	0.46	0.04	0.03	0.14
75 - 80	0.00	0.07	0.12	0.02	0.03	0.10	0.05	0.09	0.46	0.04	0.03	0.14

Table D.4: STD fitted curve values each 5 seconds. Subject 4.

D.1.1 Measurement Figures

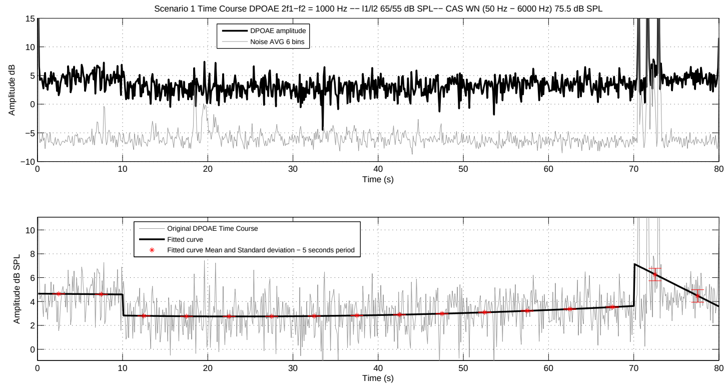

Figure D.1: Measurement subject 4, scenario 1. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

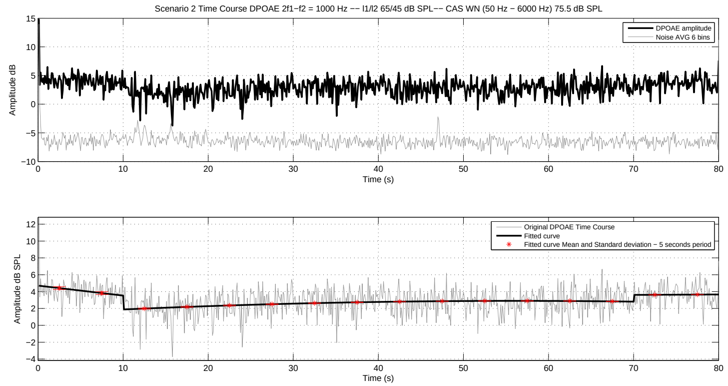

Figure D.2: Measurement subject 4, scenario 2. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

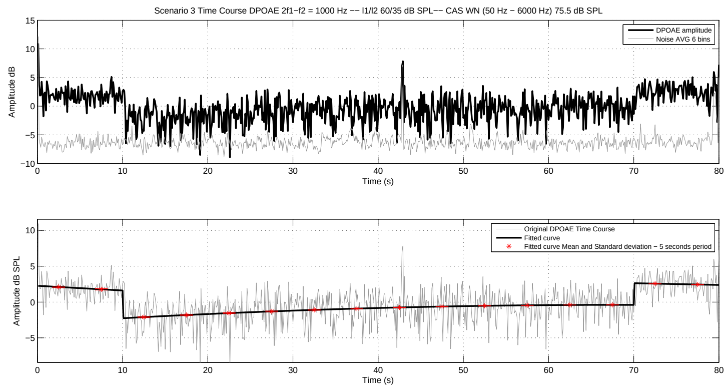

Figure D.3: Measurement subject 4, scenario 3. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

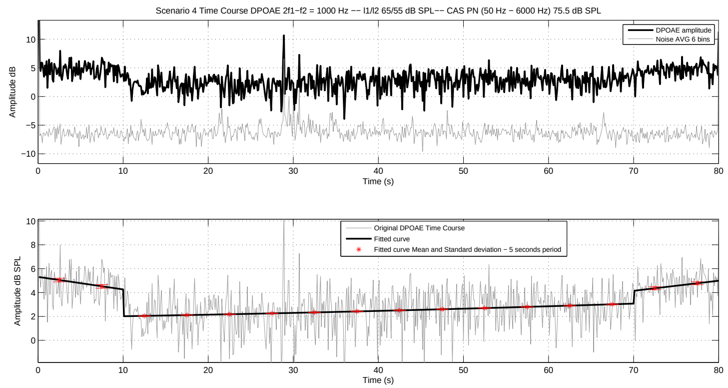

Figure D.4: Measurement subject 4, scenario 4. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

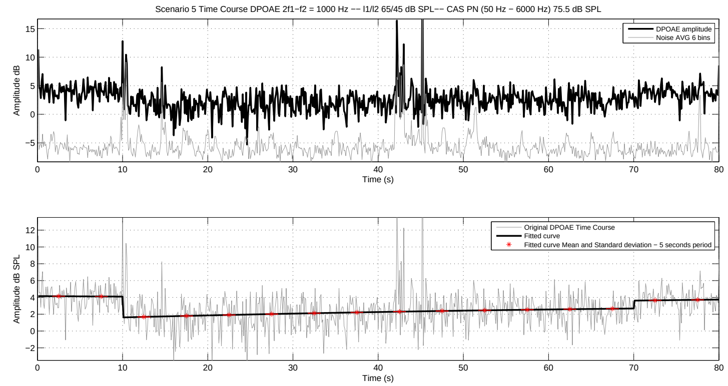

Figure D.5: Measurement subject 4, scenario 5. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

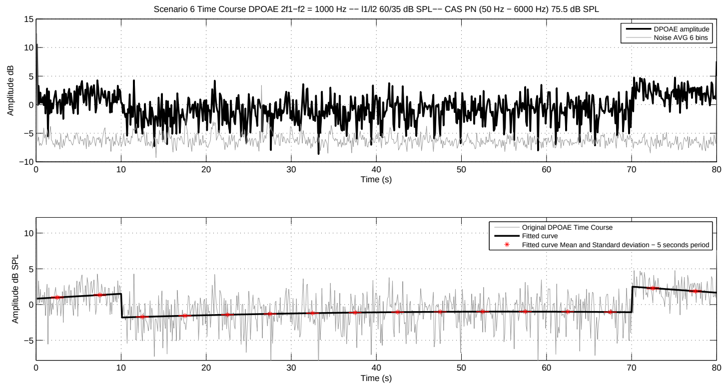

Figure D.6: Measurement subject 4, scenario 6. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

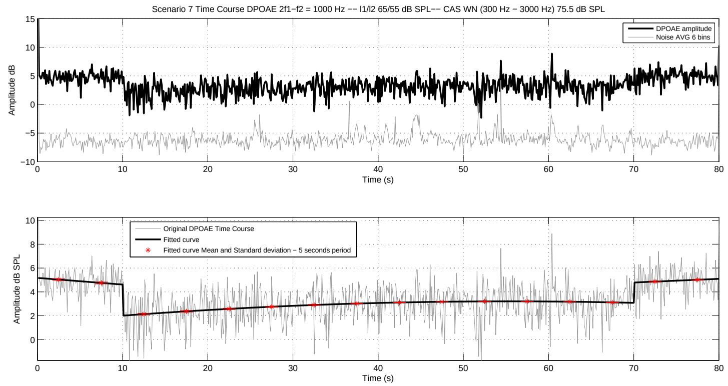

Figure D.7: Measurement subject 4, scenario 7. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

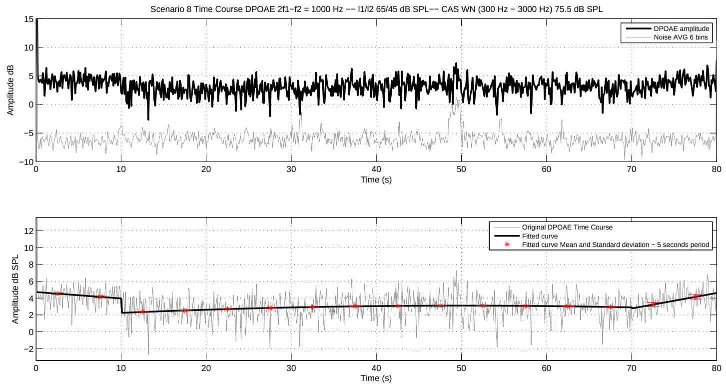

Figure D.8: Measurement subject 3, scenario 8. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

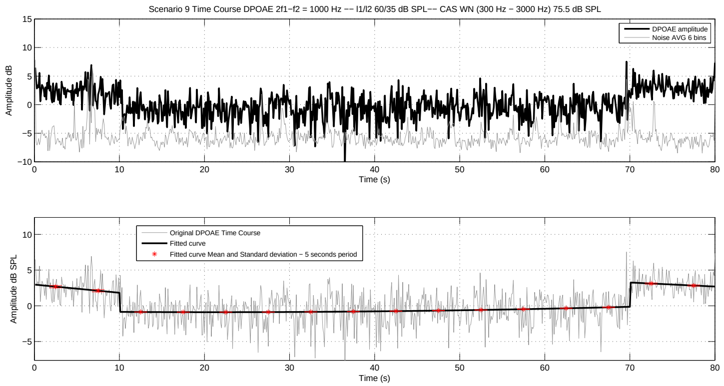

Figure D.9: Measurement subject 4, scenario 9. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

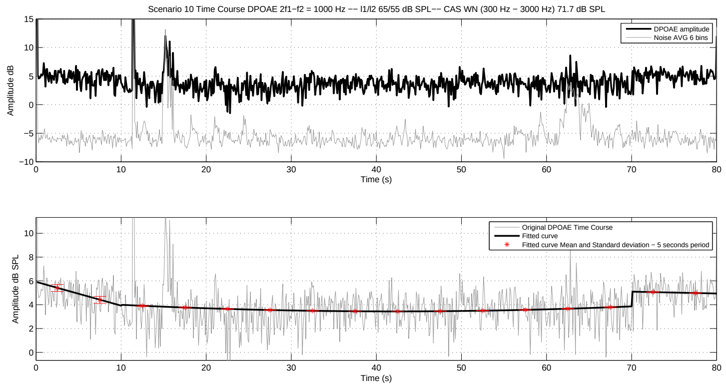

Figure D.10: Measurement subject 4, scenario 10. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

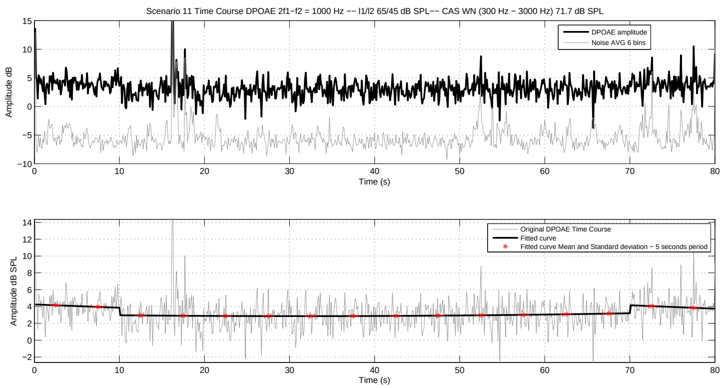

Figure D.11: Measurement subject 4, scenario 11. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

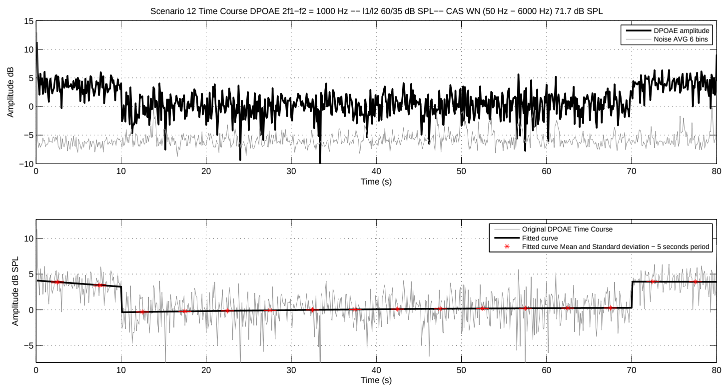

Figure D.12: Measurement subject 4, scenario 12. Top figure: DPOAE amplitude time course and Noise Avg. Bottom figure: DPOAE amplitude and fitted curve.

Appendix E

Introduction to the subject

Thank you for participating in the experiment.

Use the time you need to read and fully understand the task and the attributes. Ask if you have any questions.

The test you will participate consists in the measurement of Distortion Product Otoacoustic Emissions (DPOAEs).

A hearing evaluation consisting of an audiometry and a tympanometry will be performed before DPOAE measurement. This will take approximately 30 minutes.

After the hearing evaluation, an ear-probe will placed in one of your ears for DPOAE measurements and other earphone will be placed at the opposite ear for contralateral acoustic stimulation.

6 different DPOAE measurements will be carried out. Each measurement is repeated 3 times. This procedure takes approximately 35 minutes.

Tympanometry and DPOAE measurement don't require response from you. Body movements, swallowing, or talking can ruin these tests, therefore breaks are presented during these tests for you to relax.

You can stop the test whenever you need, but we will appreciate you finishing it. You can communicate with us for any additional information or troubles you have through the intercom in front of you.

The data will be kept anonymously.

Thank you!

Appendix F

Final Test Measurements

Plots for all subjects and all scenarios with DPOAE response, fitted curve and noise floor are shown following:

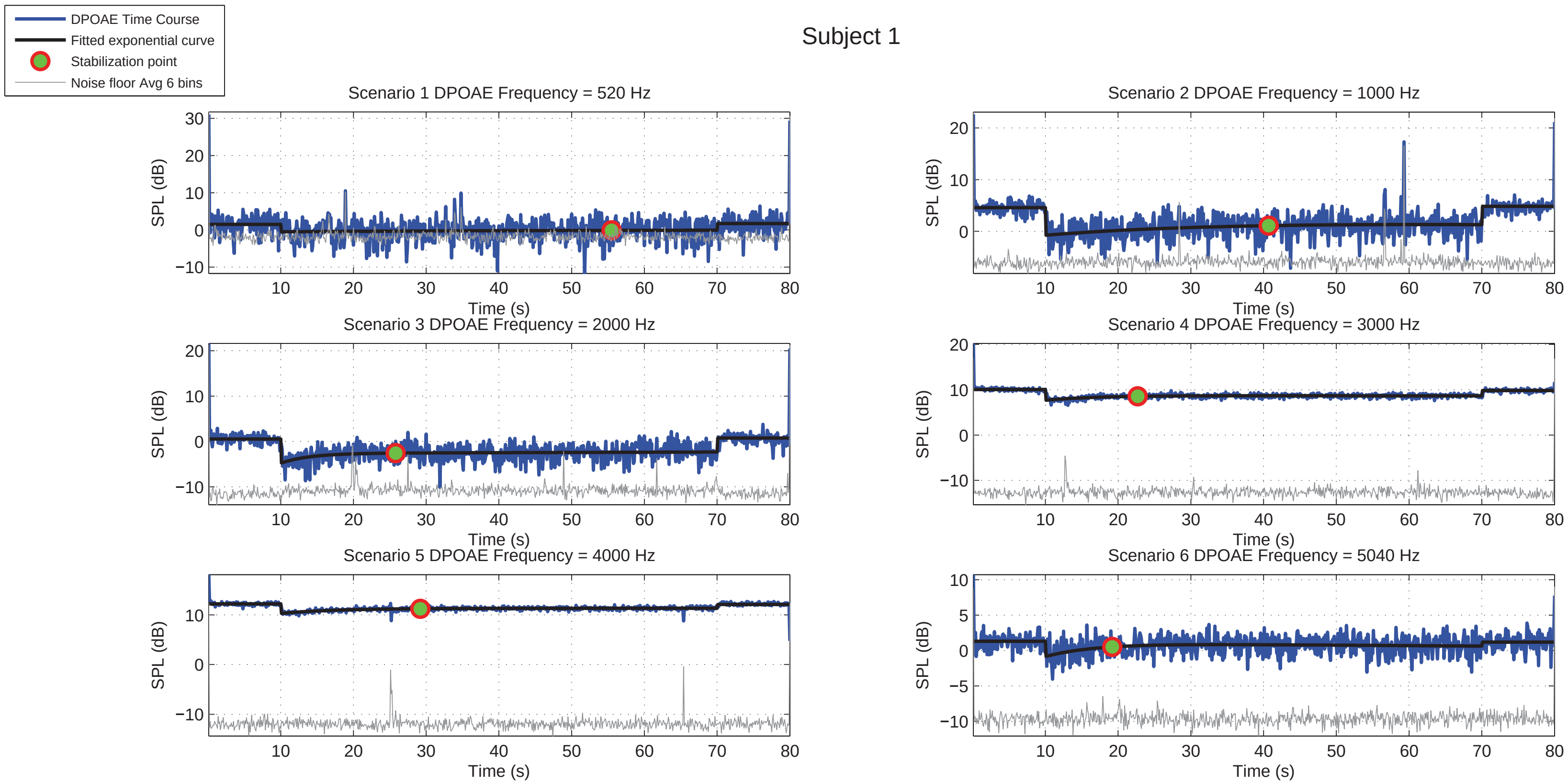

Figure F.1: Final test. Subject 1. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	1.75	2.01	-0.26	55.50	-0.08	2.59	2.21	-0.51	2.26	0.31	-1.94	1.74	2.74
2	4.67	4.98	-0.31	40.70	1.25	2.15	3.68	-0.75	5.42	2.05	-6.00	7.30	2.07
3	0.46	0.83	-0.37	25.80	-2.47	1.75	2.97	-4.75	5.21	2.61	-10.77	8.63	1.72
4	10.00	9.84	0.15	22.70	8.66	0.37	1.18	7.69	2.30	0.97	-12.58	21.24	0.39
5	12.20	12.05	0.15	29.20	11.30	0.29	0.71	10.30	1.90	1.04	-11.90	23.24	0.31
6	1.29	1.24	0.05	19.20	0.74	1.21	0.55	-0.81	2.10	1.50	-9.59	10.28	1.24

Table F.1: Results of Subject 1 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

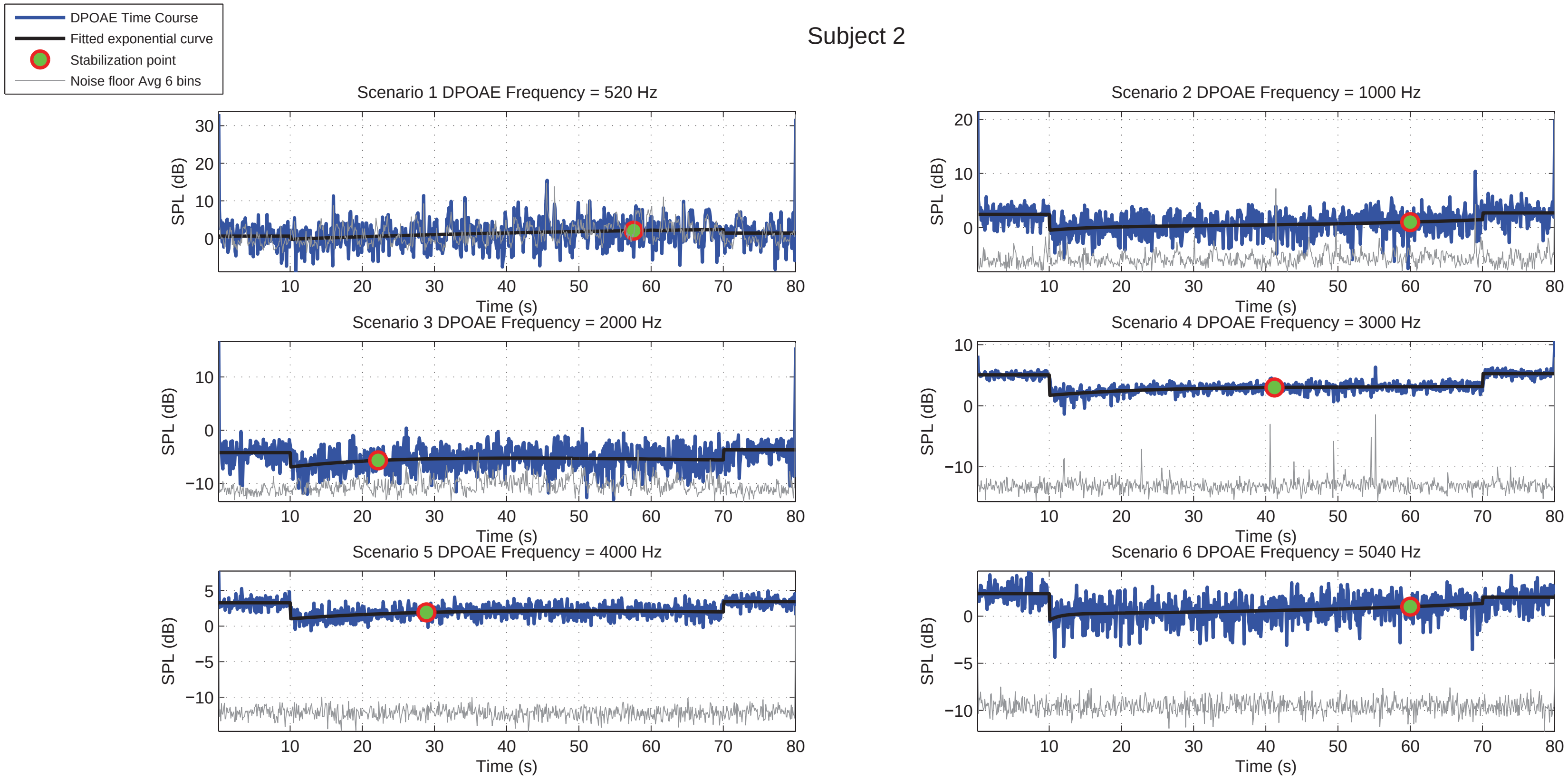

Figure F.2: Final test. Subject 2. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	0.26	1.52	-1.26	57.60	2.18	3.42	-0.49	-0.19	0.46	2.20	2.49	-0.48	3.42
2	2.49	2.88	-0.38	60.00	1.18	2.09	1.69	-0.50	3.00	1.69	-5.41	6.59	2.04
3	-4.11	-3.52	-0.60	22.20	-5.36	2.26	1.87	-6.89	2.77	1.50	-10.24	4.85	2.23
4	5.08	5.28	-0.21	41.20	3.07	0.66	2.13	1.72	3.35	1.43	-13.19	16.34	0.69
5	3.27	3.34	-0.07	28.90	2.10	0.83	1.26	1.04	2.23	1.04	-12.29	14.37	0.83
6	2.32	2.01	0.32	60.00	1.08	1.22	0.92	-0.38	2.70	1.46	-9.54	10.62	1.29

Table F.2: Results of Subject 2 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

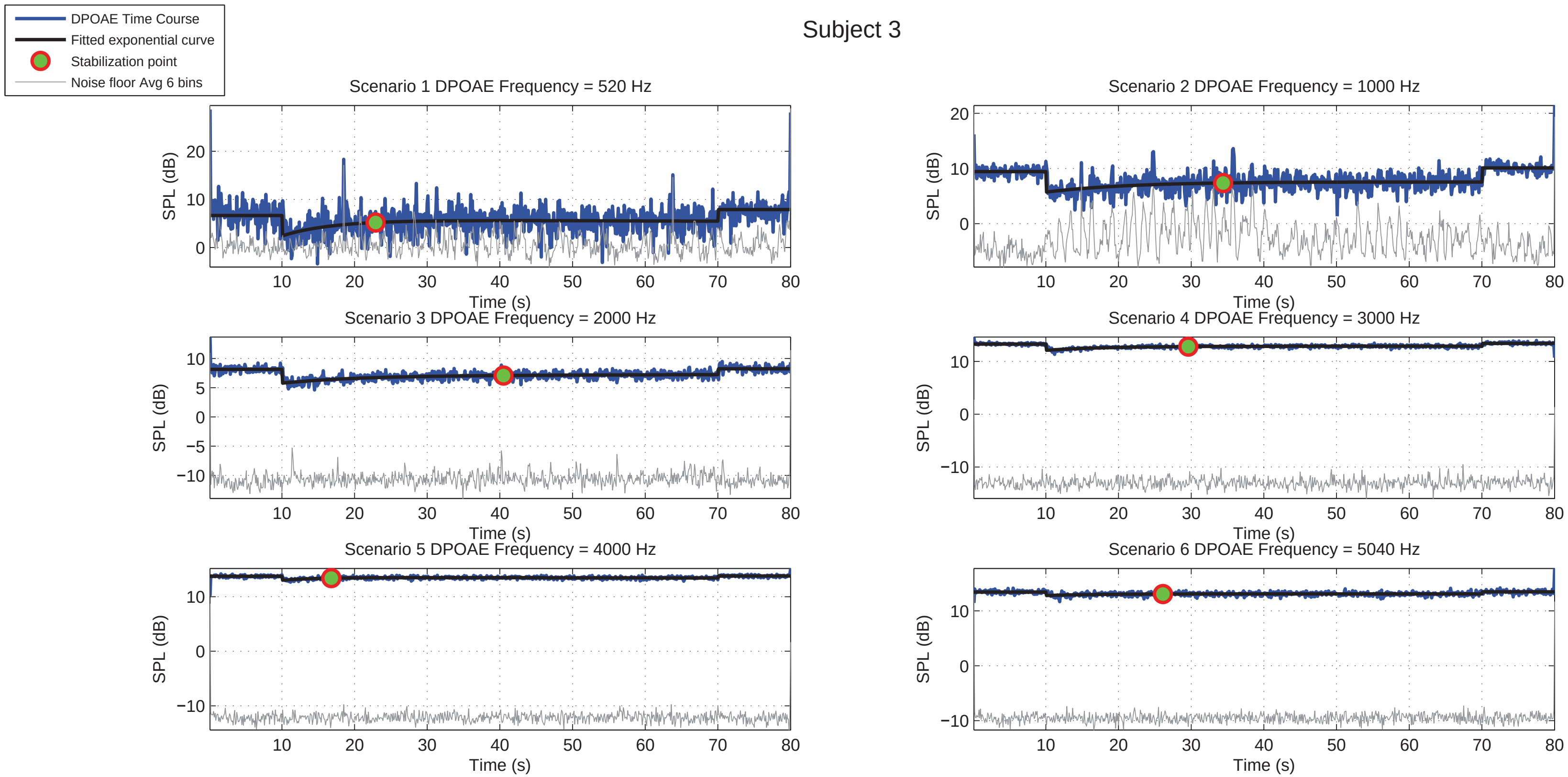

Figure F.3: Final test. Subject 3. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	6.55	8.03	-1.47	22.90	5.51	2.43	2.41	2.45	4.10	3.17	0.52	5.10	2.53
2	9.53	10.07	-0.54	34.40	7.52	1.48	2.41	5.74	3.79	1.91	-2.93	10.59	1.53
3	8.06	8.19	-0.13	40.50	7.17	0.54	0.98	5.78	2.28	1.44	-10.33	17.55	0.57
4	13.28	13.37	-0.09	29.60	12.87	0.21	0.49	12.12	1.17	0.77	-12.90	25.78	0.22
5	13.75	13.79	-0.04	16.80	13.48	0.21	0.33	13.04	0.72	0.43	-12.19	25.66	0.21
6	13.42	13.50	-0.08	26.10	13.09	0.31	0.38	12.80	0.63	0.32	-9.39	22.50	0.32

Table F.3: Results of Subject 3 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

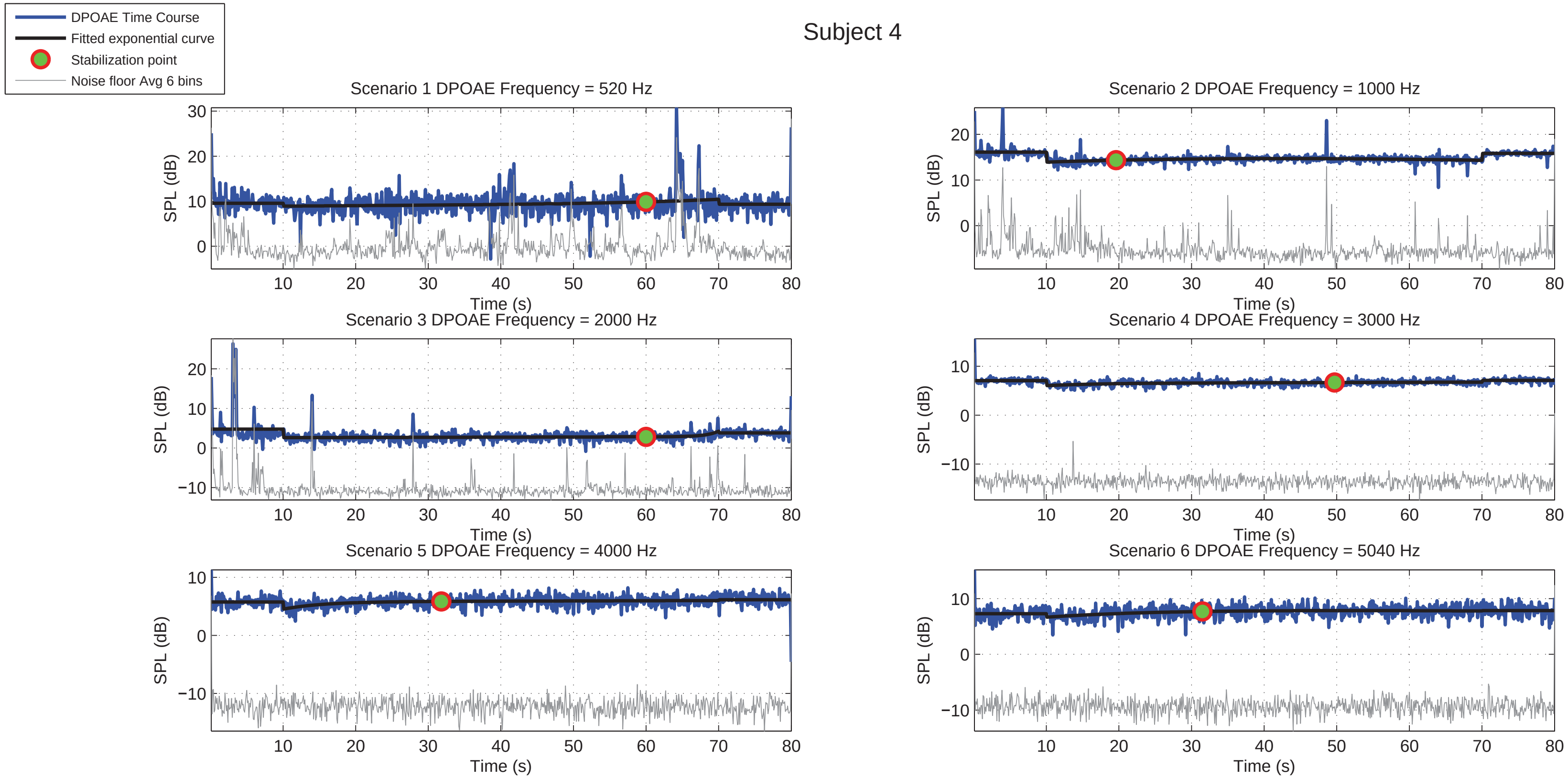

Figure F.4: Final test. Subject 4. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	9.38	9.32	0.06	60.00	10.35	4.02	-1.04	8.91	0.47	1.45	2.02	8.34	2.50
2	15.92	15.78	0.14	19.60	14.56	0.75	1.43	13.92	2.00	0.44	-5.50	19.86	0.77
3	3.71	3.79	-0.09	60.00	3.11	1.07	0.69	2.62	1.09	0.48	-10.34	13.45	1.03
4	7.07	7.15	-0.07	49.70	6.74	0.45	0.33	6.05	1.02	0.76	-13.60	20.42	0.50
5	5.83	6.03	-0.20	31.80	5.93	0.88	0.05	4.54	1.29	1.45	-12.21	18.19	0.85
6	7.45	7.80	-0.35	31.50	7.82	0.97	0.01	6.67	0.78	1.12	-9.41	17.21	1.00

Table F.4: Results of Subject 4 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

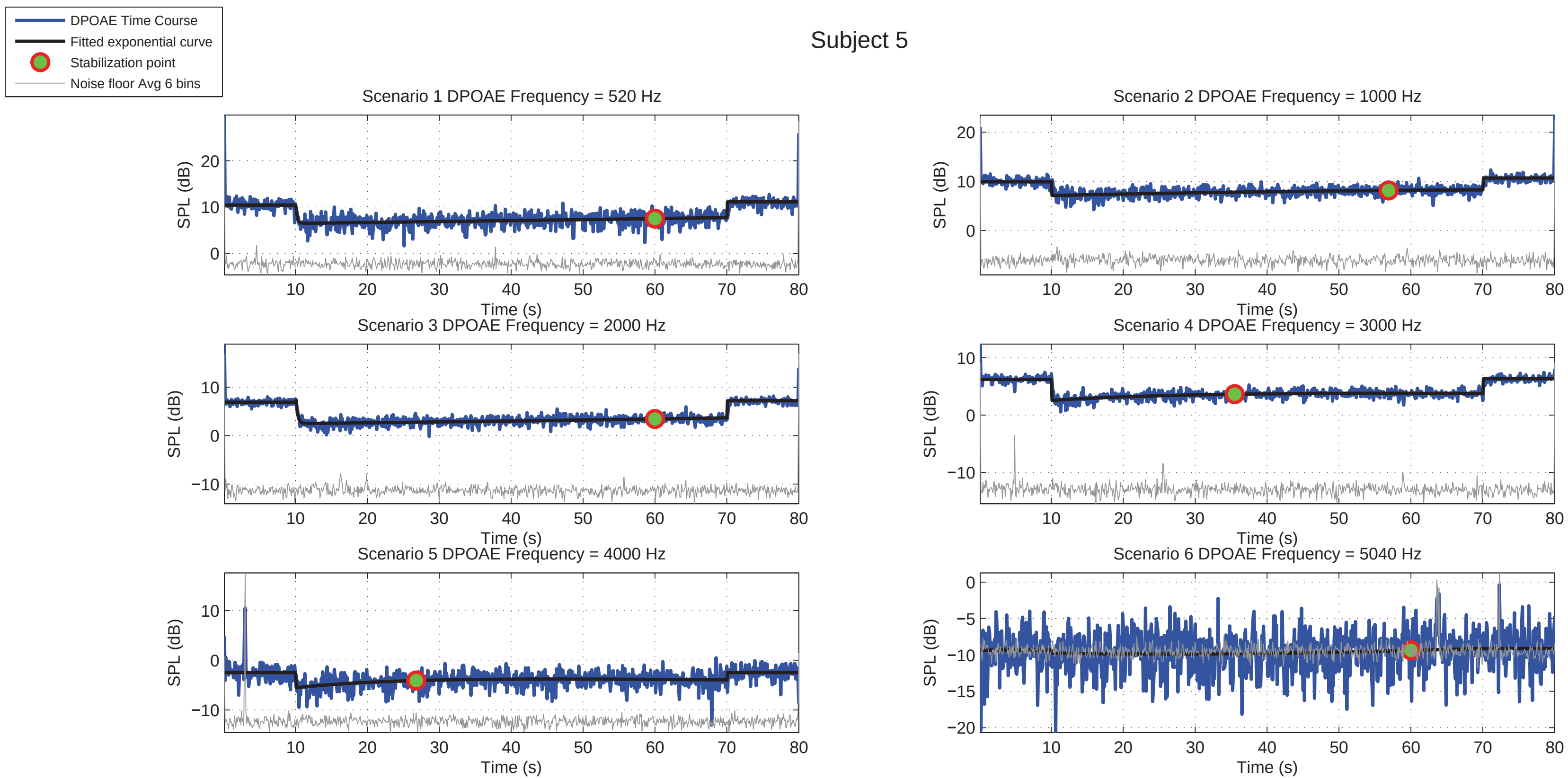

Figure F.5: Final test. Subject 5. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	10.40	11.14	-0.73	60.00	7.52	1.29	3.62	6.49	3.91	1.02	-2.27	9.78	1.35
2	9.96	10.78	-0.83	56.90	8.27	0.78	2.57	7.12	2.83	1.09	-6.10	14.32	0.87
3	6.95	7.20	-0.25	60.00	3.47	0.71	3.73	2.50	4.45	0.97	-11.37	14.84	0.77
4	6.34	6.37	-0.03	35.50	3.76	0.56	2.60	2.57	3.77	1.20	-13.11	16.88	0.63
5	-2.78	-2.65	-0.13	26.80	-3.87	1.51	1.28	-5.54	2.76	1.61	-12.47	8.54	1.53
6	-9.39	-9.39	-0.01	60.00	-9.05	2.89	-0.33	-9.88	0.48	0.82	-9.17	0.11	2.85

Table F.5: Results of Subject 5 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

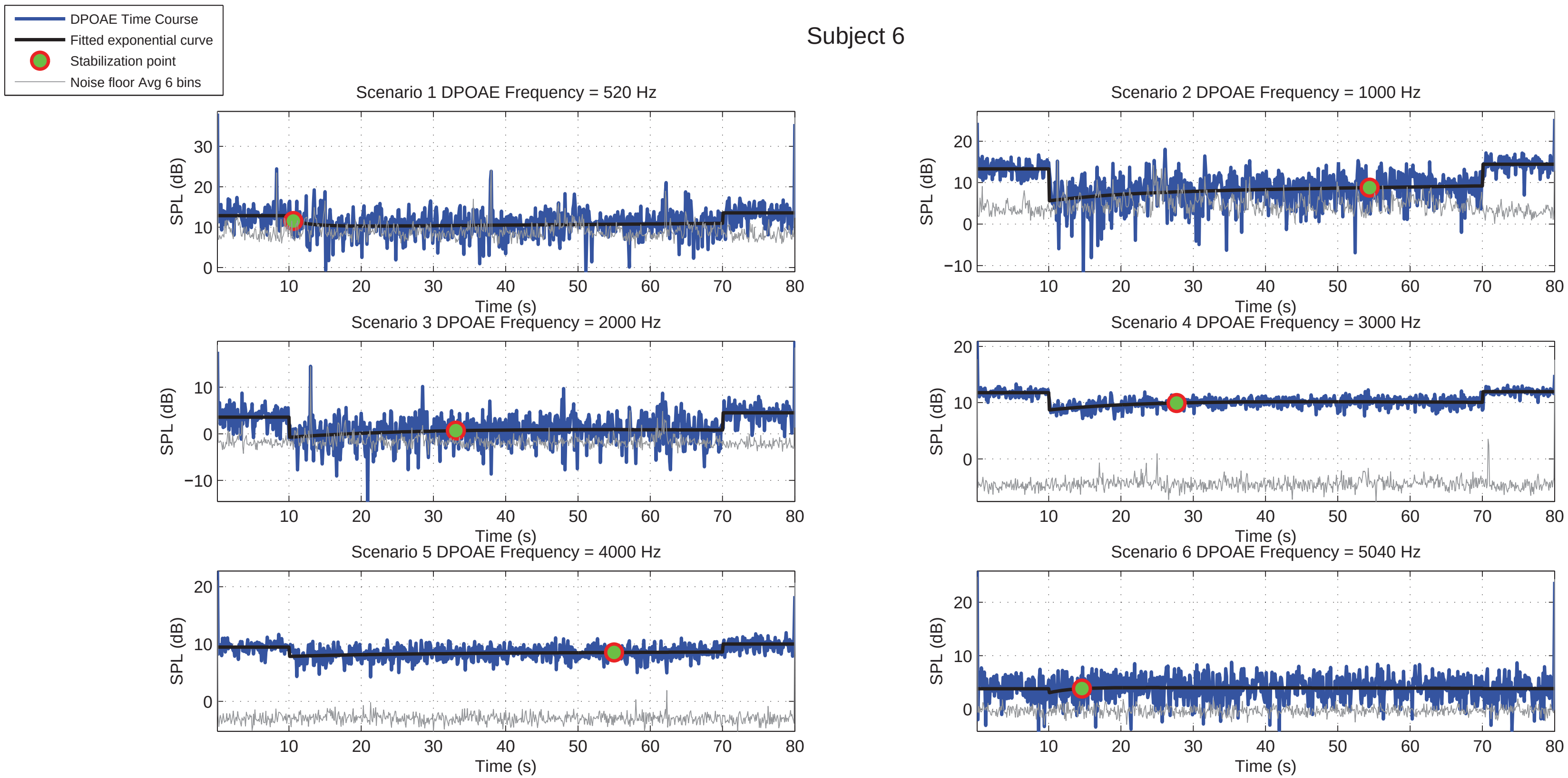

Figure F.6: Final test. Subject 6. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	12.97	13.47	-0.51	10.60	10.58	3.10	2.55	10.27	2.69	0.65	9.34	1.58	3.10
2	13.14	14.39	-1.25	54.40	9.15	3.01	5.17	5.62	7.52	3.60	4.99	4.23	3.73
3	3.54	4.39	-0.85	33.10	0.83	2.82	3.65	-0.74	4.28	1.48	-1.31	2.05	2.96
4	11.76	11.94	-0.17	27.70	10.10	0.76	1.85	8.70	3.07	1.39	-4.28	14.37	0.78
5	9.54	10.05	-0.51	55.00	8.52	1.12	1.38	7.85	1.69	0.82	-2.95	11.62	1.14
6	3.77	3.99	-0.22	14.60	3.98	2.28	0.02	3.08	0.70	0.90	-0.32	4.29	2.28

Table F.6: Results of Subject 6 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

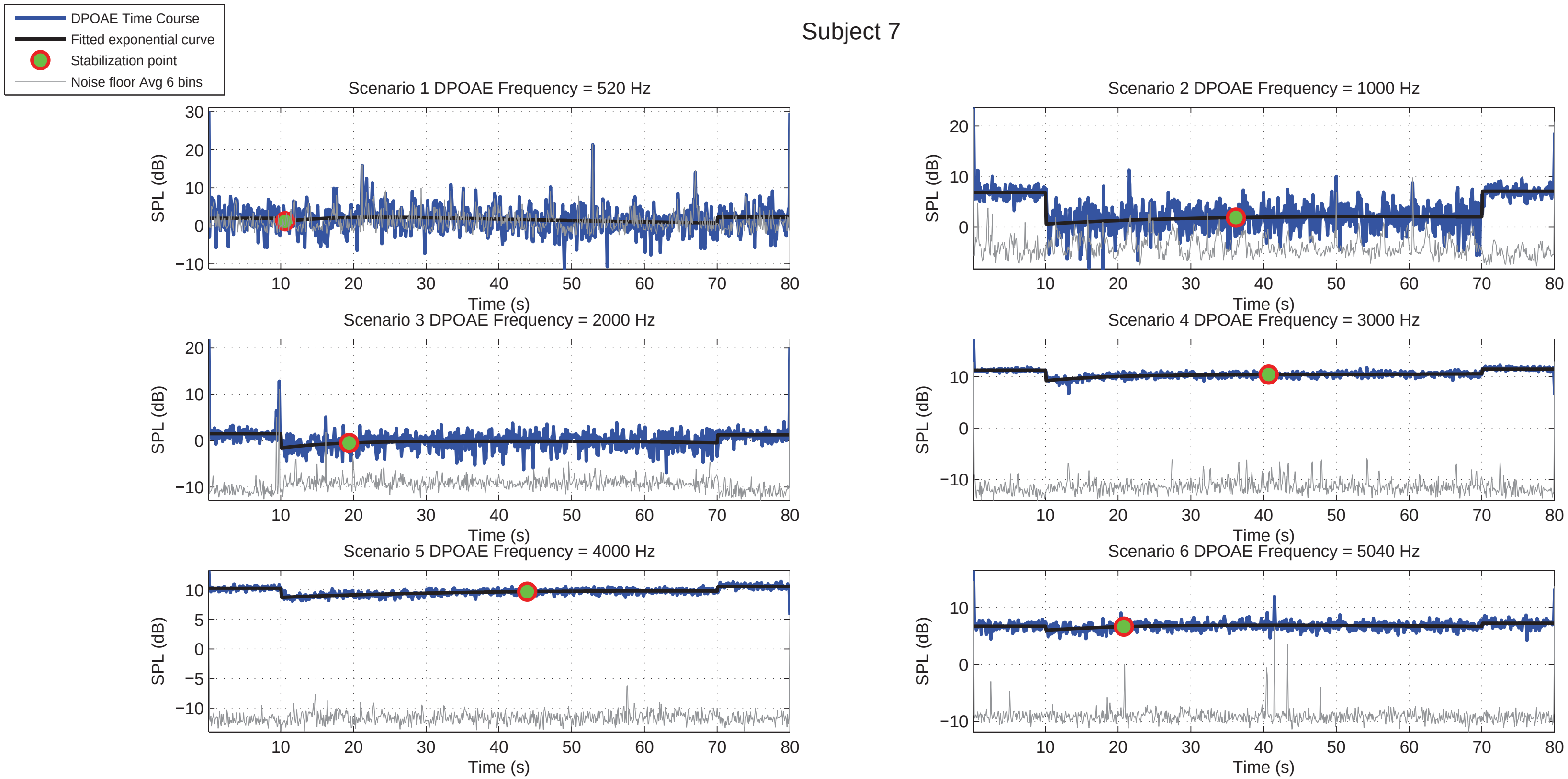

Figure F.7: Final test. Subject 1. DPOAE SPL and Noise average 7 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	1.58	2.64	-1.06	10.60	1.61	3.44	1.68	0.76	0.82	0.20	1.19	-0.23	3.41
2	6.91	7.18	-0.27	36.20	2.07	2.51	5.15	0.64	6.27	1.39	-3.83	5.86	2.61
3	1.54	1.28	0.26	19.40	-0.22	1.73	1.74	-1.57	3.11	1.12	-9.00	8.55	1.72
4	11.27	11.41	-0.15	40.70	10.48	0.42	0.89	9.22	2.04	1.30	-11.31	21.84	0.44
5	10.31	10.49	-0.19	43.90	9.80	0.37	0.69	8.74	1.56	1.06	-11.32	21.12	0.40
6	6.83	7.25	-0.41	20.80	6.79	0.67	0.52	5.98	0.85	0.74	-9.32	16.04	0.68

Table F.7: Results of Subject 7 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

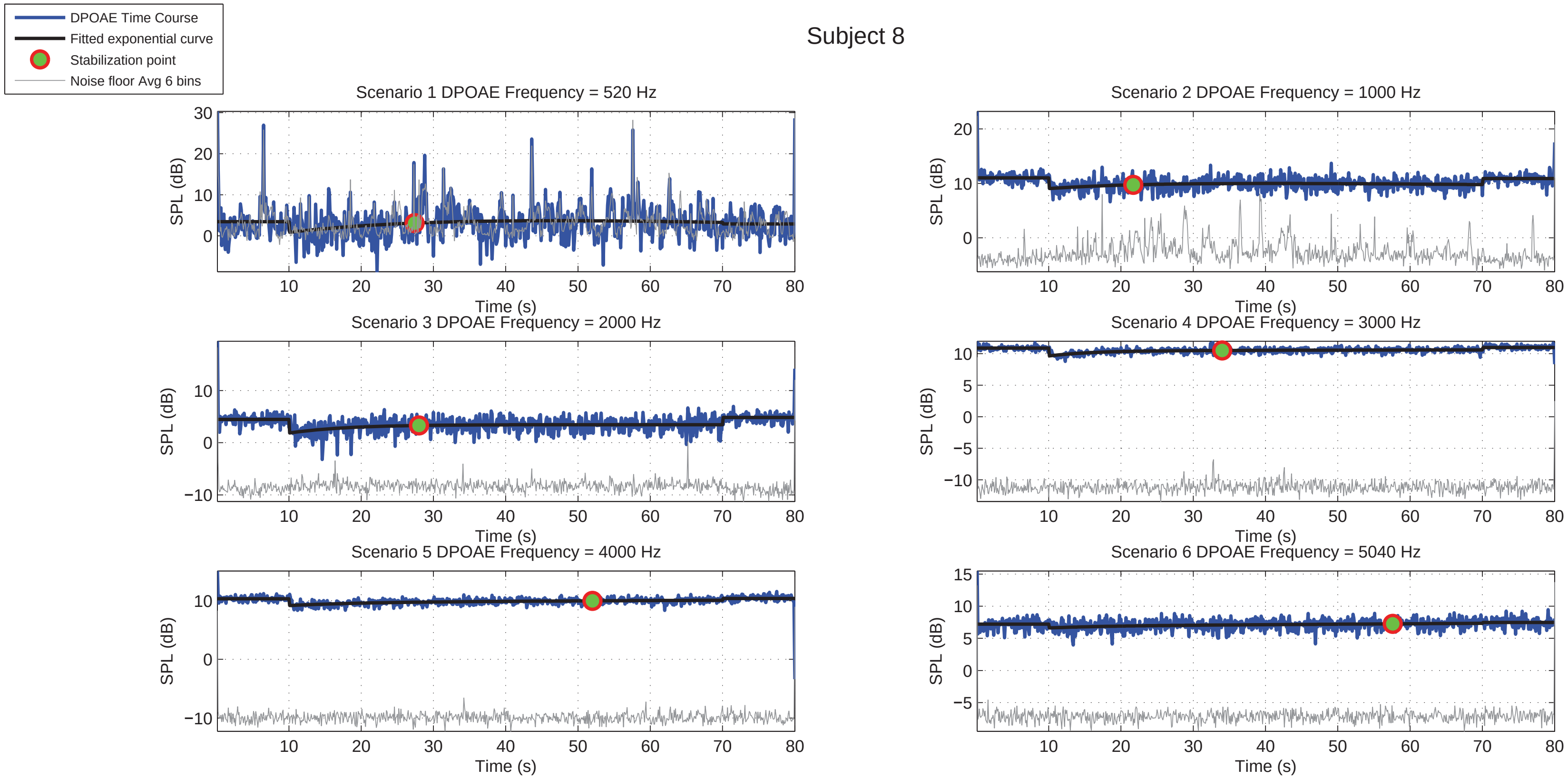

Figure F.8: Final test. Subject 8. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	3.79	2.82	0.97	27.40	3.62	3.93	-0.28	0.86	2.93	2.24	3.23	-0.13	3.85
2	11.00	11.01	-0.01	21.70	9.90	1.08	1.18	9.06	1.94	0.77	-2.86	12.69	1.09
3	4.50	4.82	-0.32	28.00	3.43	1.23	1.28	1.87	2.63	1.67	-8.02	11.55	1.31
4	10.89	10.96	-0.07	34.00	10.56	0.34	0.37	9.65	1.25	0.95	-11.24	21.84	0.35
5	10.35	10.27	0.08	52.00	10.04	0.42	0.25	9.18	1.17	0.84	-9.94	19.96	0.44
6	7.19	7.43	-0.24	57.60	7.34	0.74	0.11	6.62	0.57	0.70	-7.19	14.52	0.81

Table F.8: Results of Subject 8 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

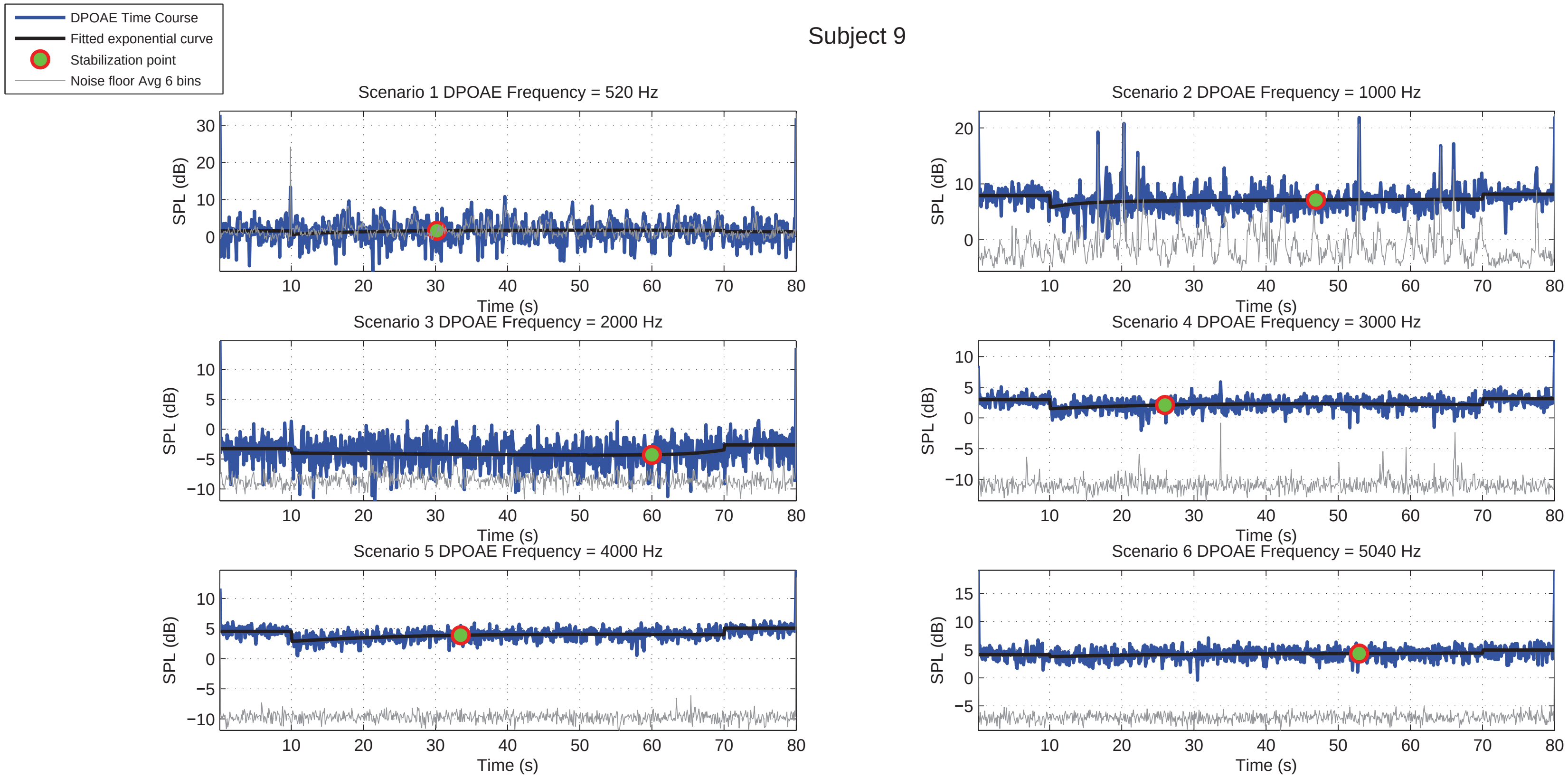

Figure F.9: Final test. Subject 9. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	1.43	1.71	-0.29	30.20	1.75	2.98	-0.05	0.66	0.77	1.10	1.94	-0.17	3.06
2	7.84	8.40	-0.56	46.90	7.20	2.10	1.01	5.84	2.00	1.55	-0.74	8.13	2.23
3	-3.20	-2.57	-0.63	60.00	-3.84	2.26	1.28	-4.33	1.13	0.49	-8.66	4.82	2.34
4	2.99	3.11	-0.12	26.00	2.26	0.98	0.95	1.51	1.49	0.66	-10.66	12.82	1.00
5	4.54	5.25	-0.71	33.50	4.03	0.85	1.17	2.89	1.64	1.18	-9.63	13.71	0.86
6	4.03	5.07	-1.04	52.90	4.36	0.99	0.65	3.76	0.27	0.66	-7.12	11.54	1.04

Table F.9: Results of Subject 9 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

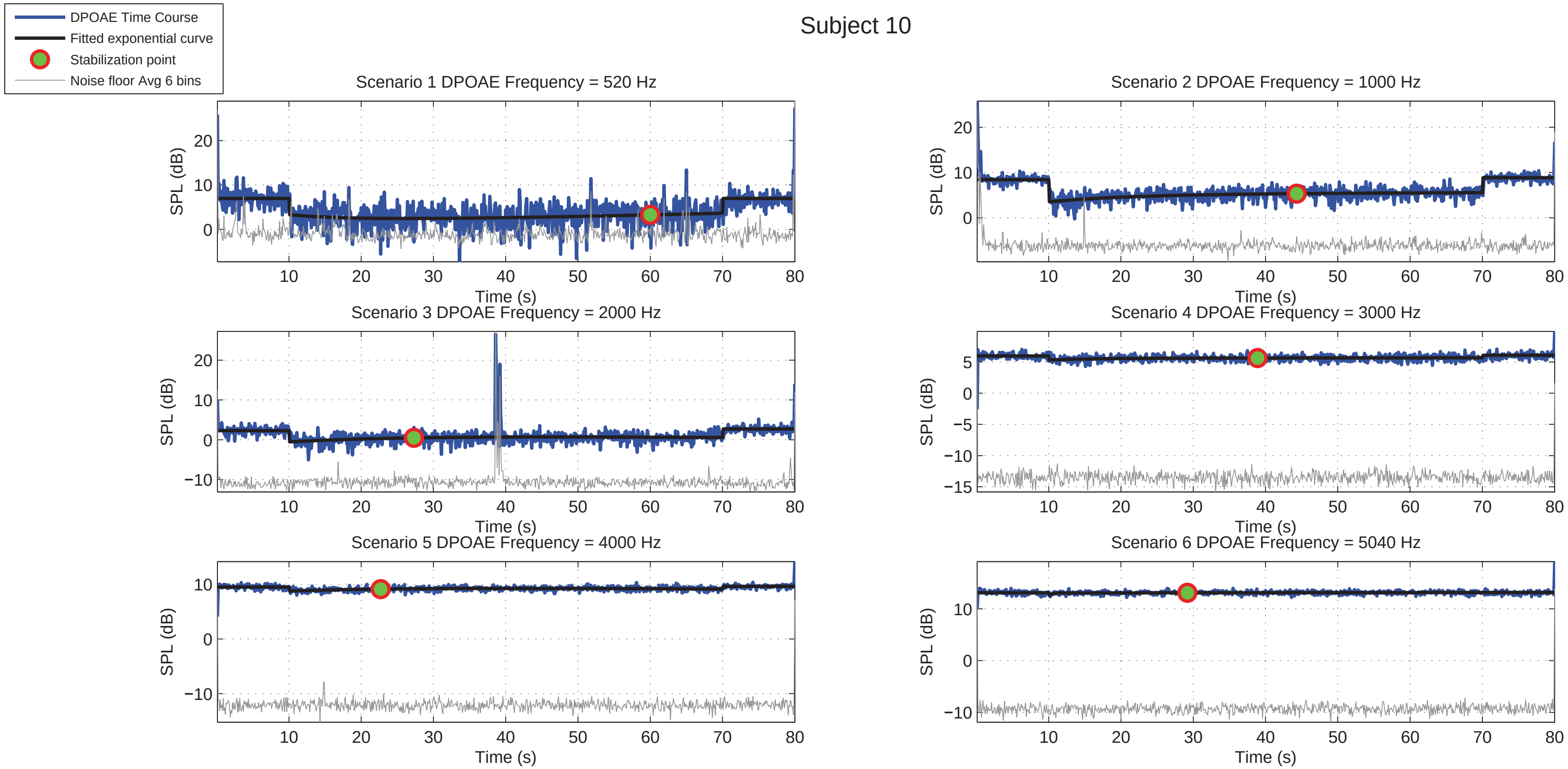

Figure F.10: Final test. Subject 10. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	6.86	7.10	-0.24	60.00	3.39	2.70	3.71	2.44	4.41	0.95	-0.75	4.14	2.63
2	8.54	8.89	-0.35	44.30	5.47	1.14	3.29	3.55	4.99	2.05	-6.06	11.66	1.20
3	2.34	2.71	-0.37	27.30	0.65	2.15	2.11	-0.53	2.87	1.13	-10.69	11.30	1.95
4	5.88	6.10	-0.21	38.90	5.65	0.45	0.41	5.32	0.56	0.36	-13.44	19.12	0.45
5	9.42	9.66	-0.23	22.70	9.20	0.36	0.49	8.75	0.67	0.42	-12.23	21.40	0.36
6	13.03	13.21	-0.18	29.20	13.12	0.30	0.07	12.60	0.43	0.54	-9.24	22.38	0.30

Table F.10: Results of Subject 10 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

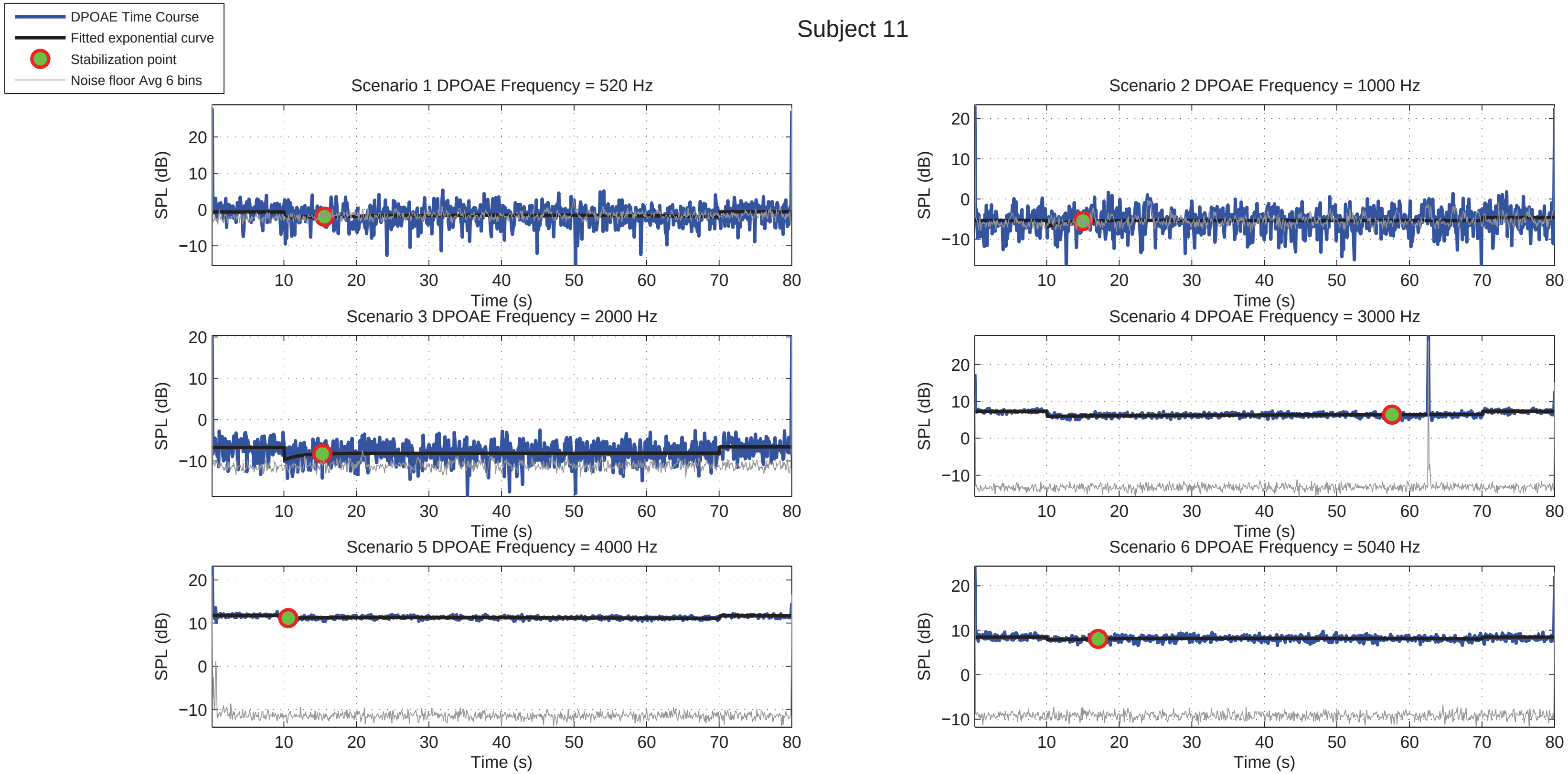

Figure F.11: Final test. Subject 11. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	-0.68	-0.33	-0.35	15.60	-1.71	2.81	1.61	-2.15	1.47	0.21	-1.66	-0.28	2.81
2	-4.85	-4.96	0.11	15.00	-5.33	2.90	0.24	-6.89	2.04	1.69	-5.04	-0.17	2.91
3	-6.95	-6.31	-0.64	15.30	-8.17	2.45	1.71	-9.70	2.75	1.68	-11.07	3.05	2.45
4	7.31	7.33	-0.02	57.60	6.43	1.99	0.82	5.92	1.39	0.59	-12.63	19.14	1.00
5	11.78	11.64	0.14	10.60	11.22	0.30	0.48	11.10	0.68	0.05	-11.46	22.62	0.30
6	8.51	8.47	0.03	17.10	8.13	0.53	0.41	7.87	0.64	0.20	-9.22	17.29	0.52

Table F.11: Results of Subject 11 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

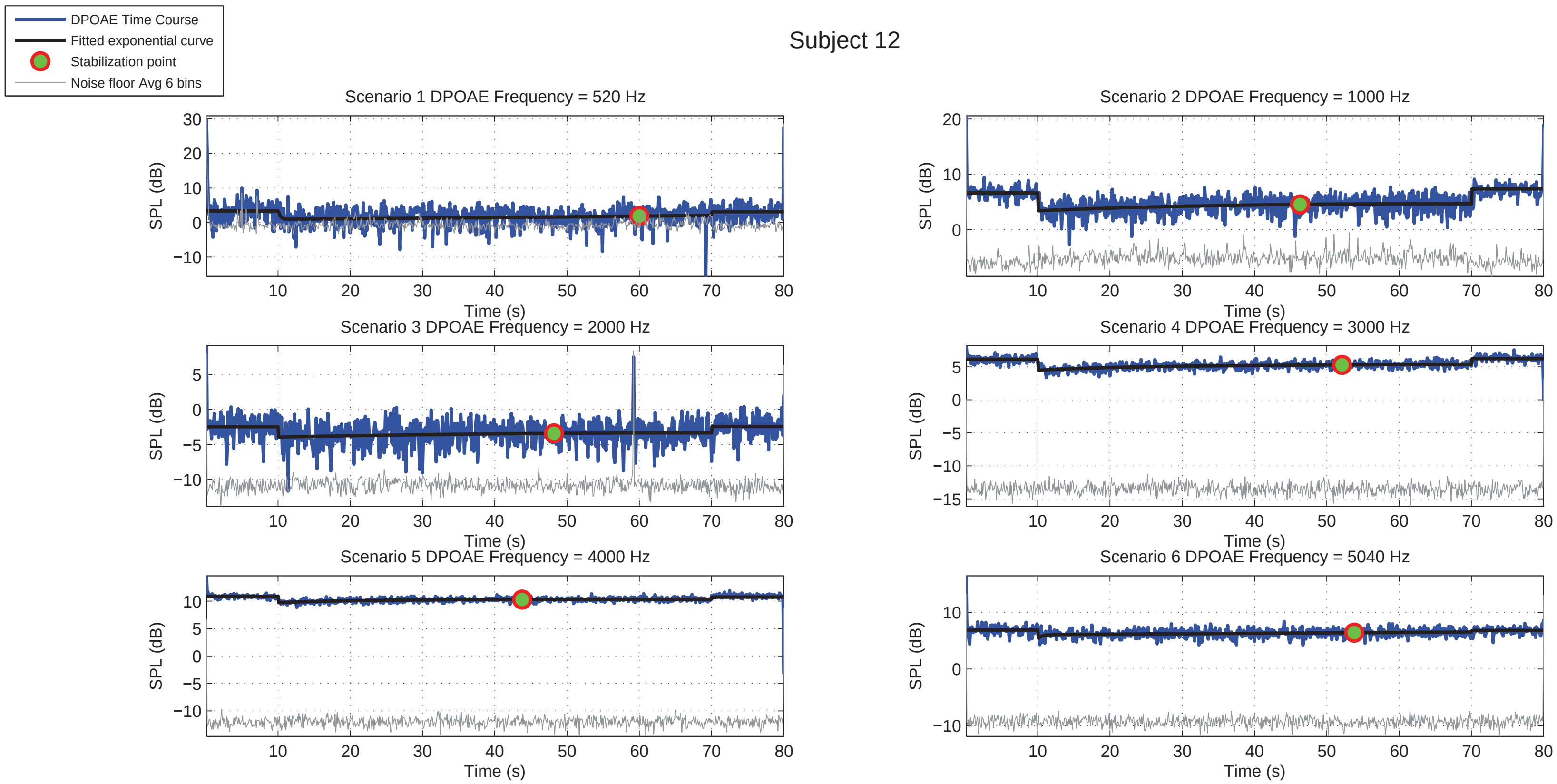

Figure F.12: Final test. Subject 12. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	3.37	3.48	-0.11	60.00	2.25	3.01	1.23	1.01	2.36	1.23	0.10	2.15	2.67
2	6.56	7.43	-0.87	46.30	4.65	1.52	2.73	3.41	3.15	1.29	-5.00	9.71	1.53
3	-2.44	-2.43	-0.01	48.20	-3.36	1.77	0.99	-3.93	1.48	0.51	-10.92	7.51	1.76
4	6.17	6.12	0.05	52.10	5.36	0.44	0.72	4.48	1.70	0.92	-13.51	18.91	0.46
5	10.79	10.60	0.19	43.80	10.31	0.32	0.25	9.72	1.08	0.64	-11.98	22.33	0.33
6	6.85	6.80	0.05	53.80	6.46	0.66	0.33	5.41	1.44	1.06	-9.27	15.74	0.69

Table F.12: Results of Subject 12 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

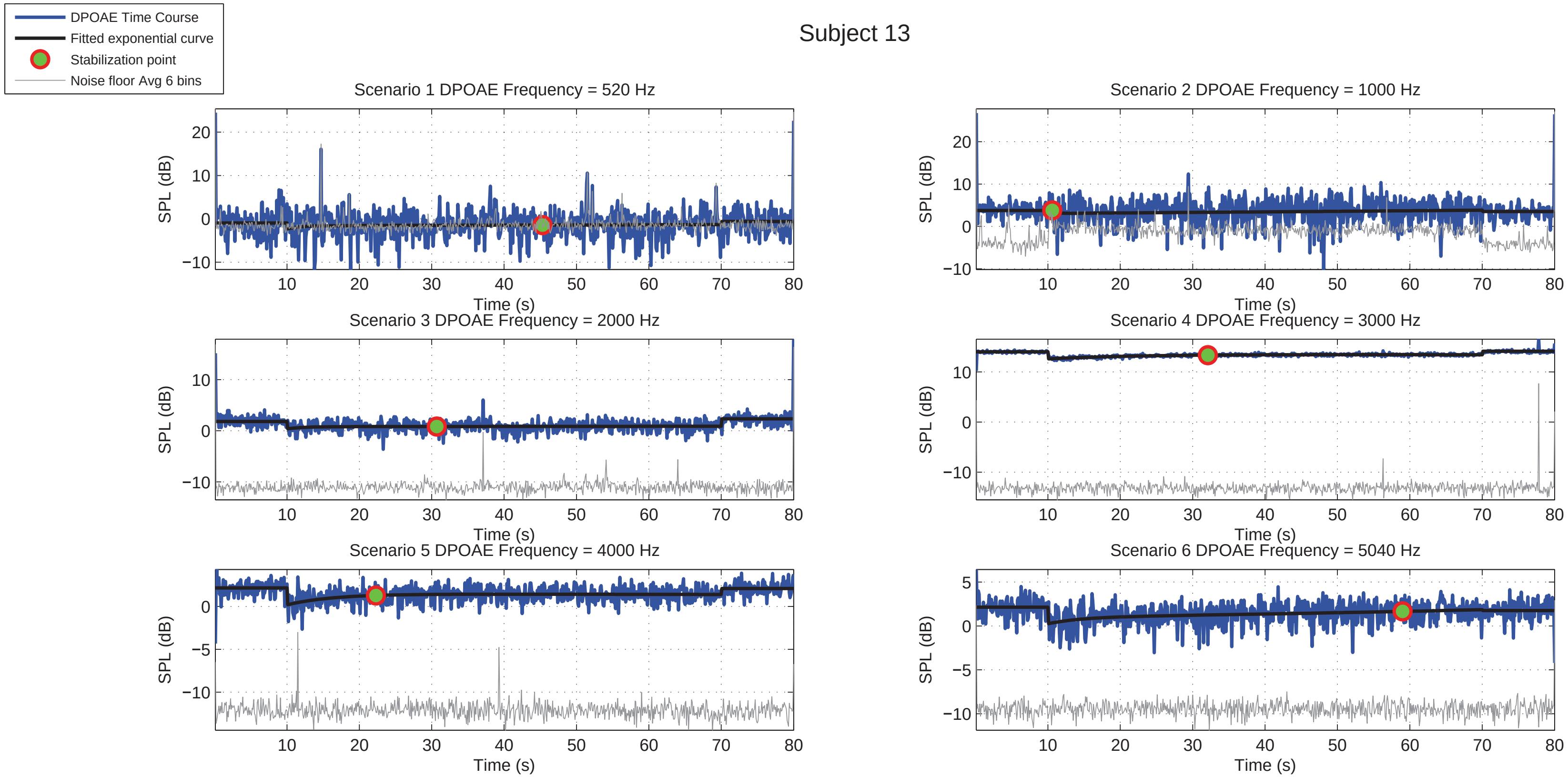

Figure F.13: Final test. Subject 13. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	-0.97	-0.54	-0.43	45.30	-1.41	3.09	0.87	-2.30	1.33	0.89	-1.15	-0.26	3.14
2	3.72	3.78	-0.07	10.60	3.45	3.05	0.03	3.11	0.61	0.64	-0.84	4.60	3.05
3	1.86	2.35	-0.49	30.70	0.83	1.03	1.51	0.38	1.48	0.46	-11.03	11.87	1.03
4	14.00	14.12	-0.12	32.10	13.42	0.19	0.68	12.62	1.39	0.82	-13.11	26.55	0.20
5	2.22	2.18	0.04	22.30	1.41	0.83	0.74	0.21	2.01	1.22	-12.29	13.72	0.86
6	2.22	1.79	0.43	59.00	1.67	1.02	0.14	0.26	1.96	1.38	-9.53	11.17	1.19

Table F.13: Results of Subject 13 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

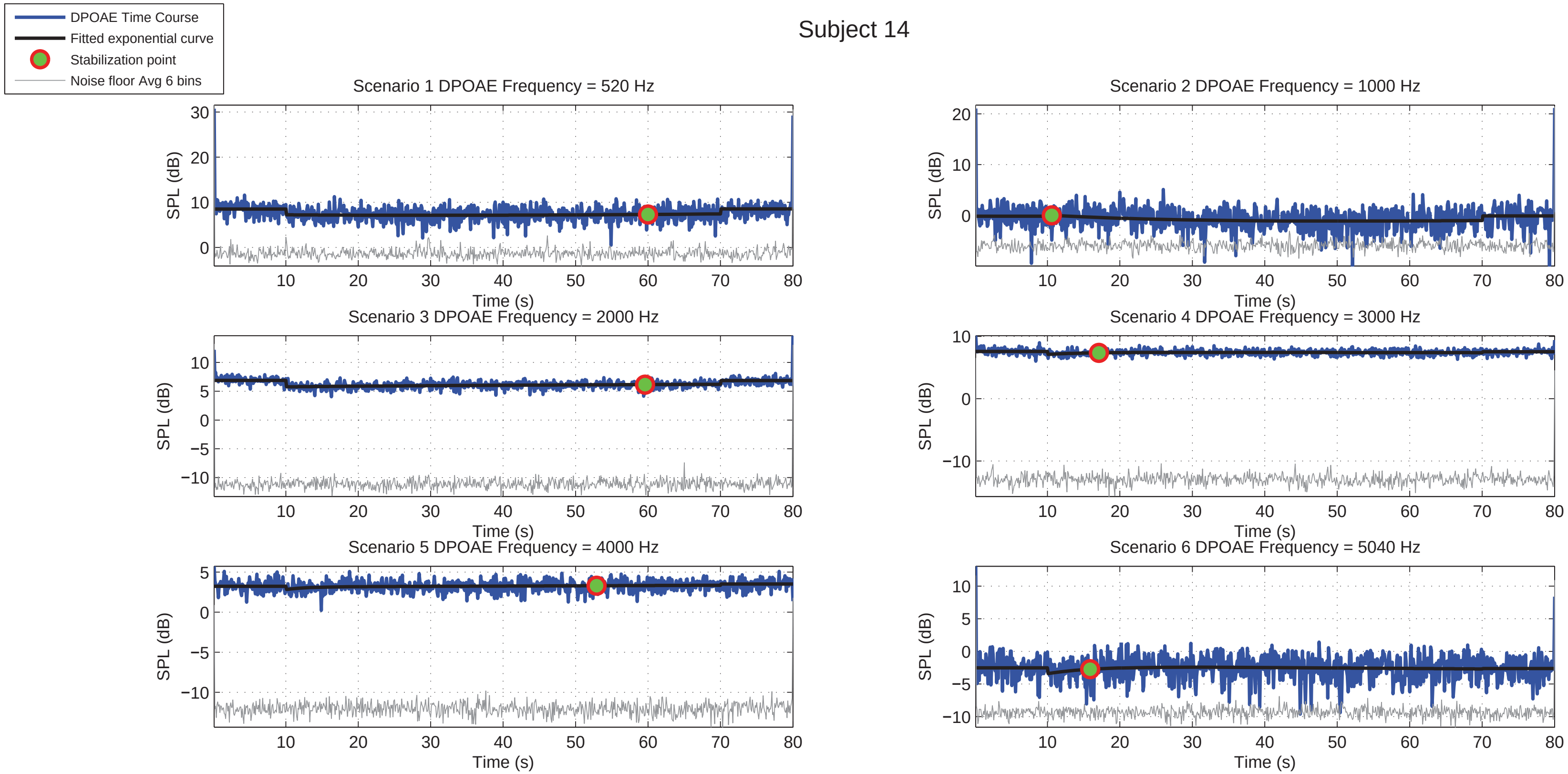

Figure F.14: Final test. Subject 14. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	8.28	8.64	-0.36	60.00	7.31	1.63	1.33	7.11	1.17	0.20	-1.28	8.59	1.56
2	-0.13	-0.14	0.01	10.60	-0.85	2.11	0.59	-1.08	0.95	0.35	-5.82	5.09	2.08
3	6.83	6.92	-0.09	59.60	6.20	0.52	0.72	5.77	1.06	0.43	-11.05	17.25	0.56
4	7.55	7.60	-0.06	17.10	7.41	0.42	0.24	7.11	0.43	0.25	-12.92	20.28	0.42
5	3.25	3.56	-0.31	52.90	3.37	0.64	0.19	2.84	0.41	0.54	-12.17	15.54	0.68
6	-2.77	-2.57	-0.20	15.90	-2.54	1.93	-0.04	-3.41	0.64	0.88	-9.35	6.82	1.90

Table F.14: Results of Subject 14 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

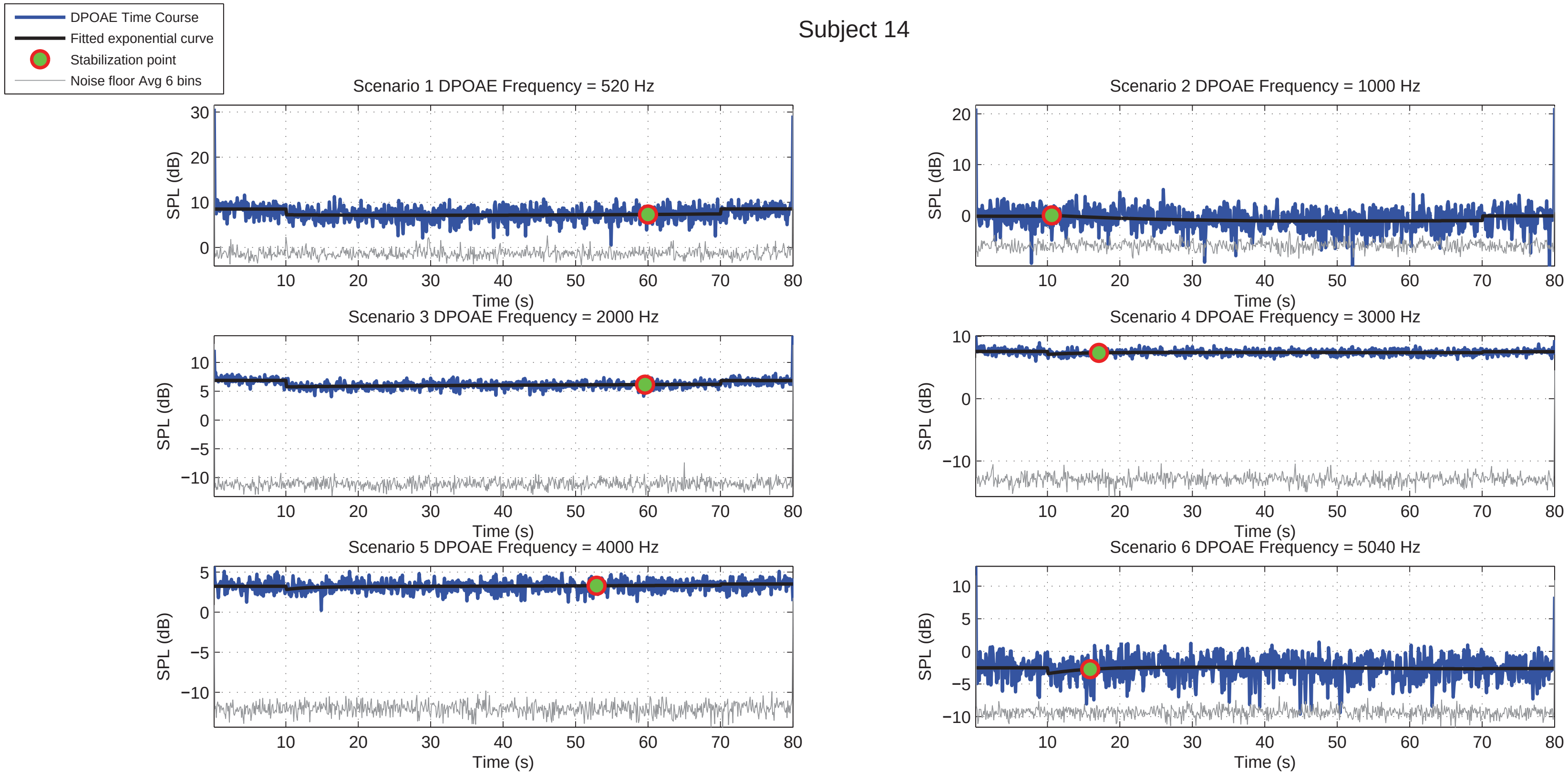

Figure F.15: Final test. Subject 15. DPOAE SPL and Noise average 6 bins around DPOAE frequency.

Scenario	A	B	A - B	E	C	STD C	B - C	D	A - D	C - D	Noise Avg	C - Noise Avg	Fitting rmse
1	0.06	0.55	-0.49	12.20	-0.44	2.69	0.86	-4.30	4.36	3.99	-2.08	1.77	2.72
2	2.06	2.76	-0.71	10.60	1.54	1.59	1.03	1.33	0.72	0.40	-6.46	8.19	1.58
3	9.96	9.85	0.11	23.40	9.00	0.41	0.83	8.41	1.55	0.60	-11.17	20.19	0.42
4	7.21	7.20	0.01	18.10	6.71	0.41	0.53	5.88	1.33	0.79	-13.37	20.05	0.41
5	13.73	13.75	-0.02	42.60	12.66	0.23	1.04	11.23	2.50	1.48	-12.15	24.86	0.26
6	5.54	5.36	0.18	44.20	5.12	0.69	0.19	4.27	1.27	0.91	-9.49	14.66	0.72

Table F.15: Results of Subject 15 in final test. All values are expressed in dB SPL units except stabilization point E, which is expressed in seconds.

Appendix G

Latency and Accuracy of the measurement system

Equipment used for the measurement introduces latency that have to be controlled for synchronization purposes and accurate SPL levels respetively.

Latency of the system was measured with a loop from output to input of the sound card. Several cosines with frequencies in the range (100 Hz - 16000 Hz) were played and recorded using *Playrec* function available for Matlab software, for more information about *Playrec* see [Humphrey, 2013].

Measured latency of the system is about 48 ms and stable for almost all frequencies tested see figure G.1. In order to study the change in signal's amplitude, RMS values of the original signal and the recorded signal (removing the first 48 ms of the recorded signal), converted to dB and compared. Differences between orginal and recorded signals are about 0.70 and 0.86 dB, see figure G.2.

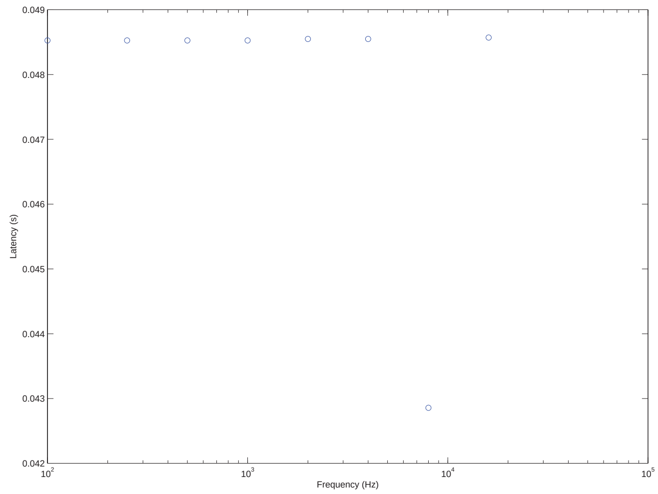

Figure G.1: Measured latencies of the system

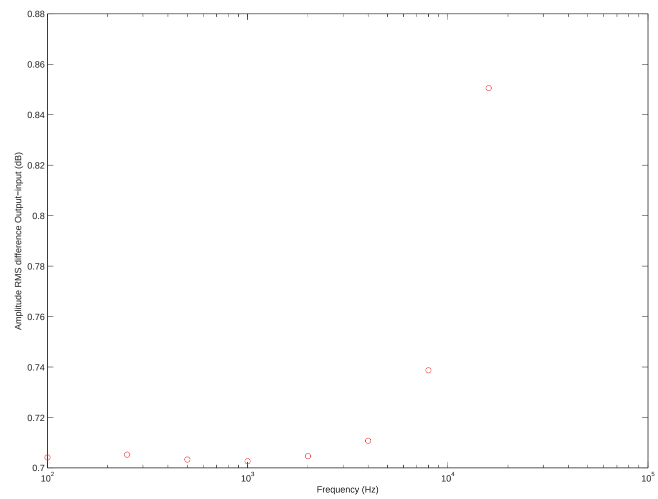

Figure G.2: Amplitude differences between original and recorded signal

Appendix G

Latency and Accuracy of the measurement system

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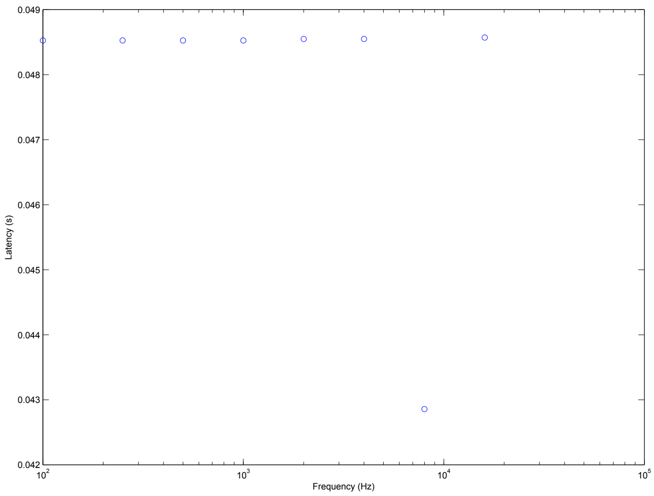

Figure G.1: Measured latencies of the system

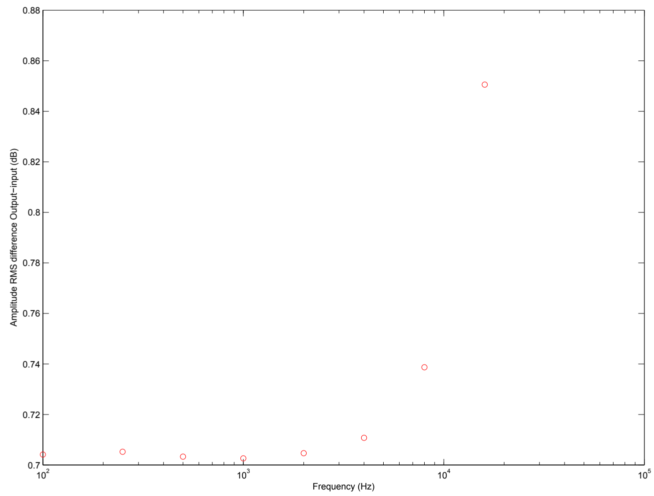

Figure G.2: Amplitude differences between original and recorded signal

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