HELSINKI UNIVERSITY OF TECHNOLOGY
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Measurement Apparatus and Modelling Techniques of Ear Canal Acoustics

Master's Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

Espoo, 24 Nov, 2008

Supervisor:	Professor Matti Karjalainen
Instructors:	D.Sc. (Tech.) Antti Kelloniemi

HELSINKI UNIVERSITY OF TECHNOLOGY	ABSTRACT OF THE MASTER'S THESIS

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Name of the thesis:	Measurement Apparatus and Modelling Techniques of Ear Canal Acoustics
Date:	24 Nov, 2008 **Number of pages:** vii + 85
Faculty:	Faculty of Electronics, Communication and Automation
Department:	Department of Signal Processing and Acoustics
Professorship:	S-89
Supervisor:	Prof. Matti Karjalainen
Instructors:	D.Sc. (Tech.) Antti Kelloniemi

Each one of us perceives the sounds around us differently. The acoustic characteristics of the outer ear have a significant influence to the sensation of hearing. The tendency of the ear canal to shape the spectral structure of sounds has not been studied systematically and the role of the ear canal as a part of the outer ear is not yet completely known. Our research focused on scrutinizing the effects of varying physical dimensions of the outer ear and particularly those of the ear canal to the pressure at the eardrum. The main emphasis was on determining the influence of the length of the ear canal to the frequency response at the eardrum and thereby to the sensation of hearing. In addition, the eardrum's damping of the resonance frequencies was studied.

Two ear canal simulators and one dummy head were manufactured for the pressure frequency response measurements. The target was to physically model the acoustic behaviour of the human head, pinna, and ear canal as accurately as possible. In addition, the frequency responses were measured from the ear canals of human test subjects in various acoustical conditions. A physics-based computational model and equations of the physics of sound were used to validate the results obtained from the measurements.

The behaviour of the ear canal was investigated in normal listening conditions as well as in free field conditions. In addition, the behaviour was studied in a situation where the canal entrance was blocked with an insert earphone. A special pair of earphones with in-ear microphones was constructed for this purpose. The earphone was also used for studying two important phenomena related to insert earphones, namely the occlusion effect and sound leakage.

From our research we may conclude that the physical dimensions and especially the length of the ear canal have a considerable effect to the pressure frequency response at the eardrum. In addition, we may conclude, that it is possible to accurately model the acoustic behaviour of the human outer ear with physical simulators.

Keywords: Ear canal, Outer ear, Eardrum, Frequency response.

TEKNILLINEN KORKEAKOULU DIPLOMITYÖN TIIVISTELMÄ

Tekijä:	Marko Tapio Hiipakka
Työn nimi:	Korvakäytävän akustisten ominaisuuksien mittaus ja mallinnus
Päivämäärä:	24.11.2008 **Sivuja:** vii + 85
Tiedekunta:	Elektroniikan, tietoliikenteen ja automaation tiedekunta
Laitos:	Signaalinkäsittelyn ja akustiikan laitos
Professuuri:	S-89
Työn valvoja:	Prof. Matti Karjalainen
Työn ohjaajat:	TkT Antti Kelloniemi

Ulkokorvan akustiset ominaisuudet vaikuttavat merkittävästi ihmisen kuuloaistimukseen. Yksilölliset erot ulkokorvan rakenteissa ovat yksi syy siihen, että kuulemme meitä ympäröivät äänet hieman eri lailla. Korvakäytävän taipumusta muokata kuulemiemme äänten spektrirakennetta on tutkittu vähän, eikä sen akustisia ominaisuuksia tunneta vielä täysin. Tutkimuksessamme keskityttiin kartoittamaan ulkokorvan ja erityisesti korvakäytävän fyysisten ulottuvuuksien vaikutusta tärykalvolla mitattavaan äänipaineeseen. Tutkimuksen pääpainona oli selvittää korvakäytävän pituuden vaikutus taajuusvasteeseen tärykalvolla ja sitä kautta kuuloaistimukseen. Lisäksi tutkittiin tärykalvon aiheuttamaa vaimennusta korvakäytävän resonansseihin.

Taajuusvasteiden mittauksia varten rakennettiin kaksi uudentyyppistä korvakäytäväsimulaattoria sekä yksi keinopää. Tavoitteena oli mallintaa fyysisesti ihmisen pään, korvalehden ja korvakäytävän akustinen käyttäytyminen mahdollisimman tarkasti. Lisäksi tutkimuksessa käytettiin koehenkilöitä, joiden korvakäytävien taajuusvasteita mitattiin erilaisissa olosuhteissa. Korvakäytäväsimulaattorin laskennallinen malli sekä äänen fysiikan laskukaavat toimivat mittaustulosten teoreettisina perusteluina.

Korvakäytävän käyttäytymistä tutkittiin normaaleissa kuunteluolosuhteissa ja vapaakenttäolosuhteissa. Lisäksi tutkittiin tilannetta, jossa korvakäytävään on asetettu korvakäytäväkuuloke (engl. “insert earphone”). Tätä käyttötilannetta ja sen tutkimista varten valmistettiin korvakäytävämikrofonit sisältävä korvakäytäväkuulokepari, jolla tutkittiin myös kuulokekuuntelun kannalta tärkeitä okkluusioilmiötä ja äänen vuotoa.

Tutkimuksen lopputuloksena voidaan todeta, että ulkokorvan ulottuvuuksilla ja erityisesti korvakäytävän pituudella on suuri merkitys taajuusvasteeseen tärykalvolla. Lisäksi voidaan todeta, että fyysisillä simulaattoreilla on mahdollista tarkasti mallintaa ihmisen ulkokorvan akustinen käyttäytyminen.

Avainsanat: Korvakäytävä, Ulkokorva, Tärykalvo, Taajuusvaste.

Acknowledgements

Research for this Master's thesis was conducted in the Department of Signal Processing and Acoustics at the Helsinki University of Technology with funding from Nokia Oyj.

I want to thank Professor Matti Karjalainen for his enthusiastic participation in the planning, research and practical realizations needed for this Thesis to be completed. In addition, his indispensable guidance and supervision have helped in solving theoretical and practical problems.

I wish to thank Dr. Antti Kelloniemi for sharing his expertise and for instructions as to research directions. My gratitude also goes to Dr. Jouni Knuuttila, Jarkko Kuntanen, Heidi Linden and Timo Toivanen for a successful cooperation.

I would also like to thank my co-workers Miikka Tikander, Jussi Rämö and Ville Riikonen for cooperation and shared efforts within our research. I also have the staff and co-researchers of the Department of Signal Processing and Acoustics to thank for help and support, and also for the great spirit you have built up at the 'laboratory'.

I am deeply indebted to friends, family and relatives who have supported me on my path to graduation.

Finally, I would like to thank the Polytech Choir as well as Driving School's principal Veikko Sompa and his pupils for their irrecoverable help in the avoidance of an overhasty graduation.

Otaniemi, 24 November, 2008

Marko "Magge" Tapio Hiipakka

Contents

Abbreviations

Adecs	Adjustable ear canal simulator
B&K	Brüel & Kjær
Dadec	Dummy head with adjustable ear canals
Efim	Earphone with fitted in-ear microphone
FFT	Fast Fourier Transform
HATS	Head and Torso Simulator
HRTF	Head-related transfer function
IEC	International Electrotechnical Commission
ILD	Interaural level difference
ITD	Interaural time difference
ITU	International Telecommunication Union
Madecs	Multi-adjustable ear canal simulator
SPL	Sound pressure level

Chapter 1

Introduction

It is well known that the outer ear contributes to the spectral shaping of sounds we hear in everyday life. People have different ears and different ear canals, hence the sound pressure at people's eardrums are not similarly distributed in the frequency domain. In part therefore, people perceive sounds differently. The middle ear, the inner ear and the nervous system also affect the way we hear. The research for this thesis, though, was limited to, and focused on the spectral shaping characteristics of the outer ear and especially the ear canal, which is the innermost part of the outer ear.

In normal listening situations the whole outer ear contributes to the spectral shaping of sound before they reach the eardrum. The ear canal acts like a quarter-wave resonator and hence amplifies the resonance frequencies. The locations of these resonance frequencies in the frequency domain depend mainly on the length of the ear canal. The shape and size of the pinna, and the curvature of the ear canal also have an effect on the pressure frequency response at the eardrum.

Insert type earphones are commonly used when listening to music and together with mobile phones etc. The sound transmission path from the insert earphone to the eardrum is different from the case when a loudspeaker is used as the sound source. The sound wave travels through the ear canal only, an ear canal that is suggestive of a half-wave resonator. The half-wave resonance frequencies are pronounced at the eardrum, and the locations of these frequencies depend once again on the length of the ear canal. In addition, the overall structure of the ear canal has an effect on the shape of the frequency response at eardrum. Furthermore, the pressure chamber effect and the occlusion effect are important factors regarding insert earphones.

Objectives

It is the objective of this thesis to study the acoustical behaviour of the ear canal. The target is to gain knowledge that will be useful in future research projects related to e.g. sound reproduction with hearing aids or headphones. The behaviour is investigated in normal listening acoustics and in free field conditions. In addition, a thorough study on the ear canal behaviour when it is blocked with an insert type earphone is performed. It is in our special interest to study the varying physical dimensions of the ear canal as to what effect they have on the frequency response at the eardrum.

Furthermore, the goal of the research related to this thesis is to model the ear canal and the whole outer ear as accurately as possible. Two approaches are applied: the building of physical simulators and physics-based computational modelling, the emphasis being on simulators. The aim is to validate the use of both approaches as parallel modelling techniques.

Finally, we hope that the results obtained in our research can help focusing future research projects.

Outline

This thesis consists of three main parts; first, the basics of hearing and technologies related to this thesis are presented. In the second part, a look at physical simulation and physics-based computational modelling is taken. In the third part, the acoustic behaviour of the outer ear and the ear canal is viewed through measurement results.

The basics of sound and hearing are overviewed in Chapter 2. The different parts of the human auditory system from the pinna to the inner ear are presented. In addition, the basics of binaural hearing are briefly presented. Headphone and microphone technologies are presented in Chapter 3.

Ear canal simulators, dummy heads and physics-based computational modelling are presented in Chapter 4. The physical simulators used in the research for this thesis were self-made and they were intended to copy the acoustical behaviour of the outer ear.

In Chapter 5 the acoustic behaviour of the ear canal in normal listening conditions and when the canal entrance is blocked with an insert earphone is studied. The novel ear canal simulators and a dummy head were used for measuring the effects of varying physical parameters such as the ear canal length and the overall shape of the outer ear.

Conclusions and future work scenarios are discussed in Chapter 6.

Chapter 2

Acoustics of hearing

The basics in the acoustics of hearing and the human auditory system are reviewed in this Chapter. First, the basics of sound and hearing are presented. The characteristics of the different parts of the human ear, as depicted in Figure 2.1, are described briefly.

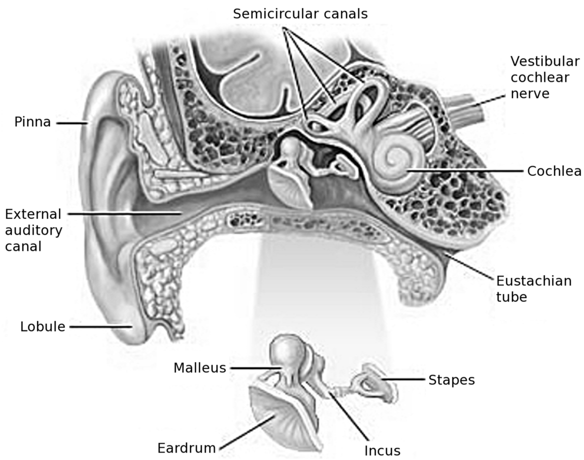

Figure 2.1: The ear consists of external, middle and inner structures. [3]

The effects of the pinna, the head and the shoulders are reviewed because of their overall effect on the transfer function from a sound source to the ear canal but also due to their significance especially in directional hearing. A brief look at this field of acoustics is taken, even though it is not within our main area of focus.

2.1 Sound and hearing

Sound can refer to either an auditory sensation in the brain or the disturbance in a medium that causes this sensation [55]. Hearing is the process by which the ear transforms sound vibrations into nerve impulses that are delivered to the brain and interpreted as sounds. Sound waves are produced when vibrating objects produce pressure pulses of vibrating air. The auditory system can distinguish different subjective aspects of a sound, such as its loudness and pitch. [16]

Pitch is the subjective perception of the frequency, which in turn is measured in cycles per second, or Hertz (Hz). The normal human audible range extends from about 20 to 20,000 Hz, but the human ear is most sensitive to frequencies of 1,000 to 4,000 Hz. Loudness is the perception of the intensity of sound, related to the pressure produced by sound waves on the tympanic membrane. The pressure level of sound is measured in decibels (dB), a unit for comparing the intensity of a given sound with a sound that is just perceptible to the normal human ear at a frequency in the range to which the ear is most sensitive. On the decibel scale, the range of human hearing extends from 0 dB, which represents the auditory threshold, to about 130 dB, the level at which sound becomes painful. [16] [55]

In order for a sound to be transmitted to the central nervous system, the energy of the sound undergoes three transformations. First, the air vibrations are converted to vibrations of the tympanic membrane and ossicles of the middle ear. These, in turn, become vibrations in the fluid within the cochlea. Finally, the fluid vibrations set up travelling waves along the basilar membrane that stimulate the hair cells of the organ of Corti. These cells convert the sound vibrations to nerve impulses in the fibres of the cochlear nerve, which transmits them to the brain stem, from which they are relayed, after extensive processing, to the primary auditory area of the cerebral cortex, the ultimate centre of the brain for hearing. Only when the nerve impulses reach this area does the listener become aware of the sound. A simplified scheme of the human peripheral hearing is depicted in Figure 2.2. [30] [16]

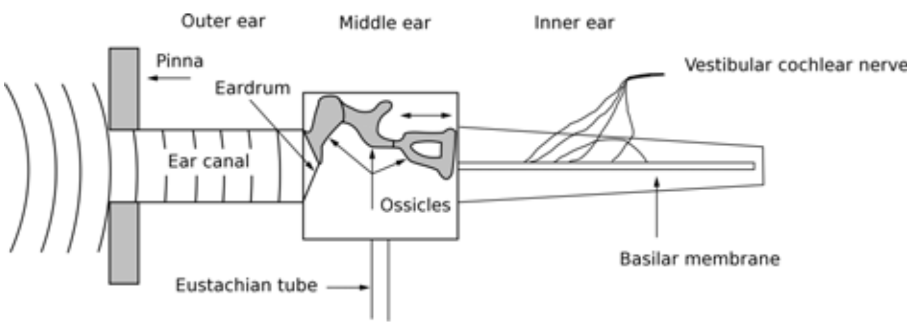

Figure 2.2: Structure of the human peripheral hearing. [30]

The ear has an enormous range of response, both in frequency and in intensity. The frequency range of human hearing extends over three orders of magnitude, from about 20 Hertz to about 20 kHz. The minimum audible pressure amplitude, at the threshold of hearing, is about 10^{-5} Pascal, or about 10^{-10} standard atmosphere, corresponding to a minimum intensity of about 10^{-12} Watt per square metre. The pressure fluctuation associated with the threshold of pain, meanwhile, is over 10 Pascals, which is one million times the pressure or one trillion times the intensity of the threshold of hearing. In both cases, the enormous dynamic range of the ear dictates that its response to changes in frequency and intensity must be nonlinear. [16]

Relating frequency to pitch as perceived by the musician, two notes will sound similar if they are spaced apart in frequency by a factor of two, or octave. This means that the tuning of musical scales and musical intervals is associated with frequency ratios rather than absolute frequency differences. [16]

The audio frequency range comprises nearly nine octaves. Over most of this range, the minimum change in the frequency of a sinusoidal tone that can be detected by the ear, called the just noticeable frequency difference, is about 0.5 percent of the frequency of the tone, or about one-tenth of a musical half-step. [16]

2.2 Outer ear

In spoken language, the word “ear” is used referring only to the visible part of the ear. In science, the visible part is named the pinna, which is Latin for “feather” [37]. From an acoustic perspective, an important part of the pinna is the concha, which is the horn-like cavity that connects the pinna and the ear canal. Even thought the ear canal is not visible to the plain eye it is still a part of the outer ear. The outer ear ends at the eardrum.

2.2.1 Pinna

The pinna, which is also known as “auricle”, acts as a sound reflector and it is formed primarily of cartilage without any useful muscles. The pinna works differently for low and high frequencies. Sound waves with frequencies below 1 kHz are not affected by the pinna. Above 1 kHz and especially around the important speech frequencies (2 kHz to 3 kHz) the sound pressure is boosted significantly. Here the behaviour is similar to a reflecting dish as it directs sounds toward the ear canal. [17]

The direct and the reflected signals arrive to the ear canal mainly in phase. However, at high frequencies, the reflected waves enter the ear canal at a very slight delay, which translates into phase cancellation or destructive interference. The greatest interference occurs when the difference in total path length is a half wavelength. This produces a “pinna notch” around 7-10 kHz. The boosting effect starts at frequencies above 1 kHz, since the size of the pinna is noticeable only when wavelength is close to or less than four times the size of the pinna. The wavelength of a sound wave is

$$\lambda = \frac{v}{f}, \tag{2.1}$$

where v is the speed of sound, and f is the frequency of the sound signal. In 20°C air at sea level, the speed of sound is approximately 343 m/s. The pinna offers a certain differentiation of sounds from the front as compared to sound from the rear. The rather significant impact of individual pinnas to directional hearing is discussed in Chapter 2.5.

The size and shape of the pinna varies between individuals. Furthermore, the pinna tends to grow bigger when people age. The concha (or the bowl), which is the part of the pinna that is closest to the ear canal, forms a horn-like entrance to the ear canal.

2.2.2 Ear canal

The ear canal (external auditory meatus, external acoustic meatus) can be described or modelled as a tube that extends from the concha to the eardrum. The ear canal acts as a quarter-wave resonator and it boosts the incoming sound around frequencies the wavelength, λ, of which are close to

$$\lambda = 4 \cdot n \cdot L, \tag{2.2}$$

where L is the length of the ear canal and n is an odd number (1, 3, 5...).

An average human ear canal is 26 mm in length and 7 mm in diameter. The outer part of the canal consists of a cartilaginous soft body and a 0.5 - 1.0 mm thick skin with glands and hair follicles. The glands produce ear wax, which has an important role in keeping the ear canal clean and protecting it from bacteria, fungi and insects. The outer soft part of the canal forms one third to one half of total canal length. The remaining inner part of the canal rests on the opening of the bony skull and the skin in this part of the canal is tightly applied to the bone. The skin here is approximately 0.2 mm thick and it is easily injured or ruptured. [4]

Figure 2.3: Pinna and ear canal seen from the front. [60]

In literature, the ear canal is often depicted with various different interpretations, which is because ear canals are different in size and shape between individuals. A slightly curved tube, as in Figure 2.3 is to be the most common shape of the canal when viewed from the front.

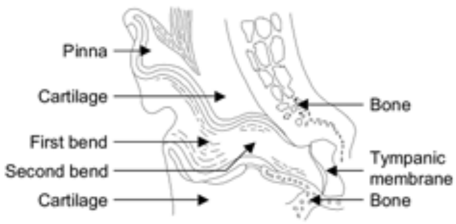

Figure 2.4: Medial section of the outer ear and ear canal seen from the top of the head. [44]

Seen from below, there are two more or less pronounced bends (see Figure 2.4), the first of which is in the lateral part of the canal near the canal entrance. The second bend is placed near the junction of the cartilage and the bony parts. Usually the ear canal narrows down towards the second bend. This notwithstanding a flaring sometimes occurs from the first bend towards the second bend, which can be seen from e.g. deep impressions of the canal. Furthermore, the shape of the ear canal might change when moving the jaws. [4] [44]

The eardrum terminates the ear canal (as depicted in Figure 2.3) and hence separates it from the middle ear cavity.

2.2.3 Eardrum

The eardrum (tympanic membrane, tympanum, myrinx), is a thin membrane that separates the external ear from the middle ear. It transmits sound from the ear canal to the ossicles inside the middle ear. The malleus bone bridges the gap between the eardrum and the other ossicles.

The eardrum is a smooth, translucent membrane with an average thickness of 0.074 mm. The shape is elliptical the height being approximately 10 mm and the width 8 mm. The mass of the eardrum is approximately 14 mg.

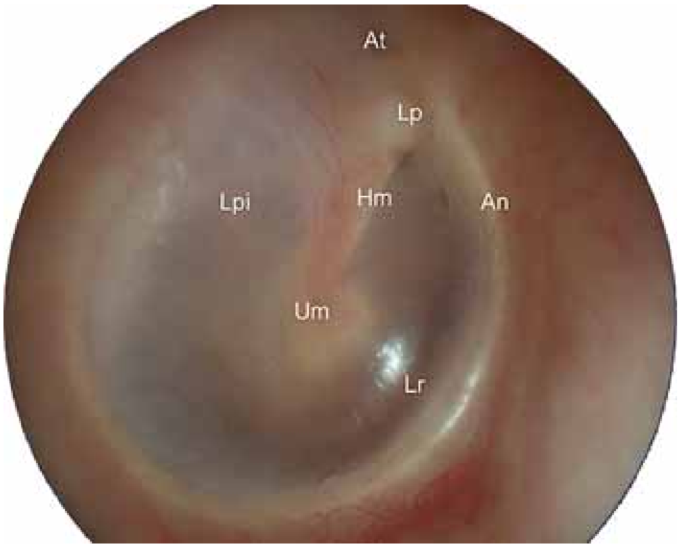

Figure 2.5: A photo of a human eardrum. The different parts are annotated as follows: **An** - *Annulus fibrosus*; **Lpi** - *Long process of incus*, which is sometimes visible through a healthy translucent drum; **Um** - *Umbo*, the end of the malleus handle and the centre of the drum; **Lr** - *Light reflex*, also known as *Antero-inferioirly* or *Cone of light*; **Lp** - *Lateral process of the malleus*; **At** - *Attic* also known as *Pars flaccida*; **Hm** - *handle of the malleus*, also known as *manubrium of malleus*. [61]

One rather important characteristic is that the eardrum does not terminate the canal perpendicularly. It may be even be considered to form the innermost part of the canal wall, a canal that converges or narrows towards the lower end of the canal. In other words, the eardrum is slanted so that the upper wall of the ear canal is shorter than the lower part of the wall. The slanting forms an angle of approximately $40\,^\circ$ with the lower part of the ear canal wall. This angle is smaller at birth, however, when the eardrum is nearly horizontal.

The eardrum is concave, which means that it is inwardly displaced by about 2 mm. At its centre, there is an outshot caused by the inferior tip of the handle of the malleus.

Considering its thinness, the eardrum is tough and resilient. This is due to the layered architecture consisting of an outer cutaneous layer, a middle fibrous layer (or lamina propria) and an internal layer (or serous membrane). The cutaneous (skin-related) layer is continuous with the lining of the external auditory canal and the internal layer is continuous with the lining of the middle ear. Rupture or perforation of the eardrum can lead to conductive hearing loss.

The eardrum can be divided into four quadrants, with the centre of the four quadrants being the umbo. The chorda tympani nerve, and arteries pass through the layers of the superior portion of the membrane. Therefore, when the tympanic membrane needs to be operated on, cuts will always be made through the inferior and posterior part of the membrane to avoid the vasculature, nerves, and bones associated with the membrane. [4]

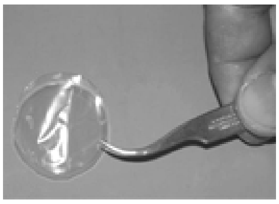

Figure 2.6: An artificial eardrum produced using human skin cells. [2]

The researchers in Ear Science Institute of Australia have introduced a process, which has allowed them to produce a new eardrum using human skin cells. A specimen is depicted in Figure 2.6. An artificial eardrum could be used for replacing a damaged eardrum. [2]

Acoustic reflex

At high sound pressure levels the muscles of the middle ear, the tensor tympani and the stapedius, can influence the transmission of sound by the ossicular chain. Contraction of the tensor tympani pulls the handle of the malleus inward and tenses the eardrum. Contraction of the stapedius pulls the stapes footplate outward from the oval window and thereby reduces the intensity of sound reaching the cochlea. The stapedius responds reflexly with quick contraction to sounds of high intensity applied either to the same ear or to the opposite ear. For sinusoidal stimulus, this effect starts between 90 and 95 dB SPL. The reflex has been likened to the blink of the eye or the constriction of the pupil of the eye in response to light and is thought to have protective value. [16]

2.3 Middle ear

The middle ear is limited by the eardrum and the oval window of the cochlea. The air-filled space of the middle ear is also known as the tympanic cavity, or cavum tympani.

The middle ear contains three ossicles - the small bones found in the ears of all mammals (the root word ‘os’ refers to bones). These bones are the smallest bones in a person’s body and they couple vibration of the eardrum into waves in the fluid and membranes of the inner ear. The malleus (hammer) is the bone attached to the eardrum and the second ossicle, the incus (anvil) as depicted in Figure 2.7. The third of the ossicles is the stapes (stirrup), which is connected to the inner ear. The ossicles together are a very important part of the hearing system. They act as a lever that boosts the very small pressure exerted by a sound wave on the eardrum into as much as 30 times bigger a pressure at the oval window of the inner ear. This magnification is mainly due to the difference in the areas of the eardrum and the oval window, the lever action of the ossicles provides a force multiplication factor of about 1.5. [55]

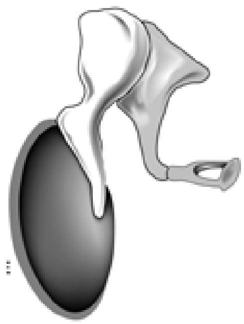

Figure 2.7: The eardrum transfers the sound vibration to the ossicles. From left to right: eardrum, malleus, incus and stapes. [48]

When the eardrum vibrates, it pushes the malleus, which then begins to vibrate in sync with the sound. When the malleus vibrates against the incus, it also begins to vibrate and transfers the vibration to the last ossicle, the stapes. The plate at the end of the stapes lies on top of the oval window of the cochlea and the vibration of the plate creates pressure waves into the fluid-filled cavity of the cochlea.

The Eustachian tube (auditory tube, pharyngotympanic tube) is a tube that joins the tympanic cavity with the nasal cavity (nasopharynx). Usually the Eustachian tube is closed, but it can open to keep the pressure difference between the two cavities at minimum. In addition, mucus (a slimy substance, typically not miscible with water, secreted by mucous membranes and glands for lubrication, protection, etc.) is transferred through the Eustachian tube from the middle ear. The Eustachian tube of an adult is approximately 35 mm long. The upper one third of the tube is made of bone and the rest is composed of cartilage.

2.4 Inner ear

2.4.1 Inner ear structure

The cochlea is a small threaded conical chamber of bone in the inner ear as depicted in Figure 2.8. It is filled with fluid, and lined with about 18,000 microscopic hair cells, on top of which are hair-like structures called stereocilia, and it transforms fluid motion into electric energy. It is a coiled structure consisting of two and three quarter turns and if it were elongated, the cochlea would be approximately 30 mm long. The entire volume of the fluid in the inner ear is only 0.2 ml.

The spaces of the cochlea are made of three parallel canals: an outer scala vestibuli (ascending spiral), an inner scala tympani (descending spiral) and the central cochlear duct (scala media). The vestibular (Reissner's) membrane separates the cochlear duct from the scala vestibuli. The basilar membrane, in turn, separates the cochlear duct from the scala tympani. The organ of

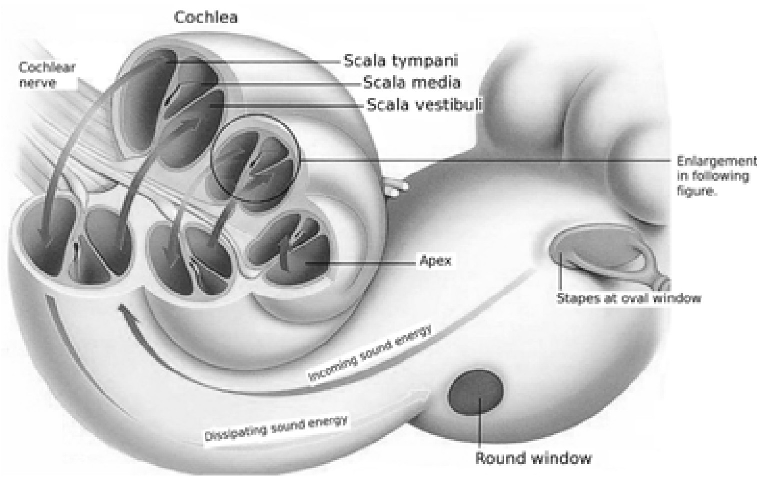

Figure 2.8: A diagram of the cochlea. [1]

Corti resides within the cochlear duct on the basilar membrane as depicted in Figure 2.9. The tectorial membrane is attached to the roof of the organ of Corti. [14]

The hair cells located in the organ of Corti transduce mechanical sound vibrations into nerve impulses. They are stimulated when the basilar membrane, on which the organ of Corti rests, vibrates. At the top of the hair cell is a hair bundle containing stereocilia, or sensory hairs, that project upward into the tectorial membrane, which lies above the stereocilia in the cochlear duct. The outer hair cells contract rhythmically in response to tonal stimuli. The ability of an outer hair cell to respond to a particular frequency may depend not only on its position along the length of the basilar membrane but also on its mechanical resonance, which probably varies with the length of its bundle of stereocilia and with that of its cell body. The inner hair cells are much more uniform in size. Local groups of outer hair cells act not only as detectors of low-level sound stimuli, but, because they can act as mechanical-electrical stimulators and feedback elements, they are believed to modify and enhance the discriminatory responses of the inner hair cells. Inner hair cells are situated in one row and the outer hair cells in 3-5 rows on the organ of Corti. The total number of outer hair cells in the cochlea has been estimated at 12,000 and the number of inner hair cells at 3,500. [16]

The cochlear nerve starts from the cochlea and extends to the brainstem, where its fibres make contact with the cochlear nucleus, which represents the next stage of neural processing in the auditory system. Although there are about 30,000 fibres in the cochlear nerve, there is considerable overlap in the innervation of the outer hair cells. A single fibre may supply endings to many hair cells. Furthermore, a single hair cell may receive nerve endings from many fibres. The actual distribution of nerve fibres in the organ of Corti has not been worked out in detail, but it is known that the inner hair cells receive the major share of afferent fibre endings without the overlapping and sharing of fibres that are characteristic of the outer hair cells. [16]

2.4.2 Inner ear function

Movement of the stapes results in transmission of fluid waves into the scala vestibuli. These sound waves are transmitted through the apex of the cochlea to the scala tympani and finally dissipated at the round window. [43] [30]

From the scala vestibuli, the waves are transmitted through the vestibular (Reissner's) membrane into the liquid of the cochlear duct (scala media) where they generate a travelling wave along the basilar membrane. [43] [30]

The basilar membrane varies in width and tension from base to apex. Hence, different portions of the membrane respond to different frequencies. High frequencies resonate close to the oval window and low frequencies close to helicotrema (cochlear apex), which is the part of the cochlear labyrinth where the scala tympani and the scala vestibuli meet. [30] [43]

The displacement of the basilar membrane stimulates the hair cell receptors of the organ of Corti. Vibration causes bending of stereocilia and this opens ion channels, which modulates a potential within the hair cell. Activation of the hair cell releases a neurotransmitter to synaptic junctions between a hair cell and neural fibres of the auditory nerve. A neural spike is generated that propagates in the auditory nerve fibre to the cochlear nuclei and further nuclei up to the auditory cortex, where they are interpreted as sounds we can recognize. [30] [14] [43]

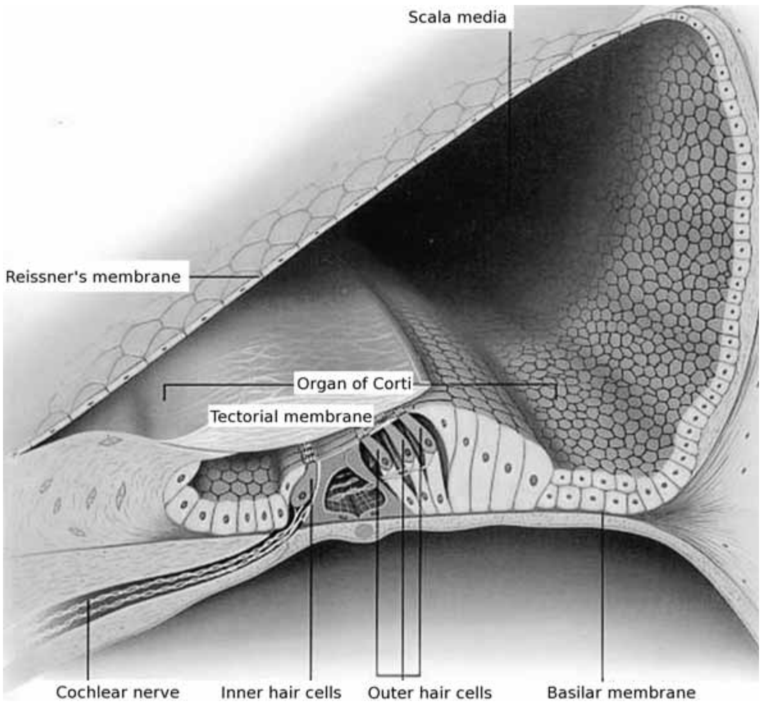

Figure 2.9: A diagram that shows the cochlear duct (scala media). [1]

2.5 Sound source localization

The human auditory system uses two ears for listening, which naturally is a great advantage compared to monaural hearing. Information of the direction, distance and loudness of sound sources are based on a complex series of direct sounds, early reflections and reverberation of the space. Together these form the binaural and monaural cues used for sound localization. Without these cues, it would be difficult or impossible to localize the sound source and it would easily be located inside the listener's head. This lateralization effect occurs e.g. when music intended for loudspeakers is listened to with headphones. Directional cues are formed completely before the sound has arrived into the ear canal and the ear canal itself does not add any directional information to the signal. [30] [8]

If a person's ears were substituted with those of another, the individual would not immediately be able to localize sound, as the patterns of enhancement and cancellation would be different from those patterns the person's auditory system is used to. However, after some weeks, the auditory system would adapt to the new head-related transfer function. [26]

2.5.1 Binaural cues

Binaural localization is based on the comparison of the two separate audio signals detected with each of our ears. According to the duplex theory of sound localization, the two main cues of sound source localization are the interaural time difference (ITD) and the interaural level difference (ILD). An interaural time delay (ITD) arises as it takes more time for the signal to reach the farther ear. An interaural level difference (ILD) is produced since the head is preventing some of the energy from reaching the far ear. This mechanism is presented in Figure 2.10. ILD is more pronounced at higher frequencies. The human auditory system is capable of interpreting these cues separately in different frequencies. Thereby, the system resolves the approximate direction of the sound source. [65] [55] [30] [8]

Both the ITD and the ILD are used across the whole audible spectral range, but their relative importance in producing directional information is unclear. The more consistent cue, one that suggests the same direction in a broad frequency range, is perceived as more reliable. [50]

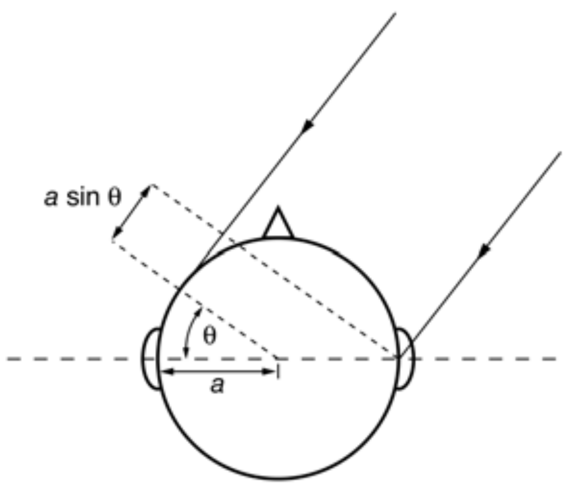

Figure 2.10: Sound arriving from the right (with angle θ) reaches the listener's left ear delayed and attenuated relative to the sound received by the right ear. [65]

2.5.2 Monaural cues, HRTF's

The pinna imposes spectral coloration on the signals arriving at the ear canal. This information is useful in the neural determination of source localization in the vertical plane, and the amount of front-back confusion in sound sources. This ability is learned from years of listening experience. Sounds presented binaurally with the original time and intensity differences but without the spectral cues introduced by the external ears are typically perceived as originating inside the listener's head [13]. [30]

To find the sound pressure that a sound source produces at the eardrum, we need only the impulse response from the source to the eardrum. This response is called the head-related impulse response (HRIR), and its Fourier transform is known as the head-related transfer function (HRTF) also called the anatomical transfer function (ATF). It describes how a given sound wave input (parameterized as frequency and source location) is filtered by the diffraction and reflection properties of the head, pinna and torso, before the sound reaches the eardrum. HRTF's are also known as free-field to eardrum transfer function and the pressure transformation from the free-field to the eardrum. The HRTF's of one test subject with different sound source directions are presented in Figure 2.12. [30][41]

Figure 2.11: A common way to measure HRTF's is to insert a miniature or a probe microphone into the subject's ear canal.

HRTF's are commonly measured by using a sine sweep signal with exponentially varied frequency as excitation signal (see Chapter 5.1.1). HRTF's are typically measured in an anechoic chamber with a probe or miniature microphone at the entrance of or inside the subject's ear canal. If the microphone is placed at the ear canal entrance, the ear canal can be either blocked or open. With a blocked ear canal, no information of the behaviour of the ear canal is obtained, but the measurement will not be as sensitive to the position of the microphone. With an open ear canal, the ear canal is included in the measurement, but the applying of the result is not as straightforward. HRTF's are measured at small increments of the lateral angle between the median plane and the sound source. [41]

Because of anatomical differences between people, there are individual differences in human HRTF's [40]. The significance of individual HRTF's is pronounced in headphone listening where HRTF's are used to achieve spatial hearing. A sound image can be localized at an arbitrary point

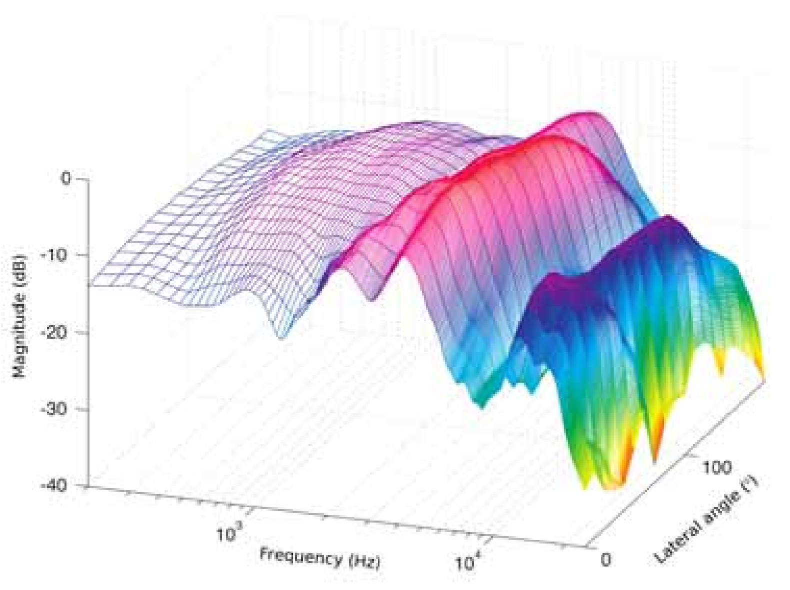

Figure 2.12: HRTF's of one test subject measured in free field and blocked ear canal with different sound source directions in the horizontal plane. 0 ° is in front of the listener. [30]

by applying corresponding HRTF's to both headphone channels. It is well known that exact sound localization cannot be obtained with an unsuitable HRTF. [28]

Variations between individual HRTF's are greater when measured with open ear canal compared to measurements with blocked ear canal at the same point. A result of this, according to Møller [40], is that the directional characteristics of the sound source are best described by HRTF's measured with blocked ear canal. Møller also concluded that for most directions the individual variation in HRTF's (the direction-dependent peaks and dips) is small up to approximately 8 kHz. Furthermore, he stated that even above 8 kHz, it is possible to find a general structure, but the variation is larger. [40]

2.5.3 The precedence effect

In natural listening environments, sound is reflected from different surfaces before reaching the ears. Although the direct sound is followed by multiple reflections, which would be audible in isolation, the first-arriving wavefront dominates many aspects of directional hearing. Despite the fact that reflections arise from many directions, the human auditory system is able to determine the location of the direct sound rather accurately. Localisation is based upon the first arriving sound, if the subsequent arrivals are within 25-35 milliseconds. If the delay between the first and a later arrival of a sound is longer than this, the latter is heard as distinct echo or as a sound coming from a separate source. Directional cues from the direct sound are given more importance than those related to reflected sound. This phenomenon is known as precedence effect. [65] [36]

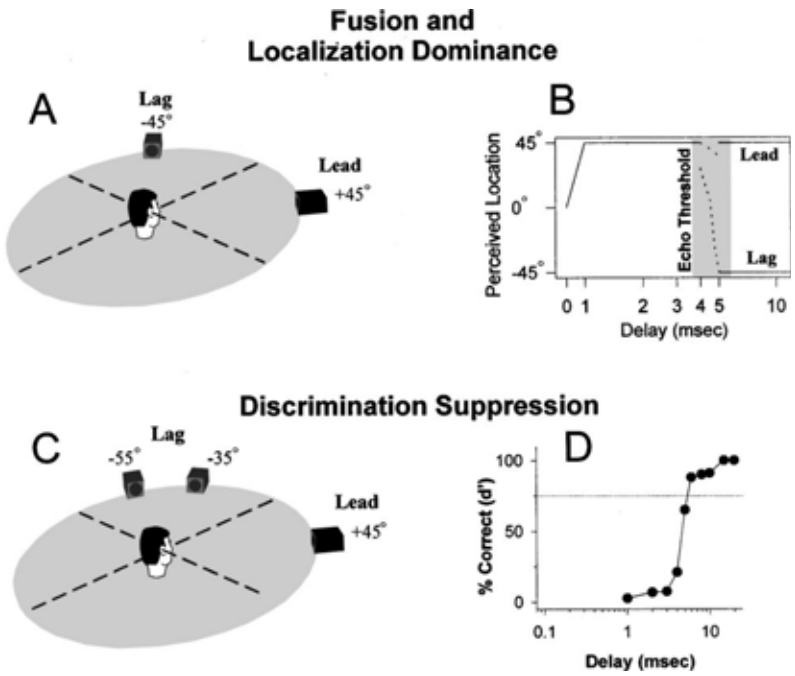

Figure 2.13: Schematic diagram of spatio-temporal relation for a lead - lag click-pair. [36]

The precedence effect is visualized in Figure 2.13, where part A gives an example of stimulus configuration for a localization task. The loudspeakers are stimulated by identical sounds such that the onset of the lag sound is delayed relative to the onset of the lead sound.

Part C of the picture gives an example of stimulus configurations for a discrimination task, where the listener is asked to localize the lag sound image. The lead sound suppresses the lag sound making it difficult to localize correctly the lag sound.

In picture part A the lead is at $45\,^\circ$ to the right whereas the lag is at $45\,^\circ$ to the left. Picture part B shows the changes in perceived locations of the auditory events as a function of delay. When no delay is present, a fused image is heard at a "phantom" location between the loudspeakers. Between 0 and 1 ms, the image shifts toward the lead. Between 1 ms and the "echo threshold" a fused image is heard at the location of the lead loudspeaker. When echo threshold is reached, a second image appears, initially near the lead location, and at longer delays at the lag location. In part C the lead is at $45\,^\circ$ to the right, and the two lag locations are at $35\,^\circ$ and $55\,^\circ$ to the left. Panel D shows sample data for the discrimination task, in which performance is poor at delays up to 4 ms. Above 5 ms the performance improves and the location of the lag sound is localized correctly. [36]

Chapter 3

Headphone and microphone technology

Headphones (earphones, earbuds, stereophones, headsets) are loudspeakers used very close to the ear for listening to audio signals. Different applications set different requirements for headphones. For example, for hearing aid use, the earpiece should not consume too much power and it should be as small as possible. For home music listening the main requirement is good sensitivity and good frequency response [59]. Headphones can be categorized by the way they are used or by their technological realization. A brief look at the different types of headphones is taken.

3.1 Headphones

3.1.1 Headphone categories

By visual and type-of-wear categorization, there are roughly four types of headphones. The **circumaural** type is the traditional large headphone that covers the pinna completely. Earpads or cushions fit around the ear and embed the ear inside the headphone cavity. This type of headphone is commonly used in places where a high attenuation of surrounding sounds is required, in recording studios and among audio enthusiasts. The dynamic range of this type of headphone can easily be made sufficiently large due to the large dimensions of the headphone driver.

Supra-aural headphones are lighter and they only cover the pinna, but do not seal the ear as tightly as the circumaural type. They have pads that sit on top of the ears, rather than around them.

Supra-concha earphones are intended to rest upon the ridges of the concha cavity and have an external diameter greater than 25 mm and less than 45 mm. This type does not come with pads.

There are two distinct types of headphones that are worn inside or on the ear canal entrance. The more old-established one is the **earbud** (earphone, intra-concha, on-the-ear) type of earphone, which is placed at the entrance of the ear canal inside the concha. These button-like earpieces do not seal the ear canal entrance completely and hence they attenuate external noise only slightly. Because they do not provide isolation, they are not capable of delivering the same dynamic range offered by many full-sized headphones.

The earphones of most interest in our study are the **insert earphones**. They are the newest kind of headphones, and the vocabulary around them is not yet well established. Depending on the manufacturer and the source of information, these earphones may be called “in-ear monitors”, or “IEM’s”, "in-the-ear headphones" and “in-the-canal earphones”. Insert earphones block the ear canal entrance completely and seal the ear canal giving rise to numerous interesting acoustical phenomena. First, they work as earplugs as they block out environmental noise. In addition, since the entrance of the ear canal is blocked (occluded) the bone-conducted portion of the users own voice arriving to the ear canal and eardrum is captured inside the canal and hence boosted significantly. Furthermore, insert earphones are sensitive to individual differences in the size and shape of the users ears and ear canal entrances and might therefore be difficult or unpleasant to wear for some users or may not seal their ear canal entrances adequately, which results in inferior performance.

Headphone technologies in general have been studied intensively, but not much has been published on insert type earphones [59]. Because insert earphones of correct size block the ear canal entrance completely and hence significantly affect the acoustics of the ear canal, they were of special interest in our research. Our research and measurements with an insert earphone is presented in Chapter 5.3.

Figure 3.1: A pair of in-ear monitors, also known as in-the-ear headphones, in-the-canal earphones or insert headphones. [59]

In telecommunication and for example in augmented reality audio systems a “headset” is defined as a combination of headphone and microphone. [22]

3.1.2 Headphone transducers

A transducer is a device that converts variations in a physical quantity, such as pressure, into an electrical signal, or vice versa. The term transducer is commonly used in two senses, the first of which is the sensor used to detect an acoustic quantity in one form and report it in another. The second is an actuator, which converts variations of electrical voltage or current into variations of another energy type. A microphone is one type of sensor, whereas a loudspeaker is an actuator. The most common transducer techniques used in headphones are briefly presented in this chapter. Each transducer type has different limitations and requirements and therefore the choice of transducer depends on what kind of usage the headphone is developed for.

Moving-coil transducer

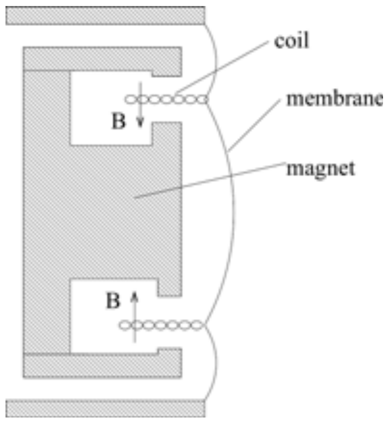

Figure 3.2: A schematic view of a moving coil transducer. [59]

The moving coil transducer (dynamic driver) is the most common transducer type used in headphones. The principle of operation is that a stationary magnetic element sets up a static magnetic field. The magnet is fitted to the frame of the headphone. In headphones, the magnetic element is usually composed of ferrite or neodymium. Attached to a coil of wire (voice coil) is the diaphragm, which is typically made of cellulose, polymer or carbon material. The voice coil is immersed in the magnetic field of the stationary magnet. The diaphragm is driven by the voice coil when a current is passed through the coil. The hereby-generated magnetic field reacts against the static magnetic field and causes the coil (and attached diaphragm) to move. This kind of transducers can be made very small and they are therefore commonly used in e.g. insert earphones (see Chapter 4.2.1). [59] [6]

Other headphone transducers

Electrostatic transducers consist of a conducting membrane and one or two stator plates (electrodes). The membrane is charged by adding a high bias voltage, which creates a high electric field between the membrane and the backplates. When the sound signal modulates the electric field the membrane moves accordingly. A drawback is the need of a high voltage source, which limits the system's mobility. Electrostatic headphones are usually more expensive than moving-coil transducers. Thanks to the extremely thin diaphragm and the absence of moving metalwork, the frequency response of these transducers usually reaches easily above 20 kHz with extremely accurate impulse response characteristics. [6]

An **electret driver** works with the same principle as an electrostatic driver. However, the electret driver has a permanent charge in the membrane. Electret headphones are cheaper and lower in technical capability and fidelity than electrostatics. [35][6]

When a **piezoelectric** material is subjected to an electrical signal, it deforms mechanically. Piezoelectric materials can be used directly as transducers or they can be connected to other surfaces. Piezoelectric transducers are used in alarm clocks and anywhere where loud alarm signals are needed. This kind of transducer can be made very small, but the dynamic range of the piezo actuator is not large enough for high fidelity sound reproduction. Some bone-conducting receivers use piezoelectric transducers. [59] [6]

A **balanced armature** transducer has a moving magnetic armature that is pivoted so it can move in the magnetic field of the permanent magnet. When electric current is added to the coil, it magnetizes the armature and causes it to rotate about the pivot thus moving the diaphragm to make sound. Nowadays balanced armature transducers are typically used only in in-ear headphones and hearing aids because of their small size and low impedance. They generally are limited at the extremes of the hearing spectrum and more than other types of drivers, they require a seal to deliver their full potential. [24]

The membrane of an **orthodynamic** (isodynamic, magnetostatic) driver consists of a thin and very light material with embedded conduction wires in it. The membrane is fitted between a system of magnetic rods that create a magnetic field that is in plane with the membrane and perpendicular to currents in the conductors. When the current changes in the conductors, the membrane moves as a plane between the rods. This technology has fallen into disuse as companies increasingly favour moving-coil designs. [59]

The **Air Motion Transformer** (AMT) is an audio transducer that moves the air in an augmented, semi-perpendicular motion using a folded sheet, which is structured around a series of aluminium struts placed in a high intensity magnetic field [25]. This type of transducer is not common due their dipole sound radiation, which makes enclosing of the headphone difficult.

3.1.3 Pressure Chamber Effect

With the same electric power consumption an insert earphone produces a higher SPL in the ear canal than an intra-concha earphone, let alone larger headphones or loudspeakers. This is in part caused by the so-called pressure chamber effect.

When the wavelength of the sound signal is large compared to the ear canal, the sound pressure is distributed uniformly in the canal, if the canal is blocked tightly and no significant leaks are present. Furthermore, the phase of the sound wave is the same in all parts of the canal and sound waves reflected from the eardrum are in same phase with the sound wave propagating from the transducer towards the eardrum.

When the pressure inside the ear canal is in phase with the volume displacement of the earphone's transducer and its amplitude is proportional to it, the adiabatic compression law gives

$$pV^{1.4} = constant, \tag{3.1}$$

where p is the pressure (sound pressure added with atmospheric pressure), V is the volume of the cavity, and the factor 1.4 is the ratio of specific heats at constant pressure and constant volume. The sound pressure per unit volume displacement is

$$\frac{dp}{-dV} = \frac{1.4 * 100\ \mathrm{kPa}}{V}, \tag{3.2}$$

where the factor 100 kPa is the normal atmospheric pressure. [46]

Leakage is an important factor that affects the headphone sound reproduction at frequencies below 2 kHz. The pressure chamber effect does not occur unless the system is tightly sealed [46].

With circum- and supra-aural headphones, the sound can leak through the headphone itself, through the porous cushion and between the cushion and the skin. Insert earphones that block the ear canal completely can at best be fitted very tightly to the ear canal entrance. Because the leak is variable, its influence to the frequency response is also variable [45]. [54]

The sound pressure produced by a loudspeaker is proportional to the volume acceleration of the loudspeaker's membrane, whereas in headphones it is proportional to volume displacement. Hence, the loudspeaker requires a larger displacement and more power to produce low frequencies.

3.2 Microphones

3.2.1 Microphone categories

Condenser microphones

The mechanical structure of a condenser microphone, also known as a capacitor or electrostatic microphone, is simple. An incident sound pressure creates motion on a stretched diaphragm, changing the capacitance between the diaphragm and a backplate. The two methods of detecting the change in capacitance are DC-biased and carrier techniques.

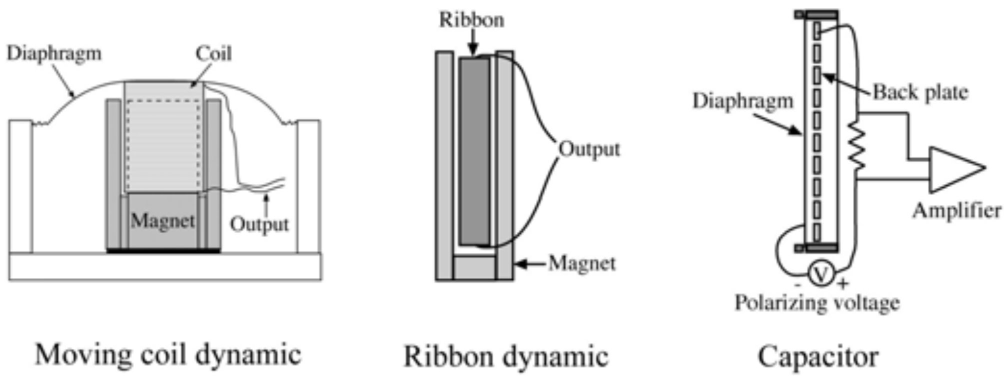

Figure 3.3: Microphone transducer types. [29]

The most common method, known as **DC-biased method**, of extracting an audio output from the transducer is to apply a fixed charge on the plates of the membrane-backplate capacitor. Motion of the membrane changes the voltage between the plates. The charge between the plates is maintained by a high voltage (polarization voltage), which is connected to the plates through a large resistor. One advantage of this method is that it produces little thermal noise, which makes it possible to detect small sound pressure levels.

The voltage maintained across the capacitor plates changes according to the capacitance equation

$$Q = \frac{C}{V} \tag{3.3}$$

where Q = charge in Coulombs, C = capacitance in Farads and V = potential difference in Volts. For a parallel-plate, capacitor the capacitance is inversely proportional to the distance between the plates. The charge between the plates stays nearly constant and the voltage seen across the capacitor changes instantaneously above and below the bias voltage and reflects the change in capacitance. The change in voltage is seen across the resistor and this voltage is amplified for further use. [67]

In **carrier technique** (RF condenser technique) the membrane-backplate capacitor is in parallel with a low-noise oscillator driven at some high carrier frequency. Now, the motion of the membrane results in modulation of the carrier voltage. The change in capacitance can frequency modulate the oscillator or the capsule can be connected to a resonant circuit that modulates the amplitude of the oscillator signal. By demodulating the signal a low-noise audio signal with a low source impedance is obtained. [69] [5] [67]

With **electret condenser microphones** the externally-applied charge used in condenser microphones is replaced by a permanent charge in an electret material. Hence, they require no polarizing voltage, but they normally contain an integrated preamplifier, which does require power.

The preamplifier is phantom powered in sound reinforcement and studio applications. In terms of noise levels most electret microphones are not as high-quality as the best DC-polarized microphones. This is still not a result of limitations in the physical structure of the electret. Albeit, high-quality electret microphones are expensive to manufacture. Electret microphones are used in e.g. high-quality recording, small sound recording devices and telephones.

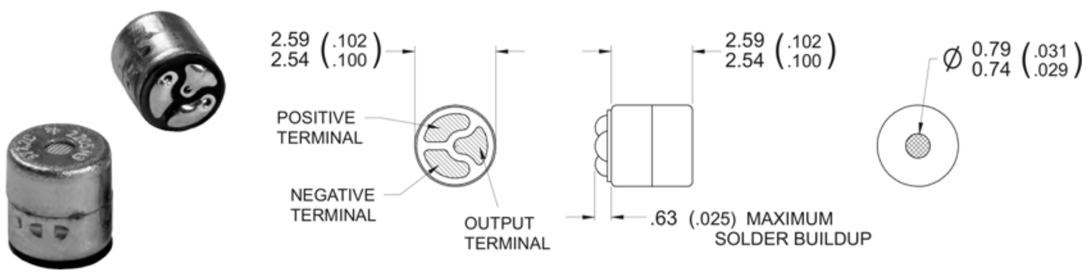

Figure 3.4: Knowles miniature omnidirectional microphone. [33]

The Knowles FG Series microphone, described in Figure 3.2.1, is the world's smallest electret condenser microphone and it is used in many acoustical measurements where traditional, bigger condenser microphones would not be applicable. The FG Series microphones can also be used in directional applications as a matched omni-directional pair. In the research for this thesis, most of the measurements were performed using Knowles FG-23329 miniature microphones. [32]

Other microphone transducers

Dynamic microphones function with the principle that when sound pressure varies, the microphone's diaphragm moves in response to the changing force applied by the moving air. The coil, which is attached to the diaphragm induces a small voltage as it moves in the fixed magnetic field. This voltage is fed to an external amplifier optimized for low input impedance and high gain. [29]

A second type of dynamic microphone is the **ribbon microphone**, in which a small ribbon of corrugated metal is placed within a magnetic field and allowed to move in response the acoustic velocity rather than the pressure of the sound wave. The ribbon microphone is unique in that it responds to the air velocity of the sound wave, not to the pressure variation. Because ribbon microphones are very sensitive, they cannot be used where they will suffer mechanical shocks. Ribbon microphones are bidirectional and can be used to pick up sounds coming from both sides of the microphone equally well. [55][16]

A **carbon microphone** is a capsule containing carbon granules pressed between two metal plates. Changing pressure deforms the granules, causing the contact area between each pair of adjacent granules to change, and this causes the electrical resistance of the mass of granules to change. The changes in resistance cause a corresponding change in some property of an electric circuit producing the electrical signal. [16]

A **piezoelectric microphone** uses the phenomenon of piezoelectricity to convert vibrations into an electrical signal. A piezoelectric material has the ability to produce a voltage when subjected to pressure. Saddle-mounted pickups on acoustic guitars are generally piezos that contact the strings passing over the saddle. [29] [55]

Laser microphones use a laser beam to detect sound vibrations in a distant object. The laser beam is directed to the object and it returns to a receiver. The beam has been modulated by the vibration of the reflecting surface. The receiver converts the modulation of the beam to an audio signal.

MEMS microphones (Micro Electrical-Mechanical System) are also called microphone chips or silicon microphones. The pressure-sensitive diaphragm is etched directly into a silicon chip by MEMS techniques, and is usually accompanied with an integrated preamplifier. Most MEMS microphones are variants of the condenser microphone design. [67]

3.2.2 Microphone sensitivity

In addition to frequency response, sensitivity is one of the basic characteristics of a microphone transducer. Sensitivity indicates the microphone ability to convert acoustic pressure to output voltage. In general there is a trade-off between sensitivity and frequency response. Small microphones tend to have lower sensitivity, but they operate at both low and high frequencies, while large microphones possess high sensitivity but are useful mainly at lower frequencies. The frequency response of a 25 mm (1") condenser microphone is virtually flat to 20 kHz while that of a 1/4" microphone is flat to about 100 kHz. The definition of sensitivity (S) is the following:

$$S = \frac{electrical\ input}{acoustic\ input}$$

The voltage sensitivity of a microphone is measured in millivolts per Pascal (Pa) at 1 kHz. The sensitivity of e.g. the Knowles miniature microphone presented in Chapter 3.2.1 is approximately 2.2 mV/Pa. [32]

3.2.3 Microphone directional sensitivity

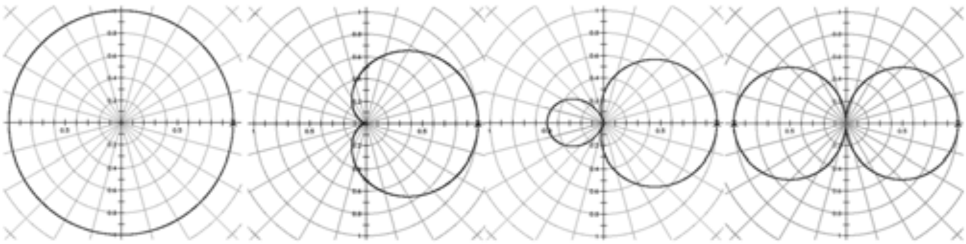

Figure 3.5: Polar patterns and their polar equations. [29]

Microphones may be classified by their directional sensitivity as well as by their transducer type. Pressure microphones are sensitive only to the pressure around the capsule and have no way of determining from which direction the pressure wave originates. Pressure gradient microphones produce an output proportional to the difference in pressure between the front and back of the capsule and therefore react differently to sounds from different directions. [29] [55] [51]

The polar patterns in Figure 3.2.3 show the various spatial sensitivity patterns and the equations that describe them. The radius r is a measure of the microphone's sensitivity at the angle θ relative to the front of the microphone, which here is the positive x-axis. It can be seen that the overall spatial sensitivity is the sum of contributions from an omnidirectional (pressure) term and a bi-directional cosine (pressure gradient) term. By varying the ratio of the terms, many different polar pattern can be created. [29] [55] [51]

Chapter 4

Outer ear models

The subjective sensation of hearing cannot be measured with the technology available today. The way people hear different sounds depends on a large amount of variables, only some of which are known. Our knowledge of and possibilities to examine the path of a sound from source to consciousness diminishes as we approach the inner ear and the nervous system. It is, however, possible to certain extent to model the external ear and measure its transformational characteristics.

In this Chapter, a brief look at the available techniques for acoustic modelling and measuring of the ear canal is taken. For specific measurements, we needed to develop and build additional apparatus, such as adjustable ear canal simulators. These new measuring devises and their basic functionalities are presented in detail. The results obtained from measurements are presented later in Chapter 5.

4.1 Physical simulators

The first approach to the modelling of the outer ear is building physical simulators and dummy heads. These apparatus are widely used for binaural recordings, measurements of headphone transfer functions and studies on HRTF's. Ideal dummy head recordings can be replayed with an appropriate reproduction system to such a high fidelity that the listening impression in best case is practically identical to the natural sound field. In addition, an ideal dummy head would prove to be useful with measurement of the headphone to eardrum transfer function. It is, however, impossible to build one "ideal" dummy head because the diversity of the external ear geometry among subjects is large. The individual differences would have to be taken into account.

4.1.1 Dummy heads

The first significant studies aiming at a standard dummy head were presented in the 1960s by the pioneering work by Burkhard and Sachs, by Zwislocki and by Shaw and in 1972 KEMAR was introduced (Figure 4.1 left). Its first main application was measurement of hearing aids under in-situ conditions. KEMAR, however, is used as reference dummy head in a wider sense. It serves for instance as reference for a database of HRTF still today.

In addition to the head and torso, the properties of the ear canal must also be determined. To improve the usability of dummy heads, ear simulators (artificial ears) were developed and standardized. [63]

Figure 4.1: KEMAR [19], HMS III [23] and HATS [10].

The main problem of research to be solved was the definition of an “average head”. The aim was to find the most appropriate head with respect to standardization. The design criteria for a standard dummy head included average dimensions of an adult human, an ear canal and eardrum to match real ears in open and closed ear use. In addition, an acoustically and dimensionally average and exchangeable pinna was needed. [63]

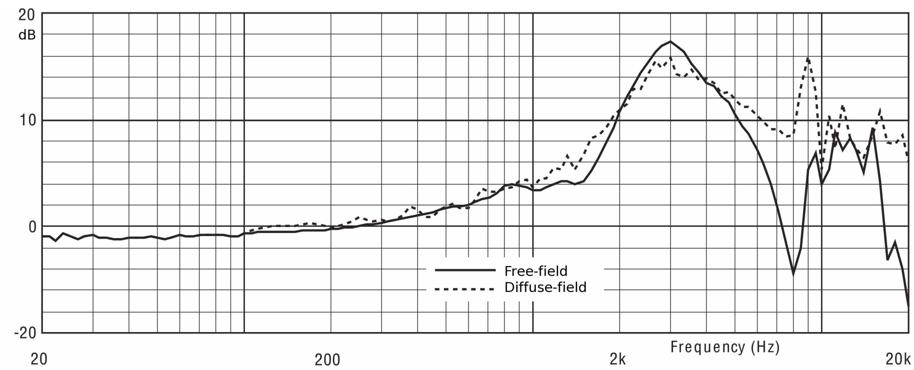

Figure 4.2: Free-field and diffuse-field frequency responses measured with HATS. Sound source is located straight in front of the simulator. Adapted from [10].

Further research aimed at a simpler description of head and torso geometry with the same acoustic behaviour as that of replicas that are more natural. Based on elliptical and cylindrical elements a mathematical diffraction model was developed, where the pinna was also simplified to the cavum conchae and the asymmetric ear canal entrance. This lead to the development of the Head Acoustics HMS II and III series (Figure 4.1 centre), which are widely used in the area of sound quality and sound design in automobile industry. Another dummy head with geometrical elements is the Bruel&Kjær HATS (Figure 4.1 right), except for the pinna, which is identical with the original KEMAR pinna. [63] [19] [23] [10]

A recent study by Minnaar et al. [38] has resulted in the conclusion that a well-selected human head (fitted with probe microphones) is superior to dummy heads. Dummy heads, which were created from an individual selection process and a copy of an individual human (rather than from an average) are almost as good as human heads.

4.1.2 Ear canal simulators

The main reason why ear canals are often modelled as straight rigid wall tubes is related to the wavelength of audible sound waves. The diameter of the ear canal is much smaller than the wavelength of the highest audible frequencies. The skin on the canal walls has little or no effect on the acoustics of the canal. Hence, a straight rigid wall tube acts as a good starting point when building physical ear canal simulators.

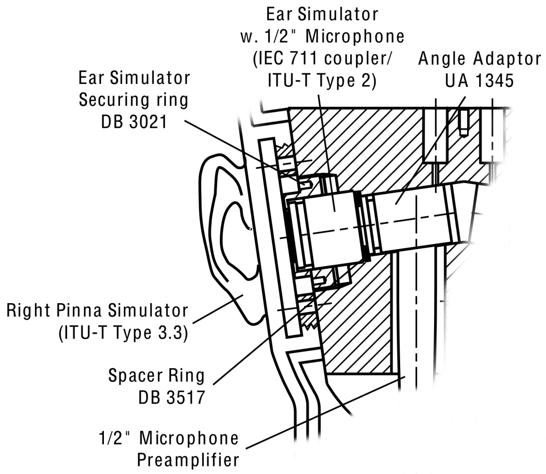

Figure 4.3: Cross-section of HATS with the right ear simulator fitted. Adapted from [10].

Since Zwislocki (in 1970) presented his ear-like coupler, many other simulators have appeared, which are supposed to model the acoustical behaviour of the human ear canal. These devices are important in testing sound sources of high output impedance. [15]

Newer variations of the Zwislocki design have the advantage that they simulate the input-to-eardrum transfer impedance of the average normal adult ear as well as the input (driving point) impedance. Thus, a microphone recording made in this type of ear simulator is supposed to represent the sound pressure that a sound source would have delivered to the eardrum of an adult listener having a normal ear with average acoustical properties. When used in combination with a dummy head, the Zwislocki-type ear simulator has numerous applications that include calibration tests of headphones and hearing aids. [15]

In our research, we used and tested numerous ear canal simulators that to some extent resemble the Zwislocki-type ear simulator. The simplest version of an ear canal simulator is a straight rigid wall tube with stiff 'eardrum'.

This model has been used also in previous studies by [53]. In order to study the effect of different ear canal shapes, numerous variations of the basic model were developed. The goal was to develop a simulator and an artificial head that would model the acoustic behaviour of the human ear, whether blocked or open, as accurately as possible.

4.1.3 Tubes as ear canal simulators

For a variety of different modelling and measurement situations, plastic tubes were used to simulate ear canals. Tubes made of soft plastic material were suitable for studying the effect of different shapes of the ear canal, as they could be compressed and bended to imitate the structure of the average human ear canal. Tubes with various inner diameters were tested and used, the most common diameter used being 8 mm.

The human eardrum is sloping and forms an angle of approximately 40° with the lower part of the ear canal wall. Most ear canal simulators though, come with an orthogonal eardrum in relation to the canal. For studies of the effect of the angle between the eardrum and the canal, two simulators with sloped eardrums were manufactured. The ear canals were made of plastic tubes with inner diameter of 8 mm and length of 30 mm. The slanted eardrums were made of aluminium and attached to the tubes. The angles chosen were 25° and 45°. Small holes in the centre of the eardrums were drilled for the miniature ‘eardrum’ microphones. In addition, one otherwise similar device, but with a straight eardrum, was also manufactured.

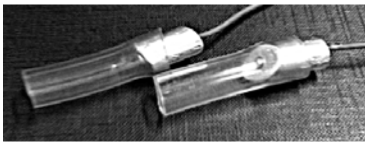

Figure 4.4: Tubes with slanted ‘eardrums’. A miniature microphone is fitted to the centre of each eardrum.

4.1.4 Adjustable ear canal simulator (Adecs)

Ear canal simulators, such as the Brüel&Kjær Type 4157 simulator, have been widely used for ear canal measurements [11]. For better understanding of the acoustic behaviour of the ear canal we needed to study the frequency responses of a large variety of different sizes of artificial ear canals. For that purpose the available simulators were not suitable. Therefore, a new device, the Adjustable ear canal simulator (Adecs), was built.

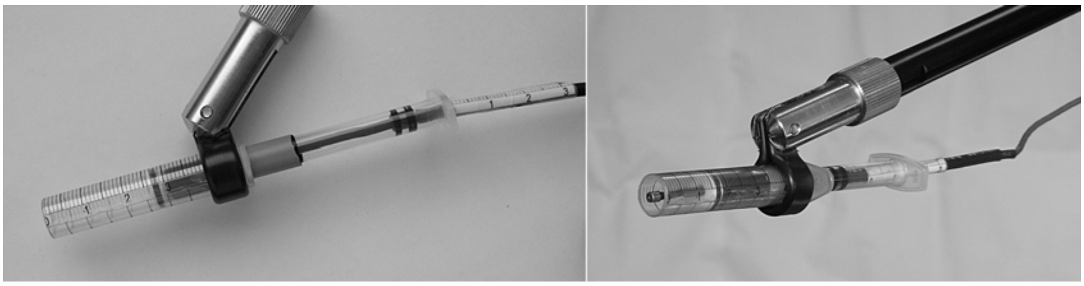

Figure 4.5: The adjustable ear canal simulator (Adecs) mounted to a microphone stand. In the picture on the right, the eardrum microphone has been moved to the canal entrance.

The ‘ear canal’ is made of a hard plastic tube with a diameter of 8.5 mm and a total length of 49 mm. The canal entrance is simply an open round hole. The ‘eardrum’ is made of a movable plastic piston so that the simulator canal length can be adjusted from 0 mm to 39 mm. A millimetre scale is attached to the side of the canal for easier control of the canal length.

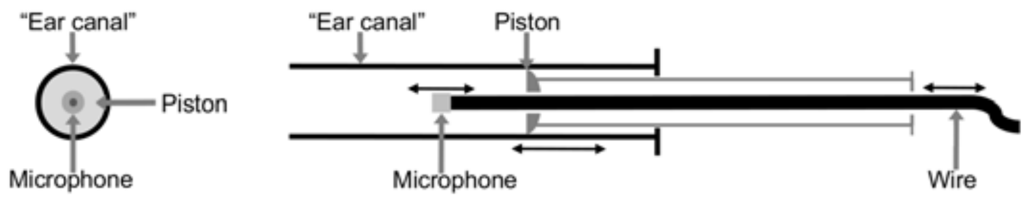

Figure 4.6: A diagram of Adecs. Cross-sections from the front (on the left) and from the side (on the right).

In the centre of the piston is a round hole, where a miniature Knowles [32] microphone is fitted. The position of the eardrum microphone is adjustable by hand. It can be located at level with the eardrum piston or pushed out as far as 57 mm into the canal towards (and outside of) the canal entrance. The exact position of the microphone is supervised with a millimetre scale at the back end of the simulator, as can been seen in Figure 4.5.

4.1.5 Multi-adjustable ear canal simulator (Madecs)

A simulator with a stiff eardrum has a frequency response that is significantly different from that of a human ear. Resonance frequency peaks and antiresonance notches are sharp when measured with rigid wall simulator, whereas with real ears they are smoother. When the simulator is blocked with an insert earphone, in the region of 2 kHz, a deep notch is found in the pressure frequency response when measured at the simulator's entrance. The notch is caused by sound wave reflecting from the rigid 'eardrum' end of the simulator. The essence of this topic will be discussed further in Chapter 5.3.

The human eardrum normally softens the mentioned notch by damping the sound wave that reflects from the drum. The impedance of the eardrum determines the magnitude of the reflecting wave at different frequencies. For achieving a better analogue with the human ear a new artificial eardrum was manufactured.

The piston used in Adecs was replaced with a piston made of aluminium and consisting of the microphone and an adjustable Helmholtz resonator. An opening for the resonator's neck was drilled on the membrane and the resonator's cavity was mounted behind the eardrum piston. A diagram of the simulator is depicted in Figure 4.7. As with Adecs, the position of the eardrum piston is adjustable from 0 mm to approximately 40 mm. In addition, the volume of the resonator's cavity can be changed by sliding the back wall of the cavity. In contrast to Adecs, the position of the eardrum microphone is not adjustable - it is fitted tightly to the eardrum.

The Helmholtz resonator act as damper at the eardrum as some of the sound energy inside the ear canal is stored in the resonator. Its resonance frequency was initially set to approximately 2 kHz to smoothen the antiresonance notch at the ear canal entrance. The resonance frequency was calculated using equation

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{V \cdot L}}, \tag{4.1}$$

where c is the speed of sound, A is the cross sectional area of the neck, V is the volume of the resonator's cavity and L is the length of the neck.

One important parameter related to resonators such as the ear canal and the Helmholtz resonator is the quality factor or Q factor. The quality factor Q for a resonator is the energy stored in the resonator divided by the energy dissipated in one period. The Q factor determines the contour of the frequency response curve for a resonator. A low value of Q results in a resonance spreading over a wide frequency band. At higher values of Q, a resonance will be confined to a considerable narrower frequency band. [51] [55]

Madecs consists in fact of two resonators, namely the ear canal and the eardrum. The Q factor of the eardrum affects the impedance but also the Q factor of the ear canal. With a high Q factor of the eardrum the damping effect of the drum is concentrated around the resonance frequency of the Helmholtz resonator. A lower Q in the Madecs eardrum would cause a spreading of its damping effect. In order to spread the damping effect to a larger frequency range, absorbing material was added inside the resonator's cavity. The Q factor of the Helmholtz resonator was thereby lowered. Finally, the wider damping effect resulted in the lowering of the Q factor of the Madecs ear canal with all ear canal lengths.

Pressure frequency responses with different resonator adjustments are presented in Chapters 5.2 and 5.3.

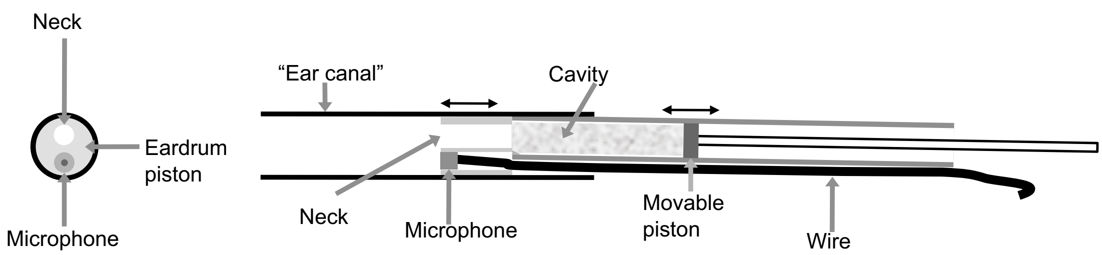

Figure 4.7: A diagram of Madecs. Cross-sections from the front (on the left) and from the side (on the right).

The simulator was named 'Multi-adjustable ear canal simulator (Madecs)' owing to its multiple adjustable parameters.

The IEC 60711 occluded ear simulator uses a somewhat similar system to generate the eardrum impedance. It applies two Helmholtz resonators and damps the resonators with narrow slits. The resonators are tuned by adjusting the thickness of shims (at the slits) to control the mid frequency behaviour of the ear simulator transfer impedance. In the coupler the two resonators are tuned to approximately 1,300 Hz and 5,000 Hz covering the mid frequency range. [42]

4.1.6 Artificial pinnas

The studies of the acoustics of the outer ear called for the introduction of artificial pinnas. An ear canal simulator without pinna (or head) is suitable only for occluded ear measurements. For measurements in free field and a listening room, an artificial rubber-made pinna was attached to the ear canal simulators, as depicted in Figure 4.8. The first pinna used was made of rubber and it represented an average adult ear, the size and shape of which were close to those of the KEMAR pinna [19]. Its outer dimensions were 5.8 cm in height and 3.8 cm in width.

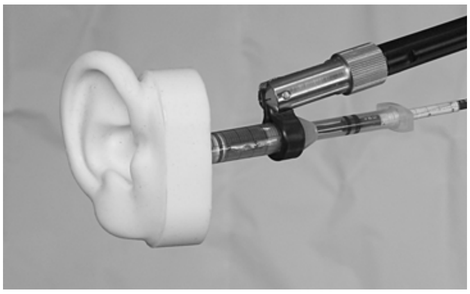

Figure 4.8: An artificial pinna attached to Adecs for open ear canal measurements.

Later, when the effects of different shapes and sizes of the pinna were investigated, new pinnas were constructed. Two larger pinnas were made of hardening plasticine. The first of these ('cuplike ear') had a very deep and large concha, its outer dimensions were 7.5 cm in height and 5 cm in width. The second larger version ('big ear') was 8.5 cm in height and 4.5 cm in width, but the overall shape was close that of an average human pinna. The new pinnas (in Figure 4.9) were used in measurements together with a dummy head.

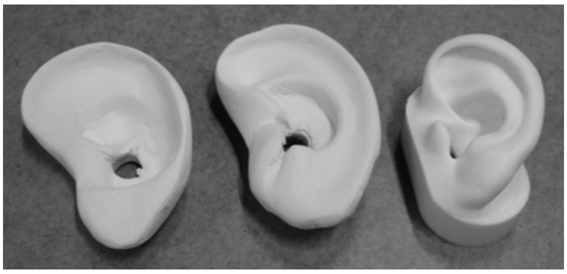

Figure 4.9: Artificial pinnas that were used in measurements: 'cuplike ear', 'big ear' and the rubber-made 'normal' artificial pinna.

4.1.7 Dummy head with adjustable ear canal (Dadec)

With an acoustically realistic ear canal simulator and artificial pinnas ready, the next step in our research was to build a complete dummy head for acoustic measurements. A manikin head was modified by replacing the ears with our artificial pinnas and fabricating a torso with dimensions of an adult human as depicted in Figure 4.10. The pinnas were mounted so that they were exchangeable and the two ear canal simulators (Adecs and Madecs) were attached in the same manner.

Figure 4.10: Dadec prepared for outdoor measurements.

The dummy head was later used in various free field and listening room measurements, and it became to be known as Dadec (Dummy head with adjustable ear canals). Henceforward by default the term ‘Dadec’ refers to the dummy head equipped with the normal size rubber-made pinna and either Adecs or Madecs as ear canal.

4.2 Computational modelling

Physics-based computational models seek to represent the physical mechanism by which the external ear transforms the incident sound pressure. In physics-based modelling of the external ear it is important to take into account that its size is of the same magnitude as the sound wavelengths of interest. In addition, the geometry of the external ear is very complex and an analytic solution to the boundary value problem for this system is probably impossible. Furthermore, the individual differences are significant and a physical model would have to be individualized to account for the psychoacoustic consequences of small geometry change. Different models of the ear canal include various amounts of anatomical details. A sophisticated model can be used for a large range of sound frequencies and such a model can have good accuracy. [57] [13]

4.2.1 Lumped element and transmission line modelling

One common way to model acoustical systems is to use electrical analogies where the acoustical system under investigation is turned into lumped electrical elements such as capacitors, resistors and inductors. Complex mechanical and acoustical systems are modelled with equivalent circuits consisting of these components. The main benefit from this technique arises from the possibility to easily change whatever acoustical parameters without laborious physical adjusting. Another major advantage in this technique is the large number of available software and tools for working with electrical circuits. [59]

	Electrical	Mechanical	Acoustical
Voltage	Voltage u	Force F	Pressure p
Current	Current i	Velocity v	Volume velocity q
Resistance	ohm Ω $R_e = \frac{u}{i}$	Ns/m $R_m = \frac{F}{v}$	Pas/m^3 $R_a = \frac{p}{q}$
Capacitance	farad F $C_e = \frac{dq}{du}$	m/N $C_m = \frac{dx}{dF}$	m^3/Pa $C_a = \frac{dV}{dp}$
Inductance	henry H $L_e = \frac{d\Phi}{di}$	kilogram kg $L_m = \frac{dI}{dv}$	kg/m^4 $L_a = \frac{pdt}{dq}$

Table 4.1: Basic analogous quantities in different physical domains (impedance analogy). q = volume velocity, x = distance, V = volume, ϕ = magnetic flux and I = inertia [59].

In electrical analogies pressure p in the acoustical domain corresponds to voltage u in the electric domain, and volume velocity q (acoust.) is equivalent to current i in the electric domain. Impedance is defined as the quotient of voltage and current in the electric domain, whereas in the acoustical domain impedance is the quotient of pressure and volume velocity. Basic analogous quantities in different physical domains are presented in Table 4.1.

The lumped element model of electronic circuits makes the simplifying assumption that each element is a finite-size object in space, and that the wires connecting elements are perfect conductors. The model is valid whenever $L_c << \lambda$, where L_c denotes the characteristic length of the circuit, and λ denotes the circuit's operating wavelength. The length of the ear canal is close to 26 mm, which corresponds to the wavelength at approximately 13 kHz. Electrical analogies should therefore be used with caution when modelling the ear canal. [59]

The transmission line model assumes that the resistance, capacitance and inductance are distributed across the whole transmission line. Each circuit element is infinitesimally small. Any circuit where wave reflections can be significant will usually need to be analysed as distributed elements.

Insert earphone modelling

Insert type earphones are of special interest in our studies because they block the ear canal completely and hence change the acoustics of the canal significantly. In order to be able to model the ear canal when it is blocked with an insert earphone a brief look at earphone modelling is taken.

Insert earphones (as well as all other types of headphones), which normally use a moving-coil transducer, can be modelled with simple equivalent circuits.

An example of a schematic view of a moving-coil transducer is depicted in Figure 4.11. The voice coil, which is in a static magnetic field, is in contact with the membrain. When the current in the voice coil changes, the magnetic field moves the coil and the membrane. [46] [59]

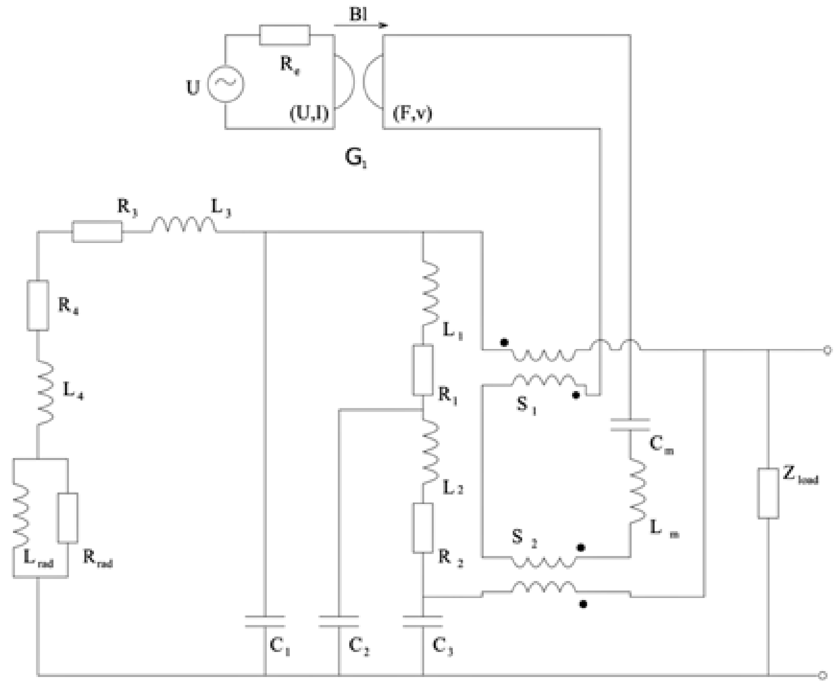

Figure 4.11: Equivalent circuit of a moving coil headphone. Modification from [46] as presented in [59].

There are three domains that need to be considered in earphone modelling: electrical, mechanical and acoustical. The acoustical components of earphones are volume compliance *C*, which is connected to the ground, porous element (*R, L* in series) and compliant membrane (*R, L, C* in series). The analogous quantities in different physical domains are presented in Figure 4.1. The function of the earphone includes converting the electric sound signals (electric domain) into membrane movement (mechanical domain) and the movement into sound pressure waves (the acoustical domain). [59]

In order to apply these modelling steps into one circuit diagram, we need to use transformers and gyrators. In Figure 4.11 the equivalent circuit of a moving-coil earphone is depicted. The different domains are modelled separately, but connected with a gyrator (G_1) and two transformers (S_1 and S_2). The gyrator is in the upper part where the electric domain is connected to the mechanical domain. The transformers connect the mechanical domain to the acoustic domain. Z_{load} is the acoustic load seen by the earphone.[46] [54]

The quantities in the mechanical domain *(F, v)* are related to the electric domain *(U, I)* with equations:

$$\bar{F} = \bar{B}\times\bar{I}l \text{ and} \tag{4.2}$$

$$\bar{U} = \bar{B}\times\bar{v}l, \tag{4.3}$$

where *B* is magnetic field density and *l* is the length of the wire in the voice coil. Force, field density, current and velocity are vector quantities but because the vectors are always perpendicular to each other due to construction of the transducer, the quantities can be considered as scalars.

Thus, Eq. (4.2) and (4.3) can be written as $F = BIl$ and $U = Bvl$. The domains are connected with a gyrator having force factor Bl as transconduction. [59]

Ear canal modelling

The simplest way to model the ear canal is to consider it as an ideal volume compliance with rigid walls. The ear canal has a length of approximately 20 to 30 mm and a diameter of 6 to 8 mm. With these dimensions the volume of the open ear canal varies between 0.6 cm^3 and 1.5 cm^3. Hence, with a blocked ear canal, when the earphone is inserted into the canal, the volume between the eardrum and the earphone can vary between approximately 0.4 cm^3 and 1 cm^3 for normal ears. The eardrum terminates the ear canal and connects it to the middle ear. The ear canal can be considered as a transmission line from ear canal entrance to the eardrum. [59]

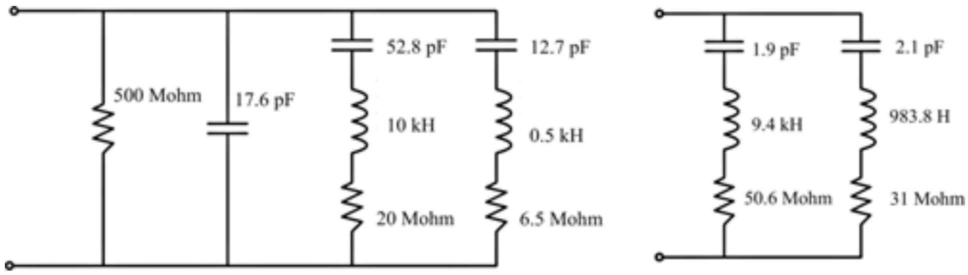

Figure 4.12: Left: A model for an ear canal impedance specified in IEC Publication 318 (Type3.1). Right: An eardrum impedance model used in IEC60711 ear simulator. [59]

A real ear does not behave like an ideal tube with rigid walls. The eardrum impedance contributes to the total ear canal impedance seen by the earphone. In a simple model the eardrum impedance can be added in parallel to the ear canal volume compliance. The main parts in the middle ear that contribute to the eardrum impedance are the tympanic membrane, the ossicle chain, the cochlea and the middle ear cavity. Due to this complex structure of the eardrum impedance, the impedance of the ear canal is different at different frequencies. [64]

Figure 4.12 on the left depicts an equivalent circuit that models an artificial ear proposed by IEC (Type 3.1). The two branches on the left (resistance and capacitance) represent the volume compliance and the two resonator branches on the right model the eardrum impedance. Figure 4.12 on the right shows an eardrum impedance model used in IEC 711 ear simulator (ITU-T 1996) for insert earphones. Figure 4.13 depicts an electrical equivalent diagram of a B&K Ear Simulator Type 4185 [9] using an impedance type analogue. The circuit is seen from the acoustical domain with associated component values in acoustic units. [59]

The lumped element modelling assumes that the wave length is much longer than the physical size of the elements. The upper frequency limit at which it is acceptable to use lumped element modelling depends on the accuracy that is required.

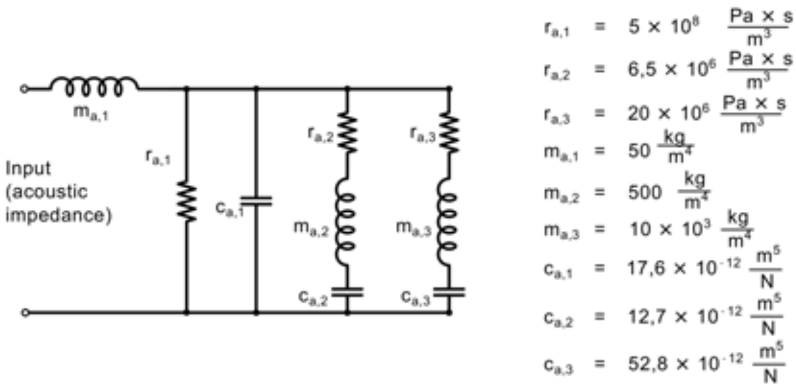

Figure 4.13: Electrical equivalent diagram of a B&K Ear Simulator Type 4185 [9].

Ear canal as transmission line

The sound pressure inside a tube can be calculated using the transmission line model, where the transmission line is a waveguide. A waveguide is a tube with a small diameter *d* compared to the wavelength λ of interest. In a waveguide the propagating sound pressure wave is a plane wave. In the case of a tube with round cross section, the maximum diameter is:

$$d_{\max} < 0.586\lambda, \tag{4.4}$$

The sound pressure in the finite waveguide can be expressed as:

$$P(\omega, x) = i\omega\rho_0(P^+e^{-\Gamma x} + P^-e^{+\Gamma x}) \tag{4.5}$$

where ω is the angular frequency. P^+ is the amplitude of the forward moving wave and P^- is the amplitude of the reflected (returning) wave. P^+ and P^- are unitless constants. ρ_0 is the density of air, which is approximately 1.2 kg/m^3. Γ is the propagation coefficient defined as:

$$\Gamma = \alpha + i\beta, \tag{4.6}$$

where α is the attenuation coefficient and β is the phase change coefficient. In a lossless tube [62]

$$e^{-\Gamma x} = e^{-\alpha x}e^{-i\beta x}, \tag{4.7}$$

$$e^{+\Gamma x} = e^{+\alpha x}e^{+i\beta x}. \tag{4.8}$$

In a tube with length *l* and and cross sectional area *A*, as depicted in Figure 4.14, the pressures p_1 and p_2 and volume velocities q_1 and q_2 in two different locations are:

$$p_1 = i\omega\rho_0(P^+ + P^-), \tag{4.9}$$

$$q_1 = A\Gamma(P^+ - P^-), \tag{4.10}$$

$$p_2 = i\omega\rho_0(P^+e^{-\Gamma l} + P^-e^{+\Gamma l}), \tag{4.11}$$

$$q_2 = A\Gamma(P^+e^{-\Gamma l} - P^-e^{+\Gamma l}), \tag{4.12}$$

from which the pressure p_2 and volume velocity q_2 can be solved as:

$$p_2 = p_1 \cosh(\Gamma l) - Z_{a0} q_1 \sinh(\Gamma l), \tag{4.13}$$

$$q_2 = -\frac{p_1}{Z_{a0}} \sinh(\Gamma l) + q_1 \cosh(\Gamma l), \tag{4.14}$$

where the acoustic impedance of the propagating wave is

$$Z_{a0} = \frac{i\omega\rho_0}{A\Gamma}. \tag{4.15}$$

For a lossless transmission line

$$Z_{a0} = \frac{\rho_0 c}{A}. \tag{4.16}$$

This technique will be applied for ear canal modelling in chapter 5.2.6. [62]

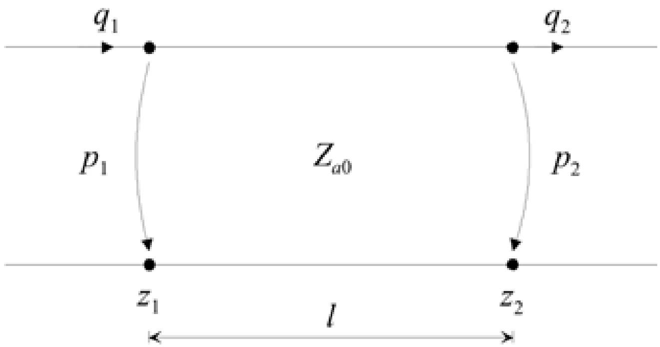

Figure 4.14: A transmission line with length *l* between points of interest. [62]

4.2.2 Estimation of pressure at eardrum

The sound pressure at the eardrum is somewhat difficult to measure. Therefore, several efforts to estimate the pressure at the eardrum have been made. Estimations are normally based on measurements along the ear canal and on computational models.

The standing waves inside the ear canal result in different pressure amplitudes in different parts of the canal. The positioning of the probe tube (or microphone) significantly affects sound pressure measurement values. Pressure measurements bordering the eardrum are difficult to obtain because of the sensitivity of the eardrum and its surrounding tissues. It is required that the introduction of measuring devices into close proximity of the eardrum be made with extreme caution. Therefore, estimates of eardrum sound pressure are typically made from pressure data collected at some distance from the drum. [12]

In a study by Sanborn in 1998 [56], the prediction of an electrical analogue model and measurement results were compared. It was found that the measured and predicted responses were similar from 300 Hz to approximately 6,000 Hz. A major source of error was probe misalignment.

In 1998 Hudde et al [27] presented the reflectance-phase method for estimating the pressure at the eardrum. It was shown that a good estimation of the pressure can be achieved, even without measuring the input impedance, by only using the minima of the pressure at the ear-canal entrance. In order to obtain correct estimations, the physical parameters of individual ear canals have to be determined. They stated that in order to become independent of the properties of audiometric earphones, the estimation of the eardrum pressure must be based on acoustical measurements at the entrance of the ear canal. The pressure can be measured with little effort using a probe tube microphone. To complete the information that can be drawn from acoustical measurements, the volume velocity must also be measured. The resulting errors of estimation remained within a limit of 3 dB up to more than 10 kHz.

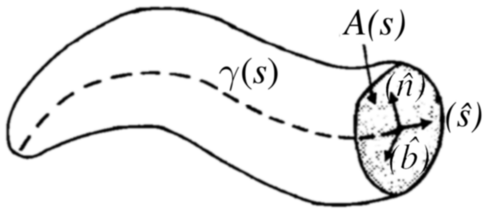

Figure 4.15: Geometrical descriptors used in the modified horn equation. $\gamma(s)$ is a general space curve that follows the centre of the ear canal and s is the arc length along the curve. At each point s, tangential $(\hat{s})$, normal $(\hat{n})$ and binormal $(\hat{b})$ unit vectors are introduced. The cross section that is defined by the n-b plane has area $A(s)$. [57]

One solution presented by Stinson [57] is to model the ear canal as a curved horn, as in Figure 4.15. In this case, a modified horn equation can be used for predicting the sound-pressure distribution along the canal. The trajectory of the canal is represented parametrically by $\gamma(s)$, where s is the position along the centre axis. The eardrum-end of the canal is set as $s = 0$. At each point s along the canal, the trajectory is specified by the tangential, normal and binormal unit vectors ($\hat{s}$, $\hat{n}$ and $\hat{b}$, respectively). The cross-sectional plane defined by $\hat{n}$ and $\hat{b}$ is perpendicular to the centre axis and (bounded by canal walls) forms the cross section of the canal, with area $A(s)$. Here it is assumed that the sound pressure depends, to first order, only on the parameter s.

The spatial variation of sound pressure p is calculated as the solution of the modified horn equation

$$\frac{d}{ds}\left(A\frac{dp}{ds}\right) + k^2 Ap = 0 \tag{4.17}$$

where k is the wavenumber. [57]

Chapter 5

Measurements

The outer ear plays a significant role in the spectral shaping of sounds before they enter the inner ear and the nervous system. The pressure frequency responses, or transfer functions, of ear canals vary greatly. The variation in responses may reach 20 dB at frequencies above 6 kHz. One of the reasons for different responses in different ears is the variation in the input impedances of individual human ears. The differences in input impedance are in turn caused by varying ear canal dimensions and eardrum impedances. [56]

The acoustic behaviour of the outer ear and the ear canal were studied through extensive measurements with ear canal simulators, a dummy head and human test subjects. The goal was to learn how the outer ear effects the overall sensation of hearing.

5.1 Measurement equipment and technology

In Chapter 4 we presented a set of new simulators that were manufactured exclusively for our research. In addition to these physical ear canal models, we needed to build measuring equipment for specific purposes. Furthermore, basic acoustic measurement equipment and software were needed for measurements on the acoustic behaviour of the outer ear and the ear canal.

5.1.1 Equipment and software

Most of the frequency response measurements were performed using the FuzzMeasure software versions 3.0.3 and 2.0.11 [58]. The software generates a logarithmic sine sweep and the signal is sent through the sound card of Apple Macintosh MacBook 4.1 to a loudspeaker or an earphone. FuzzMeasure records the swept sine through a microphone, which is connected to the sound card input. The sound pressure frequency and impulse responses are calculated and displayed in the FuzzMeasure graphic user interface.

Some of the pressure frequency responses were measured using Matlab software. Similar to FuzzMeasure, the logarithmic sine sweep was played and recorded and the pressure impulse and frequency responses were obtained thereby.

The pressure transfer function, or frequency response, is obtained by fast Fourier transformation of (FFT) the impulse response. FFT techniques using sweeps as excitation signals are found

Figure 5.1: A pair of earphones with fitted in-ear microphones.

the best choice for transfer function measurements. They are relatively tolerant of time variance and distortion and choosing a suitable sweep length allows rejection of harmonic distortion products. By employing a sine sweep signal with exponentially varied frequency, it is possible to deconvolve simultaneously the linear impulse response of the measured system, and separate impulse responses for each harmonic distortion order. After the deconvolution of the sampled response, a sequence of impulse responses appears, clearly separated along the time axis. The linear frequency response and the corresponding spectra of the distortion orders can be displayed by FFT analysing each of the impulse responses. Hence, the system is characterised completely with one, fast and simple measurement. [18]

The Knowles FG-23329 miniature omnidirectional electret condenser microphone was used in most of the measurements. Its pressure frequency response is adequately flat and it could be used in small cavities as well as in free field or in a listening room. The length and diameter of the microphone is only 2.59 mm, which was small enough to fit on the ear canal side of the earphone. According to our measurements and comparison with a high-precision microphone (B&K 4129), the frequency response of the FG-23329 is flat from 60 Hz to 10 kHz and reasonably flat from 10 kHz to 17 kHz, where there is a downswing of a few decibels in the microphone's sensitivity. Also the Brüel&Kjær 4129 measurement microphone was used in some cases for comparison.

The frequency response graphs presented in this thesis are produced with FuzzMeasure. In the figures above the graph, the text 'Frequency Response' refers to pressure frequency response. Smoothing is needed to improve readability, and the text inside brackets tells how much the graph has been smoothed. Most smoothing is normally needed with listening room measurements and least with insert earphone and ear canal simulator measurements. The text 'Magnitude' refers to signal voltage levels (sound pressure level in acoustical domain) compared to the software's maximum, which is given the value 0 dB. In some cases the levels have been normalized, in which case the average level is 0 dB.

5.1.2 Earphone with fitted in-ear microphone (Efim)

For measuring the frequency responses of a blocked ear canal, a special earphone was constructed. A Knowles miniature microphone was fitted in front of the transducer port of a Philips SHN2500 earphone as depicted in Figures 5.1 and 5.2. When the acoustic behaviour of a blocked ear canal or ear canal simulator was studied, this 'Earphone with fitted in-ear microphone (Efim)' was placed at the canal entrance and a sine sweep was excited with the earphone. The sine sweep was recorded with the fitted miniature microphone.

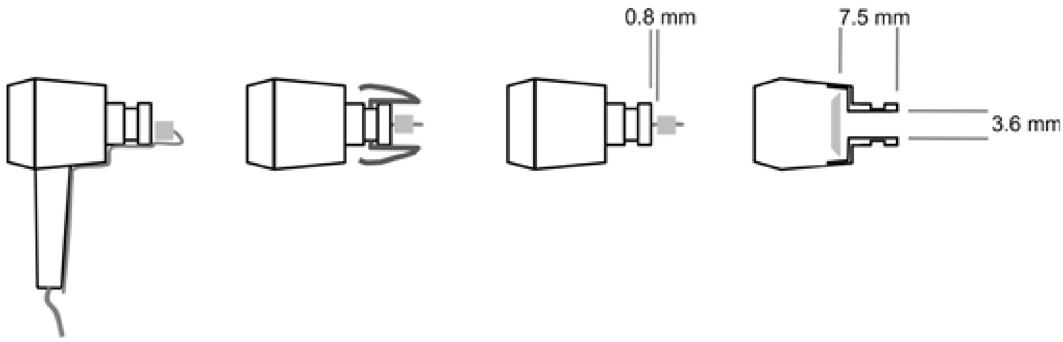

Figure 5.2: A diagram of Efim. From left to right: View from the side; rubber mould attached to the earpiece; microphone position depicted from above; cross-section depicting the transducer and the tube leading from transducer to transducer port.

The microphone was placed far enough from the transducer port to avoid blocking the port too much as shown in Figure 5.2. In the case of the microphone getting into contact with earwax the microphone sound port would easily be blocked, which would dilute the microphone's quality especially at high frequencies. Therefore, as a preventing measure, the microphone was fitted so that the transducer port was pointing towards the earphone transducer.

The transfer function from the transducer of Efim to the fitted miniature microphone when Efim is placed in free field is depicted in Figure 5.3. The strong peak in the frequency response at 6 kHz is the earphone's self-resonant frequency peak. This peak is unfortunately very close to the frequencies where the first half-wave resonance of a blocked ear appears (see Chapter 5.3). During the mounting of the microphone, the ready-fitted felt at the transducer port was removed and this made the peak at the resonant frequency somewhat sharper.

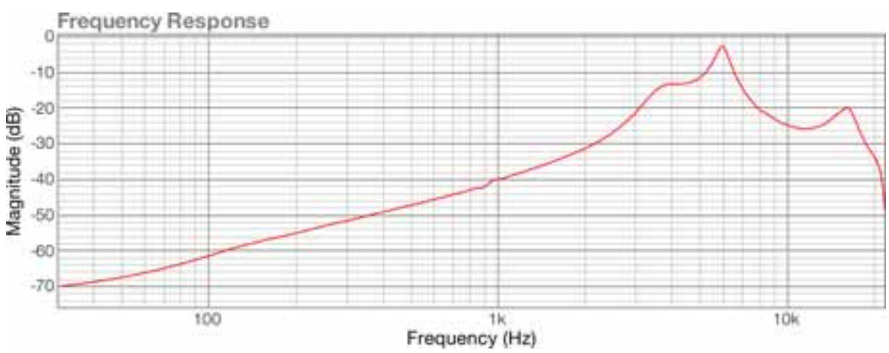

Figure 5.3: Transfer function (frequency response) from Efim's transducer to its microphone in free field conditions.

5.1.3 Measurement environments

A major part of measurements with open ear canal was made in free field in the large anechoic chamber of the Department of Signal Processing and Acoustics. A Genelec 1030A active loudspeaker was placed 2 metres from the point of measurement. A logarithmic sine sweep signal was played with the loudspeaker via the built-in output of a MacBook laptop. FuzzMeasure software was normally used to generate the signal and to capture the frequency responses. In some cases also Matlab software was used for signal generating and recording.

Listening room measurements were performed in the listening room of the Department of Signal Processing and Acoustics. Its acoustics have been designed to fit the ITU-R BS.116 standard, e.g. the reverberation time of it is constant $\approx$ 0.3 seconds at a broad frequency region. The same hardware and software as in free field were used in listening room measurements as well. [49]

With blocked ear canals it was possible to perform measurements in normal quiet room acoustics, since the signal-to-noise ratio inside the blocked ear canals was high enough. Hence, most of the blocked ear canal pressure frequency responses (with simulators and live subjects) were obtained in a normal office environment.

5.2 Acoustic properties of open ear canal

Quarter wave resonator

The ear canal, closed at the other end by the eardrum, acts as a quarter-wavelength resonator. The resonance frequencies of an open cylindrical tube, such as the ear canal, are

$$f_n = \frac{nc}{4(L + \frac{8r}{3\pi})} \tag{5.1}$$

where n is an odd number (1, 3, 5...), L is the length of the tube, r is the radius of the tube and c is the speed of sound in air (which is approximately 343 metres per second at 20 °C and at sea level). The resonator produces only odd harmonics and has a fundamental frequency an octave lower than a tube that is open at both ends. At the resonant frequency and its harmonics, a peak in the frequency response of the open cylindrical tube appears. These peaks are strongest at the closed end of the tube and weaken towards the opening of the tube.

From an acoustic point of view a pipe that is open at the other end is longer than its physical length because of the effect of the mass of attached air. The denominator $L + 8r/3\pi$ in Eq. (5.1) constitutes the effective, or 'acoustic' length of the pipe where $8r/3\pi = 0.8488r$ is the 'end correction'. It should be noted that the end corrections depend only slightly on the frequency, which is not included as a variable in Eq. (5.1). [51] [17]

5.2.1 Frequency response at the ear canal entrance

The head related transfer functions are often measured with a microphone at the ear canal entrance, either with a blocked ear canal or with the ear canal left open. With open ear canals the microphone is pushed a few millimetres into the ear canal and with blocked ear canals the measurement point is close to the ear canal entrance. [68] [40]

In order to better understand the behaviour of the frequency responses, or HRTF's, measured at the ear canal entrance, a set of measurement was performed with various measurement setups and equipment. A secondary objective was to give us means to assess the usability of the method of measuring individual HRTF's from the ear canal entrance.

Adecs in free field

When studying the pressure frequency responses of Adecs, the simulator was mounted to a microphone stand (as in Figure 4.5) in the anechoic chamber and pointed towards a loudspeaker at a distance of 2 metres. The frequency responses at different points along the ear canal were measured using the movable eardrum microphone of the simulator.

Transfer functions from loudspeaker to the Adecs ear canal entrance are depicted in Figure 5.4. Three different canal lengths were used, of which one was zero. The peaks of the resonant frequencies of the quarter-wave resonators are still visible (in Figure 5.4 around 3, 4, 10 and 12 kHz) when the response is measured exactly at the canal entrance. In the frequency domain, directly after the peaks follow the anti-resonance notches. The frequencies where these notches are located correspond to the distance between the measurement point and the eardrum, from where the reflected sound wave arrives. The existence of both peaks and notches when the frequency response is measured at the entrance of the ear canal is an indication that the acoustic entrance of the tube is outside of the physical entrance. This 'end correction' phenomenon was described in the beginning of this chapter. The resonant frequency peaks disappear when the measurement point is chosen far enough outside of the canal entrance, and only a small anti-resonance notch remains.

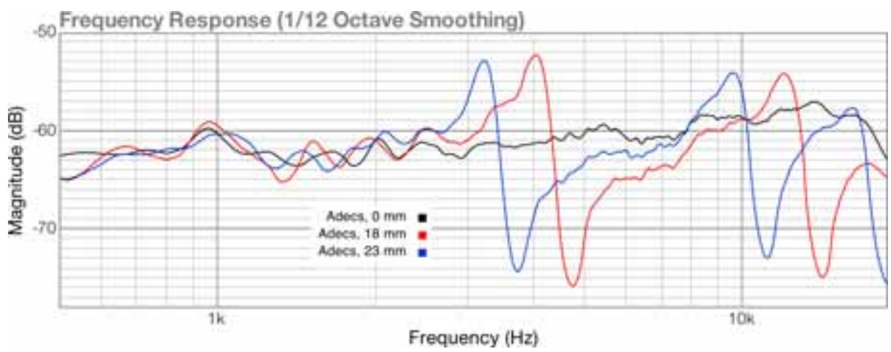

Figure 5.4: Frequency response at the ear canal entrance of Adecs with three different ear canal lengths measured in free field conditions.

We noticed during our research that when frequency responses are measured at the entrance of a straight tube ear canal simulator, such as Adecs, the results are practically unsensitive to the position of the microphone as long as the distance to the eardrum remains the same. In other words, only the position of the microphone in relation to the length of the canal is significant. This is, however, not the case with real ears of human test subjects, as can be found from literature (e.g. [21]).

Adecs with pinna in free field

The effect of the artificial pinna to the pressure at the ear canal entrance was investigated with measurements in free field. The pressure frequency responses were measured with Adecs eardrum microphone with three different ear canal lengths. The effect of only the pinna, without resonances form the ear canal, can be read from Figure 5.5, where the black line represents the case where the canal length is set to zero. The pinna notch around 9 - 10 kHz is clearly visible in all cases. Without the artificial pinna attached, and with ear canal length set to 0 mm, the pressure frequency response was flat.

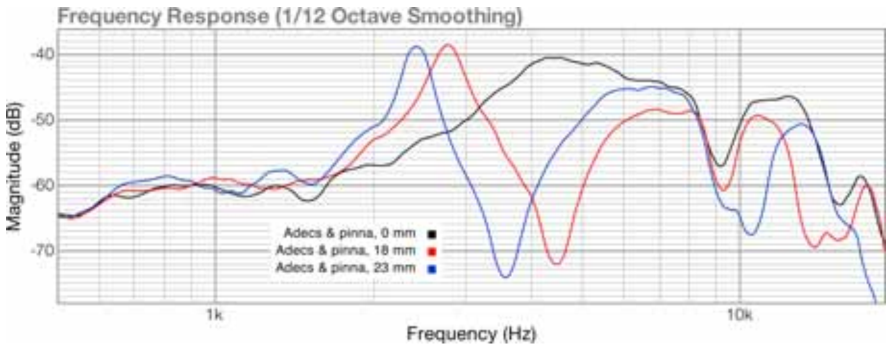

Figure 5.5: Frequency response at the ear canal entrance of Adecs when an artificial pinna is attached to it (only the pinna, as depicted in Figure 4.8). Three different ear canal lengths used in free field conditions.

The total acoustic length of the ear canal is more than the length of the Adecs canal, since the concha de facto lengthens the ear canal by approximately 8 mm. In addition, the acoustic length is more than the physical length due to the end correction phenomena. Hence, the quarter-wave resonance peak is located at frequency given by Eq. (5.1).

In Figure 5.5, with Adecs canal length 23 mm, the quarter-wave resonance is at approximately 2400 Hz given by

$$f = \frac{343\ \mathrm{m/s}}{4{\cdot}(0.023\ \mathrm{m} + 0.008\ \mathrm{m} + 0.8488{\cdot}0.005\ \mathrm{m})},$$

where 0.023 m is the canal length, 0.008 m is the length added by the concha, 0.8448 is the end correction multiplier and 0.005 m is the radius of the canal entrance of the artificial pinna.

Similarly, in Figure 5.5, the frequency of the antiresonance (3570 Hz) is calculated as

$$f = \frac{343\ \mathrm{m/s}}{4{\cdot}(0.023\ \mathrm{m} + 0.001\ \mathrm{m})},$$

where the distance from the eardrum to the microphone is 24 mm (23 mm + 1 mm end correction). This frequency is determined by only the distance from eardrum to the microphone transducer port.

Dadec in listening room conditions

Similar measurements were performed in listening room conditions using the dummy head Dadec with Adecs as ear canal. The pressure was measured at a depth of circa 5 mm inside the Adecs ear canal. The canal entrance of Adecs was circa 5 mm millimetres deeper inside the head than the canal entrance of the artificial pinna. Hence, the microphone was approximately 10 mm inside the open ear canal of Dadec. The pinna made the total acoustic length of the ear canal significantly longer than it would have been without the pinna, which moved the fourth-wave resonance peaks to lower frequencies. The places of the anti-resonance notches, though, were unaffected by the pinna, since they are affected only by the distance between the eardrum and the microphone. Naturally, the acoustics of the room made the pressure frequency responses rugged when compared to responses measured in free field.

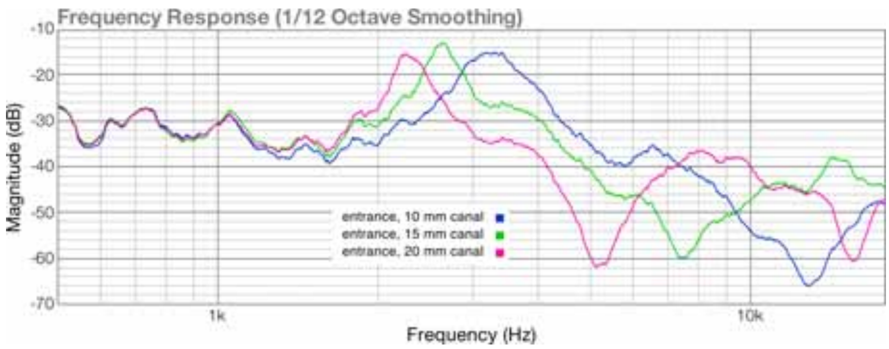

Figure 5.6: Responses at the ear canal entrance of Dadec with Adecs as ear canal. Three different ear canal lengths were used in listening room conditions.

Microphone positioning

When HRTF's are measured at the entrance of the ear canal, the positioning of the microphone has a significant effect on the obtained responses. In order to learn more about this fact we measured the pressure frequency responses in various points at the ear canal entrance of Dadec in the listening room. Figure 5.7 shows the different positions used in this measurement. A loudspeaker was placed at a distance of 1.5 metres from the ear canal entrance. The loudspeaker was pointing towards the ear. The Adecs canal length was set to 14 mm, and the pinna added approximately 8 mm to the total ear canal length. The differences in the measured pressures are outstanding as can be seen from Figure 5.8. With the same insertion depth but with different front-back positions the frequency responses vary greatly from 2.5 kHz upward.

According to Blauert [8] the pressure measured by the microphone depends on where in the modal resonance the microphone is. Dimensions in these modal resonances are small and even a slight change in microphone positioning changes the frequency response exceedingly. [34]

These results encourage us to look with extreme caution at pressure frequency response measurements made at the open ear canal entrance.

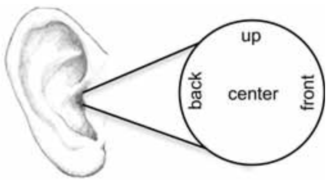

Figure 5.7: Positions of microphone used in Figures 5.8 and 5.10.

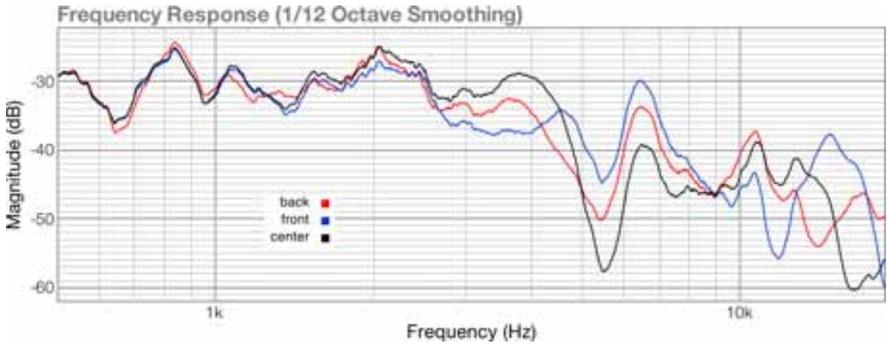

Figure 5.8: Responses at different points at the ear canal entrance. Measurement performed in listening room conditions using the Dadec with Madecs as ear canal.

Responses at canal entrance of real ears

It is common for HRTF's to be measured from the ear canal entrance or from a point inside the ear canal close to the entrance. Also, in earlier studies by e.g. Riikonen et al [53], the pressure frequency response of the open ear canal has been measured by inserting a subminiature microphone [32] into the ear canal, the insertion depth being 5 mm from the ear canal entrance. The goal has been to capture the response at the ear canal entrance and use that response for determining a target response of an insert type earphone. This frequency response, or transfer function, is said to represent the natural listening experience. [53]

Within our research, the same set of measurements was repeated first with three subjects in free field. The Knowles miniature omnidirectional microphone was placed at the subjects' ear canal entrances and a sine sweep signal was played using a loudspeaker. The speaker was located at approximately 2 m from the test subject and it was directed so that the subject's open ear canal was facing the speaker. To remove the loudspeaker's and the microphone's responses from the result, the measurement recordings have been edited in FuzzMeasure by subtracting the frequency responses of the microphone and the loudspeaker (in free field) from the measured ear canal responses. The obtained pressure frequency responses are depicted in Appendix B in Figures B.1, B.2 and B.3. The differences in the individual ear canal frequency responses were of great interest as we aimed to better understand the acoustics of the ear canal.

What can be seen from Figures B.1 and B.2 is the quarter-wave resonance of the open ear canal, which is normally located in the area of 3 kHz for an ear canal with physical length of 26 mm. The acoustic length (with end correction) of such an ear would be circa 29 mm. The quarter-wave resonant frequency peak is not at all pronounced in the frequency response graph of Subject 3 (Figure B.3).

What cannot be measured from the ear canal entrance is the spectrum of the sound as it appears at the eardrum. The variation in sound transmission from the entrance of the ear canal to the eardrum from subject to subject can for certain frequencies be as much as 20 dB. [20]

5.2.2 Frequency responses along the canal

Responses along the canal: real ears

The frequency responses at different points in the ear canal were also measured using one test subject. The same setup as above was used with the exception that the responses were measured with the microphone inserted at different depths into the ear canal. The measured frequency responses are depicted in Figure 5.9.

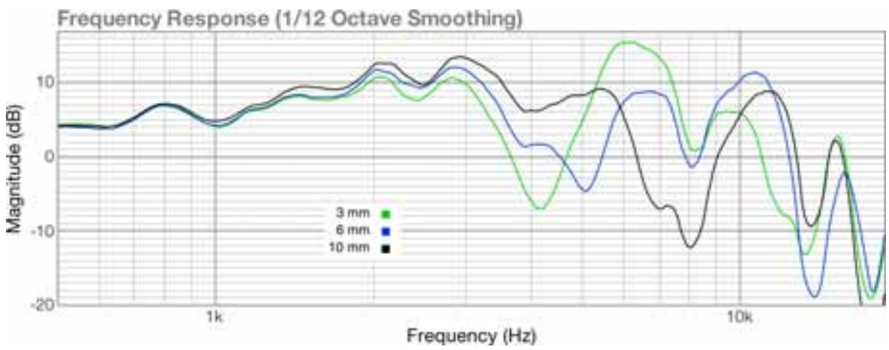

Figure 5.9: Responses measured from the open ear canal of Subject 1 with three different microphone insertion depths inside the ear canal in free field conditions. The measuring points are 3 mm, 6 mm and 10 mm from the ear canal entrance towards the eardrum.

In these measurements a miniature microphone was inserted into the ear canal of the test subject. With this setup it was impossible to monitor the exact positioning and insertion depth of the microphone. In addition, the position of the subject's head was not constant. The used microphone was omnidirectional, which means that the angle of the microphone in relation to the ear canal was inconsequential and only the position of the microphone was relevant to the result.

Even very small variations in the position of the inserted microphone cause great differences in the measured frequency responses, since the locations (in frequency domain) of notches are directly dependent of the distance between the microphone and the eardrum. Very close to the horn-like canal entrance the sound wave is not a simple plane wave, which gives cause to variations in the frequency response from the overall position of the microphone and not only the distance between eardrum and microphone.

It is well known that in the ear canal the sound signal already contains all directional information that is gathered from the room, torso, head and pinna. The ear canal may alter the sound differently at different frequencies, but it does so independently of the direction from which the sound has arrived. Literature from e.g. Møller [40] [39] rest on the assumption that the overall frequency response does not affect the way sound object locations are perceived and that only relative differences in frequency response are important. Hence, if we are interested only in the differences between direction-dependent HRTF's, a method with a microphone in the ear canal can be a reliable and functional method. Studies by Griesinger [20], though, suggest that the individual HRTF's should be measured at the eardrum even for localization purposes. Measurements from the eardrum are more reliable than those from close to the canal entrance because of their reproducibility. Varying microphone positioning cause differences between individual measurements when the measurement point is close to the canal entrance. There differences do not occur when the measurement point is close to the eardrum.

Frequency responses along the canal: simulators

When the pressure frequency response is measured deep enough inside the ear canal the above mentioned variations diminish and only the distance to the eardrum is significant. As a demonstration of this phenomenon, we measured the frequency responses deep inside the Dadec ear canal by inserting a microphone into the canal. The microphone was kept at constant distance from the eardrum, but the horizontal position and elevation was varied. As can be seen from Figure 5.10, the obtained responses are similar with all four different measurement points.

Hence, if frequency responses are to be measured from the ear canal, it would be recommendable to place the microphone deep enough into the canal where the sound wave acts like a plane wave. A 'safe' insertion depth is at least the diameter of the ear canal. In addition, if comparison between different individuals is to be done, the microphone should be placed at the same distance from the eardrum of each subject measured, since different insertion depths give different notch locations.

The position of the eardrum microphone of the adjustable ear canal simulator (Adecs) can be set to whatever chosen distance from the eardrum towards the ear canal entrance as described in Chapter 4.1.4. The frequency responses along the Adecs 'ear canal' were measured by moving the microphone tip with 1 mm steps from the eardrum towards the entrance and beyond as far as 15 mm outside the canal entrance. The effect of the position of the microphone was

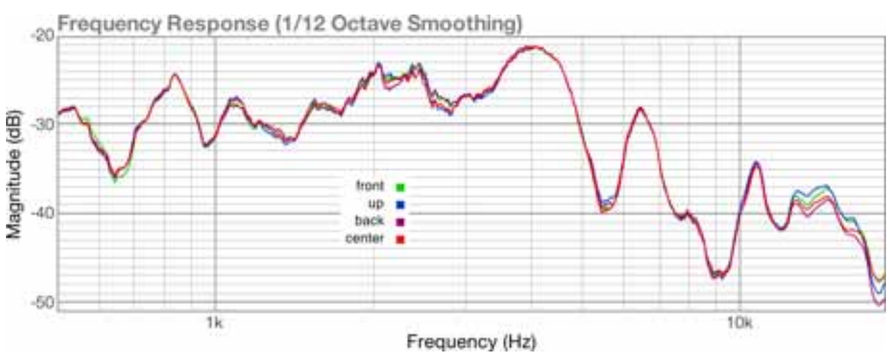

Figure 5.10: Effect of microphone position inside the ear canal. Measurement performed in a listening room using Dadec with Madecs as ear canal.

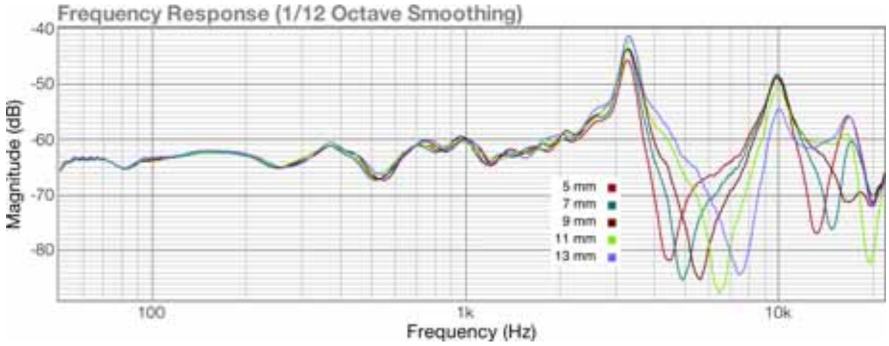

Figure 5.11: Responses measured in free field along the ear canal of Adecs by adjusting the position of the microphone. The canal length is 23 mm and the microphone positions are 5, 7, 9, 11 and 13 mm from the ear canal entrance.

investigated in free field conditions with different canal lengths. The loudspeaker was positioned in front of Adecs at a distance of 2 metres. In Figure 5.11 the responses along the Adecs canal are depicted. The resonant frequency peaks of the quarter wave resonator remain in the same positions independent of the microphone position, but the locations of the antiresonance notches depend on the distance between the eardrum and the microphone.

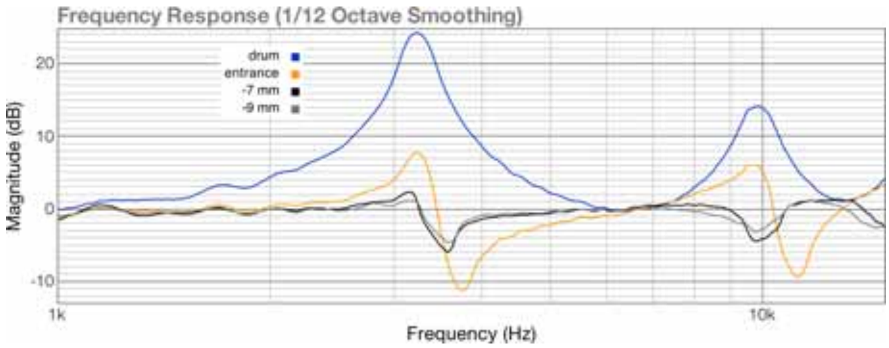

Figure 5.12: Responses measured in free field along the ‘ear canal’ of Adecs while adjusting the position of the microphone. The canal length is 23 mm.

In Figure 5.12 the microphone is pushed far enough outside of the canal entrance of Adecs to allow the peak of the resonant frequency to fade out. The other measurement points are at the eardrum and at the ear canal entrance. Obviously the terms ‘acoustic length’ and ‘end correction’ do not imply that at a distance of the end correction outside of the canal, there is an exact location, where the resonance peak and antiresonance notch disappear. According to Eq. (5.1), the acoustic length of Adecs is approximately 4 mm more than its physical length. At a distance of 7 mm from the ear canal entrance, the resonances are still visible though.

A similar study in free field was performed with Adecs when an artificial pinna was attached to it as depicted in Figure 4.8. The measurement points along the canal were at the eardrum; 11 mm inside the canal; at the entrance and 11 mm outside the canal (inside the concha). The peak in the resonant frequency at 2.4 kHz remains at a constant position and it is strongest at the eardrum. In addition, there are no notches at the eardrum. What should also be noticed from

Figure 5.13 is that the resonant frequency peak is visible even when the tip of the microphone is pushed as far as 11 mm outside of the ear canal. This suggests that the resonant frequency of the ear canal can be found with measurements from outside the ear canal entrance. The situation is, however, not that straightforward with live subjects as was discussed in Chapter 5.2.1.

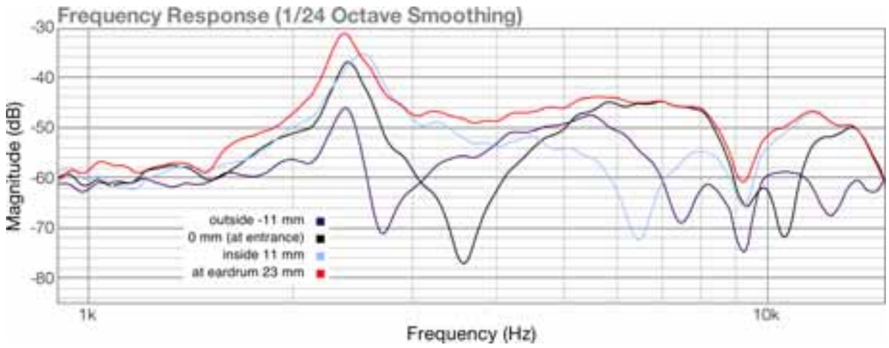

Figure 5.13: Responses measured in free field along the 'ear canal' of Adecs by adjusting the position of the microphone. The canal length is 23 mm and an artificial ear is attached to the canal entrance.

5.2.3 Frequency response at the eardrum

Adecs in free field

When a sound wave enters a tube that is closed at the other end, the sound pressure has its maximum at the closed end [17]. Antiresonance notches do not exist at the closed end, as in other parts of the tube. The pressure peaks of the resonant frequencies of the quarter-wave resonator tube are however pronounced at the closed end. The Adecs was used to study the behaviour of the resonant frequency peaks as the length of the 'ear canal' changes. In an anechoic chamber the length of the Adecs canal was adjusted with 1 mm steps from 0 to 30 mm while the pressure frequency responses were measured with the eardrum microphone. Some examples of these responses are depicted in Figure 5.14. The location of the quarter-wave resonances can be calculated with Eq. (5.1).

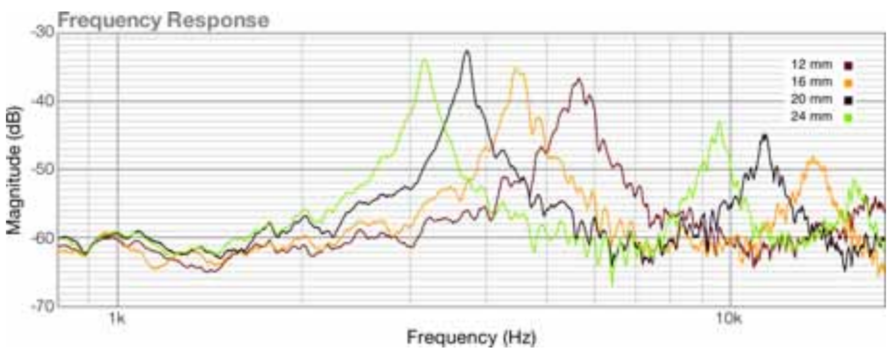

Figure 5.14: Pressure frequency response at the eardrum of Adecs with different ear canal lengths in free field conditions.

With a canal length of 24 mm and canal diameter of 8.8 mm, the calculated resonance frequency is at 3.09 kHz, which is close to the measured value 3.17 kHz. If we calculate the acoustic length based on the resonance frequency, we obtain a length of 23.3 mm for the '24 mm' canal. 9.6 kHz and 16 kHz are the measured frequencies for the second and third resonances. These too correspond well to Eq. (5.1) as we can calculate these by multiplying the first resonance frequency with 3 and 5.

Dadec with Adecs in listening room

The custom-made dummy head Dadec was first used for measuring simultaneously the pressure frequency responses at the eardrum and the ear canal entrance. In listening room conditions, the Dadec was placed at a distance of 2 metres from a loudspeaker. The eardrum responses were measured with the Adecs eardrum microphone. An additional miniature microphone was fitted 5 mm inside the ear canal. This location is, however, farther away than 5 mm from the acoustical entrance of the canal. The concha and the end correction effect cause the 'real' entrance to move outwards by several millimetres. Based on the quarter-wave resonance, in this measurement, the concha and the end correction added 17 mm to the acoustic length of the ear canal. This result was invariable with all the different canal lengths (of Adecs) used in this measurement.

The responses were measured with different ear canal lengths with intervals of 1 mm. The obtained pressure frequency responses at both ends of the tube, with canal length 20 mm is depicted in Figure 5.15. Additional results can be found in Appendix B in Figures B.5 and B.6. The responses are similar from low frequencies up to the first fourth-wave resonance. The pressure at the eardrum then drops gradually towards higher frequencies. The pressure at the entrance, though, drops rapidly towards the first antiresonance notch. The peak at the first fourth-wave resonance and the notch at the antiresonance are both very sharp. This characteristics gave reason to develop an eardrum for the simulator that would behave more like a real human eardrum, which softens the resonance and antiresonance peaks significantly.

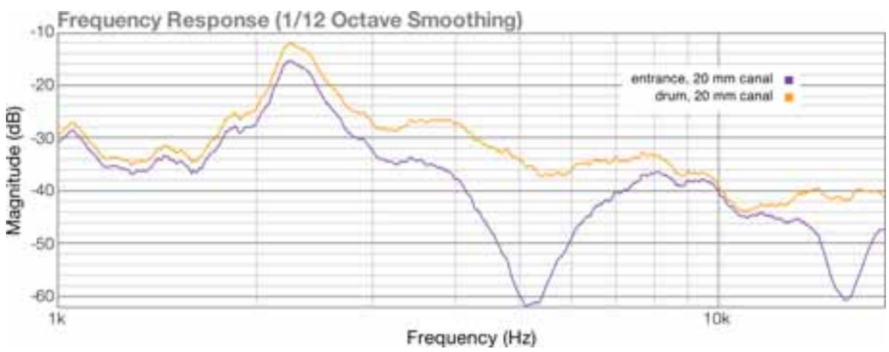

Figure 5.15: Frequency response at ear canal entrance and the eardrum measured using Dadec with Adecs as ear canal in listening room conditions.

Dadec with Madecs in listening room

The new multi-adjustable ear canal simulator (Madecs), with a damped eardrum, was manufactured as we wanted to obtain frequency responses that are close to those measured with human subjects. When finished, the Madecs was fitted to the dummy head Dadec. To investigate responses at the eardrum of Dadec with Madecs as ear canal in listening room acoustics a new set of measurements was performed.

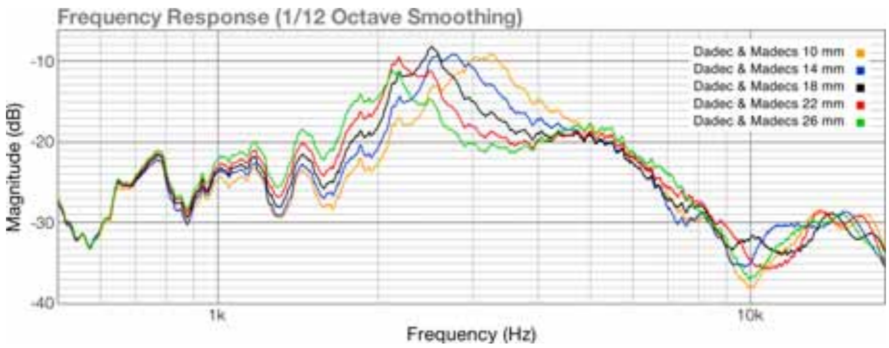

Figure 5.16: Responses with various ear canal lengths measured at the eardrum of Dadec (with Madecs as ear canal) in the listening room.

The Dadec was placed directly facing (θ = 0) a loudspeaker at a distance of 180 cm. The pressure frequency responses at the eardrum are depicted in Figure 5.16. Compared to previous measurements with Adecs, the quarter-wave resonant frequency peaks are significantly softer. This effect is caused by the damped eardrum of Madecs.

During the measurement two different ear canal simulators were attached to the Dadec, of which Madecs was the primary simulator, whereas Adecs was used mainly for reasons of comparison with Madecs but also for measuring the differences between pinna's of different sizes. The pressure frequency responses were recorded with the eardrum microphones of Adecs and Madecs, which were sequentially attached to Dadec. Responses obtained using the Adecs as ear canal are depicted in Figure 5.17.

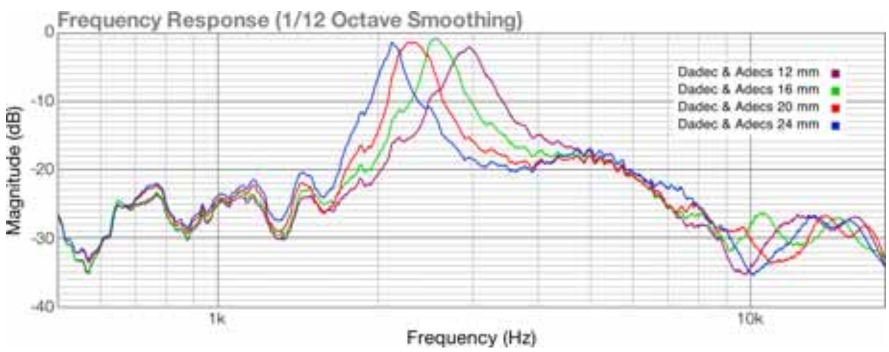

Figure 5.17: Dadec (with Adecs as ear canal) in listening room acoustics with different ear canal lengths. Frequency responses measured at the eardrum.

Dadec in free field

The Dadec was also used for studies of the frequency response at the eardrum in free field conditions. The impedance of Madecs was adjusted to significantly damp the frequencies between 1 kHz and 3.5 kHz before mounting the simulator to the dummy head. In an anechoic chamber, the angle between the head's median plane and the loudspeaker (azimuth angle) was set to 30 °. Again, the influence of the canal length on the responses at the eardrum was measured. The peak of the quarter-wave resonance frequency is apparent, but there is another peaking with constant frequency at 4.8 kHz, which is caused by the boosting effect of the pinna, as can be observed from Figure 5.18. Compared to responses in a listening room, the effect of the pinna and the ear canal are more pronounced in free field measurements. When no reflections exist, other than those of the head and pinna, the effect of individual dimensional variations become more apparent.

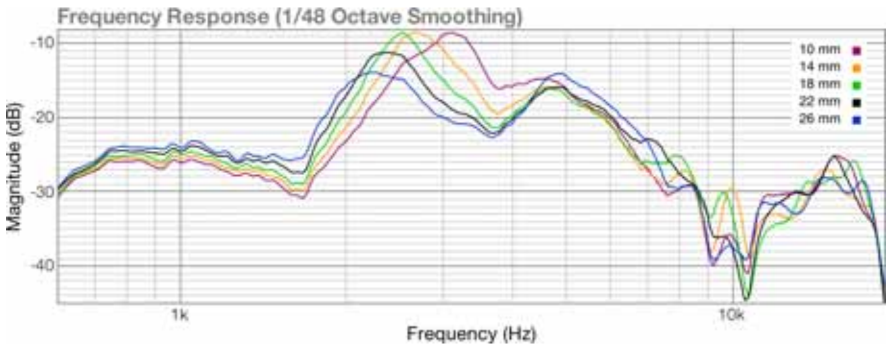

Figure 5.18: Dadec with Madecs as ear canal, in free field, with different ear canal lengths. The head is facing the loudspeaker with an azimuth angle of 30 °. Frequency responses measured at the eardrum.

Measurements at the human eardrum

The transfer function from the loudspeaker to the eardrums of a live subject (Subject 1) with one sound source direction was measured. The setup was identical to that of the preceding measurements setup with Dadec in listening room conditions, only that responses from both left and right ears were measured. A loudspeaker was placed at a distance of 1.8 metres form the listener (with azimuth angle of 0 °). A miniature microphone was inserted into the ear canal and moved very close to the eardrum, without touching it (the test subject performed the insertion by his own hands). The position of the microphone was kept stable while the logarithmic sine sweep was played with the loudspeaker. Pressure frequency responses from the eardrum were thus obtained using the inserted microphone.

The obtained responses in Figure 5.19 show the quarter-wave resonance at approximately 2.2 kHz with both ears. The pressure then drops uniformly. The effect of the pinna increases the pressure between 3 kHz and 7 kHz and the lowers it between 8 kHz and 10 kHz. The differences between the two ears at frequencies above 10 kHz are related to the curvature and overall shape

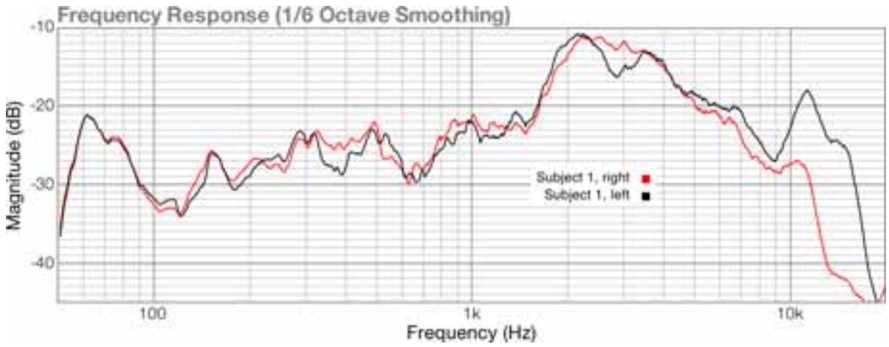

Figure 5.19: Frequency responses measured close to the eardrums of Subject 1 in listening room conditions.

of the subject's ear canals, where the more curved right ear canal causes the pressure to drop more compared to the straighter left ear.

The responses measured at the eardrum of Subject 1 Figure 5.19 are much like those measured with Dadec (Figure 5.25) with the same measurement setup. The Dadec with Madecs as ear canal hence models the human peripheral hearing fairly accurately.

5.2.4 Effect of different outer ear shapes

As mentioned in previous chapters, the length of the ear canal has a strong effect on the pressure frequency response at the eardrum, as well as at the ear canal entrance. The other parts of the outer ear also have individual differences. A large amount of measurements was performed to study as to how significant the other physical variations are to the frequency responses.

Effect of the shape of the pinna

Three different fabricated pinnas were attached to Dadec with Adecs as ear canal in order to investigate the effect they had to the pressure at the eardrum. In addition to the rubber-made pinna used in most measurements, two larger pinnas (big ear and cuplike ear) were used (see Chapter 4.1.6). In a listening room, a loudspeaker was placed in front of the Dadec (azimuth angle 0 °), at a distance of 1.8 metres. The pressure at the eardrum was measured while a sine sweep signal was played with the loudspeaker. The effect of the two large ears were measured using an Adecs canal length of 22 mm. Due to different attaching mechanisms, the acoustic length of the pinna plus ear canal was shorter with the larger pinnas compared to the small rubber pinna. Therefore, to obtain the same acoustic length with all ears, the rubber pinna was measured using a Adecs canal length of 12 mm (instead of 22 mm).

The frequency response curves in Figure 5.20 show that below 2 kHz the larger pinnas increase the pressure at the eardrum when compared to the smallest pinna. The pinna notch is clearest with the small 'rubber ear'. The overall differences in the obtained frequency responses are not striking considering the huge differences in the physical sizes of the pinnas. The differences between sizes and shapes of normal human pinnas are much smaller.

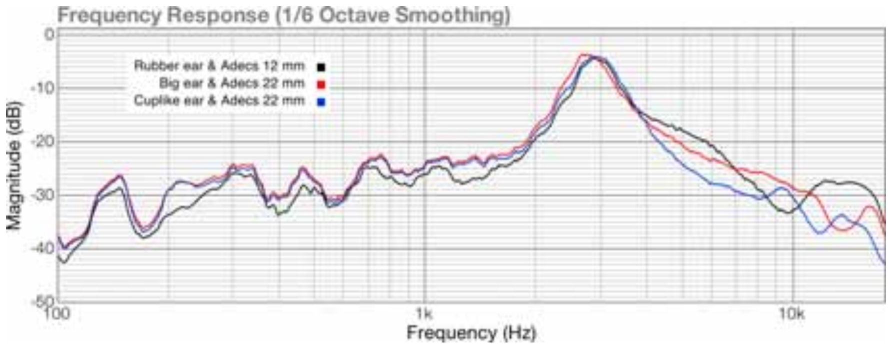

Figure 5.20: The effect of the size and shape of the pinna. Three different fabricated pinnas attached to Dadec with Adecs as ear canal. Responses measured from the eardrum of Adecs.

Effect of canal shape

Ear canals are often modelled as straight rigid wall tubes. Since the wavelengths of audible sound waves are greater than the diameter of the ear canal, we may consider the sound waves travelling only in the direction of the canal. No standing waves arise in cross-canal direction. The situation does not change much if the canal is slightly bended along its length - the sound wave 'sees' the canal as a straight tube and propagates towards the eardrum despite the curvature. The shape of the canal has, however, influence on the frequency response of the canal.

One of the most common reasons for different frequency responses of open ear canals is variable shape of the ear canal entrance. We define these variation as being related to the effect of the pinna and not the ear canal.

The effect of ear canal curvature was studied by measuring responses from the eardrum of different tubes in free field. A tube with length of 30 mm and diameter of 8 mm was first compressed in the middle part and the obtained response was compared with that of the uncompressed version. The compressing effectively decreased the canal diameter to 6 mm in the middle part of the canal. The effect of this procedure is depicted in Figure 5.21. Below 7 kHz, the compressing boosts the sound, whereas from 7 kHz to 13 kHz the effect is opposite.

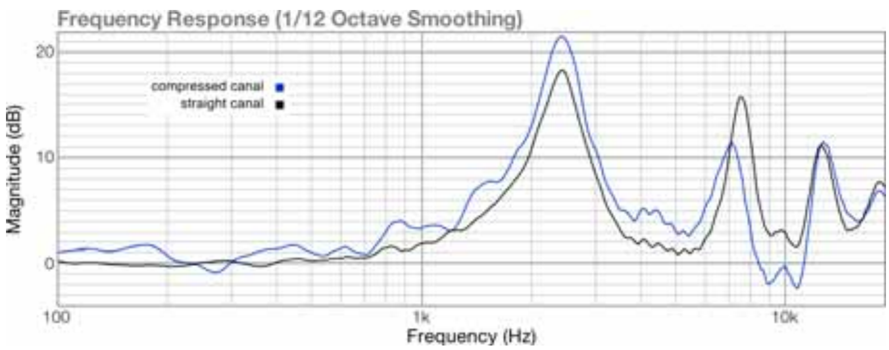

Figure 5.21: The effect of the shape of the ear canal. Responses measured at the eardrum in free field conditions with open ear canal.

In addition, the mentioned straight tube was bended to form a sheer 70 ° angle in the middle part. The bending caused also a partial blocking halfway of the canal. There are hardly any ear canals with a shape of this kind, but the effect of a violent deformation such as this gives further understanding of the acoustic behaviour of the ear canal. The frequency responses obtained from the eardrums of the straight and bended tubes are depicted in Figure 5.22. The response curves have nothing in common above 2 kHz and there is a remarkable attenuation from 5.5 kHz upwards. As a general interpretation one might conclude that the more curved the ear canal the more it attenuates high frequencies.

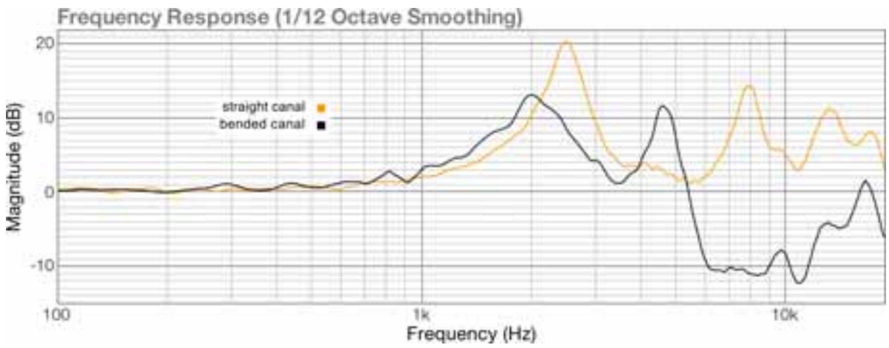

Figure 5.22: The effect of the shape of the ear canal. A straight tube and the same tube bended in the middle produce very dissimilar frequency responses. Responses measured in free field. The tubes have equal length (30 mm) and equal diameter (8 mm).

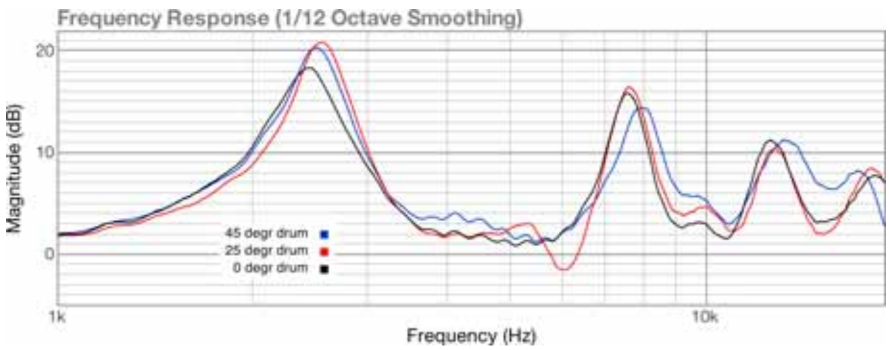

Figure 5.23: The effect of the angle of the eardrum in relation to the ear canal. The frequency responses of three tubes with different angles of the ear canal measured in free field conditions.

As a third dimensional property the angle of the eardrum in relation to the ear canal was investigated. For this study three similar tubes with three different eardrum angels were used (0 °, 25 ° and 45 °), of which the tube with eardrum angle 45 ° represents the normal human ear canal. The tubes had equal length (30 mm) and equal diameter (8 mm). All of the eardrums were made of aluminium and they had a miniature microphone fitted into the centre.

The pressure frequency responses at the eardrums of these simulators were measured in free field. The obtained responses are depicted in Figure 5.23. The difference in the responses between the 'normal' (45 °) eardrum and the straight (0 °) drum are significant above 2.2 kHz. Hence, in the development of ear canal simulators this property should be taken into account.

Effect of the head

The size of the head is an important factor in sound source localization as it determines the interaural time difference. The effect of the size and shape of the head to the HRTF was investigated with measurements in listening room conditions. The frequency responses from the ear canal entrance and the eardrum of a Dadec with Adecs as ear canal were measured, while the 'shape' of the head was altered. First, we studied the effect of added reflecting objects. Compared to the 'normal head' the altered version had a book on top of the head, which acted as a reflector. The loudspeaker was placed at a distance of two metres from Dadec with an azimuth angle of 30 °. The measured frequency responses in Figure B.4 (Appendix B) show that the added reflecting object had little effect on the pressure at both the ear canal entrance and at the eardrum. The variations related to the pinna, as discussed above, are significantly more pronounced.

In addition, the effect of a big cap with fillings, which in practice increased the diameter of the head by three centimetres, was measured. The cap was placed deep enough to cover the eyes of Dadec. In a listening room, Dadec was first facing the loudspeaker, an in the second measurement, the head was turned to a lateral angle of 90 °. As can be observed from Figure 5.24, once again, the variations had little effect on the frequency responses measured at the eardrum.

A study by Riederer [52] showed somewhat similar results, when the effect of added headpieces was investigated. With a baseball cap on top of a dummy head and with azimuth angles near the (contralateral) interaural axis (60 ° - 120 °) only moderate effects were found. Reflecting objects around the head are an important factor as to direction-dependent HRTF's. In our research though, the focus was on direction-independent spectral shaping characteristic of the outer ear.

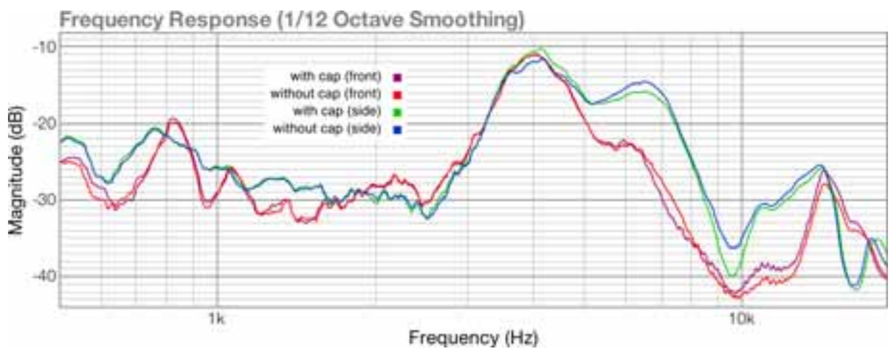

Figure 5.24: In listening room conditions, the responses measured first with Dadec wearing a cap with fillings and then without the cap. Frequency responses measured at the eardrum with a canal length (Madecs) of 7 mm. Two azimuth sound source angles (from the side and from the front) were used.

From these results we conclude that of all the different properties of the outer ear and the head, the shape and length of the ear canal are the most important factors in determining the pressure frequency responses at the ear canal entrance and at the eardrum.

5.2.5 Effect of drum impedance

The eardrum is not a rigid straight wall at the end of the ear canal. It participates in the shaping of the pressure frequency response of the ear canal in a complex way. The effect of the eardrum was studied using simulators and live subjects.

Simulator eardrums

With the unblocked ear canal, in the listening room, the effects of variable eardrum impedances were studied. The comparison was made between Adecs, which has an undamped eardrum (see: 4.1.4) and Madecs, with a damped eardrum (see: 4.1.5). Each simulator was mounted to Dadec consecutively.

Comparison between the frequency responses of the two different ear canal simulators when they are attached to Dadec in similar listening room environments is shown in Figure 5.25. There is a significant difference in the responses measured with each of the eardrum microphones. The damping effect of the Madecs eardrum is clear at the resonant frequencies of the ear canal, where the eardrum attenuates the peak of the resonant frequency by 6 to 10 dB. The damping is not at all significant at other frequencies, hence the eardrum decreases the Q factor of the oscillating ear canal.

The responses are measured at the eardrums of both simulators when the measurement signals were played with a loudspeaker at a distance of 180 cm and azimuth angle of 0° in a listening room.

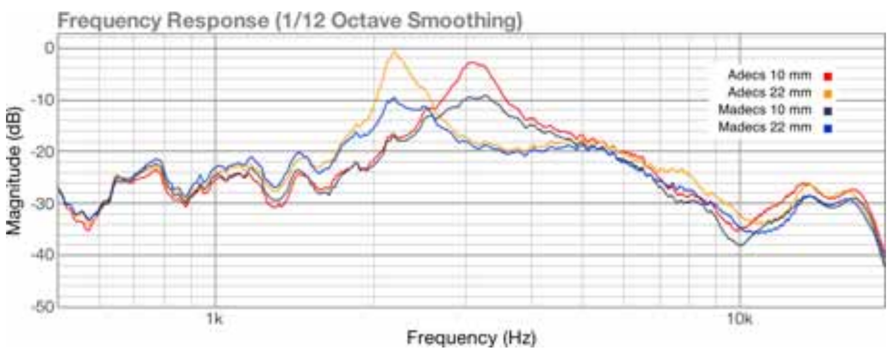

Figure 5.25: The effect of the eardrum. Responses measured with the eardrum microphones of Adecs and Madecs when mounted to Dadec in the listening room. Canal lengths set to 10 mm and 22 mm.

Real eardrums

Numerous studies have been performed to determine the impedance of the human eardrum. Measuring the impedance of the human eardrum is not an easy task and means to change the impedance are limited.

The stapedius reflex changes the impedance as the malleus pulls the eardrum inwards and makes the drum stiffer. Another way to stiffen the eardrum is to add pressure into the tympanic cavity. Blowing air from the lungs into the nasal cavity, and simultaneously blocking the nostrils, causes the additional pressure to expand from the nasal cavity to the tympanic cavity through the Eustachian tube. This pressure pushes the eardrum outwards and stiffens it significantly.

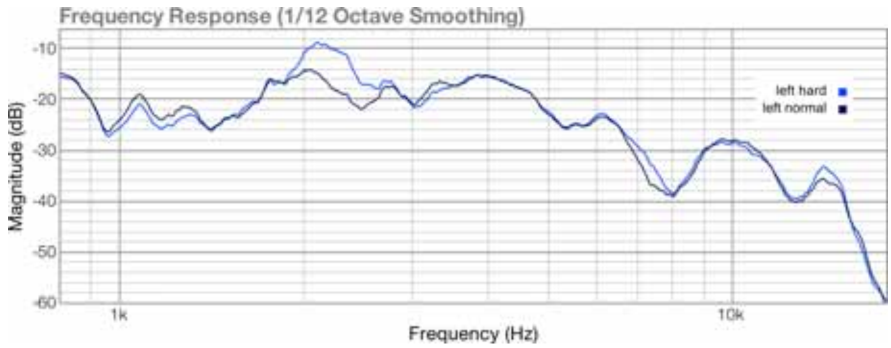

Figure 5.26: Frequency responses at the eardrum when measured in normal circumstances and with additional pressure in the tympanic cavity. The response is measured from the left ear with azimuth angle 0 ° in listening room conditions.

The effect of the impedance of the human eardrum to the frequency response measured in front of it was studied. The responses at the eardrum were measured in normal circumstances, and then with additional pressure in the tympanic cavity. A miniature microphone was inserted into the ear canal of a human test subject and moved very close to the eardrum. The frequency responses were measured from both ears of Subject 1 in a listening room. The test was performed with sound source azimuth angles 90 ° and 0 ° for both ears, in the listening room, and with a loudspeaker approximately 1.5 metres from the ear. The responses from the left ear are depicted in Figure 5.26

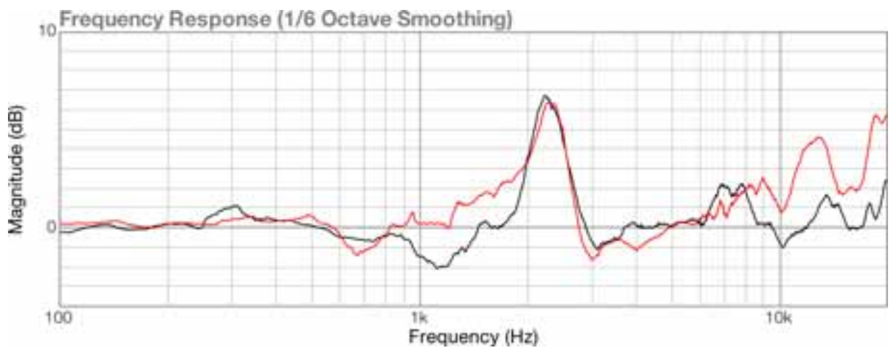

Figure 5.27: Difference between frequency responses at the eardrum when measured in normal circumstances and with additional pressure in the tympanic cavity. Red curve represents the right ear with azimuth angle 90 ° and the black curve represents the left ear with azimuth angle 0 °.

The differences in the obtained frequency responses are depicted in Figure 5.27. The pressurized tympanic cavity raises the Q factor of of the ear canal and amplifies the first quarter-wave resonance peaks by 6 dB. It might be worth mentioning, that the difference is the same as when Adecs and Madecs eardrums were compared (see Chapter 5.2.5 and Figure 5.25). Hence, the stiffened human eardrum behaves much like a rigid ear canal termination and at the same time, the damped eardrum of Madecs behaves much like a normal human eardrum.

5.2.6 A computational model

As discussed in Chapter 4.2.1, the acoustic behaviour of the ear canal can be modelled using lumped elements and transmission line models. In order to compare obtained measurements with a computational model the Adecs was modelled based on its physical parameters. The modelling was made with Matlab and it consisted of a straight rigid wall tube with a rigid eardrum. The length of the tube was set to 23 mm and the diameter to 8.5 mm. The impedance of the eardrum was set to $4 \times 10^8\ \Omega$, which represents a purely resistive impedance. The frequency responses at the canal entrance and at the eardrum were calculated by first modelling the ear canal as a lossless transmission line using the Equations from (4.5) to (4.16). The ear canal entrance quantities were determined, which were used to calculate the canal entrance to membrane pressure transmission. The loudspeaker together with the canal entrance were modelled as a sound source with radiation impedance, and the source to canal entrance pressure transmission was determined. Thereby it was possible to calculate the normalized canal entrance pressure and the normalized membrane pressure. The resulting frequency response curves are depicted in Figure 5.28. [31]

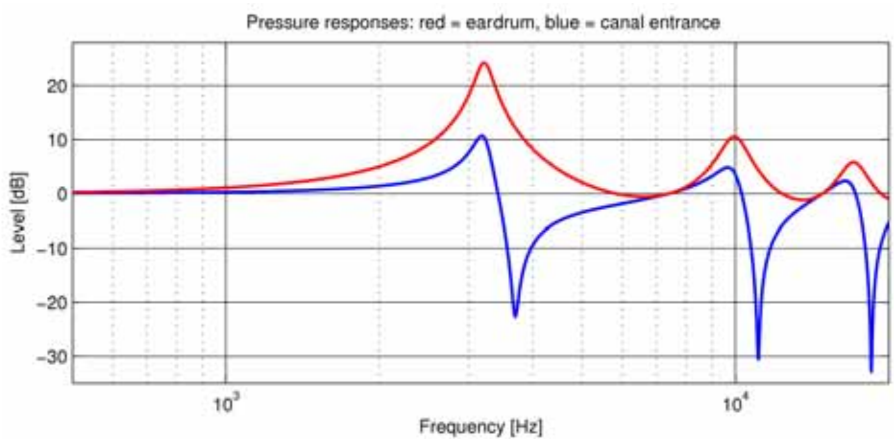

Figure 5.28: Computational ear canal model with canal length of 23 mm in free field. The blue line is the computed response from the canal entrance and the red line is the computed eardrum response.

The modelled responses are very similar to those measured with open Adecs in free field. The free field response curves were however more rugged compared to the computational model. An additional measurement with Adecs in free field was performed in order to obtain as smooth response curves as possible. By averaging several consecutive measurement sweeps and subtracting the microphone and loudspeaker frequency responses from the results, fairly smooth response curves were obtained as depicted in Figure 5.29. It should be noted that no additional smoothing has been applied to Figure 5.29. As presented in Chapter 5.1.1, most of the response curves from open ears or simulators in this work have been smoothened in FuzzMeasure.

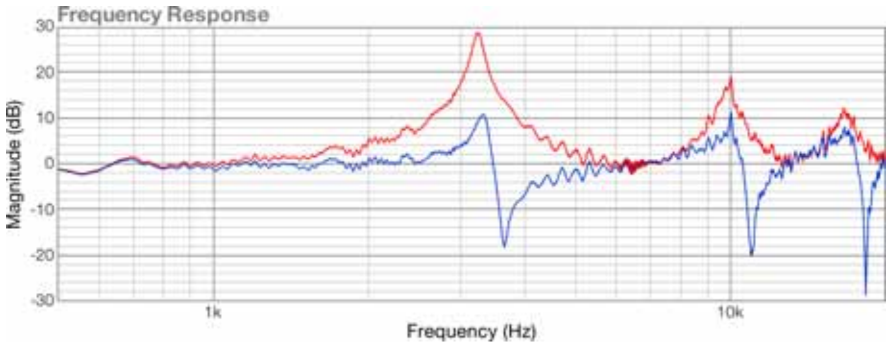

Figure 5.29: Adecs with canal length of 23 mm measured in free field. The blue line is the response from the canal entrance and the red line is the eardrum response.

The used computational model was very accurate. The modelled and the measured frequency responses are identical except for the magnitude of the peaks and notches, where there are differences of a few decibels.

5.3 Acoustic properties of blocked ear canal

Compared to normal listening conditions with unblocked ear canal, the acoustic behaviour of the ear canal is very different when it is blocked with e.g. an insert earphone. All of the outer parts of the auditory system act together to form the total transfer function when the signal is played with a loudspeaker. In a listening room, with the ear canal left open, also the acoustics of the room is shaping the frequency response of the system, that is, shaping the transfer function from loudspeaker to eardrum. When listening to e.g. music with an insert earphone the effects of the head, shoulders, pinna and concha are cancelled and only the acoustic properties of the ear canal are of significance. Nevertheless, the outer parts of the outer ear are important in shaping the way we are used to hearing external sound sources, and they should therefore not be completely forgotten when contemplating the acoustics of the occluded ear canal.

The behaviour of the blocked ear canal was studied through extensive measurements with both simulators and human test subjects. One of the most important characteristics of the ear canal is its length, the effect of which was in the centre of our research. In addition, the effect of the impedance of the eardrum was studied with simulators and a human test subject. Furthermore, the effect of ear canal curvature was investigated briefly.

An important device used was the custom-made earphone with fitted in-ear microphone, which was presented in Chapter 5.1.2. Earlier studies on the behaviour of the blocked ear canal have been made mostly related to fitting of hearing aid apparatus (see [15] and [56]). The goal of our research was to improve our knowledge of the behaviour of the ear canal when an insert earphone is used for e.g. music listening.

Half-wave resonator

In Chapter 5.2 we discussed the properties of the open ear canal and concluded that it acts like a quarter-wave resonator. The resonant frequencies of the open ear canal are more or less pronounced depending on room acoustics, location of the sound source and the shapes of the pinna and the ear canal. The pressure maximum is at the eardrum and there is a pressure minimum at the acoustic entrance of the ear canal, as presented in Chapter 5.2.2. The sound pressure level at the eardrum is highest around the quarter-wave resonant frequency in both free field and a listening room and with different angles between the head and the loudspeaker.

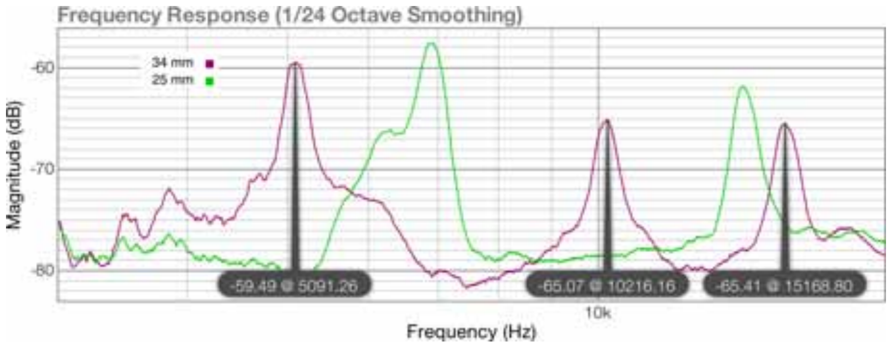

Figure 5.30: A tube closed at both ends is a half-wave resonator.

An ear canal blocked at each end could by intuition be modelled as a tube closed at both ends. E. Vente concluded in 1932, that if a tube is blocked at both ends, symmetry is restored with opportunity for vibrations in the complete harmonic series [66]. In consequence, the canal would also behave as a half-wave resonator when the canal entrance is blocked. This would most certainly be true if the ear canal was blocked with a rigid plug and the eardrum was stiff as well. When we study the behaviour of the blocked ear canal, the ear canal entrance is normally blocked with an earphone or a hearing aid. Hearing aids and earphones are not rigid plugs, but instead they have finite acoustic impedances.

A brief investigation was conducted in order to clarify the half-wave resonator issue. First, two rigid wall plastic tubes with diameter of 8.5 mm and lengths of 25 mm and 34 mm were blocked at both ends with stiff plugs. The tubes were then placed in front of a loudspeaker and a sine sweep was played. The amount of conduction through the plastic walls was enough to produce standing waves inside the tubes. The frequency responses inside the tubes were measured from one end of the tube using the piston (eardrum) microphone of Adecs. This measurement showed that indeed, the tube behaved as half-wave resonator as can be observed from Figure 5.30. The resonant frequencies are

$$f_n = \frac{nc}{2L} \tag{5.2}$$

where n is a positive integer (1, 2, 3...) representing the resonance node, L is the length of the tube, r is the radius of the tube and c is the speed of sound in air (which is approximately 343 metres per second at 20 °C and at sea level). With a canal length of 34 mm, this equation gives resonant frequencies at 5 kHz, 10 kHz and 15 kHz, which are very close to the results obtained from the measurements.

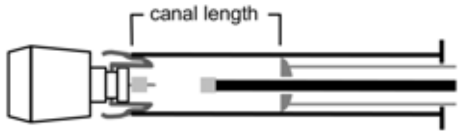

Figure 5.31: Diagram of measurement setup where Efim is fitted to Adecs and the eardrum microphone is moved towards the earphone.

A similar test was made with an earphone (Efim) blocking the tube at the other end as depicted in Figure 5.31. The system did not behave similarly to the tube blocked at both ends as can be seen from Figure B.7 in Appendix B. The resonance of the earphone (around 6 kHz) appears as an additional peak in the frequency response. Secondly, the earphone end of the tube is not a straight termination, instead there are several surfaces at different locations from where the sound pressure wave can reflect. Thus, an ear canal blocked with an insert earphone does have some of the characteristics of a half-wave resonator, but it is not purely that. The impedances of both the earphone and the eardrum should be taken into account.

With a 67 cm long tube, though, the half-wave resonator characteristics are clearer. The system with Efim blocking the entrance of the tube has resonance frequency peaks at locations that can be calculated with Eq. (5.2), as Figure B.8 in Appendix B shows.

During our research, several measurements were performed with Efim mounted to an ear canal simulator and the pressure frequency responses were captured with the in-ear microphone of Efim. These measurements showed an antiresonance notch around 2-3 kHz, as mentioned earlier in Chapter 4.1.5. A half-wave resonator tube has an quarter-wave antiresonance at

$$f_n = \frac{nc}{4L} \tag{5.3}$$

where n is an odd number (1, 3, 5...), c is the speed of sound and L is the length of the tube. The antiresonances in the frequency responses measured with Efim were not in accordance with this equation. The measured antiresonances were at lower frequencies than would have been expected.

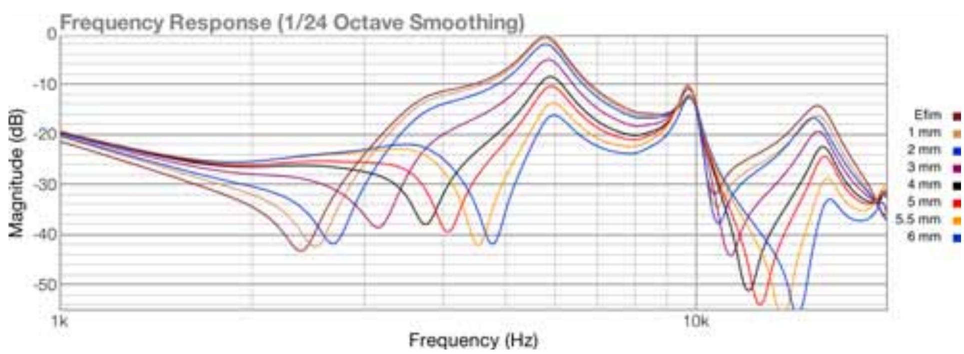

Figure 5.32: Responses measured at various distances from Efim along the Adecs ear canal.

A clarifying additional measurement was performed to study this phenomenon. The measurement setup is depicted in Figure 5.31. The eardrum microphone of Adecs was moved gradually to close proximity with the Efim in-ear microphone. The Adecs ear canal was adjusted to 20 mm. A sine sweep signal was played with the Efim and the pressure frequency responses were measured with the eardrum (probe) microphone. Figure 5.32 shows how at a distance of 6 mm from the earphone, the antiresonances behave almost according to Eq. (5.3). Very close to the earphone and at the location of the in-ear microphone (Efim), though, the antiresonances shift to lower frequencies and their locations cannot be calculated with the said equation.

Closer to the eardrum end of the simulator, the locations of the antiresonance notches depend only on the distance from the measurement point to the eardrum, as long as the canal width remains constant. This was the case also with the open ear canal as discussed in Chapter 5.2.2.

5.3.1 Frequency responses of blocked ear canal simulators

The pressure frequency responses of Adecs and Madecs, when measured with their eardrum microphones and the in-ear microphone of Efim, were in the centre of our research. Similar to the measurements with the open ear canal, the effect of the canal length was studied making good use of the adjustable simulators.

The first measurements with Adecs and Efim were performed with the setup depicted in Figure 5.33. The length of the canal was adjusted with 1 mm steps from 5 mm (minimum) to 40 mm. A sine sweep was played with Efim and the frequency responses were measured with both the Adecs eardrum microphone and the Efim in-ear microphone. In Figure 5.34 the responses from Adecs with a 26 mm ear canal are depicted. The graph shows the antiresonance notch at approximately 2 kHz at the earphone microphone. The first half-wave resonance is at approximately 7.5 kHz, which can be calculated using Eq. (5.2):

$$f = \frac{343 \text{ m/s}}{2{\cdot}(0.026 \text{ m} - 0.0035 \text{ m})} = 7622 \text{ Hz},$$

where the 3.5 mm subtraction comes from the insertion depth of Efim, which is normally between 3 and 4 mm. The peak at approximately 5.8 kHz is caused by the Efim's self-resonant frequency.

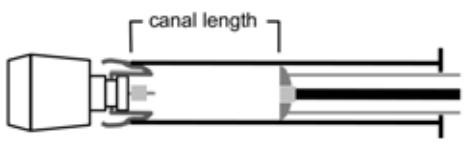

Figure 5.33: Diagram of measurement setup where Efim is fitted to Adecs and the length of the canal is adjusted by moving the eardrum piston.

A similar set of measurements was performed with Madecs. The length of the simulator's canal was adjusted as frequency responses were measured with the eardrum microphone and the in-ear microphone of Efim. The eardrum of Madecs is significantly damped, which smoothens the antiresonance notch around 2 kHz, as can be seen from Figure 5.35. In Figure 5.36 responses at the eardrum were measured using different canal lengths. The curves move in frequency domain in unison with the varying canal length.

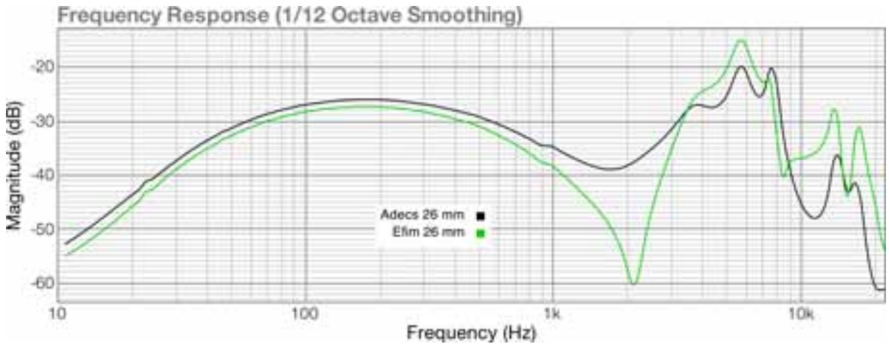

Figure 5.34: Pressure frequency responses of Adecs with canal length of 26 mm at eardrum (Adecs) and at the entrance (Efim).

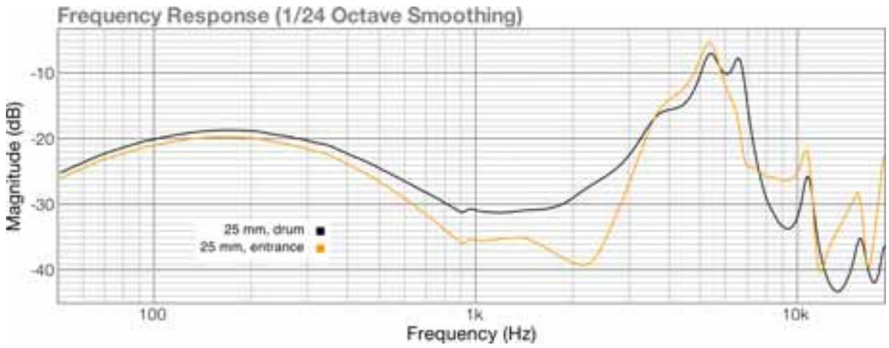

Figure 5.35: Madecs blocked ear canal frequency responses measured at the eardrum and at the ear canal entrance. The eardrum is significantly damped.

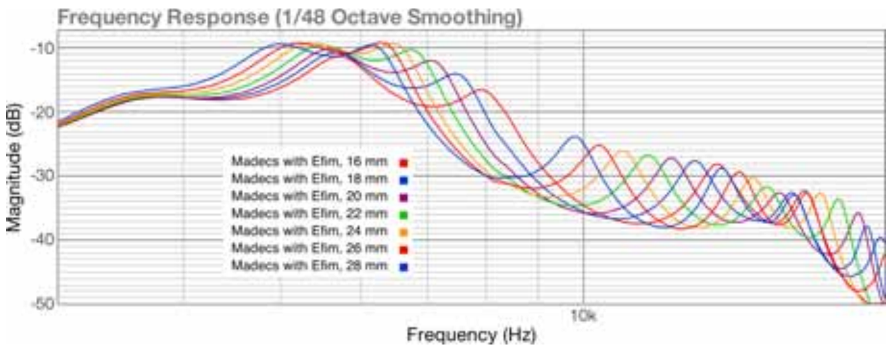

Figure 5.36: Madecs ear canal with different lengths. Frequency responses measured at the eardrum, while the sine sweep signal was played with Efim. The frequency range is from 3 kHz to 20 kHz.

In Figure 5.37 the frequency responses are measured at the ear canal entrance with the Efim in-ear microphone. From the original recorded response the transducer-to-microphone transfer function was removed. This transfer function (or frequency response) was measured with Efim in an impedance tube. The impedance tube was a long (circa 7 m) tube with a diameter of 9 mm. The far end of the tube was blocked with absorbing material in order to eliminate any reflections back towards Efim. The transfer function from the transducer to the microphone was thereby obtained.

The remaining response in Figure 5.37 should hence be that of the ear canal only. Efim's self-resonant frequency peak is, however, visible after the deconvolution. The magnitude and location of the self-resonant frequency peak changes slightly when the length of the ear canal changes, which is clearly visible in Figure B.9. This effect is caused by the place shifting notches around the self-resonant frequency.

The ear canal's resonance frequency peaks change place distinctly in unison with the changing length of the ear canal. These peaks are pronounced in frequencies around and above 10 kHz, as can be seen from Figure 5.37. The peaks move towards higher frequencies when the canal shortens.

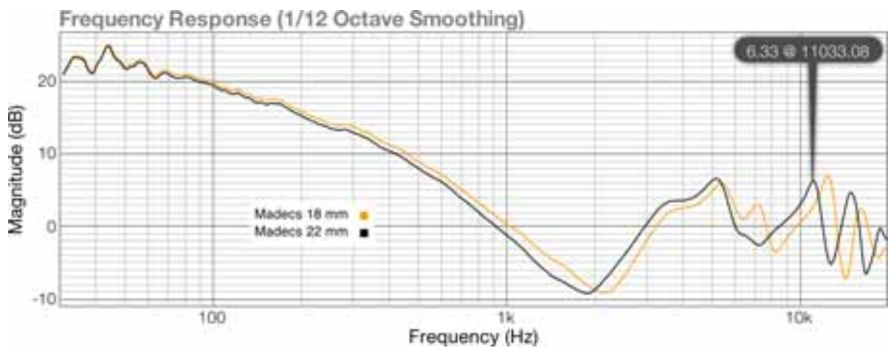

Figure 5.37: Dadec blocked ear canal responses measured at the ear canal entrance, with two different canal lengths.

5.3.2 Frequency responses of human ears

With the Efim it was easy to measure the pressure frequency responses from real ears. The test subjects were asked to place the earphone at the ear canal entrance. Then a sine sweep was played with the Efim, and the frequency response from inside the canal was measured with the in-ear microphone. Eight test subjects participated in these measurements, both ears of which were measured. The differences between individuals were significant, and in addition, the differences between right and left ears were interestingly outstanding with some of the subjects.

The responses from measurements with Subjects from 1 to 8 are depicted in Figures 5.38, 5.39, 5.40, 5.46 and in Appendix B in Figures B.10, B.11, B.12 and B.13. The left and right ear canals of Subject 6 (Figure 5.38) are remarkably similar, as there is no difference between the measured responses, whereas the canals of Subject 3 have prominent differences between each other. The lengths of the canals of Subject 5 (Figure 5.40) seem to be different, since the first half-wave resonance peaks are located at 7.3 kHz (right) and 8.3 kHz (left). Applying Eq. (5.2), the lengths of the ear canals of Subject 5 would be close to 24 mm (right) and 21 mm (left). This 'length' is the distance from the earphone to the eardrum, and it does not take into account the earphone insertion depth.

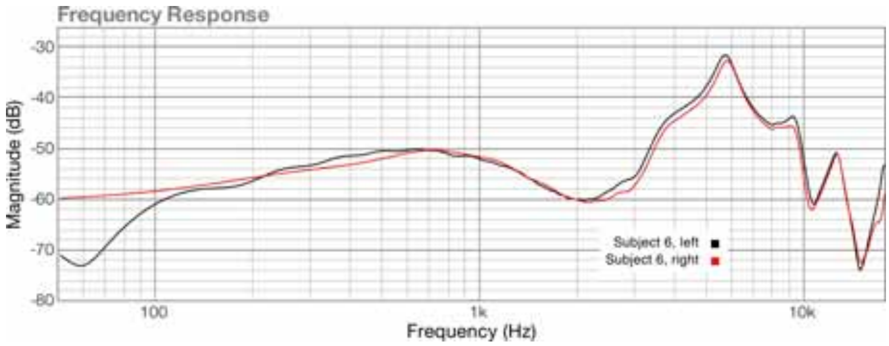

Figure 5.38: Ear canal frequency response measured at the canal entrance of Subject 6. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

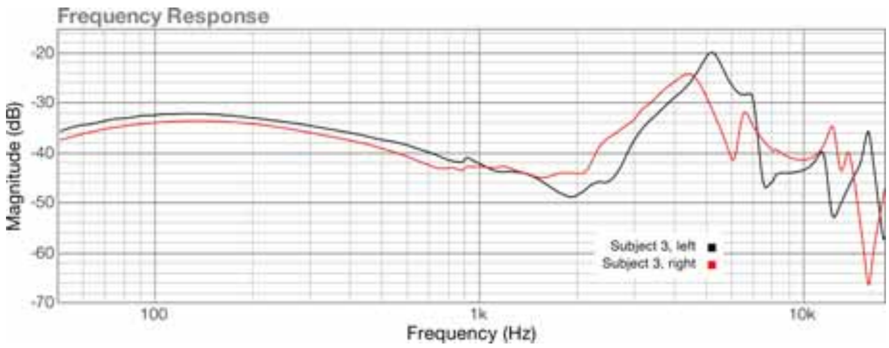

Figure 5.39: Ear canal frequency response measured at the left canal entrance of Subject 3. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

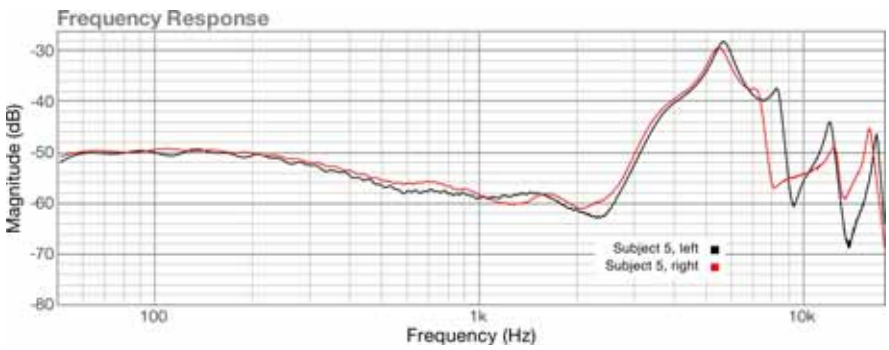

Figure 5.40: Ear canal frequency response measured at the left canal entrance of Subject 5. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

The responses obtained from real ears showed similarities with those measured with Efim using Adecs and Madecs. As one example of this, Figure 5.41 shows the responses measured with Dadec (with Madecs as ear canal) and the left ear of Subject 2. In this example, the ear canal of Madecs was set to 22 mm upon which the pinna (or the concha) of Dadec adds a few millimetres. Hence, the total ear canal length of Dadec, in this case, was approximately 28 mm.

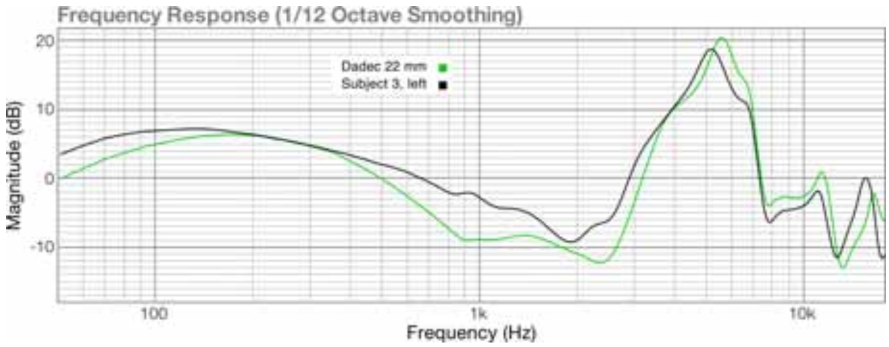

Figure 5.41: Ear canal frequency response measured at the left ear canal entrance of Subject 3 compared with similar measurement from Dadec.

5.3.3 Effect of eardrum impedance

Madecs with different eardrum impedances

The simulator with damped eardrum (Madecs) was built to copy the acoustic behaviour of a real ear canal as accurately as possible, including the impedance of the eardrum. The effect of the eardrum is remarkable especially in situations where an insert earphone is the sound source. The impedance of the eardrum determines the Q factor of the half-wave resonator, formed by the blocked ear canal. With a stiff eardrum, the antiresonance peak in the frequency response around 2 kHz is very sharp when compared to corresponding peak in the responses from real ears. The impedance of a rigid eardrum is high at all frequencies and the Q factor of the ear canal resonator is therefore also high.

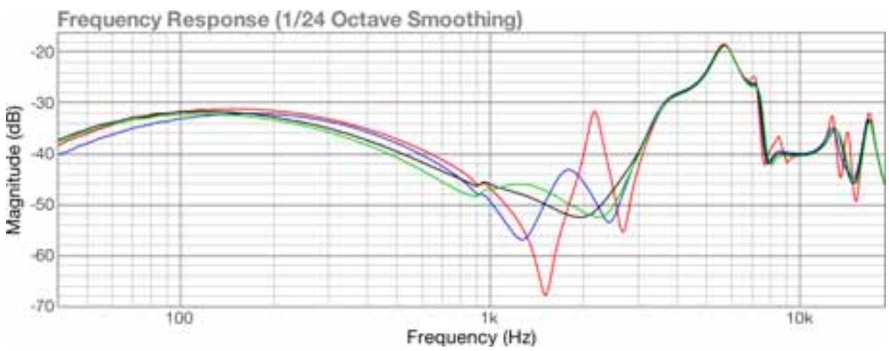

Figure 5.42: Madecs blocked ear canal frequency responses with different eardrum impedances.

The Helmholtz resonator at the eardrum of Madecs is adjustable as to the resonance frequency and the amount of damping as discussed in Chapter 4.1.5. Madecs was tuned to copy the acoustical behaviour of the human ear canal when a sine sweep is activated with Efim and the frequency response is measured with Efim's in-ear microphone. In Figure 5.42 four different responses with different resonator settings are depicted. The red curve is the response when the Helmholtz resonator is undamped. Adding absorbing material into the resonator cavity dampens the resonance and spreads the damping effect of the resonator in frequency domain. The blue curve is the response with slightly damped Helmholtz resonator. The black curve represents a setting, where the damping is similar to that of many human eardrums when the response is measured with Efim.

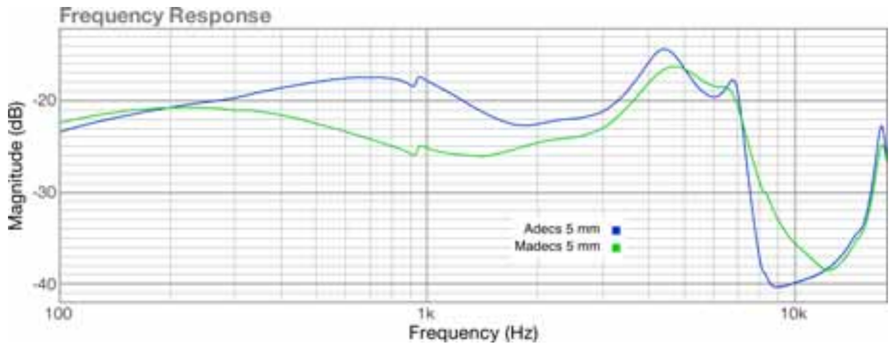

Figure 5.43: The damping effect of Madecs. Responses measured with Efim at the ear canal entrances of Madecs and Adecs. The canal length is 5 mm in both cases.

The damping effect compared to the rigid eardrum of Adecs is depicted in Figures 5.43 and 5.44. The comparison between the two simulators was made by measuring the frequency responses of each simulator with Efim. The canal length in both cases was set to 5 mm in order to keep the canal resonances at the high frequencies.

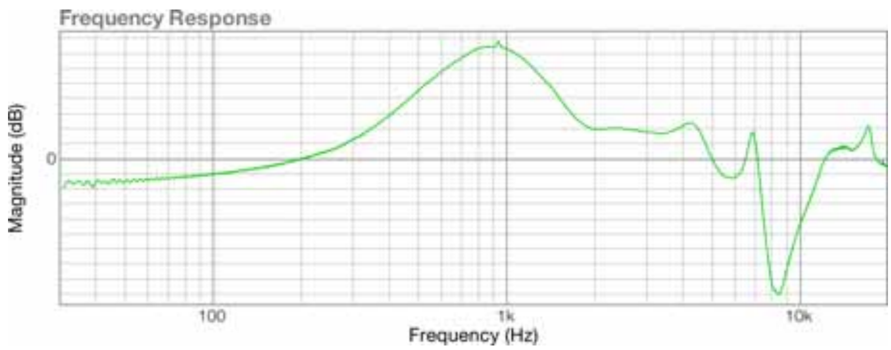

Figure 5.44: The damping effect as a difference between Madecs and Adecs. Responses measured with Efim at the ear canal entrances. The response of Adecs has been subtracted with the response of Madecs.

The curve in Figure 5.44 shows the damping effect as it is 'seen' by Efim at the ear canal entrance. At 1 kHz the Madecs eardrum attenuates (compared to the Adecs eardrum) the SPL in the canal by approximately 7 dB. At 8.5 kHz the Madecs eardrum smoothes an antiresonance that is caused by the ear canal.

In conclusion, the Madecs eardrum attenuates the sound pressure levels from 200 Hz to 18 kHz, the effect being strongest around 1 kHz. In addition, Madecs smoothes the antiresonance notches of the ear canal.

Human ears

The effect of different eardrum impedances to the frequency response at the entrance of the blocked ear canal was studied. The measurements were made with Efim at the ear canal entrance of Subject 1. The eardrum impedance was altered in the same manner as described in Chapter 5.2.5. First, the response was measured with the eardrum in normal circumstances. Then, additional pressure was brought about into the tympanic cavity while the response was measured. The blue and orange curves in Figure 5.45 depict the frequency responses obtained with pressure in the tympanic cavity. The pressure stiffens the eardrum and makes the frequency response very similar to that of the Adecs. The antiresonance notch at 2.2 kHz is sharp, just like in the Adecs responses.

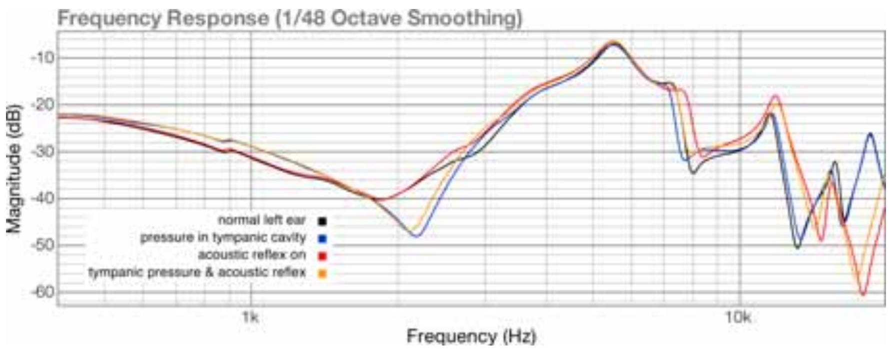

Figure 5.45: The effect of additional pressure in tympanic cavity and that of the stapedius reflex. Blocked ear canal responses obtained with Efim.

In addition, the effect of the acoustic reflex described in Chapter 2.2.3 was studied. The reflex was set on using a loud audio signal a few seconds before the measurement. The red and orange lines in Figure 5.45 represent the frequency responses obtained with the acoustic reflex set on. The reflex affects the half-wave resonance frequency peak at 7.5 kHz slightly. In addition, major changes occur at frequencies above 12 kHz.

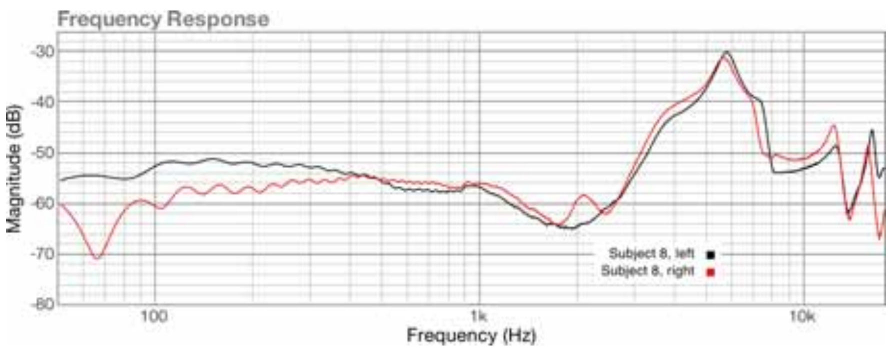

Figure 5.46: Ear canal frequency response measured at the canal entrance of Subject 8. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

The eardrums of different individuals have different impedances, which in turn affect the frequency responses of the ear canal. The differences are easily observed from measurements with Efim. Around frequencies from 1 kHz to 3 kHz, the sharpness of the antiresonance notch could be taken as a measure of the stiffness of the eardrum. In addition, as can be observed from Figure 5.46, the eardrum can cause other variations to the frequency response. A clear peak, similar to that of the Madecs in Figure 5.42, is visible at 2 kHz in the response of right ear of Subject 8.

5.3.4 Effect of canal shape

The human ear canal is not a straight tube, but instead it has two profound bends, ‘the first bend’ and ‘the second bend’. The shape of the canal was discussed in Chapter 2.2.2. The bends effectively cause the ear canal to be slightly compressed in the middle. The influence of the compression on the frequency response was studied through measurements with Efim. The earphone was placed at the entrance of a 26 mm long tube with inner diameter of 8 mm. The tube was made of plastic and it was terminated with the Madecs eardrum, which was temporarily transferred from its primary environment. The frequency response at the entrance of the canal was recorded with the Efim in-ear microphone. The response at the eardrum was obtained with the eardrum microphone of Madecs. The changes in the response due to the compressing of the canal were conciderable as Figures 5.47 and 5.48 show.

A somewhat similar measurement with an open ear canal was previously presented in Chapter 5.2.4. In that case the pressure frequency response was measured only at the eardrum. The maximum effect of the compression was in the magnitude of approximately 5 dB. In the present measurement though, with the blocked ear canal, the frequency response was measured also at the ear canal entrance.

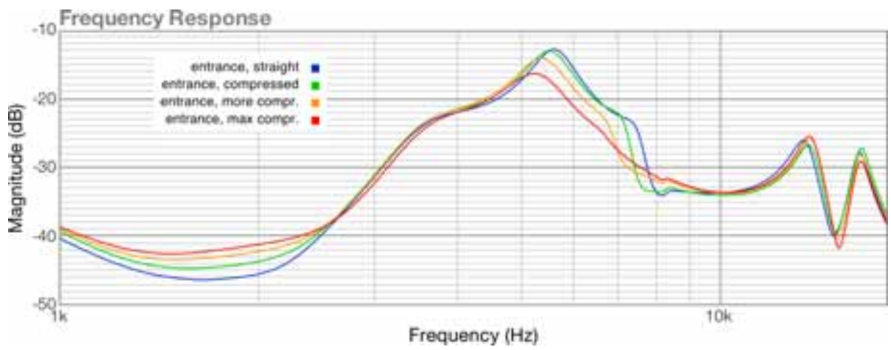

Figure 5.47: Effect of ear canal compression. The canal in gradually compressed at the middle. Response measured at canal entrance with Efim.

The compression shifted the canal resonances and caused a maximum change of approximately 10 dB in a narrow frequency range from 7 kHz to 8 kHz.

This was only a facile research related to the effect of the ear canal shape, and further research and calculations should be made in order to gain more complete understanding of this matter.

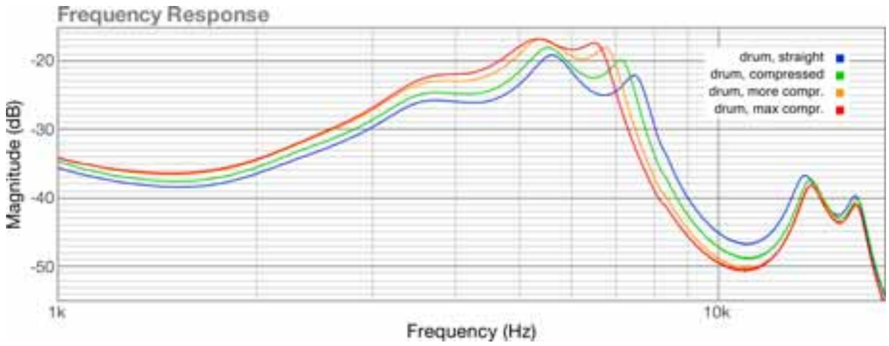

Figure 5.48: Effect of ear canal compression. The canal in gradually compressed at the middle. Response measured at eardrum with the Madecs eardrum microphone. Signal is played with Efim.

5.3.5 Leakage

From frequency response measurements with human test subjects and the Efim, it is easy to see how tightly the earphone was inserted into the ear canal entrance. With correctly inserted earphone, thanks to the pressure chamber effect, the sound pressure level remains at a high level at low frequencies (approximately from 20 Hz to 1.5 kHz). Without the pressure chamber effect, e.g. in free field, the sound pressure at low frequencies drops significantly. In Figure 5.49 four different types of Efim frequency responses are compared. The black and grey lines represent tight fitting, and the pressure chamber is effective. The response obtained with Subject 4 represents a situation where the leakage is substantial and the pressure chamber effect does not take place. Compared to the response measured in free field the pressure chamber increases the sound pressure level by 45 dB at 100 Hz. With very poor fitting (Subject 4), the pressure chamber effect is negligible.

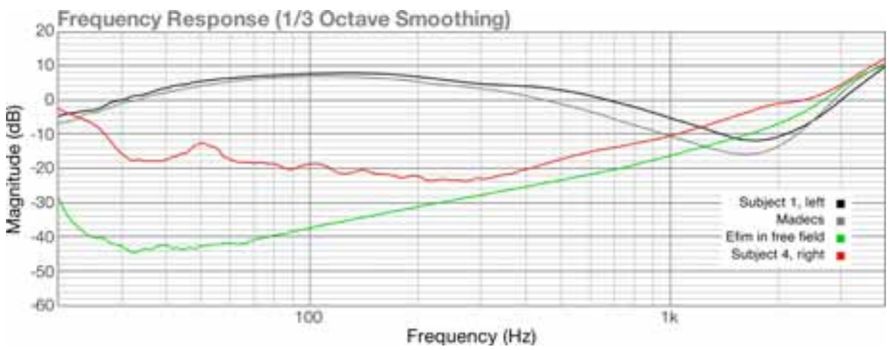

Figure 5.49: Frequency response measured with Efim at the canal entrance of Subject 1, Madecs, Subject 4 and in free field.

5.3.6 Occlusion effect

It was Thomas A. Edison, who first heard his own voice from a sound recording in 1877. He was thus the first to perceive that a recording of one's own voice sound different from the sounds one hears when speaking [47]. The first scientific research related to hearing of one's own voice was performed by Lombard in 1911. The Lombard effect describes the phenomenon of people tending to talk louder in a noisier environment.

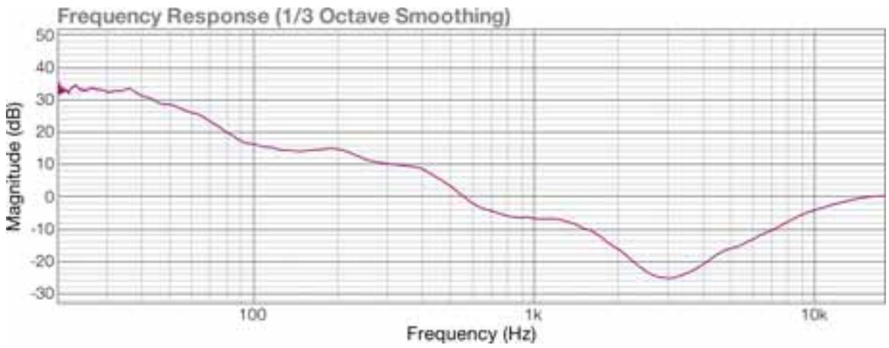

Figure 5.50: Occlusion effect. Difference between the test subject's own voice frequency responses from blocked ear canal and open ear canal. A positive magnitude means that the SPL was higher in the blocked ear canal. A negative magnitude means that the SPL was louder in the unblocked ear canal.

In 1949, it was discovered that the two sound paths relevant to hearing of one's own voice are bone conduction and air conduction. Békésy [7] in his research discovered that the loudness to the speaker of his own voice is attenuated about 6 dB when air conduction is eliminated. This demonstrated that the level of bone conduction and air conduction of one's own speech are of the same order of magnitude. Békésy also realized that for maximally useful hearing when a hearing aid or insert earphone is used not only the sounds of vocalization should be reduced, but also noises produced by chewing, swallowing, walking etc.

A brief study was performed in order to get some insight into the occlusion effect. The measurement setup was the following. In an anechoic chamber both ears of three human test subjects were used. One ear was left open while the other ear was blocked with an insert earphone. Into both ear canals a miniature microphone was inserted. The test subject was then asked to produce different sounds including fricatives and harmonic sounds. The sounds were recorded simultaneously with both microphones. The recordings were analyzed as to the sound pressure levels in each ear at different frequencies. The differences in SPL at different frequencies are depicted in Figure 5.50. The curve is the average difference between the pressure in the blocked ear canal and the open ear canal obtained from three test subjects.

According to this preliminary study, the sounds created by the test subjects were boosted in the blocked ear canal at frequencies below 550 Hz and attenuated above that. The boosting rose to 30 dB at the very lowest frequencies. The biggest attenuation, 25 dB, occurred at 3 kHz.

Chapter 6

Conclusions and Future Work

6.1 Summary

It was the objective of this thesis to study the acoustical behaviour of the ear canal. We hoped to learn what effects the varying physical dimensions of individual ear canals have to the frequency response measured at the eardrum. In addition, the goal was to compare the effects of varying overall physical dimensions of the outer ear such as the size and shape of the pinna. Furthermore, the work related to this thesis aimed at modelling the ear canal and the whole outer ear as accurately as possible.

Methods to model the acoustic behaviour of the outer ear and the ear canal were presented in this work. The first approach included physical simulators such as an adjustable ear canal simulator and a dummy head. The physics-based computational model, which included lumped element and transmission line modelling constituted the second approach to the modelling challenge.

The novel purpose-built ear canal simulators, a dummy head and an earphone with in-ear microphone were used in a large number of measurements in order to gain profound knowledge and understanding of the behaviour of the pressure frequency responses at various points along the ear canal. In addition, the ear canals of human test subjects were used in measurements and the obtained results were compared with those obtained with simulators. The measurements were performed with open ear canals as well as with ear canals blocked with an insert earphone.

Various parameters were considered as to the effect of differences in ear canal structures to the frequency responses. The effect of the length of the canal was carefully studied. The impedance of the eardrum is the second major factor in the composition of the pressure frequency response of the ear canal. The effect of differences in the impedance was therefore investigated using simulators and human test subjects. Other variable parameters included e.g. the shape and size of the pinna and the shape of the ear canal. The acoustic behaviour of the open ear canal as well as that of the blocked ear canal was thus investigated thoroughly through measurements and analysis.

The results obtained from measurements with the open ear canal simulator were compared with a physics-based computational model that applied lumped element modelling as well as transmission line modelling. The model included a lossless straight tube and a resistive ‘eardrum’.

Two important phenomena with insert earphones are leakage and the occlusion effect, which mainly affect frequencies below 1 kHz. Brief looks at these usability issues were taken.

6.2 Conclusions

Physical simulators such as ear canal simulators and dummy heads have been used widely as substitutes of human test subjects. The accuracy to which physical simulators can imitate the behaviour of the outer ear and the ear canal depend on how well different physical details have been taken into account. The goal of our research was to learn what kinds of effects the differences in physical parameters of the outer ear have to its frequency response. In addition, we aimed at constructing a physical dummy head with as accurate human-like acoustical behaviour as possible. Furthermore, we hoped to put up an accurate physics-based computational model.

The simple tube-like adjustable ear canal simulators were useful in determining the effect of the ear canal length. The frequencies of the ear canal resonances and antiresonance notches found in measurements were the same as those calculated with physics-based formulas. The acoustic behaviour of a simulator equipped with a damped eardrum was much like that of the human ear canal. In addition, the custom made dummy head used in our measurements proved to be a fairly accurate model of the human peripheral hearing. We were hence able, with good accuracy, to study the effect of the differences in human ear canal lengths and eardrum impedances.

From the measurement results we conclude that the length of the ear canal is a very important factor in determining the pressure frequency responses at the ear canal entrance and at the eardrum. In addition, the eardrum impedance determines the sharpness of the resonance peaks and antiresonance notches. For a realistic model of a human ear canal, the impedance of the eardrum needs to be taken into account.

Other physical parameters, such as the shape of the ear canal and other parts of the outer ear were studied briefly. The idea behind these investigations was primarily to enable a comparison between the effects of different variable parameters. It was found, that differences in the shape of the outer ear are a factor to be considered when modelling the outer ear. However, in comparison to the varying ear canal length the differences in the shape of the outer ear were of less importance. Further measurements are called for on the effect of the shape of the ear canal.

It was found that the physics-based computational model applied for modelling of the open ear canal simulator was accurate up to at least 20 kHz. The modelling of an ear canal simulator that is blocked with an insert earphone was not completed during the writing of this Thesis. In order to put up an accurate model for the blocked ear canal the acoustic properties of the earphone are to be determined first.

Frequency responses from the ear canal entrance of real ears with an insert earphone and in-ear microphone were measured. The responses were very similar to those measured with the ear canal simulator with damped eardrum. By adjusting the length of the simulator’s ear canal and the impedance of its eardrum it was possible to find a good match for most test subjects. The adjustable physical simulator was hence fairly accurate up to 11 kHz.

6.3 Future Work

As a first improvement and continuum to the research performed for this thesis, systematic investigation on the effect of the overall shape of the ear canal and the outer ear to the frequency response at the eardrum should be performed. Measurements and computational modelling should be applied in order to fully cover the subject.

In addition, the construction of an accurate model for real ears blocked with an insert earphone is an attainable goal.

Results presented in this thesis should be taken into account in future studies related to head-related transfer functions.

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Appendix A

Test subjects

Table A.1: Human test subjects.

Subject number	Name
1:	Marko H.
2:	Jussi
3:	Juho
4:	Henna
5:	Juha
6:	Marko T.
7:	Antti
8:	Hannu

Appendix B

Figures

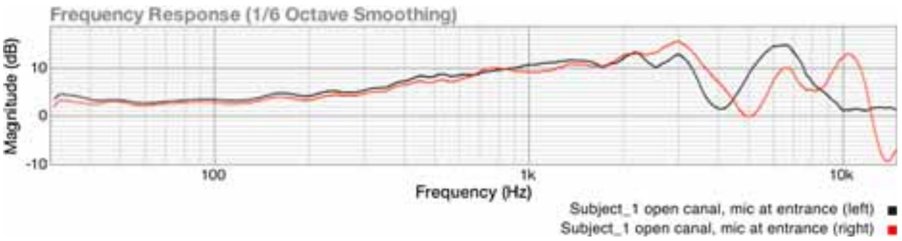

Figure B.1: Frequency responses of the ears of subject 1 as measured with a miniature omnidirectional microphone at the ear canal entrance. The sine sweep signal is played with a loudspeaker in an anechoic chamber with the ear canal entrance towards the loudspeaker.

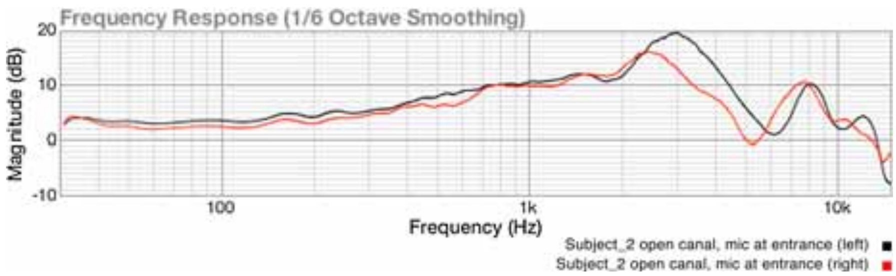

Figure B.2: Frequency responses of the ears of subject 2 as measured with a miniature omnidirectional microphone at the ear canal entrance. The sine sweep signal is played with a loudspeaker in an anechoic chamber with the ear canal entrance towards the loudspeaker.

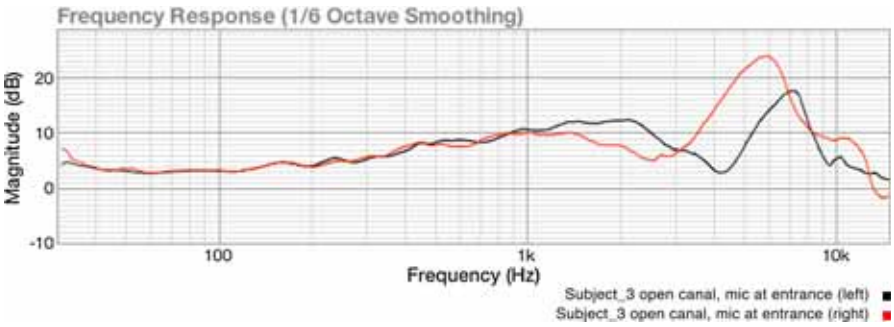

Figure B.3: Frequency responses of the ears of subject 3 as measured with a miniature omnidirectional microphone at the ear canal entrance. The sine sweep signal is played with a loudspeaker in an anechoic chamber with the ear canal entrance towards the loudspeaker.

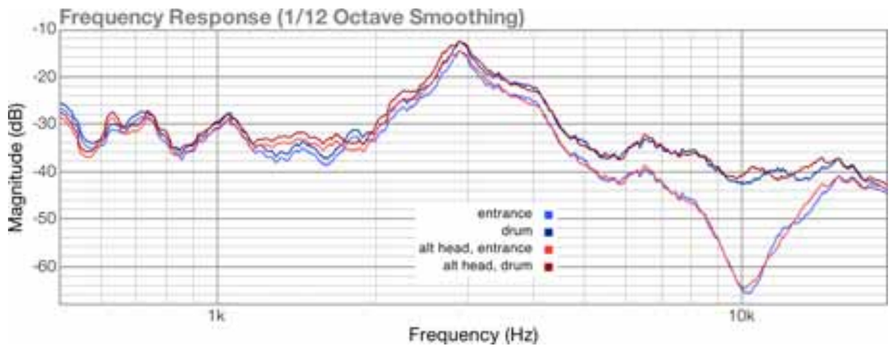

Figure B.4: Effect of reflecting objects around the pinna. Frequency responses measured at the eardrum and at the ear canal entrance. The length of the Adecs ear canal is 12 mm.

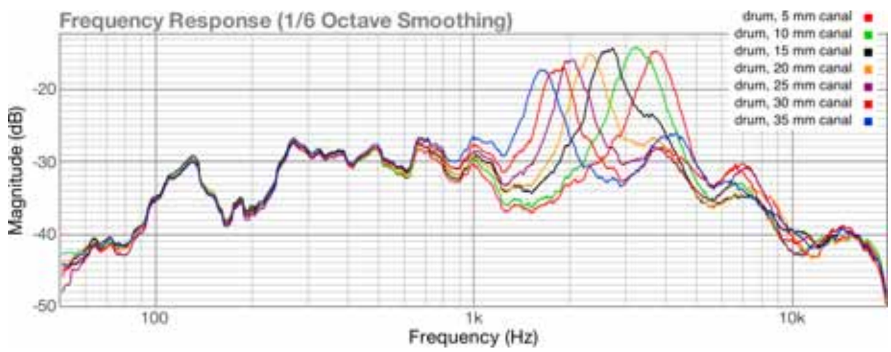

Figure B.5: Frequency response at the eardrum measured using Dadec with Adecs as ear canal in listening room conditions.

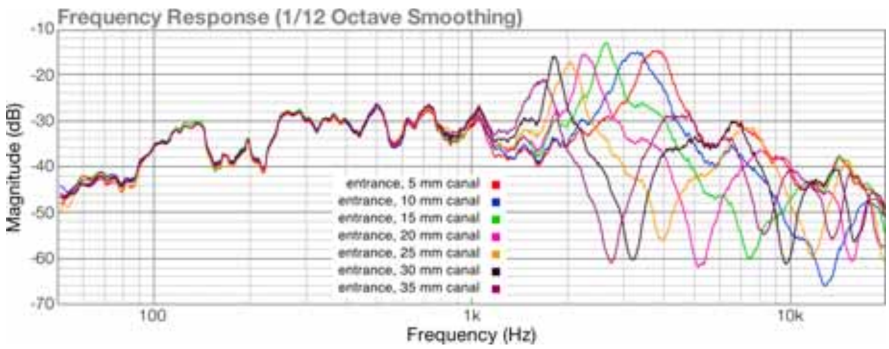

Figure B.6: Frequency response at the ear canal entrance of Dadec with Adecs as ear canal in listening room conditions.

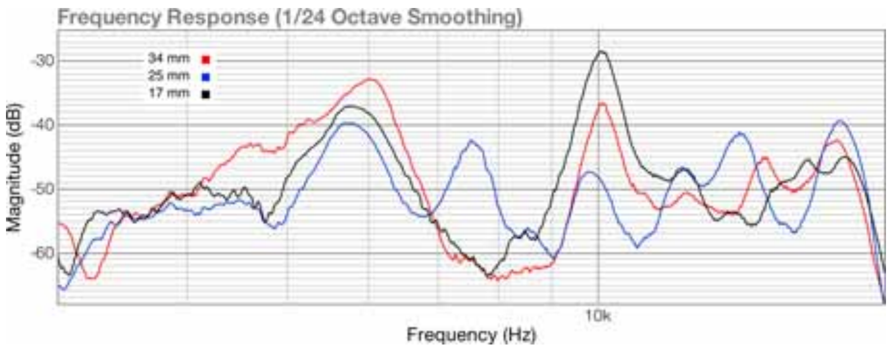

Figure B.7: A system where Efim is mounted to Adecs behaves almost like a halfwave resonator.

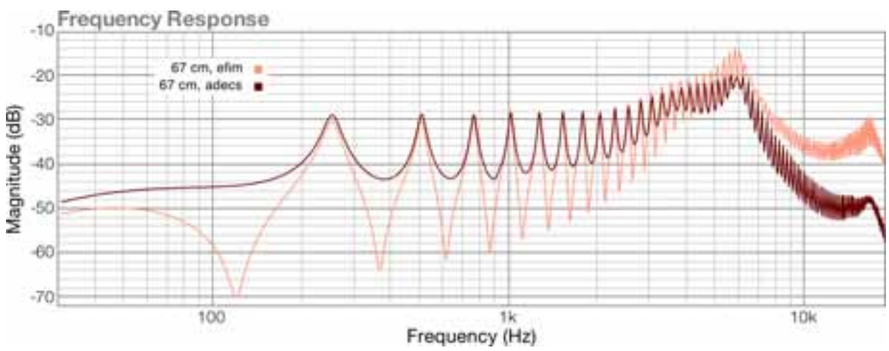

Figure B.8: When Efim is mounted to a 67 cm long tube and the frequency response is measured at the canal entrance and at the eardrum the half-wave resonances and fourth-wave antiresonances are pronounced.

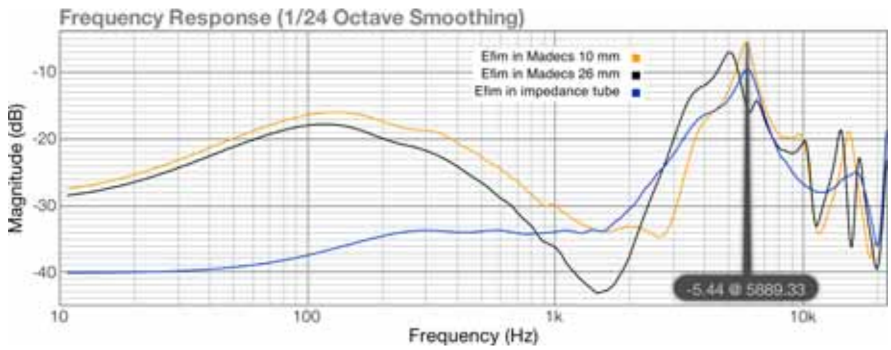

Figure B.9: Efim in Madecs and an impedance tube. Responses measured with the Efim in-ear microphone.

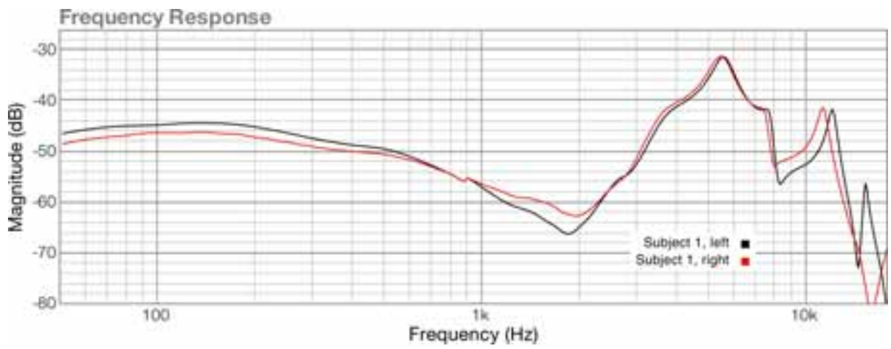

Figure B.10: Ear canal frequency response measured at the canal entrances of Subject 1. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

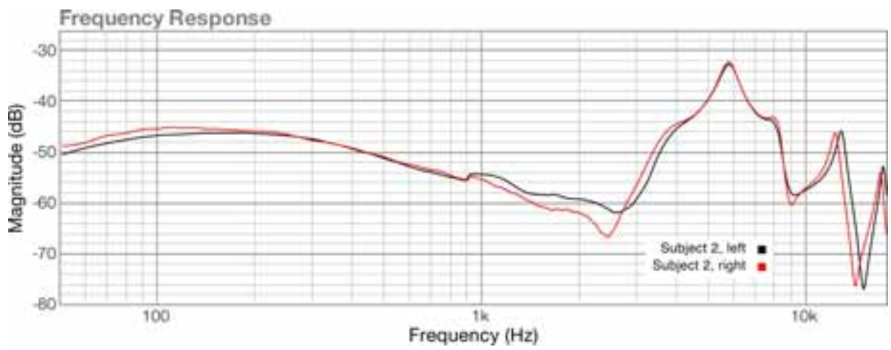

Figure B.11: Ear canal frequency response measured at the canal entrances of Subject 2. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

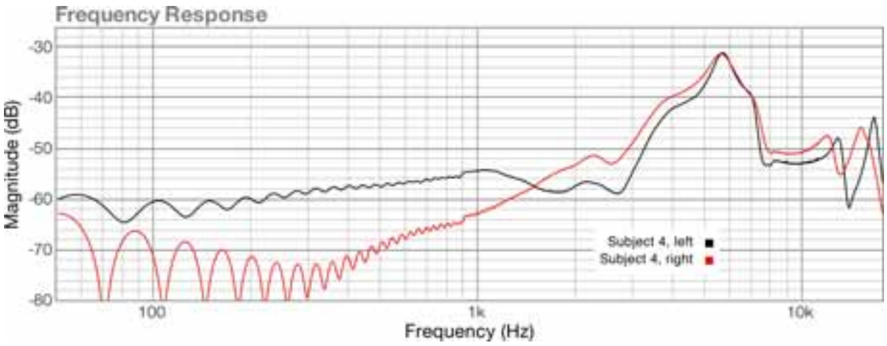

Figure B.12: Ear canal frequency response measured at the canal entrances of Subject 4. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.

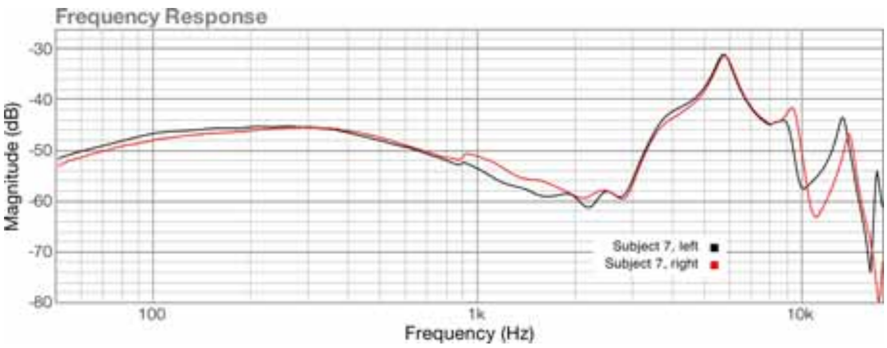

Figure B.13: Ear canal frequency response measured at the canal entrances of Subject 7. Sine sweep played with Efim and response recorded with Efim's in-ear microphone.