58th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 08 – 12 September 2014
URN: urn:nbn:de:gbv:ilm1-2014iwk:3

AN EAR-PINNA ACOUSTIC ANALYSIS COUPLED WITH AN EAR-CANAL EMULATOR 711

E. Bances[1], T. Schmidt[2], T. Helbig[1] , H. Witte[1]

1 Department of Biomechatronics, Ilmenau University of Technology. Germany
2 Department of Otolaryngology, University Hospital Jena. Germany

ABSTRACT

Simulations of the pressure on the pinna are significant contributions to the continuous improvement of hearing aids devices, i.e. they help to improve the reception of sound coming from different directions. Other interesting results are those that arise from analyses of the ear canal, leading to the implementation of ear-canal emulators, which mirror the acoustic behavior of the human ear. Analyses of the distribution of instantaneous pressure in the pinna and the ear canal allows better understanding, how the human auditory system behaves under sounds from various directions. In the present work, we present an ear pinna model coupled with an ear canal emulator, to understand how the pressure is distributed in the model covering the human hearing range of 20Hz-20Khz. Comsol Multiphysics 4.3 and its acoustic module in the frequency domain were used to analyze two different cases: when the sound source comes from the lateral plane of the pinna and when it comes from the dorsal plane.In each case the eardrum sound perception (pressure distribution) at different frequencies was studied.

Index Terms— Acoustic, Ear Canal, Pinna Simulation, Emulator 711 coupler, Comsol-Acoustic.

1. INTRODUCTION

Several studies based on finite element method / volume methods are used to analyze auditory system in human being. Hudde [2009] e.g. used a box enclosing the pinna to elucidate the characteristics of the ear canal sound field, and to identify the limits of unidimensional approaches using fundamental modes. Takemoto [2010] studied the reflection and diffraction by head and pinna in order to locate the sound source in three dimensional space. Moreover, he developed an acoustic simulator based on finite-difference time-domain (FDTD) method that can visualize temporal changes in the acoustic field (pressure distribution) and particle velocity. This simulation proved to have an accuracy similar to the results taken with a microphone, used to measure in parallel the sound pressure changes at a certain point in the space. Additionally, Makoto [2010] analyzed the surface pressure on the pinna, Head-related transfer function (HRTF) in the time and the frequency domains using numerical simulation boundary element method (BEM). His results demonstrate the extent to which part of pinna contributes to a production of HRTF spectral notches and peaks depending of the source elevation. Other studies are focussed on the evaluation and testing of ear canal emulator, Comsol [2012] simulated the thermoacoustics behavior of the standard coupler 711 and its losses using finite elements. The coupler is the device for measuring the acoustic output of sound sources with a calibrated microphone defined by the standard IEC 60318-4.

This model describes the pressure wave propagation in an ear-pinna. It refers to an artificial human head called Neumann KU80 [1]. The ear-pinna is coupled with an ear-canal emulator regarding the international standard specifications IEC 60318-4.

In this simulation an ear-pinna box of cubic shape is considered, which approximates the free space, providing an absorbing volume and using the walls of the box as external sound sources from different directions.

The simulation of the complete model was done in Comsol Mutiphysics 4.3 and the frequency simulation range covers 20Hz to 20Khz,the human hearing range.

The purpose in this simulation is to show how is the pressure distribution along the pinna surface and within the ear canal,as well as analyze and take conclusion about the behavior or the human hearing system.

2. MODEL DEFINITION

The human ear-pinna model is based on the artificial head KU80 made by Georg Neumann & Co in 1975 [1]. The ear-pinna is covered by a cube used to approximate free-field conditions and to implement external sound fields in the walls. The cube side dimension is $a = 80mm$, which have been adapted to the shape of the head around the pinna. On the other hand, an ear canal emulator (coupler 711) is a commercial device based on a standards conditions and intended for measurement of hearing aids earphones, and in our case coupled to the pinna. Finally the complete model was design using Solidworks 3D-Cad software. Consecutively, all the parts were assembled and the model was imported by Comsol multiphysics, to apply finite element method as is shown in the Figure 2.

As mentioned above, an external sound field acting onto the cube walls is activated by Comsol tools, this fields come from different directions as the Figure 1 shows.

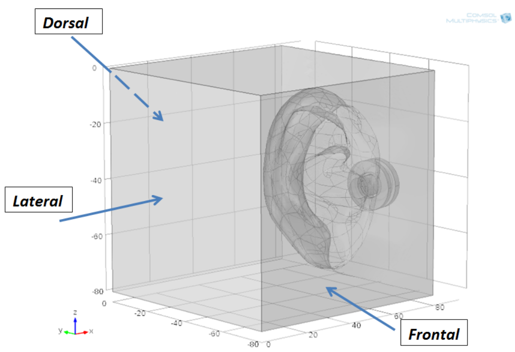


Fig. 1: Ear pinna simulation box

2.1. Geometry

The dimension of the right ear pinna model has the normal characteristic of an adult man, the scanned model is a replica of the human ear made by Georg Neumann GmbH. Furthermore, the Coupler 711 model based on the international standard IEC 60318−4 [2] was added, this device measures the acoustic output of sound sources with a calibrated microphone, the shape is described as a cylinder of length $L = 12,5mm$ and diameter $D = 7.5mm$ and two side volume as rings attached to the cylinder via slender slits of hight $h1 = 69\mu m$ and $h2 = 170\mu m$. A complete description on the geometry and parameter values could be consulted in the references [2] and [3].

The parameters considered in this simulation are given in the Table 1. All of them respond to the physical characteristics about the entire model. Furthermore, the simulation considers normal environment parameters, such as the temperature $20°C$ $(293.15°K)$, the reference pressure for air is 20 $[\mu Pa]$ and the speed of sound air $c = 343[m/s]$.

Name	Value	Description
muB0	0[Pa.s]	Bulk viscosity
Tref	20[degC]	Reference temperature
simp	1.6e^{6}[N.s/(m^{3})]	Impedance of skin
pref	20e^{-6}[Pa]	Reference pressure
pin	1[Pa]	Pressure
edimp	9.4[N.s/m^{3}]	Impedance eardrum
Cmic	0.62e^{-13}[m^{5}/N]	Microphone compliance
Lmic	710[Kg/m^{4}]	Microphone mass
Rmic	119e^{6}[N.s/m^{5}]	Microphone resistance

Table 1: Simulation parameters

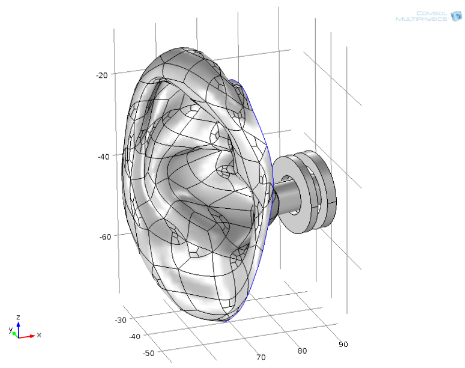


Fig. 2: Pinna & coupler

3. SIMULATION METHOD

The entire model was imported using the CAD import-module LiveLink^{TM} for Solidworks® allowing to make any necessary modification in comsol. The model solves the problem in the frequency domain using the time-harmonic Pressure Acoustic interface of Comsol (acpr).

The frequency domain, or time-harmonic formulation, uses the inhomogeneous Helmholtz equation:

$$\nabla(-\frac{1}{\rho}(\nabla p - q_d)) - \frac{\omega^2.p}{\rho.c^2} = Q_m \quad (1)$$

where:

$K_{eq} = (\frac{\omega}{c})^2$: Waves number

ρ : Density

ω : Angular frequency

c : Speed sound

p : Acoustic pressure

q_d : Dipole source $[\frac{N}{m^3}]$

Q_m : Monopole source $[\frac{1}{s^2}]$

The Frequency domain interface is designed for the analysis of various types of pressure acoustics problems in the frequency domain, in our simulation the air is as a transport medium of the sound wave. The model describes the pressure-wave propagation in ear pinna coupled to the emulator generic 711.

3.1. Boundary Conditions

3.1.1. Sound Hard Boundary (wall)

At the solid boundaries, which are the outer of the ear pinna and the ear canal emulator, the interface adds a condition for a sound hard boundary or wall, which is a boundary at which the normal component of the acceleration is zero and its specified mathematically by:

$$\nabla(-n.\frac{1}{\rho}(\nabla p - q_d)) = 0 \quad (2)$$

3.1.2. Plane wave radiation

This radiation condition allows an outgoing plane wave to leave the modeling domain with minimal reflections, when the angle of incidence is near to normal. In the first analysis we used a lateral plane, the ear receives the sound wave directly, besides in the second simulation the source is in the dorsal plane, the pinna receives the wave from the back. The Incident Pressure Field (IRF) for both simulations is of the planar type with the value of $1[Pa]$.

3.2. Impedance

The impedance is a generalization of the sound-hard and sound-soft boundary conditions. In this particular model, the main impedance taken was the skin impedance, this particular value varies depending on the sample. Furthermore, the air impedance and the microphone impedance were added to the model and are specified mathematically by:

$$\nabla(-n.\frac{1}{\rho}(\nabla p - q_d)) = -p.(\frac{i\omega}{Z_i}) \quad (3)$$

Z_i is the acoustic input impedance of the external domain and it has the unit of a specific acoustic impedance. From a physical point of view, the acoustic input impedance is the ratio between the local pressure and local normal particle velocity. $Z = \frac{p}{\nu}$

The Impedance boundary condition is a good approximation for a local reaction on the surface, where the normal velocity at any point depends only on the pressure at that exact point.

In this model we considered difference impedances values and were taken from different literatures [4], [5].

Skin impedance : $1.6e^6[\frac{kg}{s.m^2}]$

Air impedance : $411.6[\frac{kg}{s.m^2}]$

The microphone model Brel & Kjar 4192 has an impedance corresponding to the mechanical properties given by:

$$Z_{mic} = \frac{1}{i\omega C_{mic}} + R_{mic} + i\omega L_{mic} \quad (4)$$

4. RESULTS

The data presented below is the result from two simulations. The first one shows the sound pressure distribution on the pinna and the coupler 711 within a frequency range of ($20Hz$-$20KHz$). The external sound source represented by the box walls, vibrates at different frequencies approximating the sound incidence from different directions. This means in the first simulation the sound source comes from the lateral side, and in the second one from the dorsal side. Each wall is activated independently in order to achieve best analyses.

The simulation was made using the acoustic module by Comsol, the pressure analysis in the frequency domain is governing by the equation of Helmholtz **(1)** and in this particular case, la simulation considers normal environment parameters (see above). The exciting sound pressure amplitude is $1[Pa]$ in each wall. Moreover, other important parameters were considered namely skin impedance of the pinna, the microphone and air impedance.

The goal of these simulations was to analyse the behavior and the sound pressure distribution through the pinna and the ear canal (coupler), considering a deeper understanding of characteristic sound field. Furthermore is shown the pressure distribution on the microphone surface of the coupler, to simulate the eardrum reaction. Finally, the second simulation shows similar data except that the sound pressure source comes from the dorsal.

4.1. Lateral Sound Source

The lateral exciting sound source with 1 $[Pa]$ of amplitude vibrates at different frequencies, the sound wave approaches the ear. In the Figure 3, could we take an idea how the sound wave propagation and velocity direction of the particles (red arrows) considerably change due to the frequencies changes before and after the impact with the ear. Indeed, these affects provoke different results while the frequency increases (Figure 5).

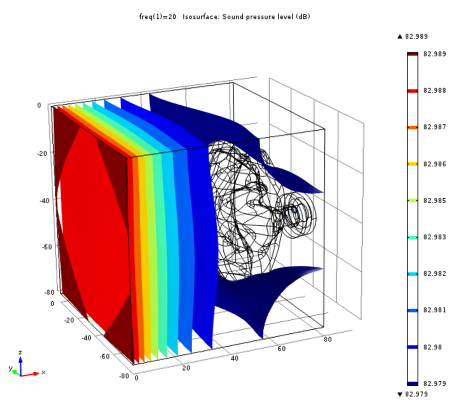
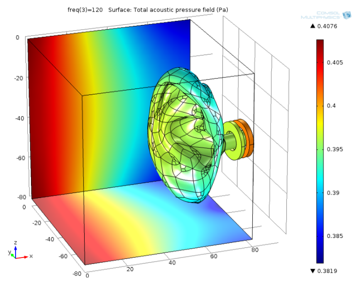
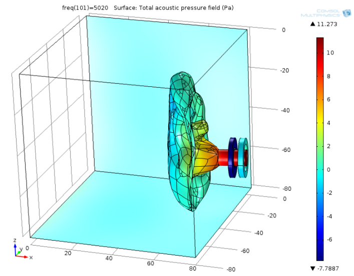


Fig. 3: Sound wave propagation

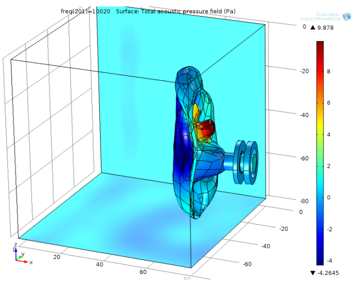
The average pressure in the pinna at lower frequencies, shows an almost constant distribution along the model such as Figure 4 displays within the model. As shown below, at low frequencies the distribution of pressure on the pinna is less than 1 Pa. Nevertheless, as the frequency increases the pressure effect within the coupler undergoes considerable changes, in particular in the cavities of the pinna such as the Tragus or the Concha, besides the eardrum (microphone).



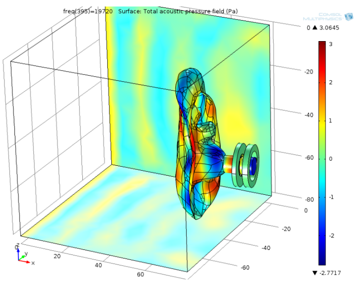
(a) 120 Hz



(b) 5020 Hz



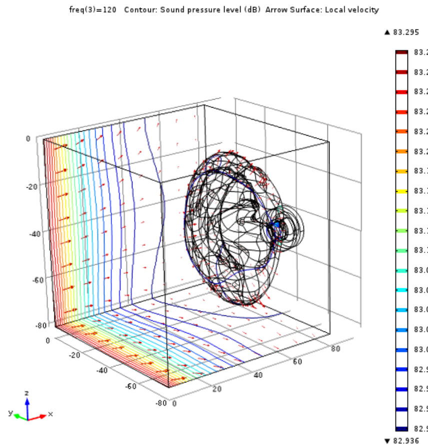
(c) 10020 Hz



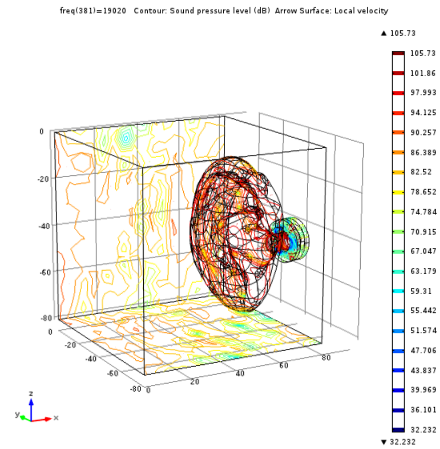
(d) 19720 Hz

Fig. 4: Acoustic Pressure Distribution- Lateral Source

Figure 6 shows a cut plane through the middle of the pinna and ear canal. Thus better can be observed how the pressure is distributed, moreover the velocity in different directions where the wave makes contact with the surface. The pressure in the pinna along the frequencies range is quite uniform, oscillating between -0.6 to 0.6 Pa. Furthermore, the pressure in the eardrum (coupler microphone) presents several changes oscillating between -19 to 13 Pa, as the Figure 7 shows. Regarding high frequencies, the pressure inside the coupler and the eardrum intensifies and the velocity is randomly dispersed.



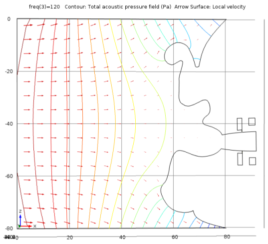
(a) Low frequency



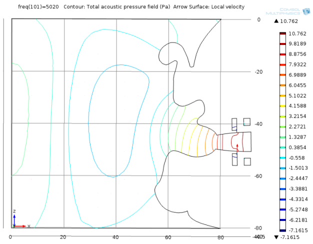
(b) High frequency

Fig. 5: Sound Pressure Level

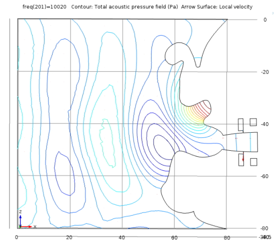
The figure 6 also displays how the sound wave impact on the surface and inside the ear canal.



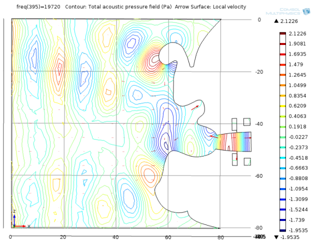
(a) 120 Hz



(b) 5020 Hz

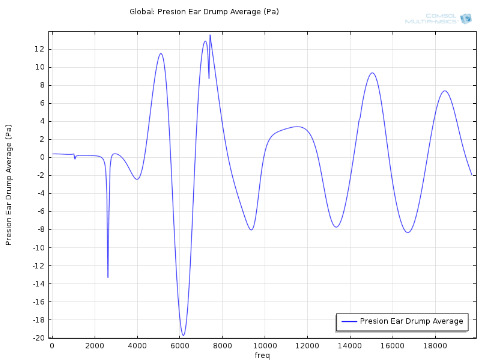


(c)10020 Hz

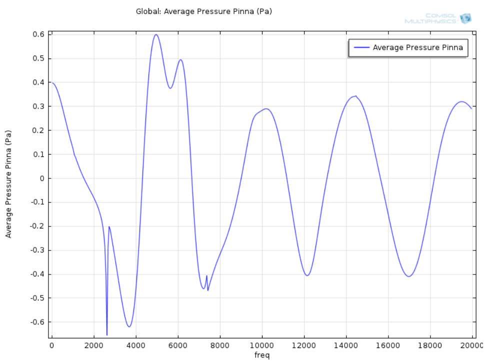


(d)19720 Hz

Fig. 6: Sound pressure distribution and velocity - Lateral Source



(a) Eardrum average pressure

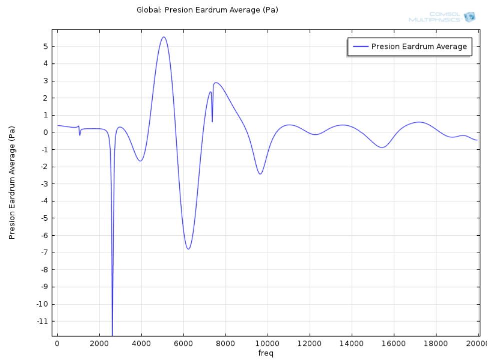


(b) Pinna average Pressure

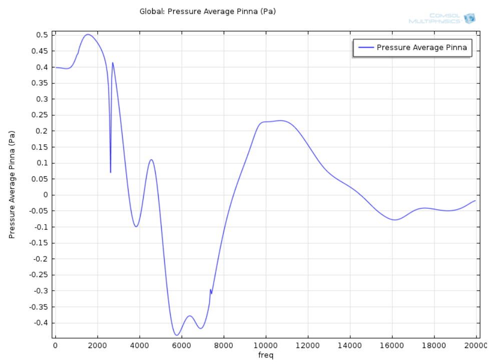
Fig. 7: Average Pressure Distribution - Lateral Source

4.2. Dorsal Sound Source

In this simulation, the sound incidence plane provides the wave behind the pinna. The average pressure in the pinna surface has no significant changes compared with the previous data, at low frequency (<4 KHZ), where the pressure ranges from -0.4 to +0.4 Pa, however at higher frequencies (>10kHz), the pressure varies from -0.2 to +0.2 Pa as shown in Figure 8 (b). Regarding surface pressure of the microphone, at medium and high frequencies changes are significant, due the sound wave impact is not directly into the ear canal (Figure 8 (a)).



(a) Eardrum average pressure



(b)Pinna average Pressure

Fig. 8: Average Pressure Distribution - Dorsal Source

4.3. 711 Microphone - eardrum analysis

The pressure distribution level in the microphone of the emulator 711 representing the eardrum using the reference sound pressure in air ($p_{ref} = 20\mu Pa$ (rms)) is calculated by:

$$L_p = 20\log\left(\frac{P_{rms}}{P_{ref}}\right)[dB] \quad (5)$$

The results shown below are further evidence of the difference in pressure distribution due to the direction of the emitted wave (Figure 9).

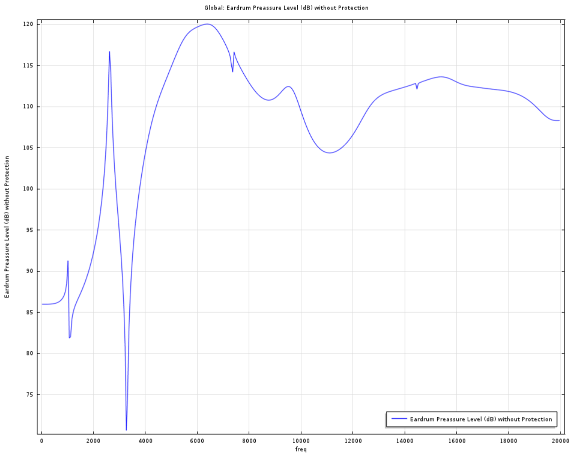


Fig. 9: Eardrum pressure level - Lateral Source

In dorsal analysis, doing a similar analysis with the microphone (eardrum), the instantaneous pressure distribution and the sound pressure level decreased considerably (Figure 10).

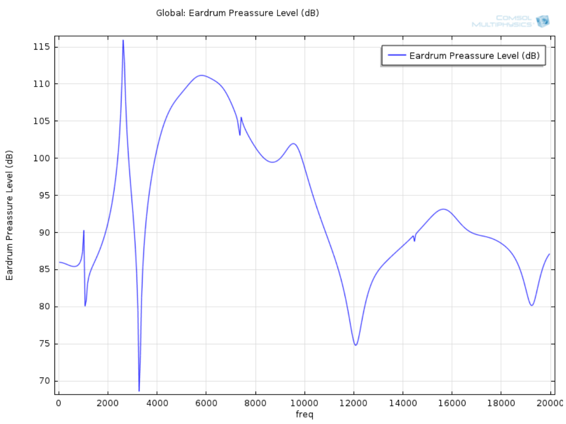


Fig. 10: Eardrum pressure level - Dorsal Source

5. CONCLUSIONS

This study served to simulate the pressure changes on the ear pinna surface coupled to the ear canal emulator, using finite element method. The free field conditions was represented by a box surrounding the pinna and used to implement external sound field from two directions activated independently, with the advantage of getting a better analysis of the sound pressure and the effects on the surfaces. To develop an optimal results,the acoustic module of COMSOL Multiphysics was used to analyze the pressure acoustics problems in the frequency domain.

In the first approach an external sound field from the lateral side was used. The pinna received the wave sound directly, however the average of the pressure on the surface does not present significant changes along the frequency range. Regarding to the values reached within the ear canal emulator (coupler), the corresponding pressure variation in the eardrum reaches values up to 18 $[Pa]$.

On the other hand, when the external sound field comes from the dorsal side, the variation range on the pinna surface does not vary significantly with regard to the previous results, except at high frequencies ($> 15[kHz]$) where the pressure tends to reach the value of pressure 0 $[Pa]$. The same phenomena is presented in within the ear canal, the eardrum pressure at high frequencies oscillates around 0 $[Pa]$ showing a considerable difference compared to the previous analysis, where the pressure at the same frequencies reached values up to 8 $[Pa]$.

The sound velocities in isosurfaces always point in the direction of propagation. Here the isosurfaces of pressure magnitude and phase and the wave fronts coincide. The phase isosurfaces almost exclusively depend on the shape of the ear canal and not on frequency.

In this paper, the inuence of the source on the sound eld in the pinna and ear canal is only investigated for external sound sources. The goal is to elucidate the characteristics of ear canal sound elds and to identify the limits of unidimensional approaches using finite elements. Hence, a deeper understanding of the characteristics of ear canal represented by a standard emulator coupler 711, can be useful in some applications, where the sound sources inuences has high signicance in the form of the eld. These sources can be positioned far or close to the pinna or in the case of different types of hearing aids they can act at the entrance or even within the ear canal.

6. REFERENCES

[1] H. W. R. Krer, G. Flege, "Artificial head for the electroacoustic recording of three dimensional sound field," Georg Neuman & Co, Audio Export, Tech. Rep., 1975.

[2] *Eletroacoustics - Simulator of human Head and ear. Part 4: Occluded-ear simulator for measurement of earphones coupled to the ear by means of ear inserts*, International Standard IEC 60318-4 Std., 2010.

[3] C. M. 4.4, "Generic 711 coupler: An occluded ear canal simulator," *Acoustic*, 2013.

[4] B. . Kjaer, *Microphone Handbook: For the Falcon range Microphone products*, 1995.

[5] R. B. Northrop, *Noninvasive Instrumentation and Measurement in Medical Diagnosis*, M. R. Neuman, Ed. CRC Press, 2002.