Evolution of human hearing simulation

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Abstract

More than 60 years ago, some of the first attempts was made to develop a simulation of the human hearing for objective measurement of devices placed close to the ear.

This paper provides an overview of the ear simulators that have been develop over the years and outlines how numerous refinements have continuously improved the simulation of the human hearing.

Some of the key features when dealing with hearing simulation involves the acoustic impedance and the geometry of the ear simulator. For the ear simulators that have been developed over the years these two features have been the primary focus in addressing the increasing need for realistic, accurate and repeatable acoustic measurements.

The paper also presents a new and standardized fullband ear simulator that provides unprecedented realism in audio testing, reduces the development time for new acoustic product and ensures product audio quality in the marketplace.

Introduction

The purpose of an ear simulator is to replicate specific properties of the human ear. Important features of an ear simulator are:

- Acoustic impedance
- Selection of measurement microphone
- Distribution of cavities
- Design of ear canal
- Simplified or human like pinna design
- Controlled leakage or sealed condition

Some of the first ear simulators intended for measurements of earphones were developed in the early 1960s. One of these early ear simulators was the Zwislocki coupler that are depictured in figure 1 together with the 2cc IEC coupler from the same time [1].

In the early 1980s the 711-coupler was established, and the actual design of the coupler was inspired by the Zwislocki coupler. Since the introduction of the 711-coupler [2] it has been used for various applications, such as characterization of hearing aids, earbuds, smartphones etc. Examples of how the 711-coupler are being used in different physical realizations as an ear simulator are shown in figure 2 and figure 3.

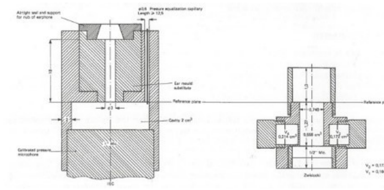

Figure 1: Two examples of ear simulators from the early 1960s. To the left the 2cc IEC coupler and to the right the Zwislocki coupler. In the Zwislocki coupler the location of the cavities can be observed as well as the cylindrical shaped ear canal. Detailed information is available in [1].

It should be noted that these designs are still in use, regardless that they were designed more than 30 years ago.

Over the years the work on ear simulators has been focus on providing simulation of adults. However, at the beginning of the 2010s the work on establishing an ear simulator family that would accommodate infants, babies, children, and adults was initiated in the European EMRP Ears and EMPIR Ears II projects. Among the outcomes of the projects were a prototype neonate ear simulator and a demonstrator ear simulator family for three different age groups, all intended for calibration of audiology equipment for hearing assessment, including hearing screening of infants [3,4,5].

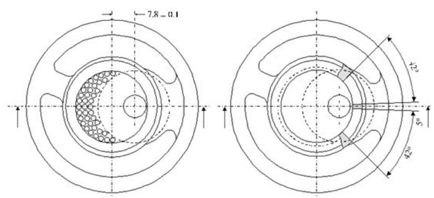

Figure 2: Two examples of a simplified pinna simulator with a controlled leakage taken from the ITU-T P.57 [6]. To the left a pinna simulator with high leakage and to the left one with low leakage. The two different leakages are simulating a handset held loosely against the ear and a handset held firmly against the ear. In both cases the 711-coupler is attached to the pinna simulator.

The ear simulators mentioned in this introduction represents a limited selection of the various ear simulators that have been developed over the last 60 years, however they each illustrates some of the important features of an ear simulator.

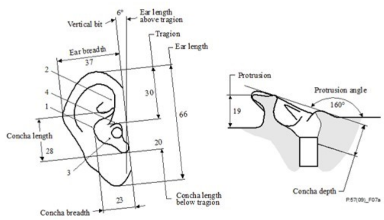

Figure 3: A human shaped pinna with a cylindrical shaped ear canal. With the 711-coupler attached to the pinna simulator it forms the Type 3.3 ear simulator. [7,8]

The Evolution of Hearing Simulation continues

An increasing need for more realistic simulation of the acoustic impedance, when measuring contemporary devices in super-wideband (16kHz) and fullband (20kHz) – poses an issue for the 711-coupler, because when it was established in 1981 the wideband (8kHz) performance was considered well suited for most applications.

Accommodating a realistic seating of in-ear devices, the cylindrical ear canal geometry of the 711-coupler, can be less suited for in-ear devices.

A more realistic ear canal and an acoustic impedance that would be valid for fullband application, constituted the starting point for designing the next generation ear simulator. The two task that had to be resolved was to accurately characterize the human ear over the full audio band by

- Determining an average adult human ear canal geometry using magnetic resonance imaging (MRI)
- Determining the corresponding average acoustic impedance for an adult human ear

How this could be accomplished in a research project that was initiated nearly 15 years ago are described in the following.

Average adult human ear canal geometry

Before enrolling a person in the project, the person would have to accepted to be informed about any signs of illness that would be discovered during the MRI scanning. Each person also had to have their ears cleaned to ensure that any earwax would have been removed prior to performing the scanning. They also had to confirm that they had normal hearing and that they would be willing to have their ear canal fill with a contrast agent (olive oil). The contrast agent was used to allow better definition of the soft areas, as can be seen in the scan in figure 4. More than 40 persons, mostly European, took part in the project. Both females (40%) and males (60%) were scanned, and the average age of those that participated was 39 years.

Figure 4: An MRI scan showing the entire ear canal of one of the persons that participated in the research project. A part of the concha is also clearly visible in the scan.

After completing the scanning, the MRI software extracted the 3D geometry data directly from the scans. From the 3D geometry data of the individual scans an average adult human ear canal was established using Shape Analysis. Figure 5 shows the average adult human ear canal that was later used as the ear canal in the new ear simulator. A center line together with numerous cross-section areas are used to describe the average ear canal. A reference plan for determining the average acoustic impedance is defined and illustrated by the red cross section area in figure 5.

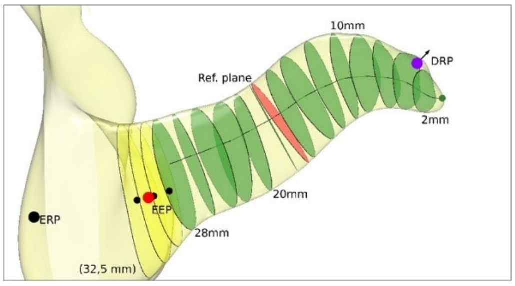

Figure 5: The average adult human ear canal geometry. To have a description of the ear canal that can be easily documented e.g., in a standard, a few cross-section areas are used. Cross-section areas in green colour relates to the ear canal geometry whereas cross-section areas in yellow colour relates the concha. The EEP marks the ear entrance point. The DRP marks the drum reference point.

Individual earplugs

The 3D geometry data was then utilized by a CAD program for creating the individual earplugs. The process that was applied is very similar to the process of creating small hearing aids (in-the-ear hearing aids). In figure 6 the 3D geometry of an ear canal and part of the concha is shown.

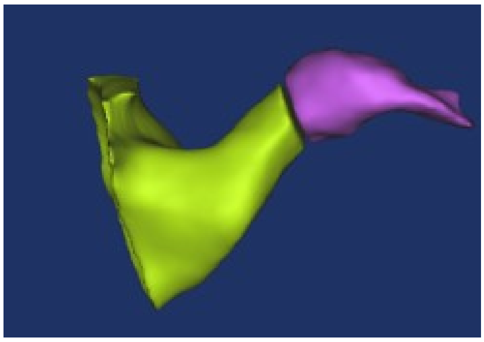

Figure 6: A 3D representation of the ear canal of one of the persons that participated in the research project. The part of the ear canal in green colour forms the basis for an individual earplug. The part of the ear canal in purple colour represents the inner section of the ear canal. The tip on the tympanic membrane is clearly visible.

To finalize the individual earplug two soft flexible tubes (figure 9, right) were embedded in the earplug, these would later be connected to the microphone arrangement (figure 8) prior to performing the actual measurements. The individual earplugs have been designed to terminated approximately 19mm (using center line) from the ear drum of each person.

Average acoustic impedance of an adult human

The microphone arrangement that was used for the measurements consists of two probe microphone (figure 8 lower left part of the photo) – one microphone is acting as a sound source and the other is used as a measurement microphone. To ensure proper measurement results several reference volumes (figure 8 upper part of photo) were needed to have sufficient information in the complete frequency range.

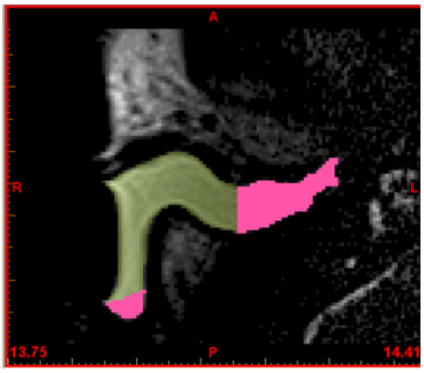

Figure 7: An MRI scan showing the entire ear canal of one of the persons that participated. The part of the ear canal marked in green shows the shape of an individual earplug. To the right in the photo the part that are marked in magenta colour represents the residual ear canal, when the earplug is placed in the ear canal. To the left in the photo the part that are marked in magenta colour represents the part of the concha that was removed during the making of the individual earplug.

Prior to the day where the person was scheduled for the measurement the person had to have their ears cleaned to ensure that any earwax would have been removed. If the person had a cold on the day where the measurement should be performed the measurement session were rescheduled. This was done to avoid an influence from a partly or fully blocked eustatic tubes.

Figure 8: The photo shows the microphone arrangement used for the measurements as well as the reference volumes required for the calibration of the microphone arrangement. In the photo one of the reference volumes are connected to the microphone arrangement via two soft flexible tubes.

In preparation for the measurements the person inserted the individualized earplug, while seated on a simple chair and with the bag supported against a wall. In this way a stable position could be maintained during the entire measurement session. After the person had inserted the earplug, the operator connected the earplug to the microphone arrangement via the soft flexible tubes embedded in the earplug.

Even though the measurements were performed in a normal quiet office room, a high signal-to-noise ratio was needed to achieve the required measurement quality. A measurement technique using a stepped sinusoidal as excitation, combined with a narrowband tracking filter made it possible to produce measurement results that had the required quality.

Figure 9: The photo shows a person where the microphone arrangement has been attached to the individual earplug. The individual earplug attached to the microphone arrangement and at the end of the earplug the two tubes can be observed.

The measurement data that had been acquired would then be used in the calculation of the actual acoustic impedance for each person. The graph in figure 10 shows the acoustic impedance that was calculated from the measurements of each of the persons. A large spread in the acoustic impedance can be observed. This spread is caused by a different measurement positions in each of the persons ear canal.

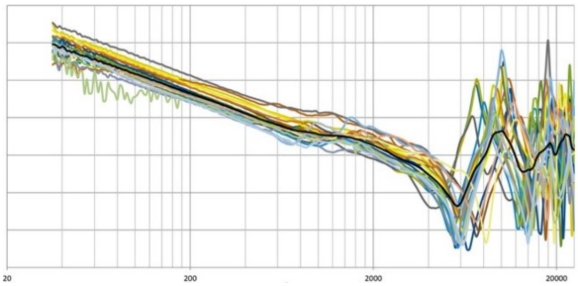

Figure 10: The graphs show the acoustical impedance for each person that were measured. The black graph shows the average acoustical impedance.

Using propagation simulation, the data was transformed to a common reference plane. This transformation reduces the spread and improve the alignment of the resonances as shown in figure 11. It is now sensible to determine an average acoustical impedance and used this as the target for the acoustic impedance of the new ear simulator.

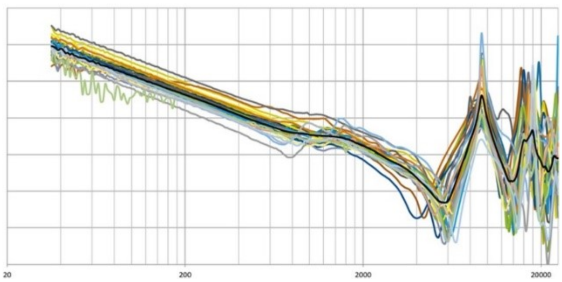

Figure 11: The graphs show the measurements that are found in Figure 10 after transformation. The black graph shows the average acoustical impedance.

The new ear simulator

Utilizing the knowledge that was established during the research work a new ear simulator with an average adult human ear canal geometry and a fullband acoustic impedance placed at the drum position could now be established.

In addition, the research produced knowledge on the soft to hard transition of the human ear canal as well as the oblique ear drum which are both features that are truly replicated in the new ear simulator (figure 12).

This new ear simulator has recently been standardized by ITU in ITU-T Rec. P.57 [6]. The application of the ear simulator in Head and Torso Simulator (HATS) has been standardized by ITU-T and are described in ITU-T Rec. P.58 [7].

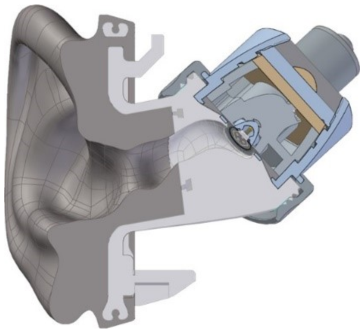

Figure 12: The photo shows how the ear simulator is realized. The pinna with concha that extends into the ear canal. At the ear drum position the measurement microphone is located and in the same plane as the diaphragm the acoustic impedance loading is provided.

Conclusion

It should be acknowledged that the 711-coupler for many years has served as the good simulation of an average adult human ear and that the industry have appreciated its performance and learned to understand its limitations.

With the new ear simulator that have been introduced in this paper, the hearing simulation is now entering a new era of unprecedented realism in audio testing.

Figure 13: A realization of the ear simulator in a HATS is commercially available. The two HATS configurations are named Type 5128-B-111 and Type 5128-C-111.

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