ACOUSTICAL IMPEDANCE OF EAR SIMULATORS AND THE REVISION OF IEC 60318-1

R Barham National Physical Laboratory, Teddington, Middlesex, UK

1 EAR SIMULATOR AND THEIR APPLICATIONS

Measurement of the acoustic output of headphones, telephone handsets, hearing aids and many other devices designed to be directly coupled (or closely coupled) to the ear, are usually carried out using ear simulators[1]. Ear simulators are devices that enable the acoustic output of a transducer to be measured objectively, while providing an acoustic load that approximates that of a nominal human (adult) ear. A range of different ear simulators are available commercially, each designed to suit a particular class of transducer and the variety of configurations used to couple them to a real ear. They can simulate either the whole outer ear or a closed (occluded) ear canal, down to the eardrum, and may or may not need to have the correct anatomical form, depending on the application. Two widely used ear simulators, often referred to as the *artificial ear* and the *occluded ear simulator*, are standardised by the International Electrotechnical Commission (IEC); in IEC 60318-1[2] and IEC 60711[3], respectively (IEC 60711 will be re-numbered as IEC 60318-4 when the current revision is complete). While this paper focuses on the artificial ear, the principles in determining acoustical impedance to be described, apply equally to the occluded ear simulator.

2 THE ARTIFICIAL EAR

The artificial ear is intended for the measurement of supra-aural and circumaural headphones (i.e. devices intended to be placed on the external pinna or on the head so as to surround the pinna, respectively). A commercial device[4], and a diagram showing the internal configuration is shown in Figure 1.

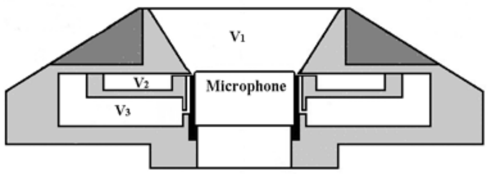


Figure 1. A commercially available artificial ear and illustration of its internal configuration.

In order to make a realistic measurement of the acoustic output of a headphone, it is important for the ear simulator to present the correct acoustical impedance. Acoustical impedance is the ratio of the sound pressure generated by a source, to the volume velocity it uses to produce the sound pressure. Headphones, being in general low acoustical impedance devices, tend towards behaving as constant volume velocity sources. The acoustic level they produce for a given electrical input, will therefore depend strongly on the acoustical impedance to which they are coupled. It is therefore important that the ear simulator has an acoustical impedance approximating that of nominal human ears. This is found to be quite complex in nature, but can be emulated in the ear simulator by the three coupled cavities seen in Figure 1. A lumped parameter representation is also included in IEC 60318-1.

3 REVISION OF IEC 60318-1

IEC 60318-1 provides a general specification for the electrical, acoustical and mechanical characteristics of the artificial ear, for use with supra-aural earphones. This is supplemented by IEC 30618-2[5] which specifies additional features to facilitate the measurement of circumaural headphones. While IEC 60308-1 specifies the acoustical impedance, it does not give a tolerance to enable devices to be tested for conformance. This issue together with a number of other new requirements are being addressed in the current revision of the Standard. The new aspects include:

- Consolidation of requirements in IEC 60318–1 and IEC 60318–2 into a single document
- Extension of the frequency range to 16 kHz
- Specification of measurement uncertainties for key parameters and measured quantities
- Introduction of a method for measuring the acoustical transfer impedance
- Specification of tolerances for the acoustical transfer impedance
- Revision of the lumped parameter description of the device

4 DEVELOPMENT OF A METHOD FOR MEASURING THE ACOUSTICAL TRANSFER IMPEDANCE

The last three points above needed underpinning by new research, the two main objectives of which were;

- to formulate and evaluate a new measurement procedure for the determination of the acoustical transfer impedance,
- to use the method to collect measurement data on a representative sample of real devices to enable a tolerance to be specified.

The nature of the objectives required a collaborative approach and the research was conducted by the National Measurement Institutes (NMIs) from Germany (PTB), Denmark (DPLA), France (LNE) and the UK (NPL) who piloted the project, and conveniently, also led the revision of the Standard. NMIs in Poland (GUM) and Russia (VNIIFTRI) also contributed to the development of the methodology.

The proposed method to be evaluated derives from reciprocity calibration of microphones[6], where typically two acoustically coupled devices are used. One microphone is then driven electrically and acts as a sound source and the other, used as a receiver, responds to the acoustic field created.

For a given volume velocity developed by the transmitter, the pressure resulting at the receiver position is determined by the acoustical transfer impedance coupling the two microphones. For close-coupled transducers, the pressure sensitivity of the transmitter microphone will determine the volume velocity produced for a given electrical current. Similarly the receiver microphone pressure sensitivity will determine the corresponding output voltage produced.

The arrangement then provides the basis for determining the acoustical transfer impedance of the ear simulator. Let the transmitter microphone, having a pressure sensitivity M_1, be driven by an electrical current *i*. If the acoustical transfer impedance of the ear simulator is Z_a, then by the chain of actions noted above, the output voltage U_2 of the receiver microphone system is given by

$$U_2 = M_2 Z_a . M_1 i \tag{1}$$

This relationship holds true whether the receiver system is considered to be the microphone capsule or the combination of a microphone, preamplifier and any other elements, provided M_2 corresponds to the pressure sensitivity of the whole system considered.

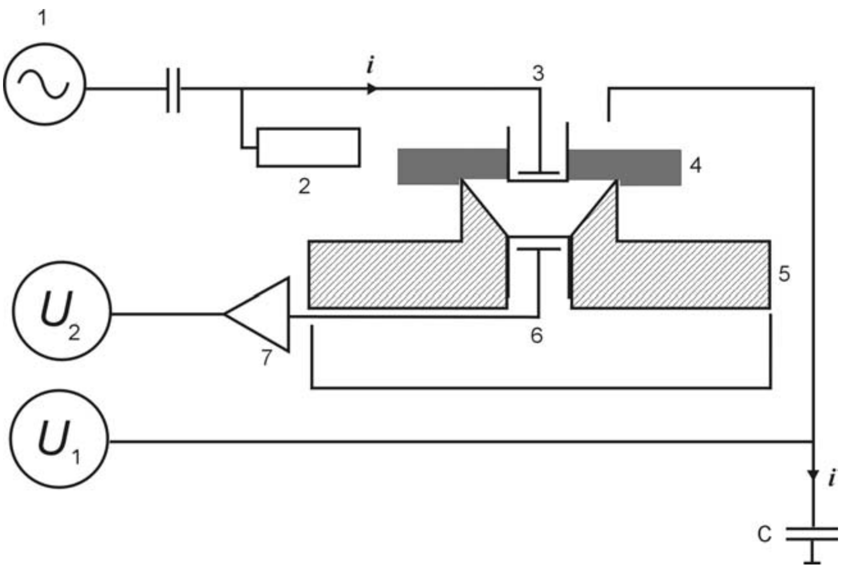
In practice the sensitivity of the transmitter microphone is taken to be its response as a receiver, while assuming that this particular device is reciprocal.
Then, directly from equation (1),

$$Z_a = \frac{1}{M_1 M_2} \frac{U_2}{i} \tag{2}$$

The practical requirements for adopting this approach are:

- having a means of calibrating the microphones at the range of frequencies, with a frequency resolution and an uncertainty appropriate for the acoustic transfer impedance,
- having a means of coupling a transmitter microphone to the ear simulator, to provide the acoustic stimulus,
- having a measurement system for determining the electrical transfer impedance.

Figure 2 shows a generalised equipment set-up for conducting the measurements necessary to implement equation (2).



Key
1 Signal generator
2 Microphone power supply
3 Calibrated transmitter microphone
4 Adapter (see Fig. 3)
5 Ear simulator under test
6 Calibrated receiver microphone (within ear simulator)
7 Microphone preamplifier and power supply

Figure 2 - Key elements of the measurement system

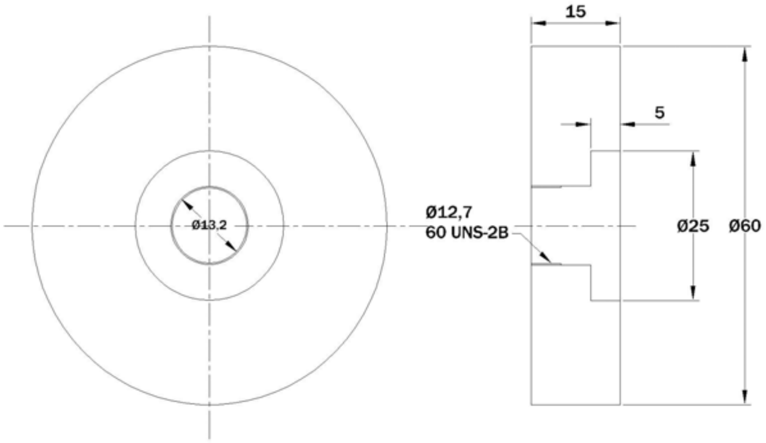
Here, the electrical current driving the transmitter microphone is determined by placing a known electrical impedance in series with the microphone, and measuring the voltage U_1 developed across it. Any type of stable electrical impedance element can be used, but a capacitor has the advantage that U_1 remains approximately constant as a function of frequency when a fixed voltage is used to drive the transmitter microphone.

In this case, and referring to Figure 2, equation (2) becomes,

$$Z_a = \frac{1}{M_1 M_2} \frac{U_2}{U_1} \frac{1}{j\omega C} \tag{3}$$

where ω is the angular frequency

The transmitter microphone is an IEC type WS2P having a nominal pressure sensitivity of approximately 12 mV/Pa, used without any protection grid in place. The microphone is mounted in a flat plate, such that the microphone diaphragm is flush with the face that couples to the ear simulator. This coupling surface is set in a shallow recess to facilitate reproducible coupling to the upper edge of the ear simulator. The microphone is placed concentrically in this recess. Figure 3 shows the adapter used.



Dimensions in millimeters

Figure 3 - Adapter to couple a transmitter microphone to the ear simulator

The receiver microphone is housed in the ear simulator and is fitted with its protection grid. The microphone and its preamplifier is calibrated as a system.

Output signals U_1 and U_2 are measured using a two-channel analyser. To reduce the effect of the measuring channel linearity, cross-talk etc. on the measurement uncertainty, the capacitance has been chosen so that $U_1 \approx U_2$, noting that the variation in the acoustical impedance with frequency, makes this possible only within an order of magnitude. Both microphones are type WS2P with nominal pressure sensitivities of 12 mV/Pa, so a capacitor having a nominal value of 100 nF is optimal.

The acoustical transfer impedance is sensitive to atmospheric pressure, which mainly influences the acoustical compliance of the volumes, and to the temperature which has greatest effect on the acoustical mass. The microphones will also have dependencies on the environment parameters. The measurements must therefore been corrected to reference environmental conditions using the lumped parameter model given in IEC 60318-1 as the basis.

Returning to the first item in our list of prerequisites above, there are a number of options for determining the sensitivities of the microphones. Primarily they include:

- reciprocity calibration if the microphones can be configured as laboratory standard types,
- comparison calibration according to IEC 61094-5,
- electrostatic actuator calibration according to IEC 61094-6.

Of these, electrostatic actuator calibration provides the best combination of frequency range, resolution, uncertainty and measurement convenience (run time, complexity etc.). However, there is nothing to preclude the adoption of other approaches.

5 RESULTS FROM PARTICIPANTS

Participants in this project were required to assemble and verify a system for the measurement of the acoustical impedance of an artificial ear, using the approach described above. After validating the performance of their system, they were then required to source and measure a sample of artificial ears in the frequency range 125 Hz to 16 kHz. Sample sizes ranging from 3 to 33 were reported.

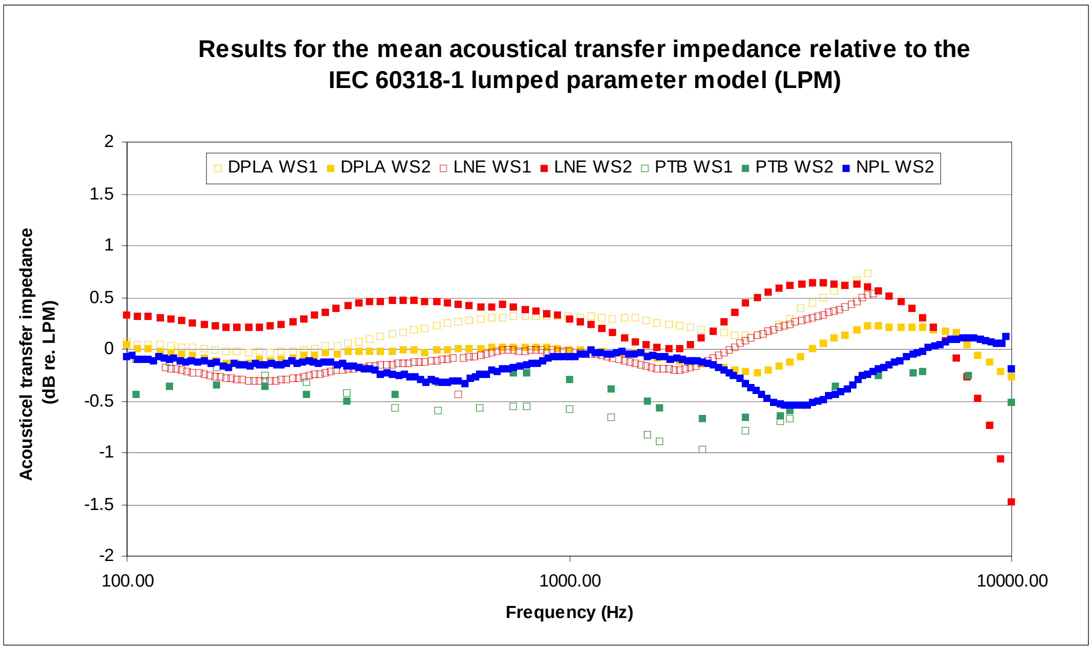


Figure 4. Graph of participant's results

Figure 4 shows the average acoustical transfer impedance data reported by each participant for their device sample. The data has been normailsed to the lumped parameter model for the device to reduce the scale and highlight the spread in the data. Some of these measurements were made with a WS1 transmitter microphone, which during the course of the project, was found to produce artifacts in the results above 5 kHz. However below this frequency, these results still provide useful data and have therefore been included above.

Participants also reported levels of repeatability in measurements on a single sample of around 0.1 dB, representing the measurement repeatability, and a typical spread in results across their measured samples of around 0.4 dB (regardless of sample size). Taken together, the data falls within a range of ±0.5 dB over the majority of the frequency range with limited instances of slightly greater spread. Taking the mean and standard deviation (SD) of the data shown in Figure 4 leads to a specification for the acoustical transfer impedance as shown in Table 1.

Frequency (Hz)	Acoustical Transfer impedance (dB re. 1 Pa s m^{-3})	SD (dB)
125	144.4	0.2
160	143.2	0.2
200	143.0	0.2
250	143.5	0.2
315	144.1	0.3
400	143.4	0.3
500	141.4	0.3
630	139.0	0.3
750	137.2	0.2
800	136.6	0.3
1000	134.4	0.2
1250	132.5	0.2
1500	131.4	0.3
1600	131.1	0.3
2000	131.0	0.3
2500	131.5	0.4
3000	130.8	0.4
3150	130.6	0.4
4000	128.4	0.4
5000	126.0	0.4
6000	124.0	0.3
6300	123.6	0.3
8000	121.0	0.2
9000	119.9	0.1
10000	118.5	0.6

Table 1. Grand mean for the acoustical transfer impedance.

6 CONCLUSIONS AND IMPACT

Through this collaborative investigation, participants have verified that the proposed measurement methodology is effective and have suggested further useful refinements that have arisen during the course of this work. This newly developed method is now embodied in the draft revision of IEC 60318-1.

The consolidated results from the participants, and the measurement uncertainty analysis that supported them, has led to the following recommendations for the revision of IEC 60318-1.

- The acoustical transfer impedance should be specified according to the data in Table 1.
- The maximum allowed measurement uncertainty should be 0.5 dB.
- The tolerance on the acoustical transfer impedance should be 1.5 dB.

The revision of IEC 60318-1 is in the final stages of the revision and should be published in 2008. The inclusion of a method for determining the acoustic impedance and the specification of a tolerance for this parameter will in future, enable devices to be tested for conformance, and ultimately improve the reliability of headphone measurements, in critical applications such as hearing assessment.

7 ACKNOWLEDGEMENT

The contributions of the various participating NMIs towards this work is gratefully acknowledged.

The author also gratefully acknowledge the financial support of the National Measurement System Programmes Unit of the UK Department for Innovation, Universities and Skills.

8 REFERENCES

1. PD 6545. Intended use of human head and ear simulators-guide. British Standards Institute. 2005.

2. IEC 60318-1. Simulators of human head and ear - Part 1. Ear simulator for the calibration of supra-aural earphones. International Electrotechnical Commission. 1998.

3. IEC 60711. Specification for occluded-ear simulator for the measurement of earphones coupled to the ear by ear inserts: International Electrotechnical Commission. 1981.

4. Brüel and Kjær Technical Review. No. 4 1961/No. 1 1962. Artificial ears (Part 1/Part 2).

5. IEC 60318-2. Simulators of human head and ear- Part 2. An interim acoustic coupler for the calibration of audiometric earphones in the extended high-frequency range. International Electrotechnical Commission. 1998

6. IEC 61094-2. Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique. International Electrotechnical Commission. 1992.