NPL
National Physical Laboratory

Report

NPL REPORT AC 6

Measurement of the acoustical impedance of artificial ears

A report on EURAMET Project 791

Richard Barham,
Knud Rasmussen,
Thomas Fedtke,
Dominique Rodrigues and
Tomasz Zmierczak.

NOT RESTRICTED

JULY 2008

MEASUREMENT OF THE ACOUSTICAL IMPEDANCE OF ARTIFICIAL EARS

Richard Barham. Quality of Life Division, NPL, Teddington, UK

Knud Rasmussen. DPLA-DFM, Lyngby, Denmark
Thomas Fedtke. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany,
Dominique Rodrigues. Laboratoire National de Métrologie et d'Essais, Trappes, France,
Tomasz Zmierczak. Central Office of Measures, Warsaw, Poland.

ABSTRACT

Ear simulators are measuring instruments for the objective evaluation of the acoustical performance of earphones and other devices designed to be coupled acoustically to human ears. A device, often referred to as the artificial ear, is used widely in audiometry, telecommunications and audio engineering, and its specification is given in IEC 60318-1. This document is currently under revision by IEC to include: an extension of the frequency range to 16 kHz, assimilation of the scope of IEC 61318-2 for the measurement of circumaural headphones, and most significantly, a method for determining the acoustical impedance. This report describes collaborative research that has been conducted by five European National Metrology Institutes to establish a new measurement method. This method has been used to produce normative data for the acoustical transfer impedance as well as the corresponding measurement uncertainty. The report then recommends a new specification for the impedance and its tolerance, as well as consequential changes to the associated lumped parameter model.

ISSN 1754-2936

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of the Managing Director, NPL
by Dr Martyn Sené, Director, Quality of Life Division

CONTENTS

1. BACKGROUND TO THE PROJECT

Ear simulators are measuring instruments for the objective evaluation of the acoustical performance of earphones and other devices designed to be coupled acoustically to human ears. They exist in many forms to cover a wide range of applications and different types of transducer[1]. One of the most widely used devices is the so-called 'artificial ear'. It is designed to present an earphone with the same acoustic impedance as an average human ear, providing a realistic objective means of measuring the output of that earphone. The electroacoustic characteristics of the artificial ear are fully specified in IEC 60318-1[2], including data on the requisite acoustic impedance. However, this standard does not currently specify tolerances for these values or a measurement method, making it impossible for this parameter to be verified by test laboratories.

IEC 60318-1 is currently under review within IEC TC29. The review is considering expansion of the current document to include:

- an extension of the frequency range to 16 kHz
- integration of the scope of IEC 61318-2 for the measurement of circumaural headphones
- a revised specification for the acoustical impedance including tolerances for the first time
- specification of a method for determining the acoustical impedance

The last two points in particular need to be underpinned by new research, the two main objectives of which are:

1) to evaluate the proposed measurement procedure given in the draft revised Standard and investigate a number of issues that have been identified, to help refine the method.
2) to collect measurement data on the acoustical impedance of a representative sample of real devices that will contribute to the data to appear in the revised Standard.

This collaborative research project has been formulated to address these two objectives. The output from the project will feed directly into the revision process for IEC 60318-1, which conveniently, is also being led by the pilot laboratory.

The project was proposed at the 2004 meeting of TC-AUV Sound-in-Air subcommittee, in Vienna. Participation in the project has varied, but those finally contributing data were

- National Physical Laboratory (NPL), UK (project proposer and pilot laboratory)
- Danish Primary Laboratory for Acoustics (DPLA), DK (who originated the idea for the project)
- Physikalisch-Technische Bundesanstalt (PTB), DE
- Laboratoire National de métrologie et d'Essais (LNE), FR
- Główny Uząrd Miar (GUM), PL

In addition, VNIIFTRI (RU), although they did not take part in the measurement trials, provided some data on the potential effect of the presence of the microphone grid.

2. REQUIREMENTS FOR PARTICIPATION

Participants in this project were required to assemble and verify a system for the measurement of the modulus and phase of the acoustical impedance of an artificial ear, based on a generic description of a system included in the project protocol. Participants were invited to develop their own implementation of the system or indeed develop a completely different approach capable of producing the required data. In the end, all participants developed their own implementation of the suggested system.

Participants were also required to have access to a small sample of artificial ears for test (three or more devices). Experience at NPL has shown that many owners/users of artificial ears have been willing to make their device available for test, if they receive information about the impedance of their device in return. This has therefore been shown to be an effective means of building a large set of data.

After validating the performance of their system, participants were required to measure the modulus and phase of the acoustic impedance of their sample of artificial ears, in the frequency range 125 Hz to 16 kHz. Since the acoustic impedance has a strong frequency dependence, measurements at $1/12^{th}$-octave, or smaller, intervals were specified.

Finally participants were requested to conduct an uncertainty analysis of the method used to gather the data and estimate their overall measurement uncertainty.

Each participant has delivered an informal report to the pilot laboratory describing the method and instrumentation used. A brief review of each system is given below.

2.1 ADDITIONAL INVESTIGATIONS

A number of details about the precise implementation of the proposed method also needed investigation. The project protocol therefore posed a number of questions for any participant that had the resources to investigate them. They were:

Q1) *What is the influence of the microphone grid on the impedance?*

A current requirement of IEC 60318-2 is for the microphone in the artificial ear to have the LS2 configuration for use above 10 kHz. Users would prefer to leave the grid in place, or have a way of adapting the existing WS2 microphone rather than needing a separate LS2 microphone for high frequency operation. It was suggested that the possibility of leaving the grid in place, or using an alternative to the LS2 configuration, could be investigated by measuring the impedance of an artificial ear fitted with

a) a microphone with grid,
b) the same microphone without a grid (this is already known to suffer resonance problems, but was worth including in the series of measurements for completeness),
c) a microphone with LS2 configuration (if the original microphone is a B&K type 4134 there is the possibility to use it with a UA0825 adaptor),
d) a microphone fitted with a specially made adaptor designed to fill the annular slot around the side of a microphone when the grid is not fitted.

Q2) *What is a suitable specification for the transmitter microphone?*

Tests had already been conducted with WS1 and WS2 microphones. While WS1 microphones give better signal-to-noise ratio, their frequency range is limited. The effect of this is also apparent in results for the acoustical impedance of an artificial ear above 8 kHz. The options are to use: (a) low sensitivity WS2 microphone, (b) a high sensitivity WS2 microphone or (c) a WS3 microphone.

These alternative transmitter microphones could be accommodated in the transmitter microphone coupling adaptors that were already in circulation, using readily available Brüel & Kjær adaptors DB0225 and DB0264 (e.g. as supplied with the Brüel & Kjær type 4143 reciprocity apparatus). In addition, pressure and free-field versions of these microphones present different acoustical impedances, which provided a further dimension to be investigated.

At the outset, it was already known that there were issues with using a WS1 transmitter microphone. Participants were therefore recommended to make measurements with at least WS1 and WS2 microphones where possible. Those conducting their measurements in the latter stages of the project were subsequently advised that they only need concentrate on the WS2 transmitter microphone after it became clear that the WS1 was unsuitable above 8 kHz.

In addition to these questions, NPL conducted an investigation on the cause of the discrepancy above 8 kHz when a WS1 microphone is used, and DPLA investigated the effect of the location of a WS2 transmitter microphone, using a special adaptor that enabled eccentric positioning of the transmitter microphone. DPLA also conducted a study on the expected dependence of the acoustical impedance on temperature and atmospheric pressure, based on the dependence of the acoustical impedance elements on these parameters.

The outcome of the additional investigations are detailed below.

3. FACILITIES DEVELOPED BY THE PARTICIPANTS

Appendix A gives an outline of the generalised method that has been prepared for inclusion in the revision of IEC 60318-1. Information on how the participants have chosen to implement this method is provided below. Appendix A also describes a new adaptor that facilitates coupling of a transmitter microphone to the ear simulator (in place of the usual headphone). Brüel & Kjær kindly manufactured a number of these adaptors for this project, and an example is shown in Figure 1.

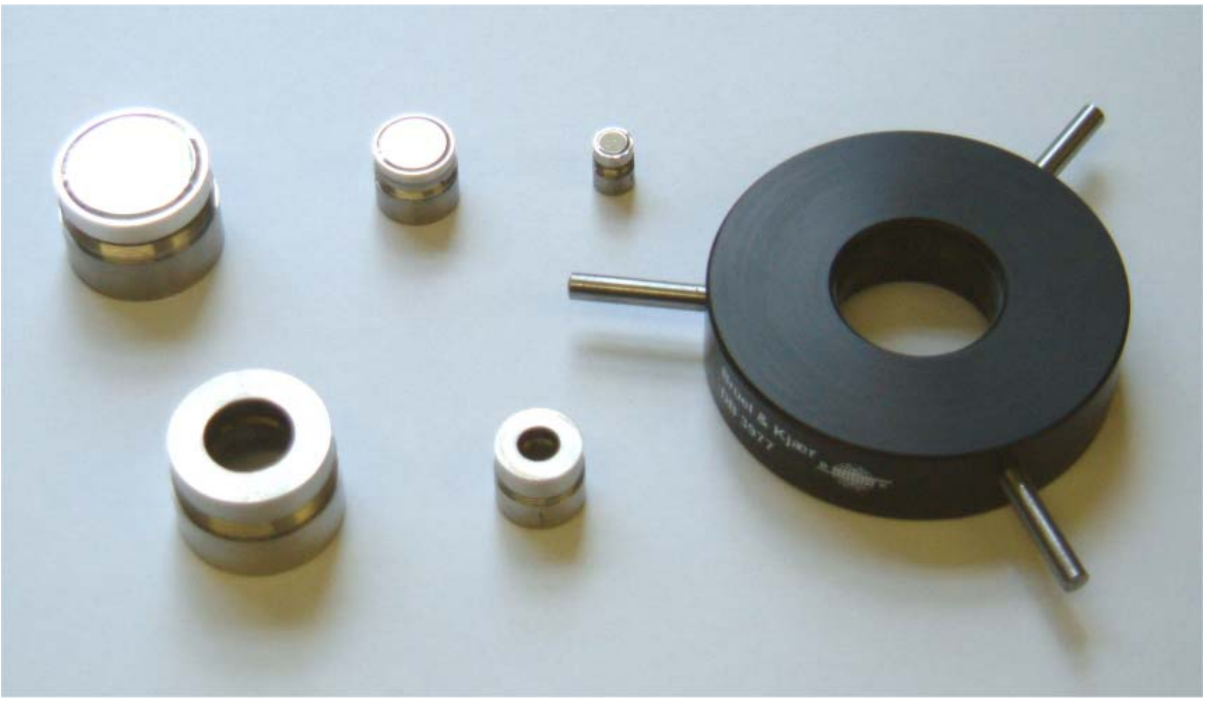


Figure 1. Adaptor for coupling the transmitter microphone to the upper rim of the ear simulator (Brüel & Kjær type DB 3977) together with various microphone & adaptor options.

3.1 NPL

A purpose built microphone transmitter was constructed using the casing and parts from an insert voltage preamplifier. The microphone (B&K type 4134 used without grid and with DB 0225 adaptor) was fitted to the supplied transmitter adaptor and coupled to the upper rim of the ear simulator. The receiver microphone (B&K type 4134) was fitted in the ear simulator as normal. The same calibrated receiver microphone system was fitted into each ear simulator in turn and was used in all the measurements. Both microphones were calibrated, the transmitter microphone by reciprocity, and the receiver microphone system (including its preamplifier) by comparison. The transmitter current was measured by passing the signal through a capacitance of 100 nF connected in series with the microphone. The complex ratio of receiver microphone output voltage to the voltage across this capacitor, was then measured using a Brüel & Kjær Pulse 2-channel analyser. A stepped-sine analysis was carried out at 1/24th-octave intervals, and repeated three times for each device tested. Polynomial fits to the frequency responses of the microphones were also established to provide the microphone sensitivity levels at the frequencies in between the third-octave centre frequencies where the calibrations were carried out.

Four ear simulators were measured for this particular project. However, NPL has in the past measured a sample of 33 devices. These measurements were conducted with a consistent, although not the latest, methodology. Therefore, while the absolute values of the measured impedances cannot now be used, the spread in the data from this large sample can still be considered representative.

3.2 LNE

Using the supplied transmitter microphone adaptor, the ear simulator was integrated into the Brüel & Kjær reciprocity calibration apparatus type 5998. This was then connected to Solartron Schumberger type 1250 vector analyser, which performed the voltage ratio measurement. A Brüel & Kjær type 4144 microphone was used as transmitter and type 4180 as receiver, for the initial measurements. However a second phase of measurements were conducted at the request of the pilot laboratory, using Brüel & Kjær type 4192 transmitter and receiver microphones. Measurements were carried out with a frequency resolution of 1/12th octaves from 19.95 Hz to 10 kHz and repeated five times for each ear simulator. The microphone orientation was rotated between measurements.

3.3 DPLA

The complex acoustical transfer impedances of a number of B&K type 4153 ear simulators were determined in 1/12-octave steps from 20 Hz to 30 kHz. The measurements were performed using essentially the same method and equipment used routinely when determining the ratio of the open circuit output voltage of the receiver microphone to the current through the transmitter microphone during the reciprocity calibration of microphones. However, in order to allow an insert calibration of the receiver microphone in this case, the ear simulator had to be separated from its usual wooden base. This modification introduced a small leak which resulted in an error of about 1 dB in magnitude and 15 degrees in phase at 20 Hz. No attempt was made to eliminate these errors.

The frequency responses of the microphones were determined by an electrostatic actuator method, yielding both the modulus and phase. The absolute sensitivity at 250 Hz was taken from the calibration sheet supplied by the manufacturer. In addition, a few WS1 microphone sensitivities were checked by use of a pistonphone. It should be noted that the actuator response is different from the pressure sensitivity due to the mutual influence of radiation impedance and microphone impedance. This is particularly the case for type WS1 microphones. These actuator to pressure response differences are known for the types of microphone used, and were applied to the actuator responses to determine the pressure sensitivity of the microphones. The acoustical transfer impedance of the ear simulator under test was then calculated by dividing the electrical transfer impedance by the corrected sensitivities of the microphones. The measurement results were also corrected so that the transmitter microphone source impedance, was not included in the resulting data for the transfer impedance of the ear simulator under test.

3.4 GUM

Measurements were carried out by adapting the GUM reciprocity apparatus. The transmitter microphone and supplied adaptor was fitted to a bespoke transmitter unit which required the transmitter microphone to be upward facing. The wooden bases of the ear simulators had to be removed so that the instruments could be positioned in an inverted configuration with the receiver microphone and preamplifier sitting on the upper side of the assembly (see Figure 2).

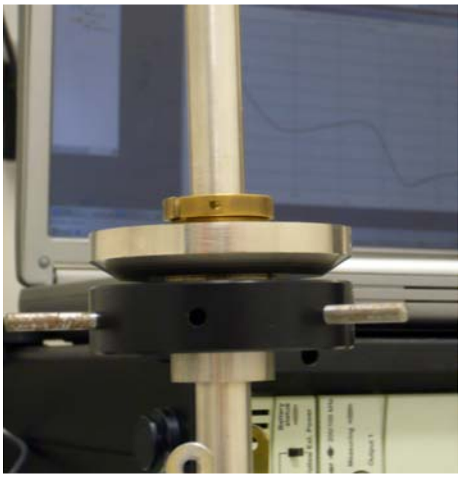


Figure 2. Measurement configuration for coupling the transmitter and receiver microphones to the ear simulator under test.

The current driving the transmitter microphone was then measured using the resistor box normally used for reciprocity calibration, but with a 100 nF capacitor added in parallel with the highest resistor in the set (1 MΩ). This resistance has a negligible effect on the combined electrical impedance in the frequency range of interest, but its value was nevertheless included in calculations. The voltage yielding the transmitter current and the microphone output voltage were measured independently using two lock-in amplifiers EG&G model 5209. The measurements were run under computer control over a frequency range of 125 Hz to 16 kHz with a resolution of 1/12th octaves.

GUM also investigated the potential of measuring the acoustical impedance of the ear simulator by comparison with a cylindrical coupler of very well defined acoustical impedance. This method is to be reported separately in the future.

3.5 PTB

PTB followed the method suggested in the protocol with the following implementation. The WS2 receiver microphone was a B&K type 4134 and both WS1 and WS2 transmitter microphones were used (B&K type 4144 and type 4134 with adaptors UA-1434 and DB 0225). The voltage ratio (see Equation (A3)) was measured by means of a frequency response analyser Solartron type 1255 with an integration time of 5 seconds for frequencies up to 8 kHz and of 3 seconds for higher frequencies. A transmitter unit B&K ZE 0796 was used to drive the transmitter microphone, the calibrated measurement capacitor having a value of 4.741 nF. The transmitter unit was connected to a modified microphone front-end Norsonic 336 which was used to provide power to the transmitter unit and also the polarisation voltage for the transmitter microphone. The selected driving voltages were 1 V r.m.s. for the WS1P transmitter microphone and 3 V r.m.s. for the WS2P transmitter microphone in order to achieve a sufficient sound pressure level in the ear simulator cavity. The transmitter adaptor B&K DB 3977 was fixed to the ear simulator under test by means of three rubber bands.

4 RESULTS AND DISCUSSION

Before discussing the principal results for the acoustical impedance, it is necessary to consider the findings of the additional investigations as these have a bearing on the validity and interpretation of the acoustical impedance data.

4.1 TRANSMITTER MICROPHONE TYPE

DPLA carried out a series of measurements to investigate the effects of different transmitter microphone types. Initially WS1P and WS1F transmitter microphones were compared and the results can be seen in Figure 3.

.

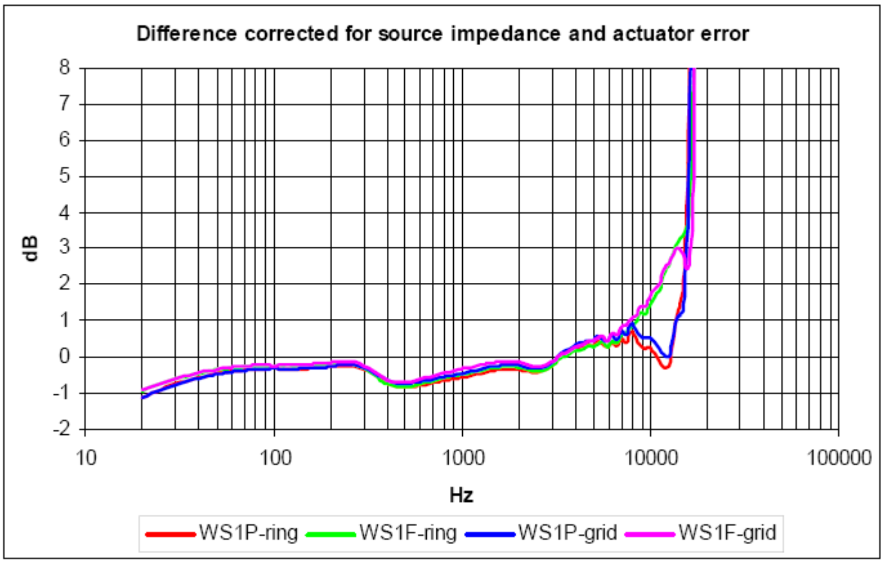


Figure 3. Difference between measured acoustical transfer impedance (magnitude) and lumped parameter model for various combinations of transmitter microphone (type WS1P or WS1F) and receiver configuration (protection grid or ring), corrected for the influence of the finite source impedance and the actuator to pressure response difference.

WS1P and WS1F transmitter microphone types gave consistent results for the acoustical impedance of the ear simulator up to about 6 kHz. However above this frequency systematic differences are observed which cannot be accounted for. It is believed to arise from an insufficient determination of the actuator to pressure sensitivity response difference. The true pressure sensitivity for a WS1 microphone cannot easily be determined above 8 kHz. Aside from these calibration difficulties, all participants have found that the use of a WS1 transmitter microphone produces results which deviate significantly from the lumped parameter model at higher frequencies, making the use of WS1 microphones unsuitable.

While a WS2 transmitter microphone appears to be a better choice, there are many more options available with high and low sensitivity versions as well as P, F and D frequency responses. Again DPLA were able to measure a representative selection of WS2 transmitter microphones, but found no systematic differences between them. This is because the acoustic impedances of all the microphones are sufficiently high so as not to influence the results significantly.

The use of a WS2 microphone has the additional benefit of making it possible to position the microphone asymmetrically on the ear simulator, and thus potentially to avoid the excitation of radial modes. To investigate this possibility, DPLA produced a special holder, as shown in Figure 4, allowing the microphone to be centred or displaced to the edge of the opening of the ear simulator.

Figure 4. Transmitter microphone mounting for asymmetrical positioning

Results for a selected WS2 transmitted microphone are shown in Figure 5. Note that the receiver microphone configuration was also studied as part of this series of measurements (see below).

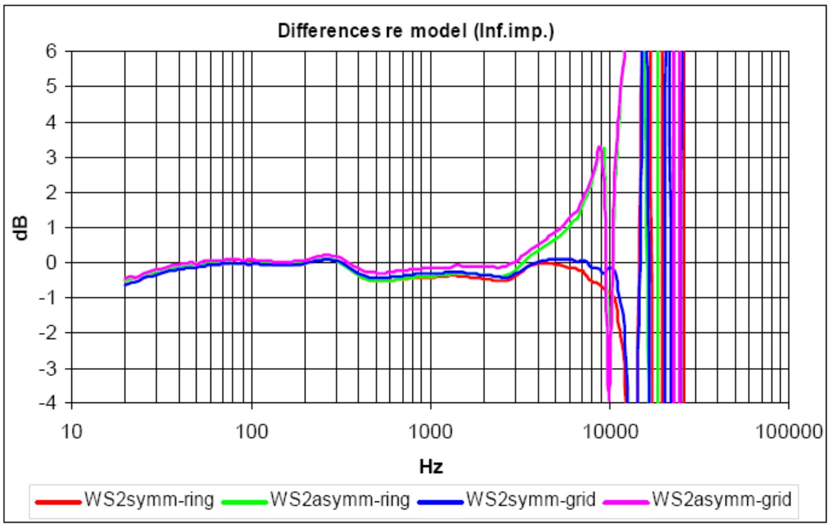


Figure 5. Difference between measured acoustical transfer impedance (magnitude) and lumped parameter model for a WS2 transmitter microphone positioned both symmetrically and asymmetrically. The receiver microphone was fitted either with a protection grid or with a LS2 ring.

Though not evident in the graph above, observations during the measurements indicated that radial modes around 18 kHz, 25 kHz and 30 kHz are significantly suppressed by offsetting the transmitter microphone. However, as *can* be seen, this also caused a mode at around 10 kHz to be strongly excited, which prevents this configuration from being used.

The conclusion of the study on different types of transmitter microphone is therefore to use any type of WS2 microphone located centrally within the transmitter adaptor.

4.2 RECEIVER MICROPHONE CONFIGURATION

NPL, DPLA and PTB all investigated the effect of different receiver microphone configurations on the measured acoustical impedance achieved by fitting different grids and adaptors to a single receiver microphone. Figure 6 shows a typical range of grids and ring adaptors.

Figure 6. Selection of grids and ring adaptors, including a straight cylinder (far right)

As is evident from Figures 3 and 5 above, all laboratories found no significant difference between results obtained with the use of production rings and grids available from manufacturers. However, one configuration of particular interest was the straight cylinder, since this provides a potential alternative to the LS2 receiver microphone configuration currently specified for high frequency use of the artificial ear. Unfortunately, this configuration still leaves annular gaps between the sides of the adaptor and the microphone within. These gaps are known to interact with the compliance of the ear simulator cavity, causing unwanted resonances.

The conclusion of the study on different types of receiver microphone configuration is that any type of grid or ring specified by the manufacturer for use with the particular receiver microphone can be used.

Since the optimum measurement configuration was determined as a result of measurements made in the early stages of the project, participants who conducted their measurements early on in the project used a variety of configurations, in some cases using only WS1 transmitter microphones. These participants were therefore invited to conduct a second series of measurements, according to an additional protocol, using the optimum configuration.

4.3 RESULTS FOR THE ACOUSTICAL IMPEDANCE

Having established the transmitter and receiver microphone types and configurations that yield consistent results, we are now in a position to examine the measurement results provided by the participants.

Each participant measured between 3 and 33 devices and reported the results for individual devices as well as the mean value. The typical standard deviation of measurements by a given participant was 0.1 dB.

Figure 7 shows all of the mean results submitted by participants. These results have been corrected for the input impedance of the transmitter microphones, but are otherwise uncorrected. The reported data has been plotted in terms of the difference from the acoustical impedance specified in the current version of IEC 60318-1. Results for both WS1 and WS2 transmitter microphones are shown where available.

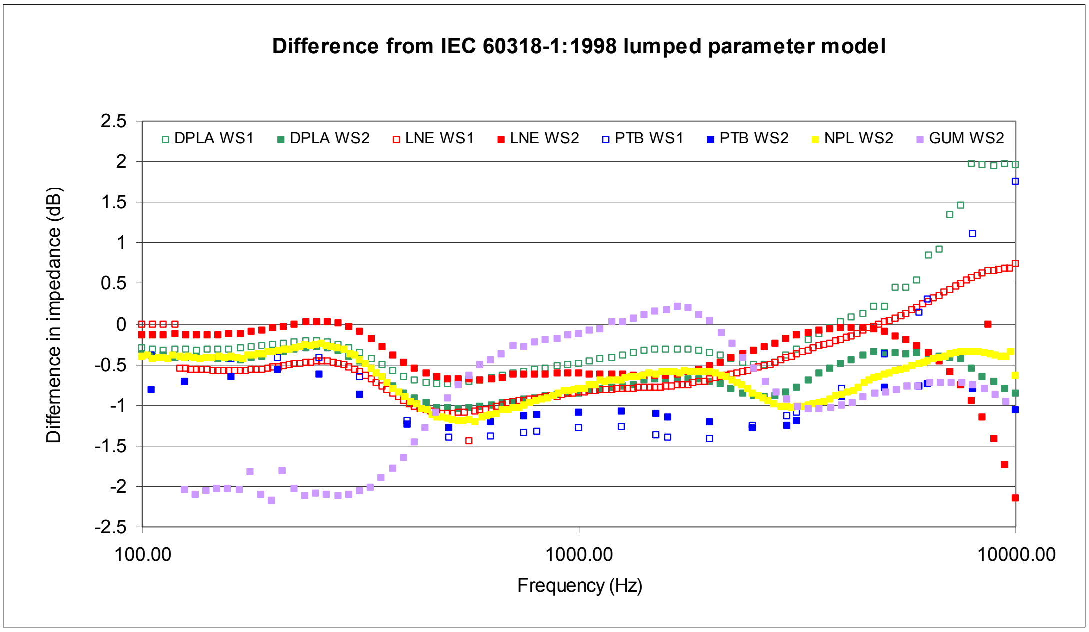


Figure 7. ‘Raw’ data submitted by participants

It is possible to make some immediate observations about these results

The data from GUM clearly has a systematic offset in the first region of the response. This is still the subject of further investigation, and for this reason, the GUM data has been discarded from further analysis.

The combined results confirm the deviations in impedance when a type WS1 transmitter microphone is used. All responses measured with WS1 transmitter microphones show the same trend. However, comparison with responses measured with WS2 transmitter microphones, show that the WS1 data is valid up to approximately 5 kHz. It was therefore decided to make use of this data in the analysis.

There is a clear systematic difference between the measurement and the lumped parameter model from IEC 60318-1:1998. Although the data has not yet been corrected for the environmental conditions during the measurements, some of the measurements were conducted close to reference conditions, so the influence of the environmental parameters cannot be the cause of the differences. In addition, the differences are unlikely to originate from the equipment used to implement the experimental method, because each laboratory used different instrumentation. Indeed, in some cases the same equipment used regularly to perform primary microphone calibration was used, and the performance of such systems have been thoroughly validated[3,4]. A second more likely possibility is that the lumped parameter model does not properly represent real artificial ears. This could perhaps be because their dimensions do not conform to the specification, but it is more likely to be because the stated dimensions do not give rise to the specified impedance.

The source of the problem is that while the standard specifies both the volume of the cavities and their effective acoustical compliance, based on $C_a = V/\gamma P_0$, it does not specify the shape the cavities are to have. In the particular design used in all commercially available devices, some of the cavities have a relatively large surface area for the given volume, leading to a degree of heat conduction that compromises the adiabatic assumption on which the simple relationship between the compliance and the volume is based. Given that the shape and geometry of the artificial ear is now effectively fixed by the large number of devices that exist, it therefore seems necessary to redefine the corresponding acoustical impedance, still in terms of lumped parameters, based on the measurement data.

Before attempting this, it was necessary to correct the measurement data to reference environmental conditions, based on the lumped parameter representation of the acoustical impedance. The lumped parameters used in the model have environmental dependencies; the acoustical compliance is a function of static pressure, the acoustical mass is a function of both static pressure and temperature, and the acoustical resistance is a function of the square root of temperature (where temperature is given in kelvin). The dependencies are sufficient to require the environmental conditions to be monitored during a measurement, and corrections made where necessary. The corrections were determined by calculating changes in the lumped parameter acoustical impedance at reference conditions after correcting each parameter as follows:

Parameter	Correction
Acoustical compliance	$P_0/(P)$
Acoustical mass	$P_0/(P) \, . \, (T_0+23)/(T_0+T)$
Acoustical resistance	$((T_0+23)/(T_0+T))^{1/2}$

where P and T are the prevailing static pressure and temperature during the measurements, measured in pascals and degrees celcius respectively and P_0=101325 Pa, T_0=273.

Figure 8 shows the magnitude of the correction of a 1°C and 3 kPa variance from the reference environmental conditions.

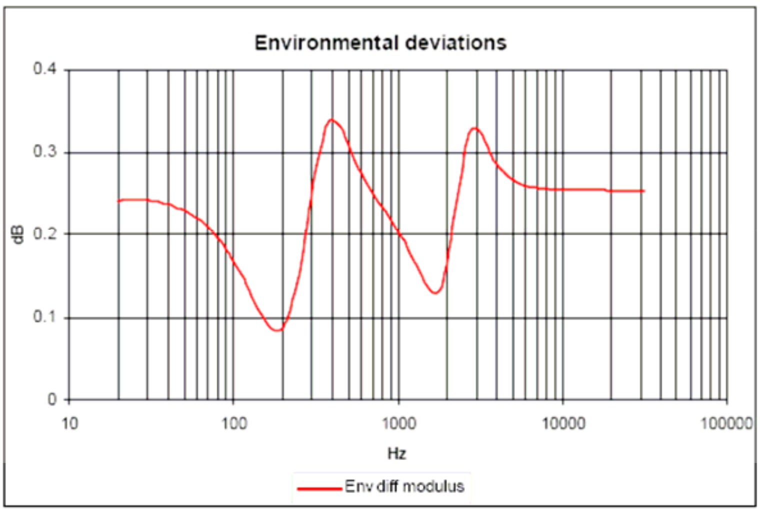


Figure 8. Correction to the lumped parameter model acoustical impedance for a 1°C and 3 kPa variance from the reference environmental conditions.

Figure 9 shows the result of applying corrections based on these environmental dependency calculations. Note also that the data from GUM and data measured with a type WS1 transmitter microphone above 5 kHz, is not shown.

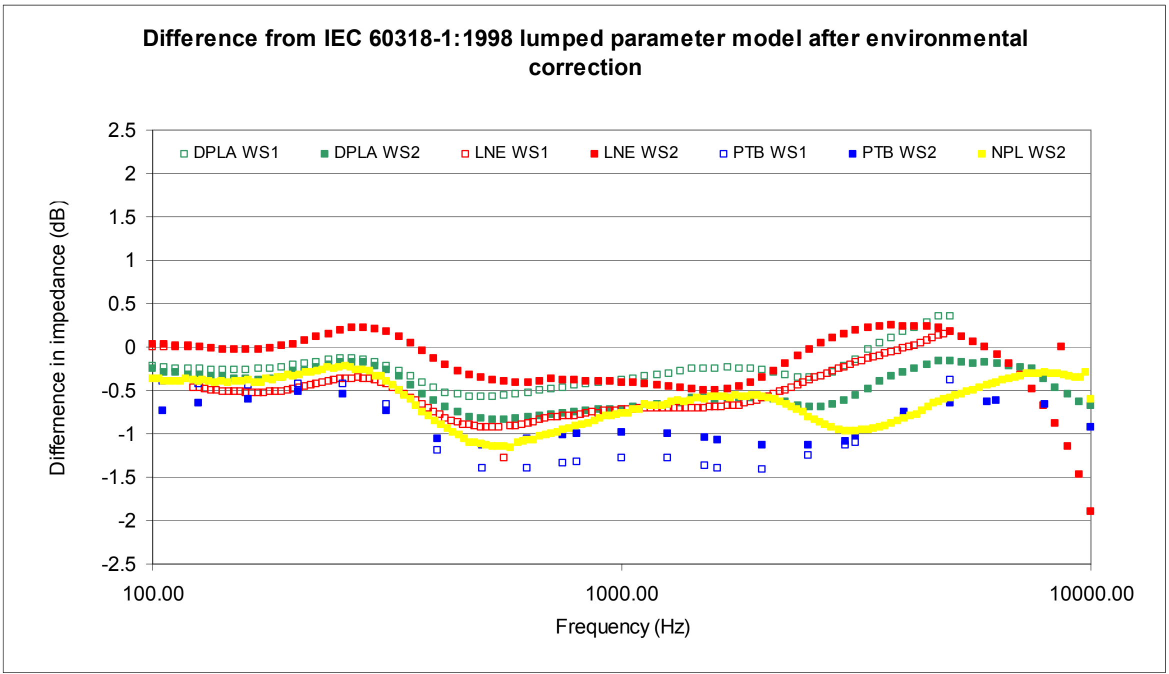


Figure 9. Selected data corrected for variation from reference environmental conditions

The data shown in Figure 9 was the basis for modifying the acoustical impedance lumped parameters to optimise the level of consistency between the measurements and the model. The optimisation process was carried out by inspection. The general variance in the data, the number of parameters involved and the ultimate precision with which it is necessary to specify these parameters, did not warrant a rigorous data fitting approach in this instance. Figure 10 shows the data re-plotted against the optimised lumped parameter model. The new lumped parameters needed to obtain this degree of consistency (and the percentage changes relative to IEC 60318-1:1998) are shown in Table 1.

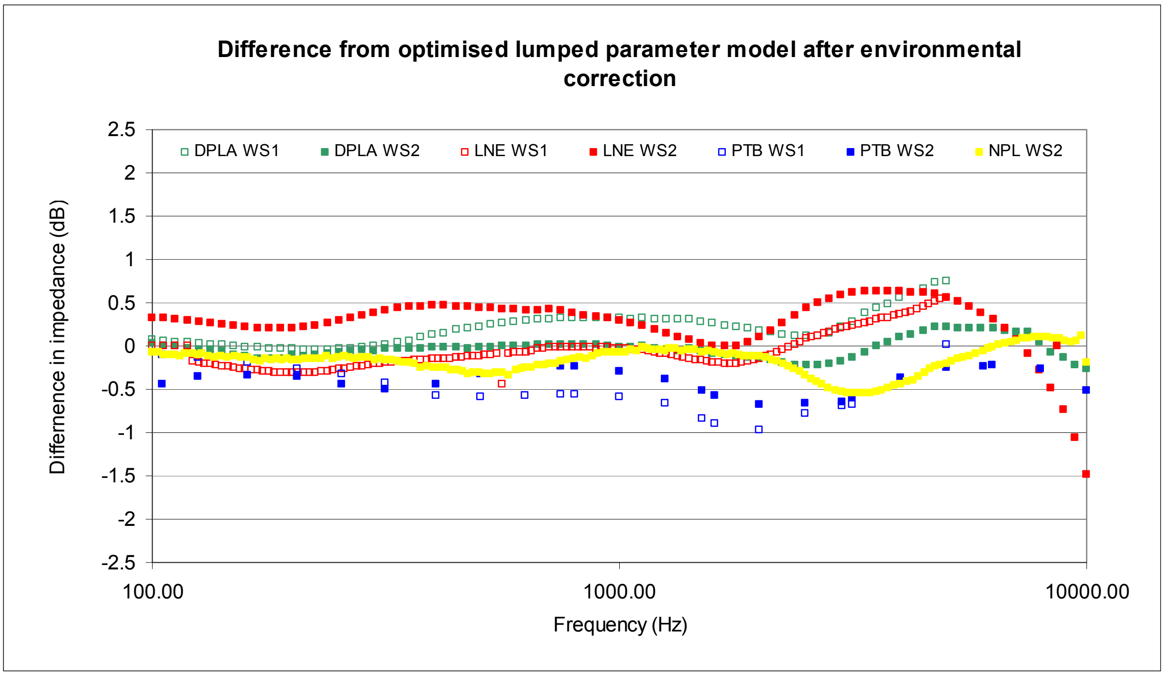


Figure 10. Measurement data relative to the optimised LPM.

IEC 60318-1	Compliance		Mass		Resistance	
	Ca1	1.76E-11			Ra1	500000000
	Ca2	1.27E-11	Ma2	500	Ra2	6500000
	Ca3	5.28E-11	Ma3	10000	Ra3	20000000

Optimised	Compliance		Mass		Resistance	
	Ca1	1.848E-11			Ra1	500000000
	Ca2	1.435E-11	Ma2	450	Ra2	6045000
	Ca3	5.28E-11	Ma3	10600	Ra3	20000000

Change (%)	Compliance		Mass		Resistance	
	Ca1	105			Ra1	100
	Ca2	113	Ma2	90	Ra2	93
	Ca3	100	Ma3	106	Ra3	100

Table 1. Optimised lumped parameters

While the lumped parameter model serves as a useful tool to denoting the impedance, the disconnection between the parameter values and the geometry of the device means that it now has limited use as the basis for the final specification of the impedance. The specification should now be based on the typical acoustical impedance of real devices, as determined in this project.

Since each laboratory used different equipment, there is, in general, no consistency in the specific frequency points or spacing used. It is therefore necessary to transpose all of the measurement data onto a common set of frequencies so that a statistical analysis can be performed in order to calculate a mean value and an associated uncertainty, and to estimate a realistic tolerance for inclusion in the standard.

This has been carried out by taking each data set and fitting a polynomial function to data local to the frequency of interest. Typically 5-7 data points and polynomials of up to 6 orders were used. An example of some fitted data is shown in Figure 11. The polynomial function was then used to evaluate the impedance at the specified frequency of interest.

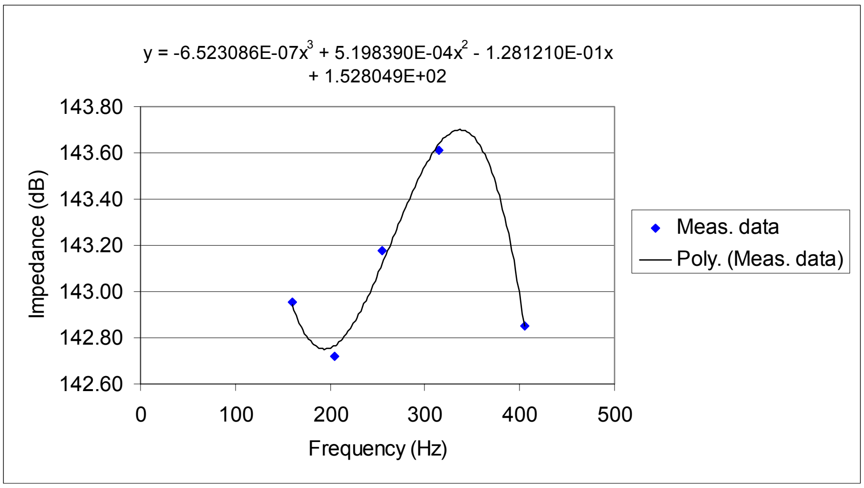


Figure 11. Example of a polynomial fit to the measured data.

This process was repeated for each data set at each frequency of interest. IEC TC29 policy is for all new documents to make use of exact third octave frequencies, rather than the nominal preferred values[5] that have been used in the past. These frequencies, plus the special frequencies used commonly in audiometry (0.75 kHz, 1.5 kHz, 3 kHz, 6 kHz and 9 kHz), have been the basis for the polynomial fitting. The results of the fitting are shown in Table 2, together with the calculated average (grand mean) and standard deviation.

For reference the values derived from the optimised lumped parameter model are also shown. However, now that a specification for the impedance can be derived from measurements, this model is of lesser importance.

	DPLA		LNE		PTB	NPL	Average	SD	LPM	Difference
	WS1	WS2	WS1	WS2	WS2	WS2			optimised	
125.89	144.4	144.5	144.2	144.6	144.0	144.3	**144.3**	0.2	**144.4**	0.1
158.49	143.3	143.4	143.0	143.6	143.0	143.2	**143.2**	0.2	**143.3**	0.1
199.53	143.0	143.1	142.7	143.3	142.7	142.9	**142.9**	0.2	**143.1**	0.1
251.19	143.6	143.6	143.3	143.9	143.2	143.4	**143.5**	0.2	**143.6**	0.1
316.23	144.2	144.2	143.9	144.5	143.6	144.0	**144.1**	0.3	**144.1**	0.0
398.11	143.6	143.5	143.3	143.9	142.9	143.1	**143.4**	0.4	**143.4**	0.0
501.19	141.6	141.5	141.3	141.8	141.0	141.1	**141.4**	0.3	**141.4**	0.0
630.96	139.2	139.1	138.9	139.3	138.7	138.7	**139.0**	0.3	**139.0**	0.0
750.00	137.4	137.3	137.1	137.2	136.9	137.0	**137.2**	0.2	**137.1**	0.0
794.33	136.9	136.6	136.5	136.9	136.2	136.3	**136.6**	0.3	**136.5**	-0.1
1000.00	134.7	134.5	134.3	134.6	134.1	134.3	**134.4**	0.2	**134.3**	-0.1
1258.93	132.8	132.6	132.4	132.6	132.1	132.5	**132.5**	0.2	**132.5**	0.0
1500.00	131.7	131.5	131.3	131.4	130.9	131.3	**131.4**	0.3	**131.4**	0.1
1584.89	131.5	131.2	131.0	131.2	130.6	131.1	**131.1**	0.3	**131.2**	0.1
1995.26	131.3	131.1	131.0	131.2	130.4	131.0	**131.0**	0.3	**131.1**	0.1
2511.89	131.7	131.4	131.6	132.0	130.9	131.2	**131.5**	0.4	**131.5**	0.1
3000.00	131.2	130.9	131.2	131.6	130.3	130.4	**130.9**	0.5	**131.0**	0.0
3162.28	130.9	130.6	130.8	131.2	130.0	130.1	**130.6**	0.5	**130.6**	0.0
3981.07	128.9	128.5	128.7	128.9	127.9	127.8	**128.4**	0.5	**128.2**	-0.2
5011.87		126.2		126.3	125.6	125.6	**125.9**	0.4	**125.8**	-0.1
6000.00		124.3		124.2	123.7	123.9	**124.0**	0.3	**123.9**	-0.1
6309.57		123.8		123.7	123.2	123.4	**123.5**	0.3	**123.4**	-0.1
7943.28		121.2		120.9	120.8	121.2	**121.0**	0.2	**121.1**	0.1
9000.00		119.9		119.7	119.4	120.1	**119.8**	0.3	**120.0**	0.2
10000.00		118.6		117.5	118.5	119.1	**118.4**	0.7	**119.0**	0.6

Table 2. Results of polynomial interpolation of measurement data, mean and standard deviation and comparison with LPM.

5. MEASUREMENT UNCERTAINTY

Some laboratories reported details of their uncertainty analysis. Table 3 summarises the components mentioned and assigns some typical values. The actual value will depend on factors such as the method used to calibrate the microphones, the transmitter adaptor used and the environmental conditions.

Component of uncertainty	Typical value
Transmitter microphone sensitivity	0.2 dB
Receiver microphone sensitivity	0.2 dB
Receiver microphone configuration (e.g. grid pattern)	0.35 dB
Capacitance (or other reference impedance)	1 nF
Linearity of voltage measurement system	0.1 dB
Transmitter microphone equivalent volume	10 mm^3
Polarisation voltages	0.1 V
Temperature – deviation from reference conditions	1 °C
Atmospheric pressure variation - deviation from reference conditions	2 kPa
Cross-talk	0.1 dB
Frequency	0.01%
Repeatability	0.1 dB
Inter-laboratory variation (derived from the typical standard deviation shown in Table 2)	0.3 dB
Rounding error	0.01 dB

Table 3. Typical components of uncertainty.

It is estimated that a determination of the acoustical transfer impedance according to this method can achieve an expanded uncertainty with coverage factor k=2, of between of 0.4 dB and 0.5 dB, when evaluated according to ISO/IEC recommendations[6].

6. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this project was to report on a number of matters critical in the revision of IEC 60318-1. The findings of this work addressing these issues can now be stated.

Measurement method and configuration
The proposed measurement method has been shown to be effective in determining the acoustical transfer impedance of the 60318-1 ear simulator. The optimum configuration comprises a type WS2 transmitter microphone flush mounted in a flat plate and concentrically located at the entrance of the ear simulator. The receiver microphone should be a low sensitivity type WS2P as specified for use in the ear simulator. It should be fitted with its regular grid, though other grid patterns have been found not to change the measured impedance.

Specification for the acoustical transfer impedance
The values recommended for specification in the revision of IEC 60318-1 are those shown in the ‘Average’ column of Table 2. Note that the frequency range is restricted to that where the

device is considered to have a realistic acoustical impedance (up to 10 kHz). The **expanded measurement uncertainty (*k*=2) is estimated to be 0.5 dB.**

Based on this measurement uncertainty and the standard deviation of the large sample of devices measured as part of this project, **a tolerance of 1.5 dB is recommended** (with 0.5 dB of this amount arising from the estimated measurement uncertainty).

Lumped parameter model

The need for a LPM is greatly diminished with the introduction of a measurement-based specification of the acoustical transfer impedance. However, the revision of IEC 60318-1 is likely to include such a representation of the impedance, for historical reasons. In this case it is recommended that the quoted lumped parameters be altered as shown in Table 1, to provide a degree of consistency with the specified acoustical transfer impedance.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and enthusiasm of colleagues at the participating NMIs. The financial support provided in the UK by NMSPU, DIUS, which enabled NPL to lead this work, is also acknowledged.

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] R. Barham, Report on key comparison CCAUV.A-K1. *Metrologia* **40** 09002. 2003.

[4] V. C. Henríquez *et al.* Final report on the key comparison CCAUV.A-K3. *Metrologia* **43** 09001. 2006.

[5] IEC 61260. Octave-band and fractional-octave-band filters. International Electrotechnical Commission. 1995.

[6] ISO/IEC Guide 98-3. Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM). International Standards Organisation. 1995.

APPENDIX - PROPOSED MEASUREMENT METHOD.

The proposed method to be evaluated derives from reciprocity calibration of microphones[A1], 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

$$U_2 = M_2 Z_a . M_1 i \quad \text{(A1)}$$

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.

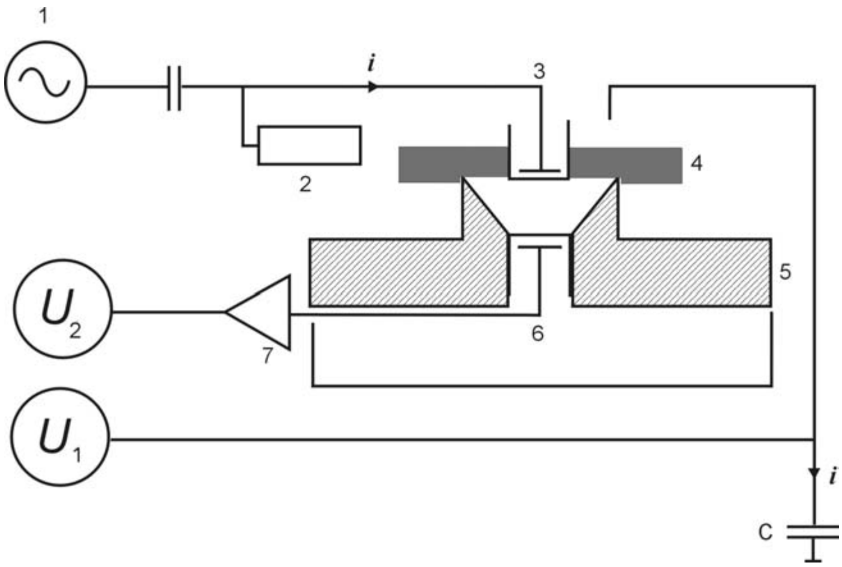
Then, directly from equation (A1),

$$Z_a = \frac{1}{M_1 M_2} \frac{U_2}{i} \quad \text{(A2)}$$

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 A1 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 Adaptor (see Fig. A2)
5 Ear simulator under test
6 Calibrated receiver microphone (within ear simulator)
7 Microphone preamplifier and power supply

Figure A1 - Key elements of the measurement system

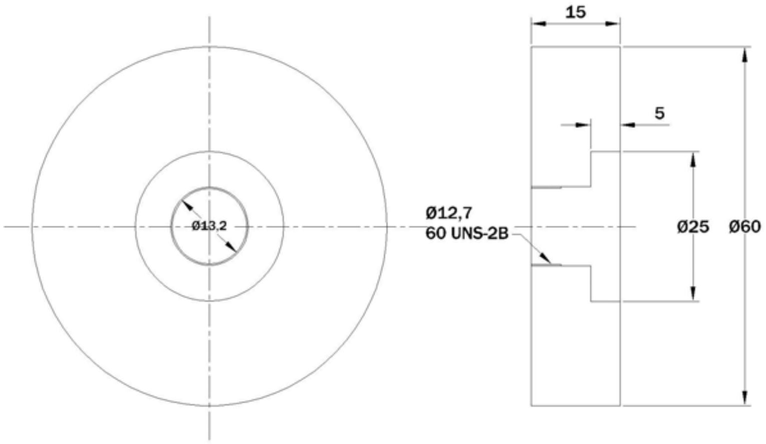
Here, the electrical current driving the transmitter microphone is determined by placing a known electrical impedance in series with the microphone, and measuring the voltage U_1 developed across it. Any type of stable electrical impedance element can be used, but a capacitor has the advantage that U_1 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 A1, equation (A2) becomes,

$$Z_a = \frac{1}{M_1 M_2} \frac{U_2}{U_1} \frac{1}{j\omega C} \qquad \text{(A3)}$$

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 A2 shows the adaptor used.



Dimensions in millimeters

Figure A2 - Adaptor 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 practical requirements 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.

[A1] IEC 61094-2. Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique. International Electrotechnical Commission. 1992.