Datafiles simulating a pressure reciprocity calibration of microphones

by

Knud Rasmussen

EUROMET Project 294

DEPARTMENT OF ACOUSTIC TECHNOLOGY
TECHNICAL UNIVERSITY OF DENMARK

REPORT PL-13a, 2004

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EUROMET Project 294

Introduction

In a pressure reciprocity calibration of microphones using closed couplers, the resulting uncertainties can be divided in three major groups referring to:

1 the measurement of the electrical transfer impedance, ie the uncertainties and errors related to the measurement technique and instrumentation used for the calibration
2 the determination of the acoustical transfer impedance, ie the uncertainties and errors related to the calculation procedure and the software used
3 determination of the acoustical impedances and other parameters of the microphones

In addition also the personal care and skill of the operator during the calibration procedure will influence the resulting uncertainty of a calibration.

In international metrology it is common practice to establish mutual confidence through bi- or multilateral intercomparisons where the same microphones are calibrated successively at the involved laboratories. However, an identification of the origin of possible differences in the results can be very difficult.

To investigate the electrical measurement system a Coupled Microphone Simulator has been designed at the National Physical Laboratory (NPL) in United Kingdom [1]. The simulator connects directly to a calibration setup and mimics two microphones type LS1 connected through a 3cc Plane Wave Coupler as specified in IEC 61094-2 [2].

It is the purpose of the present EUROMET project A 294, by construction of a set of artificial measurement data, to test the performance of the calculation procedure and software used to determine the sensitivity of the microphones. Once the electrical measurement system and the calculation procedure has been tested the uncertainties referring to the last group, the microphone parameters will be the dominating factors.

A simple and straightforward procedure for testing the various calculation procedure would be to take the measurement values from an actual calibration situation and compare the results of various calculation procedures. However, a more systematic approach has been chosen to ensure that the whole range of parameter variations is covered, for microphones as well as couplers.

This report has been divided into two parts.
The first part deals with the design of a set of idealized but representative microphones. Based upon a lumped parameter model the complex pressure sensitivity of three microphones type LS1 and LS2 covering the production spread of actual microphones has been calculated.
The second part deals with the construction of various datafiles simulating a pressure reciprocity calibration of the above-mentioned microphones. IEC 61094-2 [2] specifies a range of lengths for plane-wave couplers and gives examples on capillary tube dimensions. A set of three couplers supplied with different size of capillary tubes covering the ranges mentioned in IEC 61094-2 has been chosen for both type of microphones.
In a reciprocity calibration the electrical transfer impedance is determined by the complex voltage ratio of the receiver output voltage to the voltage across an impedance in series with the transmitter microphone and that impedance. In practice two different kind of measuring impedances are used, a suitable capacitor in parallel with a large resistance representing losses or a decade resistance in parallel with a stray capacitance. The datafiles are given for both methods.

EUROMET project 294 represents a cooperation between DPLA, NPL and PTB where DPLA acts as the pilot laboratory. Each of the participants has developed their own computer program which has been used to test the datafiles, see chapter 2.5.

This report consists of a written part (the present text) and a spreadsheet file EUR294Data.xls (Excel 97) containing the data described (only available in an electronic form).

Part 1

Theoretical determination of microphone responses

1.1 Microphone parameter variations

Laboratory Standard Microphones type LS1 and LS2 are specified in IEC 61094-1 [3], where limits are given on the electroacoustical parameters. However, the limits are set to cover various brand names and are thus not mutually compatible. In consequence the microphone parameters has been chosen to cover the range of variation for a specific type LS1 and LS2 microphone, which are available on the market today. When choosing the microphone parameters the mutual dependency has been taken into account, such as a high sensitivity corresponds to a large equivalent volume, a low resonance frequency and a high value of the static pressure coefficient. Similarly a large value of the front cavity depth corresponds to a large value of the front cavity volume.
Following these considerations the parameters for 3 microphones of type LS1 and LS2 has been chosen as shown in table 1, all representing realistic values for an actual microphone.

Table 1 - Microphone parameters

Microphone type		LS1			LS2		
Serial no.		001	002	003	004	005	006
Equiv. volume	mm^3	120	135	150	8,2	9,2	10,2
Resonance freq.	kHz	8,80	8,25	7,70	22,8	21,7	20,6
Loss factor		0,95	1,00	1,05	0,95	1,00	1,05
Compliance *)	10^{-12} m^5/N	0,845	0,951	1,057	0,0578	0,0648	0,0719
Mass *)	kg/m^4	386,89	391,3	404,3	843,4	829,9	830,6
Resistance *)	10^6 Ns/m^5	20,32	20,28	20,54	114,8	113,1	112,9
Front cavity vol.	mm^3	527,1	540	552	30,0	32,6	35,7
Front cavity depth	mm	1,94	1,965	1,99	0,45	0,48	0,52
Static pressure coefficient	dB/kPa	-0,0140	-0,0150	-0,0161	-0,0049	-0,0054	-0,0059
Temperature coefficient	dB/K	-0,0010	-0,0025	-0,0040	-0,001	-0,002	-0,003
Nominal sensitivity 250 Hz	dB re 1V/Pa	-27,70	-27,20	-26,70	-39,65	-38,75	-37,85
*) Calculated from the values of equivalent volume, resonance frequency and loss factor							

1.2 Lumped parameter model of microphones

A lumped parameter model of laboratory standard microphones has been used successfully for determination of the static pressure- and temperature coefficients of microphones [4]. The very same model, shown on figure 1, has been used for the present purpose but extended with the influence of heat conduction on the impedance of the back cavity at low frequencies.

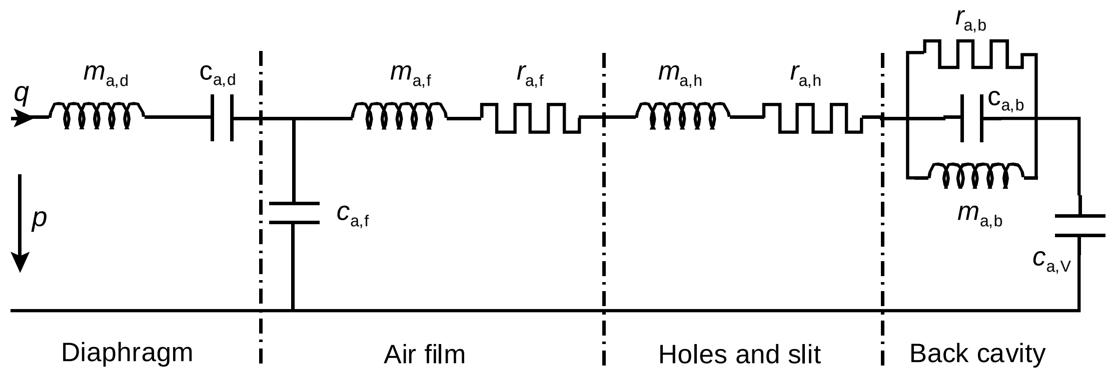

Figure 1 Lumped parameter network describing the mechano-acoustic part of the microphone

1.2.1 Influence of heat conduction on the back cavity impedance

At low frequencies and assuming adiabatic conditions, the acoustic impedance of a closed cavity of volume V_b takes the form

$$Z_{a,V} = \frac{\gamma p_s}{j\omega V_b} = \frac{1}{j\omega c_{a,V}} \tag{1}$$

where p_s is the static pressure and $\gamma = c_p / c_V$ is the ratio of specific heats of the enclosed gas. In a more general description γ is substituted by N, the coefficient of polytropic expansion, where $N = 1$ under isothermal conditions. In the transition range N takes complex values to account for the losses in the thermodynamic process and thus eq.1 can be rewritten as

$$Z_{a,V} = \frac{N}{\gamma}\frac{\gamma p_s}{j\omega V_b} = r_{a,V} + \frac{1}{j\omega c'_{a,V}} \tag{2}$$

An expression for N is given by Gerber [5] and referred in [6] for a cavity driven by a constant velocity source

$$N = 1 + (\gamma - 1)(E_{v,r} + jE_{v,i}) \tag{3}$$

$E_v = E_{v,r} + j\,E_{v,i}$ being the complex temperature transfer function defined as the ratio of the space-average of the sinusoidal temperature variation in the cavity to the sinusoidal temperature that would be generated in the absence of heat conduction.

The calculation of E_v depends on the shape of the cavity. The back cavity of a microphone is formed like a toroid but with an odd-shaped cross-sectional area. For the calculations this is equivalent to an infinite cylinder having the same but circular cross-sectional area.

As the volume to surface ratio for the back cavity is very small , about 10^{-3}, the short time solution given in [2,6] will results in significant errors at low frequencies and thus the frequency domain solution given in [5,6] shall be used. Using the same notation as in [6], the complex temperature transfer function is then given by

$$E_{\mathrm{v}} = 4\sum_{n=0}^{\infty}\frac{1}{\lambda_n^2}\frac{\mathrm{j}2\pi Y}{\lambda_n^2/4+\mathrm{j}2\pi Y} \tag{4}$$

where

$$Y = \frac{f\,\ell^2}{\gamma\,\alpha_{\mathrm{t}}}$$

λ_n is the n'th root of $J_o(\lambda_n) = 0$, ℓ is the volume/surface ratio of the back cavity (equivalent cylinder) and α_t = 21,3 Pas/m^5 is the diffusivity of air. The volume and surface area of the microphone back cavities are determined from drawings kindly put at disposal from the manufacturer of the actual microphones modelled for this purpose.

In figure 1 the impedance of the back cavity is shown as its adiabatic value, a constant compliance, see eq. 1. To take into account the heat conduction, this adiabatic value is substituted by the expression given in eq.2, ie a serial connection of a frequency dependent resistance and compliance.

1.3 Frequency response of a microphone

The pressure sensitivity of the microphones is proportional to the acoustical admittance of the diaphragm, ie to the input admittance of the lumped parameter network shown in figure 1 and corrected for heat conduction in the back cavity as discussed above.
For an individual microphone of a given type only the mass and compliance of the diaphragm and the flow resistance values of the air film trapped between diaphragm and back-electrode are subject to changes. During the manufacturing process the back cavity and back-electrode dimensions remain constant, while the diaphragm tension and thickness may vary as well as the distance between back-electrode and diaphragm.
Thus to simulate the response of the microphones given in table 1, only the values of $m_{\mathrm{a,d}}$, $c_{\mathrm{a,d}}$ and $r_{\mathrm{a,f}}$ need to be changed in the model. For each microphone these three components are then changed such that the overall values of equivalent volume, resonance frequency and loss factor given in table 1 are achieved. Table 2 shows the values of the components used for modelling the microphones given in table 1.

The effect of heat conduction in the back cavity is a slight increase in the pressure sensitivity and a small phase lag at low frequencies. The difference between the adiabatic ($N = \gamma$) and the isothermal ($N = 1$) impedance of the back cavity, see eq.2, is equivalent to a 40% change of the factor γp_{s}. This difference can also be obtained under adiabatic conditions by reducing the static pressure by 40% or approx. 40 kPa. Consequently the maximum increase in the low frequency sensitivity of a microphone can be derived from the static pressure coefficient of the microphone.

Table 2
Values of lumped parameters in figure 1

Component	LS1	LS2	Unit
$m_{a,d}$	235-260	640-690	$kg \cdot m^{-4}$
$c_{a,d}$	1,00-1,35	0,062-0,078	10^{-12} $m^3 \cdot Pa^{-1}$
$c_{a,f}$	0,05	0,012	10^{-12} $m^3 \cdot Pa^{-1}$
$m_{a,f}$	52	200	$kg \cdot m^{-4}$
$r_{a,f}$	20-21	107-113	10^6 $Pa \cdot s \cdot m^{-3}$
$m_{a,h}$	38	75	$kg \cdot m^{-4}$
$r_{a,h}$	$1075\sqrt{f}$	$2100\sqrt{f}$	$Pa \cdot s \cdot m^{-3}$
$m_{a,b}$	58	100	$kg \cdot m^{-4}$
$c_{a,b}$	1,6	0,18	10^{-12} $m^3 \cdot Pa^{-1}$
$r_{a,b}$	18	17	10^6 $Pa \cdot s \cdot m^{-3}$
$c_{a,V}$	5,18	0,952	10^{-12} $m^3 \cdot Pa^{-1}$

For LS1 microphones a typical value of the static pressure coefficient is -0,015 dB/kPa, which will result in a maximum increase of the pressure sensitivity of 0,6 dB at very low frequencies. For type LS2 microphones the corresponding values are -0,0055 dB/kPa and 0,2 dB.

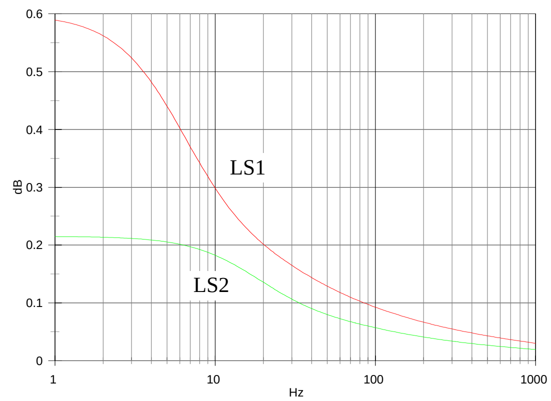

Figure 3 Increase in modulus of pressure sensitivity at low frequencies due to heat conduction in the back cavity.

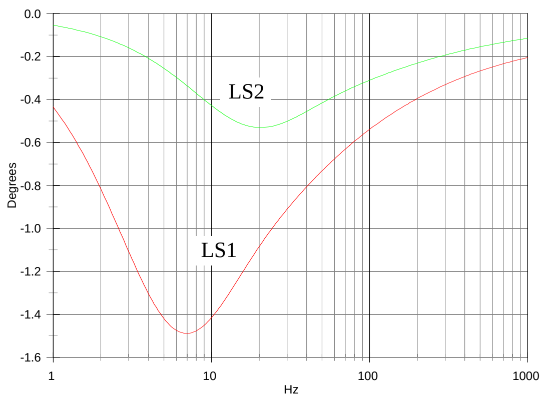

Figure 2 Influence on phase of pressure sensitivity at low frequencies due to heat conduction in the back cavity.

Figures 2 and 3 show the influence on modulus and phase of the pressure sensitivity due to heat conduction in the back cavity for typical microphones of type LS1 and LS2.

The values given above for the maximum increase of the low frequency sensitivity are only met if the presence of the static pressure equalizing vent can be neglected and if the microphone is operated using a constant charge at all frequencies.

1.4 Validity of the lumped parameter model

In order to test the validity of the model, the frequency response of a number of known and well documented microphones of type B&K 4160 and 4180 has been predicted using the same technique and compared with the results of a pressure reciprocity calibration. The sensitivities resulting from reciprocity calibrations performed in 1/12-octave steps starting at 15 Hz have been calculated in accordance with IEC 61094-2 [2].
Figure 4 and 5 show the difference between the calculated and measured pressure sensitivity normalized at 250 Hz. For both type of microphones the agreement is within +/- 0,05 dB nearly up to the resonance frequency of the microphones. It is hardly surprising that the model breaks down close to and above the resonance frequency.

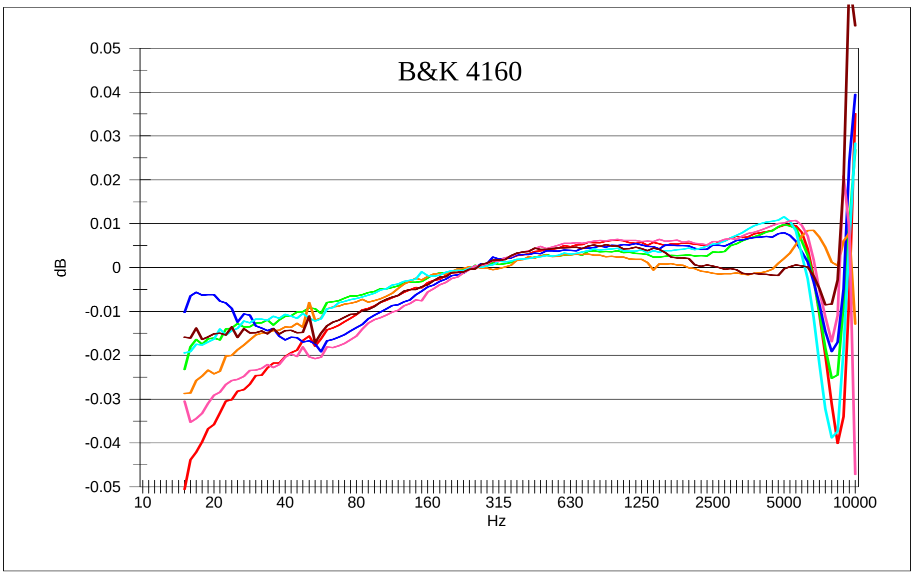

Figure 4 Difference between the calculated pressure sensitivity and the sensitivity derived from a reciprocity calibration of 7 microphones B&K type 4160, normalized at 250 Hz

However, deviations are observed at low frequencies. For type B&K 4160 the measurement results systematically underestimates the sensitivity while the opposite tendency is observed for type 4180. In the model the static pressure equalization tube has not been accounted for. This equalization corresponds to a high resistance in parallel with the back cavity impedance given in eq.2. The effect of this equalization is that the pressure sensitivity increases at very low frequencies. (Note that the definition of pressure sensitivity requires that the sound pressure acts on the outside of the diaphragm only). It is easy to introduce such resistance in the model but a recalculation show no resemblance with the measurement results. For type 4160 a possible explanation is found in the calculation procedure for the measurement result. These microphones has an inner thread in the front volume for mounting a protection grid. This thread virtually doubles the cylindrical part of the front cavity surface area and thus also doubles the heat conduction associated with this surface. In the calculations, however, the front cavity volume is considered pure cylindrical with smooth surfaces, ie the additional heat conduction is not taken into account and thus the calculated sound pressure is overestimated and the corresponding sensitivity underestimated. E. Frederiksen [7] has calculated the influence of this additional heat conduction and figure 6 shows the associated error for a standard 3 cc

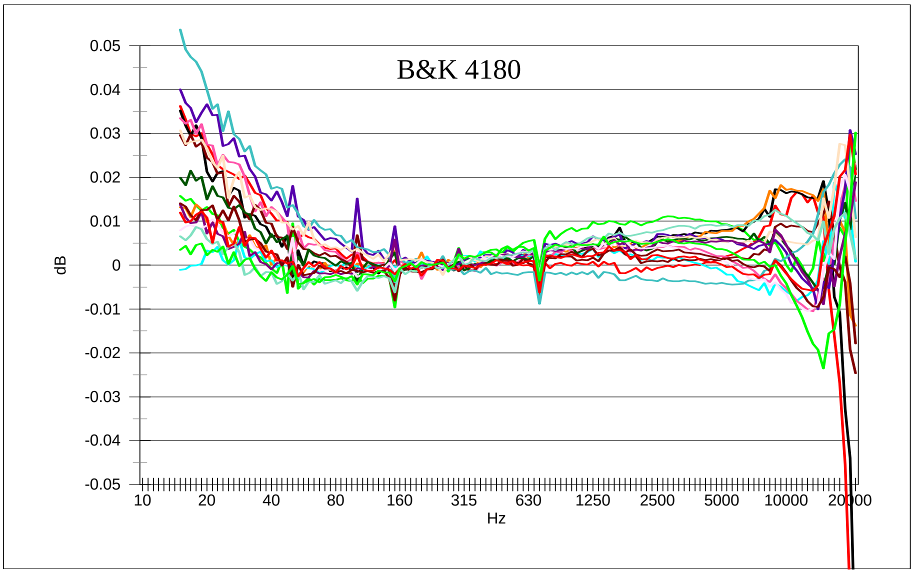

Figure 5 Difference between the calculated pressure sensitivity and the sensitivity derived from a reciprocity calibration of 18 microphones B&K type 4180, normalized at 250 Hz

coupler on the calculation results when the effect is not taken into account. As can be seen the error matches the findings in figure 4 quite well. Note that the influence of this additional heat conduction is present also at high frequencies and that the offset at 250 Hz is close to the average value at high frequencies in figure 4. These results indicate that the calculation of the influence of heat conduction in a pressure reciprocity calibration as given in [2] needs to be revised.

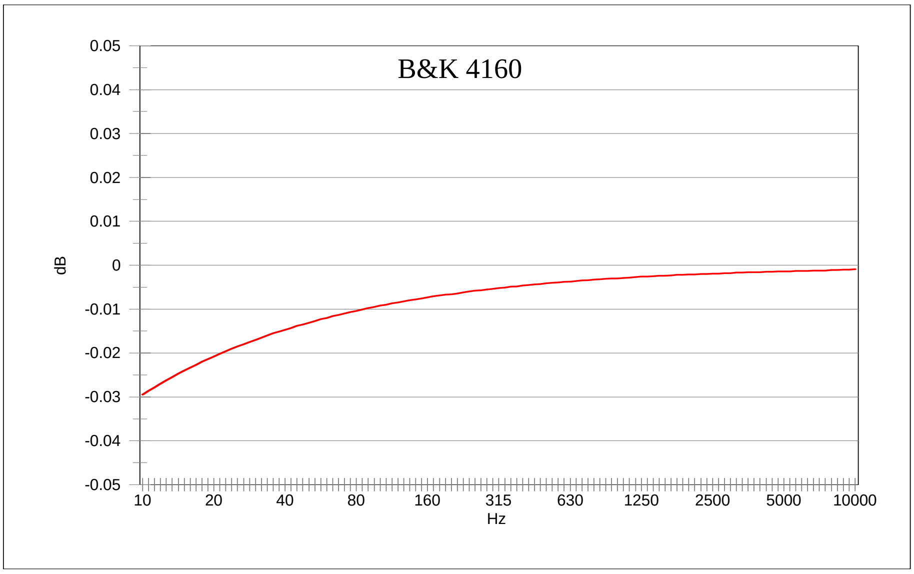

Figure 6 Error committed in a reciprocity pressure calibration of type BK 4160 microphones when neglecting the additional heat conduction due to the inner thread in the front cavity. After [7].

Another effect has not been considered either in the model, viz a possible leakage between the front and rear side of diaphragm through the sealing. In the model this corresponds to a resistance from the input terminal to the terminal of the back cavity impedance. When calibrating a microphone having such leakage the calculated sensitivity will be too low and consequently the differences shown in figure 4 and 5 will raise toward low frequencies. This behaviour can be seen for one of the type 4160 microphones shown on figure 4. A similar behaviour is seen for most of the type 4180 microphones shown on figure 5 but it is very likely that other effects are present as well.
A closer examination of the low frequency behaviour of the microphones as well as the method for calculating the results of a reciprocity calibration and the results of an electrostatic actuator calibration is under investigation and will be reported later.

For the present purpose the general conclusion is that the model gives a fairly good description of the microphones.

1.5 Target values for the pressure sensitivity of the microphones

Based upon the model and the microphone parameters given in table 1 and 2 the complex pressure sensitivity of the microphones has been calculated. Table 3 and 4 show the results in 1/3-octave steps (nominal frequencies) starting at 25 Hz. At high frequencies above 8 kHz, 1/6-octave steps are chosen.

When presenting the sensitivities the phase convention is such that an instantaneous positive sound pressure results in a positive induced open-circuit output voltage of the microphone. Consequently the phase of the pressure sensitivity will approach 180° at low frequencies and be 90° at the resonance frequency.

In the second part of this report a number of datafiles is constructed representing different scenarios and levels of sophistication as regards the calculation method used to evaluate the results of a reciprocity calibration. The output of each calculation should equal the target values given in tables 3 and 4, provided of course that the conditions for the validity of the datafiles are strictly followed.

Table 3

Target values for microphone pressure sensitivities at reference environmental conditions

Microphone sensitivities in dB re 1V/Pa

Microphone Serial no.	LS1 001		LS1 002		LS1 003	
f kHz	Modulus	Phase	Modulus	Phase	Modulus	Phase
0.025	-27.620	179.16	-27.109	179.06	-26.599	178.95
0.0315	-27.633	179.18	-27.124	179.09	-26.616	178.99
0.040	-27.645	179.19	-27.138	179.10	-26.631	179.00
0.050	-27.655	179.18	-27.149	179.09	-26.644	178.99
0.063	-27.665	179.15	-27.160	179.05	-26.655	178.95
0.080	-27.673	179.09	-27.170	178.99	-26.666	178.88
0.100	-27.680	179.00	-27.178	178.90	-26.675	178.78
0.125	-27.686	178.88	-27.185	178.77	-26.683	178.64
0.160	-27.692	178.70	-27.191	178.57	-26.690	178.42
0.200	-27.697	178.48	-27.196	178.33	-26.696	178.16
0.250	-27.700	178.19	-27.200	178.01	-26.700	177.81
0.315	-27.702	177.81	-27.203	177.60	-26.703	177.36
0.400	-27.703	177.30	-27.204	177.04	-26.704	176.74
0.500	-27.702	176.70	-27.202	176.37	-26.703	176.01
0.630	-27.697	175.89	-27.197	175.49	-26.697	175.05
0.800	-27.687	174.83	-27.186	174.33	-26.686	173.77
1.00	-27.670	173.57	-27.168	172.94	-26.666	172.24
1.25	-27.643	171.97	-27.139	171.18	-26.634	170.30
1.60	-27.593	169.67	-27.085	168.65	-26.575	167.50
2.00	-27.522	166.95	-27.008	165.65	-26.492	164.17
2.50	-27.412	163.39	-26.891	161.69	-26.368	159.75
3.15	-27.242	158.40	-26.714	156.11	-26.185	153.49
4.00	-26.993	151.08	-26.467	147.87	-25.950	144.17
5.00	-26.720	140.99	-26.238	136.46	-25.794	131.24
6.30	-26.594	125.10	-26.296	118.72	-26.107	111.62
8.00	-27.376	101.02	-27.539	93.43	-27.868	85.66
9.00	-28.492	87.37	-28.925	80.15	-29.502	73.08
10.00	-30.001	75.70	-30.624	69.35	-31.356	63.23
11.20	-32.122	65.09	-32.863	59.87	-33.689	54.78
12.50	-34.577	58.00	-35.363	53.72	-36.229	49.35

Table 4

Target values for microphone pressure sensitivities at reference environmental conditions

Microphone sensitivities in dB re 1V/Pa

Microphone Serial no.	LS2 004		LS2 005		LS2 006	
f kHz	Modulus	Phase	Modulus	Phase	Modulus	Phase
0.025	-39.593	179.58	-38.686	179.53	-37.779	179.48
0.0315	-39.604	179.58	-38.698	179.53	-37.792	179.48
0.040	-39.613	179.59	-38.709	179.54	-37.804	179.49
0.050	-39.620	179.59	-38.717	179.55	-37.813	179.50
0.063	-39.627	179.59	-38.724	179.55	-37.821	179.50
0.080	-39.632	179.58	-38.730	179.53	-37.828	179.48
0.100	-39.637	179.55	-38.735	179.51	-37.833	179.46
0.125	-39.641	179.51	-38.739	179.47	-37.838	179.41
0.160	-39.644	179.45	-38.744	179.40	-37.843	179.34
0.200	-39.647	179.38	-38.747	179.32	-37.847	179.26
0.250	-39.650	179.28	-38.750	179.21	-37.850	179.14
0.315	-39.652	179.14	-38.753	179.07	-37.853	178.98
0.400	-39.654	178.96	-38.755	178.87	-37.855	178.77
0.500	-39.655	178.74	-38.756	178.64	-37.857	178.51
0.630	-39.655	178.45	-38.756	178.32	-37.857	178.17
0.800	-39.655	178.07	-38.756	177.91	-37.857	177.72
1.00	-39.652	177.62	-38.753	177.42	-37.854	177.19
1.25	-39.647	177.05	-38.748	176.80	-37.849	176.51
1.60	-39.638	176.24	-38.738	175.93	-37.839	175.56
2.00	-39.623	175.31	-38.723	174.92	-37.824	174.46
2.50	-39.600	174.13	-38.699	173.64	-37.799	173.07
3.15	-39.561	172.57	-38.659	171.94	-37.758	171.22
4.00	-39.498	170.46	-38.594	169.66	-37.691	168.72
5.00	-39.406	167.87	-38.499	166.84	-37.595	165.63
6.30	-39.260	164.29	-38.352	162.92	-37.447	161.33
8.00	-39.038	159.10	-38.131	157.24	-37.232	155.08
9.00	-38.899	155.73	-37.997	153.54	-37.108	151.00
10.00	-38.760	152.09	-37.868	149.54	-36.996	146.59
11.20	-38.605	147.32	-37.736	144.31	-36.897	140.85
12.50	-38.471	141.65	-37.641	138.11	-36.856	134.09
14.00	-38.391	134.46	-37.631	130.34	-36.935	125.73
16.00	-38.473	124.04	-37.846	119.29	-37.307	114.14
18.00	-38.830	113.22	-38.366	108.16	-38.001	102.88
20.00	-39.471	102.77	-39.167	97.79	-38.959	92.74
22.40	-40.531	91.59	-40.383	87.07	-40.312	82.57
25.00	-41.877	81.61	-41.839	77.75	-41.860	73.91

Part 2

Construction of datafiles

A pressure reciprocity calibration of microphones is performed in a closed coupler. IEC 61094-2 [2] gives examples of recommended couplers, such as Large Volume couplers for use in a restricted frequency range and Plane Wave couplers used in a wide frequency range. For the present purpose only Plane Wave couplers are considered because of the complicated calculations procedure but also because of the very limited use of Large Volume couplers in Europe.
The current through the transmitter microphone is generally determined as the voltage across an impedance in series with the microphone. This impedance is either chosen as a fixed capacitor with some losses represented by a resistance in parallel, both of which is a function of frequency, or as a decade resistor box with some stray capacitance in parallel. For simplicity all capacitances and resistances are considered to be independent of frequency in the datafiles. In a real measurement setup even the best measurement capacitors show a slight dependency of frequency of its capacitance and the parallel resistance representing the losses usually varies inversely proportional to frequency. This frequency dependency is very important for a correct determination of the phase response of the microphones. All datafiles are constructed for both type of measuring impedance.
Finally, during a calibration the environmental conditions will often change and consequently three different sets of static pressure, temperature and relative humidity have been chosen for the three combinations of microphones. Again, for simplicity the values are considered to remain constant for a given combination.

2.1 Coupler parameter variations

Plane-wave couplers recommended for pressure reciprocity calibrations are given in IEC 61094-2 [2]. Three coupler lengths have been chosen to cover the recommended range. In addition two of the couplers are fitted with open capillary tubes for equalization of static pressure. Contrary to common sense the smallest couplers have been fitted with a short, wide capillary tube and the largest couplers with a long, narrow capillary tube. This combination of coupler and capillary tube exaggerates the influence of the capillary tube on the acoustical transfer impedance thereby making it easier to detect any errors in the calculation procedures.
The specifications for three selected couplers for both type of microphones are shown in table 5.

2.2 Measurement impedance

In the datafiles the two different type of measurement impedances are called the *C-method* (identifier C) and *R-method* (identifier R). In the *C-method* the fixed capacitance is 4,7456 nF in parallel with a fixed resistance of 100 MOhm and in the *R-method* the decade resistance varies from about 400 Ohm to 700 kOhm in parallel with a fixed stray capacitance of 400 pF.

Table 5 - Coupler dimensions

Coupler no.		9940	9945	9950	9980	9985	9990
Diameter	mm	18,6	18,6	18,6	9,3	9,3	9,3
Length	mm	5,0	7,5	10,0	3,5	4,7	6,0
Number of capillary tubes		1	0	1	1	0	1
Tube length	mm	50	-	100	50	-	100
Tube diameter	mm	0,500	-	0,334	0,500	-	0,334

2.3 Calculation procedure

The calculation procedure to be used to evaluate the results of a reciprocity calibration is given in IEC 61094-2 [2], but a few items needs to be clarified.

a) Annex F gives simple equations for determining the acoustic properties of air. Although given as an informative annex many accreditation bodies consider the content to be mandatory. IEC 61094-2 is under revision and particular this annex is expected to be heavily revised. Ref. [8] gives a thorough analysis of the latest available information on the acoustic properties of humid air and the proposed calculation procedures have been accepted by EUROMET for this purpose. For this reason datafiles using both methods of calculation has been developed.

b) Clause 7.3.3 discusses the situation where the microphone front cavity volume differs from the volume calculated from the cross-sectional area of the coupler and the front cavity depth. When developing the datafiles the excess volume has been treated as a volume (positive or negative) in parallel with the microphone impedance.

c) Clause 6.4 deals with radial wave-motion in the couplers but gives no information on how to calculate the influence on the acoustical transfer impedance. Ref. [9] gives a theoretical analysis of the radial wave-motion in Plane-Wave couplers of different lengths and for varying microphone impedances. Datafiles have been developed where this wave-motion has been neglected and where radial wave-motion based on a Bessel-function as well as a parabolic velocity distribution has been assumed in accordance with ref. [9].

d) Clause 6.5 and annex D gives some general qualitative information about the influence of the environmental conditions on the sensitivity of microphones. Ref. [4] gives information on the actual static pressure- and temperature coefficients for specific types of LS1 and LS2 microphones. Datafiles are given both for a situation where the dependence of the environmental conditions has been neglected (for the microphones only) and where the results from ref. [4] have been applied.

2.4 List of datafiles

For each coupler and for each method of measurement a series of datafiles has been constructed, identified as follows:

Series 00: The acoustical properties of air are calculated according to IEC 61094-2 Annex F using c_o = 331,45 m/s and Δ = 1,0001.
The static pressure and temperature coefficients of the microphones are neglected.
No corrections are applied for radial wave-motion.

Series 01: The acoustical properties of air are calculated according to IEC 61094-2 Annex F using c_o = 331,45 m/s and Δ = 1,0001.
The static pressure and temperature coefficients of the microphones are applied according to ref. [4].
No corrections are applied for radial wave-motion.

Series 02: The acoustical properties of air are calculated according to IEC 61094-2 Annex F using c_o = 331,45 m/s and Δ = 1,0001.
The static pressure and temperature coefficients of the microphones are applied according to ref.[4].
Corrections for radial wave-motion are applied according to ref.[9] using a Bessel-function distribution of the diaphragm displacement.

Series 03: The acoustical properties of air are calculated according to IEC 61094-2 Annex F using c_o = 331,45 m/s and Δ = 1,0001.
The static pressure and temperature coefficients of the microphones are applied according to ref.[4].
Corrections for radial wave-motion are applied according to ref.[9] using a parabolic distribution of the diaphragm displacement.

Series 10: The acoustical properties of air are calculated according to ref.[8].
The static pressure and temperature coefficients of the microphones are neglected.
No corrections are applied for radial wave-motion.

Series 11: The acoustical properties of air are calculated according to ref.[8].
The static pressure and temperature coefficients of the microphones are applied according to ref. [4].
No corrections are applied for radial wave-motion.

Series 12: The acoustical properties of air are calculated according to ref.[8].
The static pressure and temperature coefficients of the microphones are applied according to ref.[4].
Corrections for radial wave-motion are applied according to ref.[9] using a Bessel-function distribution of the diaphragm displacement.

Series 13: The acoustical properties of air are calculated according to ref.[8].
The static pressure and temperature coefficients of the microphones are applied according to ref.[4].
Corrections for radial wave-motion are applied according to ref.[9] using a parabolic distribution of the diaphragm displacement.

In total 96 datafiles have been constructed. The various datafiles are identified by a number system: <coupler ID> <method ID> <series ID>, ie file 40C01 refers to coupler 9940 (table 5), *C-method* (clause 2.2) and series 01. Similarly file 85R12 refers to coupler 9985, *R-method* and series 12. An example of such datafile is given in table 6.

The complete collection of datafiles are found in an Excel spreadsheet file available from the author. Note that in order to improve the readability, the example in table 6 shows a limited number of digits, while the full number is given in the spreadsheet file.

Table 6 - An example of a datafile

File ID		**40C00**			
Microphones:		**LS1 no. 001 & LS1 no. 002**			
Average temp:		22			
Average rel. hum. %:		40			
		Voltage ratio		Measuring impedance	
Freq. kHz	Ps kPa	Modulus	Phase	C nF	Rp MOhm
0.025	99	0.3963	28.15	4.7456	100
0.0315	99	0.4166	23.01	4.7456	100
0.063	99	0.4482	11.10	4.7456	100
0.125	99	0.4542	3.58	4.7456	100
0.25	99	0.4489	358.49	4.7456	100
0.50	99	0.4436	354.12	4.7456	100
1.00	99	0.4465	347.50	4.7456	100
1.25	99	0.4505	344.24	4.7456	100
1.60	99	0.4581	339.58	4.7456	100
2.00	99	0.4695	334.10	4.7456	100
2.50	99	0.4876	326.91	4.7456	100
3.15	99	0.5191	316.88	4.7456	100
4.00	99	0.5696	301.69	4.7456	100
5.00	99	0.6371	280.70	4.7456	100
6.30	99	0.7051	247.35	4.7456	100
8.00	99	0.6491	196.76	4.7456	100
9.00	99	0.5343	168.64	4.7456	100
10.0	99	0.4079	144.99	4.7456	100
11.2	99	0.2815	123.72	4.7456	100
12.5	99	0.1886	109.63	4.7456	100

Microphones:		**LS 1 no. 001 & LS1 no. 003**			
Average temp:		23			
Average rel. hum. %:		45			
		Voltage ratio		Measuring impedance	
Freq. kHz	Ps kPa	Modulus	Phase	C nF	Rp MOhm
0.025	99	0.4170	27.79	4.7456	100
0.0315	99	0.4379	22.68	4.7456	100
0.063	99	0.4703	10.88	4.7456	100
0.125	99	0.4763	3.41	4.7456	100
0.25	99	0.4707	358.30	4.7456	100
0.50	99	0.4652	353.80	4.7456	100
1.00	99	0.4684	346.87	4.7456	100
1.25	99	0.4729	343.45	4.7456	100
1.60	99	0.4812	338.56	4.7456	100
2.00	99	0.4936	332.78	4.7456	100
2.50	99	0.5133	325.18	4.7456	100
3.15	99	0.5473	314.52	4.7456	100
4.00	99	0.6008	298.30	4.7456	100
5.00	99	0.6681	275.81	4.7456	100
6.30	99	0.7203	240.45	4.7456	100
8.00	99	0.6247	189.00	4.7456	100
9.00	99	0.4993	161.54	4.7456	100
10.0	99	0.3743	138.87	4.7456	100
11.2	99	0.2558	118.68	4.7456	100
12.5	99	0.1709	105.35	4.7456	100

Microphones:		**LS1 no. 002 & LS1 no. 003**			
Average temp:		24			
Average rel. hum. %:		50			
		Voltage ratio		Measuring impedance	
Freq. kHz	Ps kPa	Modulus	Phase	C nF	Rp MOhm
0.025	99	0.4387	27.43	4.7456	100
0.0315	99	0.4603	22.36	4.7456	100
0.063	99	0.4933	10.66	4.7456	100
0.125	99	0.4993	3.25	4.7456	100
0.25	99	0.4934	358.12	4.7456	100
0.50	99	0.4877	353.50	4.7456	100
1.00	99	0.4913	346.31	4.7456	100
1.25	99	0.4961	342.74	4.7456	100
1.60	99	0.5052	337.60	4.7456	100
2.00	99	0.5187	331.64	4.7456	100
2.50	99	0.5400	323.63	4.7456	100
3.15	99	0.5765	312.43	4.7456	100
4.00	99	0.6334	295.34	4.7456	100
5.00	99	0.7022	271.57	4.7456	100
6.30	99	0.7436	234.32	4.7456	100
8.00	99	0.6126	181.47	4.7456	100
9.00	99	0.4744	154.32	4.7456	100
10.0	99	0.3478	132.53	4.7456	100
11.2	99	0.2346	113.51	4.7456	100
12.5	99	0.1563	101.16	4.7456	100

2.5 Evaluation of calculation results

When writing a computer program to calculate the results of a reciprocity calibration numerous errors and approximations are possible and several errors may occur simultaneously which makes it difficult to locate the individual errors. The datafiles have been constructed so as to enable a systematic check of a computer program. It is recommended to run all the files in a given series starting with the basic series 00 or 10 and study the deviations from the target values. Through a detailed analysis of the deviations between the microphones versus coupler dimensions etc. it will normally be possible to locate the source of the error.
For example, deviations in the mid-frequency range indicates a wrong calculation of the effective coupler volume, ie the sum of geometrical coupler volume, microphone front cavity volumes and microphone equivalent volumes.
Deviations at low frequencies are caused by a wrong determination of the heat conduction correction or capillary tube impedance. An error in the heat conduction calculation will affect the results for all couplers, the largest deviations being found for the smallest couplers.
An error in the determination of the capillary tube impedances will not affect the results for couplers 9945 and 9985 at all as no capillary tubes are mounted. The maximum deviation is found for coupler 9980. As an example figure 7 shows the error committed when the capillary tube impedances are taken from the tables in Annex B of the IEC standard [2]. These tables give the capillary tube impedance under reference environmental conditions and not for the actual values of static pressure, temperature and humidity stated in the datafiles. For a correct determination of the tube impedance eqs. B1 - B3 in [2] shall be used (note the missing power of -1 of the brackets in eq. B2).

Deviations at high frequencies are normally caused by a wrong calculation of the microphone impedances or the handling of the excess volumes (see clause 2.3 b), the largest deviations occurring for the longest couplers. Note that the excess volume is zero for microphone LS1-001 and LS2-005, negative for LS2 004 and positive for the other microphones. The excess volume of a microphone only concerns the sensitivity of that microphone and does not affect the sensitivity of the other microphones in a calibration setup.
Also it should be recalled that when the diaphragm compliance is expressed in terms of an equivalent volume the value is calculated for reference environmental conditions and not for the actual conditions prevailing during the calibration, cf. [3] clause 6.2.2 and [2] eq. 3.
Note also that the measurement data for couplers 9945 and 9985 refers to the reference static pressure 101,325 kPa and that the average temperature is 23 °C which means that the application of static pressure and temperature coefficients for the microphones will not influence these data (see clause 2.4, series 00 versus series 01)

When testing a program the true data from the spreadsheet file should be used, also for microphone and coupler data. If rounded values are used, random perturbations around the target values can be expected.

In general, random deviations of the order of 0,001 dB are caused by the limited precision of computer languages and the standard mathematical functions used. Particular attention should be drawn to the precision of Bessel functions etc. However, systematic deviations of the same order of magnitudes indicates an error in a constant somewhere, such as using a reference static pressure of 101,3 kPa rather than 101,325 kPa or in the calculation of the speed of sound etc.

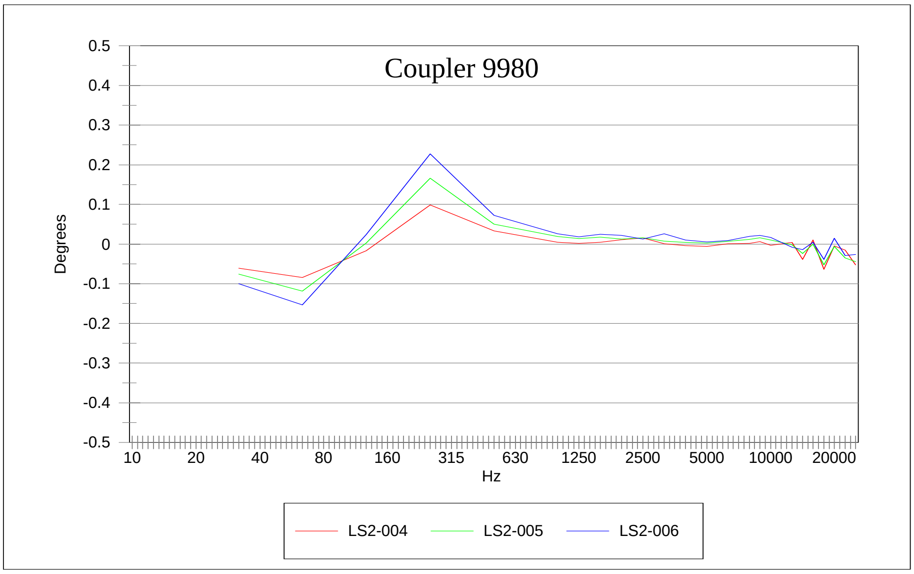

Figure 5 Typical deviations in modulus and phase from the target values using values for the capillary tube impedances at reference environmental conditions (see text above and IEC 61094-2, Annex B) rather than at the actual conditions

2.6 Acknowledgement

The author would like to express his gratitude to his colleagues, noticeable D. Jarvis and R. Barham at NPL and U. Richter and Th. Fedtke at PTB for their assistance by testing the datafiles and for their useful discussions during the project.

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