Recent Developments in the Primary Free-Field Reciprocity Calibration of Laboratory Standard Microphones at NPL - A Contribution to Euromet Project A295

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Abstract

Following an EC/BCR (Community Bureau of Reference) intercomparison on the primary free-field reciprocity calibration of laboratory standard microphones in 1991, discrepancies remained that could not be attributed to the measurement uncertainty claimed by the laboratories involved. This report describes research undertaken at NPL as part of a Euromet project aimed at discovering the causes of the discrepancies. In the case of calibrations undertaken at NPL, it is concluded that a small error may be caused by a reflection from the floor of the free-field chamber used, and that the effect of this reflection is similar to the introduction of an additional air attenuation factor. When the measured data is processed according to a theoretical model which accounts for this reflection, the frequency response for a given microphone becomes smoother and the repeatability of the measurements improves.

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1 INTRODUCTION

For any microphone, two sensitivities may be defined. The pressure sensitivity relates the microphone output voltage to the sound pressure at the microphone diaphragm. The free-field sensitivity relates the output voltage to the sound pressure at the position of the microphone before introducing the microphone into the sound field. By application of the so-called reciprocity method of calibration under the appropriate experimental conditions, either of these sensitivities may be determined as a fundamental property of the microphone. In practice, pressure calibration is technically more straightforward than free-field calibration and can be accomplished with greater accuracy using a more compact and less expensive facility, with much shorter measurement times. Consequently, pressure calibration of certain well defined types of microphone used as laboratory standards is the most widely adopted means of establishing a primary standard of sound pressure.

Nevertheless, the practical measurement of noise relates more directly to the free-field sensitivity of a microphone. The free-field sensitivity is generally derived from the pressure sensitivity by applying standardised values for the difference between the two, and it falls to laboratories such as NPL to determine and gain international agreement on these free-field/pressure sensitivity differences.

The specification and calibration of measurement microphones are being standardised in IEC 1094, which is being published in a number of parts. To assist in the writing of the part concerned with primary free-field calibration of laboratory standard microphones, NPL began developing a new facility to enable such calibrations to be performed. This research period culminated in 1991, with NPL's participation in an intercomparison of free-field calibrations between four European metrology laboratories: the Technical University of Denmark (Denmark), the Laboratoire National d'Essais (France) and the Physikalische Technische Bundesansalt (Germany) and NPL. The facility and NPL's contribution to this project have been described previously[1,2].

The conclusion of this initial intercomparison was that no consensus on the values for the differences between the free-field and pressure sensitivity levels could be reached. Although the technical difficulty in performing the measurement lay at the lower end of the frequency range, the discrepancies were found in the upper half of the range. These discrepancies ranged up to 0.2 dB for LS1P microphones and 0.5 dB for LS2P microphones. When the results were disseminated more widely, it was found that results from other national metrology laboratories were similarly inconclusive. Clearly further work was required, and in Europe the initial intercomparison was followed up by a project organised under Euromet to resolve the differences found in the first exercise. The Euromet project was led by the Danish Technical University (DTU) and this report describes the research undertaken at NPL as a contribution to that project.

The work at NPL on developing the free-field reciprocity system is ongoing and although this report represents the conclusion of our part in the Euromet project, work will continue at NPL in order to verify the operation of the system at frequencies up to 50 kHz. A more comprehensive report will be produced when that work is complete and our partners in the Euromet project have had the opportunity to comment on the work presented here.

The research focussed on the two main aspects of the calibration process: the integrity of the electrical measurements and the acoustical analysis on which the calibration process is based. Improvements in these two areas are discussed separately.

2 ELECTRICAL MEASUREMENTS

The heart of the NPL facility is a free-field chamber containing a receiver microphone mounted on a fixed stem standing on the floor of the chamber and a transmitter microphone mounted on a moveable stem descending from the ceiling of the chamber. One of the criticisms of the NPL results in the initial intercomparison was that the levels of electrical noise and cross-talk were sufficient to influence the results. The NPL system measured directly the electrical current through the transmitter microphone, using a method similar to that used in pressure reciprocity. This minimises the need to have system components calibrated, but requires low level signals from a high impedance source to be measured at the end of long cable runs, which are highly susceptible to noise and cross-talk. Other participants in the intercomparison adopted an alternative approach. They placed an amplifier and the reference impedance needed to measure the current, immediately behind the transmitter microphone. This avoided many of the problems experienced with the NPL system, but introduced others associated with traceability. It was decided to adapt the NPL facility to use this type of transmitter to see if this could be the cause of the discrepancy.

The exercise proved more difficult than it initially appeared. Additional equipment such as controllable amplifiers were required and significant changes to the software had to be made. Also the results then depended on the gains of the amplifiers used in the system. To develop such a system that could provide reliable results would have required resources similar to those used to commission the original system. Development of the system was pursued until it could be used to make some measurements and a limited amount of data was acquired. The results appeared to show some reduction in the level of noise, which may have been further improved with better quality amplifiers. However the discrepancies in the results still seemed to remain, although the situation was clouded somewhat by the increased calibration uncertainty. It was concluded that the use of this style of microphone transmitter was not the root of the discrepancy and the NPL facility was returned to its original form.

The electrical measurements in free-field reciprocity calibration are notoriously difficult and influenced greatly by the electrical shielding and grounding arrangements used. After reverting to the original system, attempts were made to improve it in these areas. To try to reduce cross-talk, the cables in sensitive parts of the system leading to and from the transmitter microphone were changed to a highly screened type. The cable used also had a low inherent capacitance which might otherwise have had an adverse effect on the measurements. To enable these cables to be used the microphone transmitter mounting had to be redesigned to remove a restriction and allow the cables to be connected to the transmitter. At the same time the assembly of the transmitter was improved to avoid the internal electrical connection being twisted and strained. Changes to components in the electrical circuit used to polarise the transmitter microphone were also made, resulting in a larger current being fed to the microphone for a given input signal level which improved the signal-to-noise ratio significantly.

The reference electrical impedance used in the system also came under scrutiny. This is used to measure the current flowing in the transmitter microphone and provides the traceability for the measurement. A π-network of resistors is used and its impedance has a direct influence on the free-field sensitivity values derived from the experiments and needs to be known accurately. Previously the impedance was calculated from the d.c. resistance of the individual components with some allowance made for stray capacitance introduced by the circuit layout. However the resistors are a wire wound type and although wound non-inductively, there is the possibility that they have some small inherent inductance. A method of measuring the impedance of the resistors in-situ as a function of frequency was developed and the suspicions were confirmed. It was found that the inductance at 25 kHz was as much as 10% of its resistance, acting in quadrature with it. The presence of both capacitance and inductance in the circuit complicated the corrective procedure and a more sophisticated method of estimating the stray impedance elements was devised. However the conclusion at the end of the exercise was that the magnitude of this effect was small compared to the overall measurement uncertainty and was not sufficient to account for the differences in sensitivity observed in the intercomparison. For completeness the results have been incorporated into the measurement of the electrical transfer impedance.

Having made these changes, the microphones used in the original intercomparison were calibrated once again. To see the direct effect of the changes, the measurements were processed by the procedure used previously. Briefly, this plotted the data as a function of the separation between the transmitter and receiver microphones, in a form that should have resulted in a straight line through the origin. If there was then any offset on the separation axis, the separation corresponding to each measurement point was modified by this amount and the process repeated. This continued until the line passed through the origin, whereupon its gradient gave the reciprocal of the product of the sensitivities of the two microphones. This process therefore attributed all the inconsistencies in the data to errors in the separation between the microphones rather than to errors in any other factor.

The results showed a smaller scatter, indicating the success of the measures taken to reduce noise in the system. However the resulting free-field sensitivities for the microphones were found to be similar to before. That is, the discrepancy at high frequencies was still evident and remained of a similar magnitude. Although this result did little to solve the problem it did point the way to the line of further investigation. Given that the facility underwent substantial changes between the two sets of measurements and there was little scope for further significant improvement, some confidence could now be placed in the accuracy of the electrical measurements being made. Attention therefore focused next on the acoustical aspects of the measurement.

3 ACOUSTICAL FACTORS

On implementing the reciprocity method, the product of the sensitivities M_1 and M_2 of the two microphones used as transmitter and receiver can be shown to be given by

$$M_1 M_2 = \frac{2d}{\rho f} \exp(\alpha d) \frac{U}{i} \tag{1}$$

where ρ is the air density, f is the frequency, α the air attenuation coefficient, d the apparent separation between the microphones, that is the physical separation corrected for the acoustic centres of the microphones, and U/i is the measured electrical transfer impedance.

The approach that has been adopted at NPL is to measure U/i as a function of d and calculate a factor y where

$$y(d) = \frac{\rho f}{2 \exp(\alpha d) \, U/i} \tag{2}$$

So that

$$y(d) = \frac{1}{\text{[illegible]}} d \tag{3}$$

and the sensitivity product follows from the gradient of the line when $y(d)$ is plotted against d. If each of the parameters in (1) were correct, the line from (3) would pass through the origin. In practice however, this line is generally found not to pass through the origin. Under these circumstances it is not valid to use the gradient of the line to find the sensitivity product and one or more parameters in (2) needs to be adjusted until the line has the expected form.

Clearly there is no scope to alter some of the parameters: ρ, f, and U/i can all be considered to have a well-defined and sufficiently low uncertainty to prevent them being varied. There is some uncertainty in microphone separation, and this can be attributed to a possible error in the position of the acoustic centres. Let this error be Δ, so that the actual separation is d-Δ. Equation (3) then becomes

$$y(d) = \frac{\exp(-\alpha\Delta)}{M_1 M_2}(d-\Delta) \tag{4}$$

Now it is found that accounting for the d-axis offset by adjusting Δ results in only small changes in the sensitivity product. This is because the offset is proportional to $\Delta \exp(\alpha\Delta)$ whereas the sensitivity product is proportional to $\exp(\alpha\Delta)$ and therefore less dependent on the value of Δ. The other parameter that can be adjusted is α and in this case the offset and the sensitivity product have the same dependence on α, so the consequential change in the sensitivity product is greater when α is adjusted to remove the offset.

Since the original data fitting method involved adjusting Δ to account for the offset, the alternative approach of adjusting α was tried. It was found that this process significantly improved the repeatability of measurements of sensitivity product, but required α to be increased by a factor of approximately four. It was thus concluded that the right approach in processing the data had been taken, but for the wrong reason. Attention then turned towards other mechanisms that could cause such an error.

It has been noted in the past that the method of measuring U/i at many microphone separations reduces the effect of most types of reflection in the free-field chamber. It was also noted however, that this is not so in the NPL facility for a reflection from the floor because the difference in length between the direct and reflected paths (the distance from the receiver microphone to the floor, and back) is independent of the microphone separation[2]. So while the reflection results in a deviation from ideal free-field behaviour, this has a systematic dependence on d and is not removed by the fitting that is performed. Furthermore the floor is perhaps the most likely of all the surfaces to produce a reflection because the mounting hardware for the receiver microphone cannot be lined with absorbent material as efficiently as other areas.

Thus a model was formulated to examine the effect of a reflection from the floor on the sensitivity product. This is discussed in the Appendix, where it is shown that the reflection can in fact be approximated by a factor that has the same functional dependence as the air attenuation factor.

4 RESULTS

The microphones used for the original intercomparison were again distributed amongst the participants by DTU. Having made improvements to the electrical measurements as described above, the free-field sensitivity levels of the microphones received at NPL were remeasured. The range of microphone separations used was 0.2 - 0.6 m for the LS1P microphones and 0.1 - 0.5 m for the LS2P microphones as before. However, the frequency range for these measurements concentrated on the areas where the discrepancies existed, that is 2.5 - 12.5 kHz for the LS1P microphones and 6.3 - 20 kHz for the LS2P microphones.

The data for the free-field sensitivity levels of the microphones in Table 1 have been obtained by the fitting method outlined in the Appendix . The suggested values for the position of the acoustic centre in IEC 1094-3[3], and the equations for the air attenuation in ISO 9613-1[4] were used. The measurements were made over a range of environmental conditions, but have been corrected to 23 °C and 101325 Pa. The uncertainty in the free-field sensitivity level that was estimated previously remains valid, though with the results now processed differently to account for the floor reflection. At the 95% confidence level, this uncertainty is 0.07 dB and 0.08 dB for LS1P and LS2P microphones respectively.

If the results for the free-field sensitivity level are compared with those from the original intercomparison[1] they are found to be higher. For example, the sensitivity of a type LS2P microphone at 20 kHz is now found to be on average 0.45 dB greater than before. Also, repeated measurements on the same microphone now yield results which have a standard deviation of less than 0.1 dB, compared to previous values of as much as 0.3 dB.

Frequency (Hz)	Free-field sensitivity level (dB re 1 V/Pa)							
	Type 4180 (LS2P)				Type 4160 (LS1P)			
	1503925	1503927	1503932	1503933	811014	811029	811041	811044
2500	-	-	-	-	-24.27	-24.88	-24.54	-24.30
3150	-	-	-	-	-23.36	-23.87	-23.70	-23.31
4000	-	-	-	-	-21.86	-22.39	-22.28	-21.92
5000	-	-	-	-	-20.20	-20.65	-20.52	-20.15
6300	-35.84	-36.10	-36.38	-36.11	-18.51	-18.80	-18.79	-18.49
8000	-34.37	-34.72	-34.91	-34.67	-18.61	-18.67	-18.67	-18.54
10000	-32.60	-32.97	-33.27	-32.97	-21.13	-21.19	-21.18	-21.23
12500	-30.67	-30.97	-31.34	-30.87	-26.26	-26.11	-26.29	-26.47
16000	-29.33	-29.59	-29.95	-29.48	-	-	-	-
20000	-30.45	-30.55	-30.84	-30.44	-	-	-	-

Table 1 Free-field sensitivity levels for the microphones supplied by DTU

Frequency (Hz)	Free-field -pressure sensitivity level difference (dB)							
	Type 4180 (LS2P)				Type 4160 (LS1P)			
	1503925	1503927	1503932	1503933	811014	811029	811041	811044
2500	-	-	-	-	1.65	1.58	1.59	1.63
3150	-	-	-	-	2.35	2.38	2.26	2.41
4000	-	-	-	-	3.58	3.57	3.44	3.52
5000	-	-	-	-	5.01	5.02	5.01	5.04
6300	2.37	2.46	2.40	2.38	6.85	6.89	6.89	6.83
8000	3.61	3.61	3.65	3.59	8.31	8.33	8.42	8.34
10000	5.09	5.08	5.05	5.01	9.16	9.17	9.31	9.19
12500	6.77	6.81	6.74	6.83	8.90	8.95	9.02	8.96
16000	8.32	8.32	8.27	8.34	-	-	-	-
20000	8.58	8.60	8.53	8.64	-	-	-	-

Table 2 Free-field - pressure sensitivity level differences for the microphones supplied by DTU

If the data for the pressure sensitivity is also considered, the values for the free-field - pressure sensitivity level differences given in Table 2 result. Although a comparison with the other participants is beyond the scope of this report, it is interesting to note that for each of these microphones, the values agree well with the corresponding mean value reported by DTU. The agreement is found to be within 0.06 dB at most frequencies and 0.1 dB at all frequencies.

5 CONCLUSIONS AND RECOMMENDATIONS

Significant reductions have been achieved in the electrical noise and cross-talk in the NPL facility, and the results of the electrical measurements have remained stable throughout. It has also been found that significant improvements in the results of free-field calibrations of laboratory standard microphones can be achieved by making allowances for a reflection from the floor of the free-field chamber. When the measured data is processed according to a model which accounts for this reflection, the frequency response for a given microphone becomes smoother and the repeatability of the measurement improves.

The results of this work are now offered to the other participants in the Euromet project for further discussion.

The next step in the development of the facility is to extend its capability so that calibrations can be performed at frequencies up to 50 kHz.

6 ACKNOWLEDGEMENTS

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REFERENCES

1. D R Jarvis and R G Barham, 'Free-field sensitivity level calibration of laboratory standard microphones by the reciprocity technique: measurements for the 1991 EEC intercomparison', NPL report RSA(EXT) 043. (1993)

2. RG Barham, 'Free-field reciprocity calibration of laboratory standard microphones', PhD Thesis, Southampton University. (1995)

3. International Standard, IEC 1094-3:1995, 'Measurement microphones - Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique.'

4. International Standard, ISO 9613-1:1993, 'Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere.'

APPENDIX - THE EFFECT OF A REFLECTION ON THE ACOUSTICAL TRANSFER IMPEDANCE

When free-field reciprocity calibration is attempted in the presence of a reflection, account must be taken of the true acoustical transfer impedance between the microphones. Clearly, if the receiver microphone is subject to additional pressure from a reflection of the direct wave, then the acoustical transfer impedance will be altered.

If a reflection comes from a side wall of the chamber then its path difference changes as the transmitter microphone is moved and the effect of the reflection will be averaged out when measurements are taken at different distances. However there are some refelections where this is not the case.

The following analysis will derive the form of the sensitivity product when the reflection comes on a path which does not change with microphone separation (e.g. in our case from the floor).

First define the following constants (at 20 kHz):

$f := 20000$ Hz	frequency	and
$\alpha := 0.05$ Np m^{-1}	attenuation	$\omega := 2\cdot\pi\cdot f$
$c := 343$ m s^{-1}	speed of sound	$k := \frac{\omega}{c} - \quad \cdot\alpha$
$\rho := 1.2$ kg m^{-3}	density	

Let us begin by deriving the form of the acoustical transfer impedance. Two point sources are taken to represent the microphones, as in the conventional analysis. Let the distance between the points be d. This is derived by adjusting the physical separation between the microphones by the positions of the acoustic centre of the microphones. In our facility, the value of d can be varied between approximately 0.1 m and 0.6 m by moving the transmitter position.

$d := 0.01, 0.02 .. 0.6$ m

The receiver microphone is a fixed distance above the floor, the reflecting plane. This distance is approximately 1 m.

$D := \quad$ m

The acoustical transfer impedance is given by the ratio of the pressure at the receiver point to the source volume velocity. In a perfect free field this has been shown to be given by

$$Z_a(d) := \frac{i\cdot\rho\cdot f}{2}\cdot\frac{\exp(-i\cdot k\cdot d)}{d}$$

Because the acoustic impedance of the microphone acting as the source is so high, the presence of a reflection will not affect the source volume velocity which is given by

$$u_0 := \frac{2}{i\cdot\rho\cdot f}\cdot(A\cdot\exp(i\cdot\omega\cdot t))$$

If the reflection coefficient is R, the pressure at the receiver is the sum of the direct and reflected pressures.

$$p(d) := \left[\qquad \frac{R\cdot\exp(-i\cdot k\cdot(d+2\cdot D))}{d+2\cdot D} \right]\cdot$$

In this case then the acoustical transfer impedance is

$$Z_{ar}(d,R) := \frac{i\cdot\rho\cdot f}{2}\cdot\left[\qquad d \qquad\qquad \frac{R\cdot\exp(-i\cdot k\cdot(d+2\cdot D))}{d+2\cdot D}\right]$$

Now if this expression was used to find the sensitivity product, the fitting process would be rather cumbersome. However it can be shown that the behaviour due to the additional terms in the acoustical transfer impedance can be approximated by multiplying the free-field acoustical transfer impedance by a factor exp(-Bd), that is

$$Z_{ae}(d,B) := \frac{i\cdot\rho\cdot f}{2}\cdot\frac{\exp(-i\cdot k\cdot d)}{d}\cdot\exp(-B\cdot d)$$

(Notice that the form of the correction is very similar to modifying the air attenuation factor. However this is an artefact of the form used to approximate the acoustical transfer impedance and the sum α+B has no physical meaning. α is a property of the air while B is governed by the material covering the floor and the geometry of the system.)

The factor B now becomes the only term needed to account for the reflection and is chosen during the fitting process. All the other terms are assumed to be known within their uncertainty and are fixed at this stage. At 20 kHz we observe that B is approximately three times the attenuation coefficient and the change in acoustical transfer impedance that this produces results in a change in the microphone sensitivity of approximately 0.4 dB. So

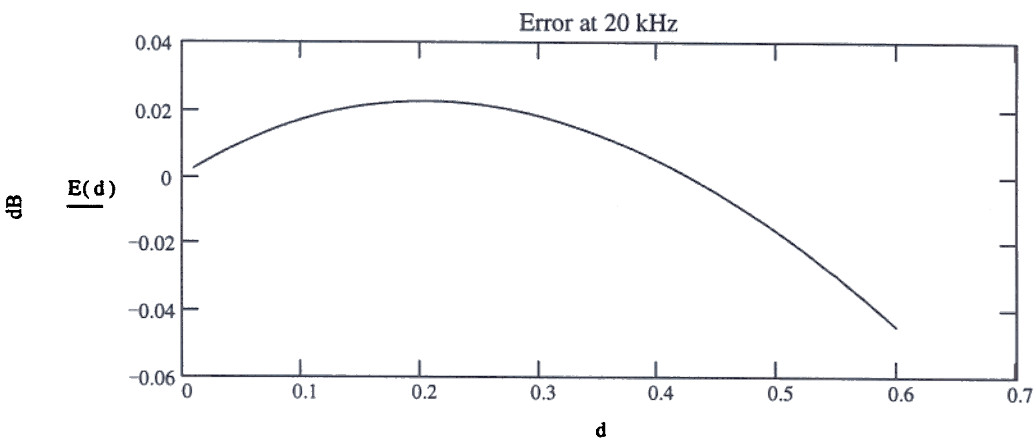
$$B := 3\cdot\alpha$$

and this would be the result of a value for R of approximately

$$R := \frac{-2\cdot D\cdot B}{\exp(-i\cdot k\cdot 2\cdot D)}\cdot\left(\frac{2\cdot D + 0.35}{2\cdot D}\right) \qquad R = 0.287 + 0.263i$$

The error in the sensitivity of a microphone (in dB) associated with this *approximation,* assuming that the error is the same for each determination of a sensitivity product, is then given by

$$E(d) := 20\cdot\log\left(\left|\frac{Z_{ae}(d,B)}{Z_{ar}(d,R)}\right|\right)$$



The error remains of a similar magnitude at other frequencies.

The error does not directly enter calculations of the uncertainty of the calibrations because it has the effect of warping the line that is plotted rather than affecting its fitted gradient. This error appears in the results mixed with errors due to noise and other causes of spread about the best fit to the line and has already been taken into account along with the random uncertainties. It does however limit the resolution of the system: if all noise were eliminated from the system then there would still remain a deviation in the data of about 0.02 dB about the best fit line.