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Methods for determining the pressure sensitivity of IEC type WS3 measurement microphones

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ABSTRACT

Primary measurement standards for sound in air are realised by the reciprocity calibration of laboratory standard microphones. The laboratory standard microphone has an exposed diaphragm and is designed for precise coupling to small cavities. For everyday measurements a working standard microphone (a measurement microphone with a protection grid) is preferred because it is more robust and less expensive. Metrology laboratories are therefore presented with the problem of calibrating the working standard microphones by comparing them with laboratory standard microphones. A previous report has proposed methods for IEC type WS2 microphones, this report extends those methods to type WS3 microphones.

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CONTENTS

1 INTRODUCTION

Working standard microphones[1] are those microphones used to transfer the standard of sound pressure from one acoustical measuring instrument to another. They are used for the calibration of sound calibrators, sound level meters, sound intensity instruments, audiometers, and reference sound power sources. These instruments are used in turn for the measurement of environmental and workplace noise, hearing acuity, and the noise emitted by aircraft, motor vehicles, machinery, etc.

The development of methods for determining the pressure sensitivity of working standard microphones type WS2 was conducted as a Euromet project[2] but that project did not consider microphones type WS3 (commonly known as `quarter-inch' microphones). This is a report of work done at NPL to extend the principles developed in the earlier project to these smaller microphones. The report should be read as a supplement to the earlier report as it will be assumed that the reader is familiar with the principles and terminology adopted there.

At first one might consider that extending methods for WS2 microphones to WS3 microphones would be a simple matter of scaling but this is not the case for two reasons:

- First, no LS3 (laboratory standard microphones of this size) exist with which to compare the WS3 microphones. Even if they did exist then a primary calibration of such small microphones by reciprocity would have a large uncertainty. Hence, at least for one link in the chain of traceable measurements, a WS3 microphone must be calibrated by comparison with a LS2 microphone.

- Second, although part 4 of IEC 1094[1] defines a ground shield configuration for WS3 microphones, there is no example of this in commercial production in an insert voltage preamplifier. Hence, at present, all WS3 microphones must be calibrated as microphone systems i.e. calibrated in terms of the voltage output of their associated preamplifier rather than in terms of the open-circuit voltage of the microphone alone.

The second problem is easily solved but the uncertainties associated with the comparison of a WS3 microphone with a LS2 microphone required detailed study. This is because the pressure sensitivity of a microphone is defined in terms of a *uniform* sound pressure across the diaphragm of the microphone. If the sound pressure is not uniform then different sized microphones will experience different effective mean pressures.

The essential question to be answered before the method could be extended to WS3 microphones was `**What arrangement of LS2 and WS3 microphones, in either a jig or a coupler, would allow the systematic uncertainties associated with the pressure distribution across the microphones to be kept small and calculable?**'. As there was no method of independently verifying a LS2/WS3 comparison it was decided to experiment with WS1/WS2 and LS1/WS2 comparisons in a jig because then both microphones could have independent calibrations by the reciprocity method. The expectation was that the principles learnt with these microphones could then be applied to comparisons of smaller microphones.

2 EXPERIMENTS WITH JIGS FOR WS1/WS2 COMPARISON CALIBRATIONS

No coupler for simultaneous comparison calibration of WS1 microphones was available at NPL so effort concentrated on designing jigs. Figures 1 to 5 show the five arrangements that were investigated, in all cases the microphones were used without their protection grids fitted. The arrangements are labelled A to E for ease of reference.

The microphones were mounted in front of a loudspeaker so that the sound was incident along their axis of cylindrical symmetry. The loudspeaker was driven with sinusoidal signals at a range of frequencies to generate a sound pressure level of approximately 74 dB and the microphone outputs were measured on a Norsonics 830 real time analyser. During the measurements the microphones were swapped to eliminate any differences in the sound field or the gains of the preamplifiers and analyser input channels. A correction was applied to account for the different electrical loading on the preamplifiers between the WS1 microphones and the WS2 microphones. Sinusoidal signals were used rather than pink noise to avoid any errors due to the very different frequency responses of the two microphones at the frequencies of interest.

Theoretical models of the sound pressure distribution over the diaphragms and the resulting influence on the apparent microphone sensitivity were developed for each arrangement. The theory was based on that used for analysing radial wave motion in couplers used for the pressure calibration of laboratory standard microphones[3,4] by reciprocity. The predicted influences on a microphone sensitivity level were of the order of 0.01 dB at 1 kHz rising to over 1 dB at 10 kHz.

Initial measurements were made with all five arrangements in order to identify the arrangement that warranted more detailed study. Arrangement A proved difficult to model theoretically (too many boundaries are undefined) but the empirical results were similar to those for arrangement B. For the remaining four arrangements, as reciprocity calibrations were available for all the microphones, it is possible to plot the difference between a sensitivity level determined by comparison (after correction for any pressure non-uniformity over the diaphragms) and that determined by reciprocity. This is shown in Figure 6. If the theoretical model is a good representation of reality then the difference between the two sensitivity levels should be close to zero. The main area of interest is the frequency range below 5 kHz as any method suitable for WS2 microphones up to 5 kHz is likely to be suitable for WS3 microphones up to 10 kHz.

The results for arrangement B were not encouraging but the remaining arrangements looked more promising. This was probably because the representations of rigid boundaries in the models were more accurate than those of open boundaries. The results for arrangements C, D and E were all similar but arrangements C and D both had the disadvantage of needing to screw an enlarging adaptor onto the smaller microphone. Past experience with these adaptors has shown that there is a risk of changing the microphone sensitivity when such adaptors are used. (The locking ring on the microphone can be disturbed thus changing the tension in the diaphragm). So as arrangements C and D had no significant advantage over arrangement E, it was E that was chosen for further study.

Two Brüel & Kjær microphones type 4134 (a WS2P microphone) were each calibrated by comparison with two microphones type 4160 (a LS1P microphone) using arrangement E. Corrections for pressure non-uniformity were calculated according to the model given in the Appendix and applied to the results. Figure 7 shows the sensitivity level for the two microphones determined by this method relative to their sensitivity level determined by reciprocity. It also shows typical repeatabilities (1 standard deviation) for the measurements and it can be seen that the discrepancies between the two methods is less than the typical repeatability. Once the method was chosen, work concentrated on improving the repeatability. Consequently the differences in Figure 7 are less than those shown for the same method in

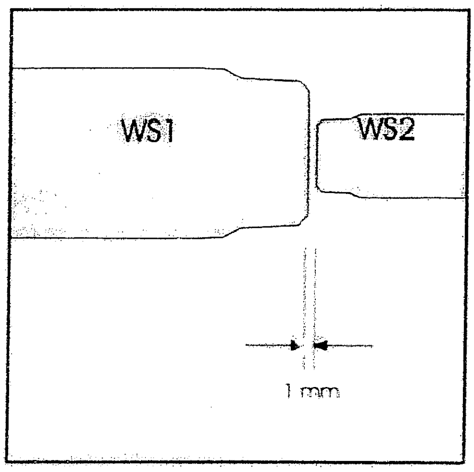

Figure 1 Arrangement A

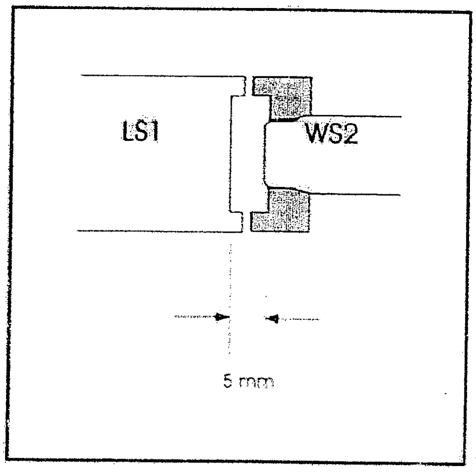

Figure 4 Arrangement D

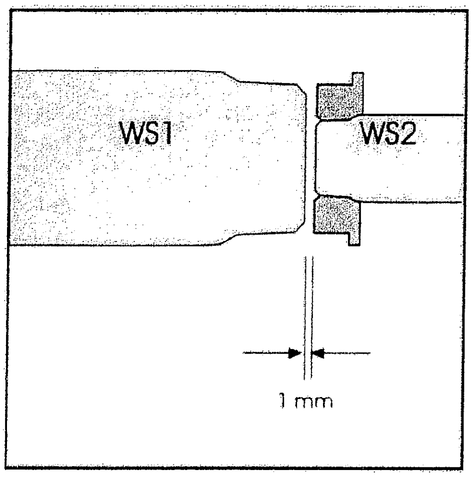

Figure 2 Arrangement B

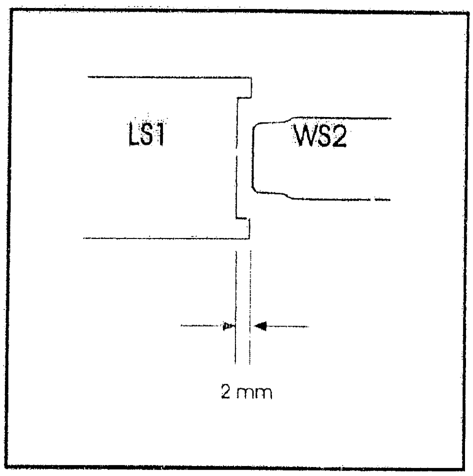

Figure 5 Arrangement E

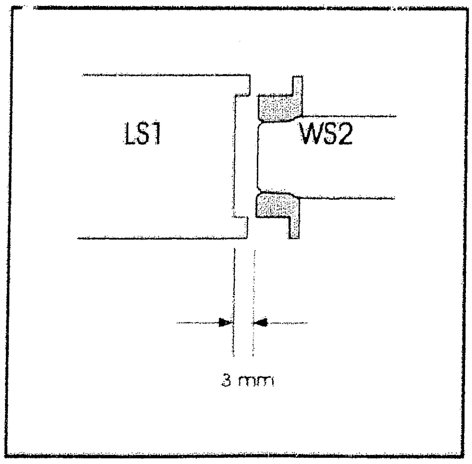

Figure 3 Arrangement C

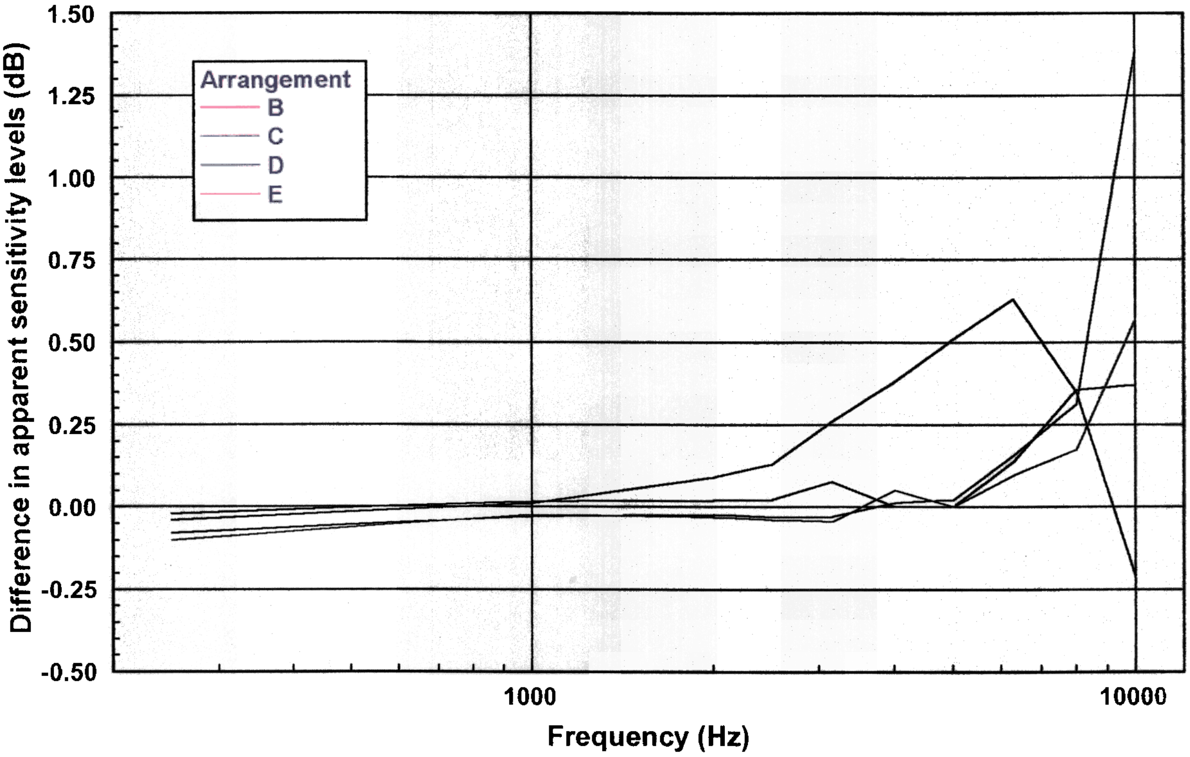

Figure 6 Difference in measured sensitivity level between a comparision calibration and a reciprocity calibration using the various arrangements

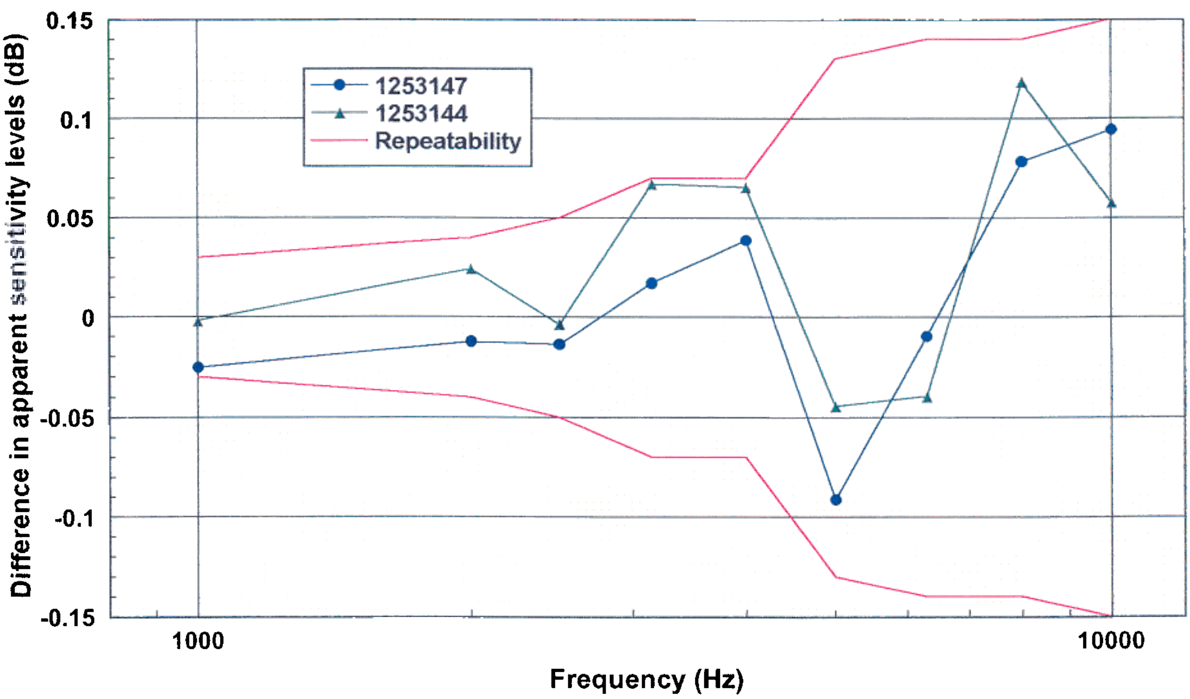

Figure 7 Difference in measured sensitivity level between a comparision calibration and a reciprocity calibration for two microphones type 4134 using arrangement E.

Figure 6 and what looked at first to be a method which would be suitable only up to 5 kHz could in fact be extended to 10 kHz if sufficient care is excercised.

As corrections of over 1 dB are being applied at 10 kHz resulting in residual differences of less than 0.1 dB, these results give considerable confidence in the ability of the theoretical model to accurately predict the effects of using this type of jig.

3 A JIG FOR LS2/WS3 COMPARISON CALIBRATIONS

Following the success of arrangement E for the LS1/WS2 comparisons, the natural choice of an arrangement for a LS2/WS3 comparison was that shown in Figure 8.

Corrections were calculated for this arrangement according to the model in the Appendix and are given in Table 1. No correction is necessary below 1 kHz. The corrections are to be added to the sensitivity level of the WS3 microphone and assume that the reference microphone is a type LS2Pa. The uncertainty on the corrections is estimated to be 10% of their value, which is equivalent to the change in the correction which would result from doubling the distance between the microphone diaphragms.

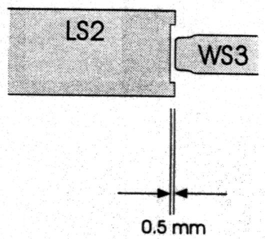

Figure 8. The microphone arrangement used in the LS2/WS3 jig.

Three microphones were calibrated by this method: two Brüel & Kjær type 4135 microphones (IEC type WS3F) and one Brüel & Kjær type 4136 microphone (IEC type WS3P). For frequencies from 63 Hz to 2 kHz a pink noise source was used and the output from the microphones was analysed in third octave bands. For frequencies from 2 kHz to 10 kHz sinusoidal signals were used to avoid any uncertainties arising from the different frequency responses of the test and reference microphones or the change in the corrections between adjacent third octave bands. As the sensitivity level of a typical WS3 microphone can be 10 or 20 dB lower than that for a WS2 microphone initial tests showed a poor signal-to-noise ratio and the source sound pressure level was consequently increased to 90 dB. Additional calibrations at 250 Hz were done in a Brüel & Kjær type 4226 multi-frequency calibrator as a check measurement. The results are given in Figures 9 to 11, where the labels a and b denote two independent sets of calibrations.

Frequency kHz	Correction dB
1	-0.003
1.25	-0.005
1.6	-0.008
2	-0.013
2.5	-0.020
3.15	-0.031
4	-0.050
5	-0.079
6.3	-0.125
8	-0.201
10	-0.314

Table 1. Corrections to be applied to the sensitivity level of the WS3 microphone when using the arrangement in Figure 8.

The microphone 4135 1901601 suffered a small (0.05 dB) change in sensitivity between the two sets of calibrations which was confirmed by the check measurements. However the other two microphones repeated well (typically within ±0.02 dB below 5 kHz and within ±0.05 dB from 5 to 10 kHz).

Although the method works well it does require the microphones to be handled with care and precision. When such susceptible devices are held so close together there will always be some risk. Practical implementations of the method will require the risk to be minimised.

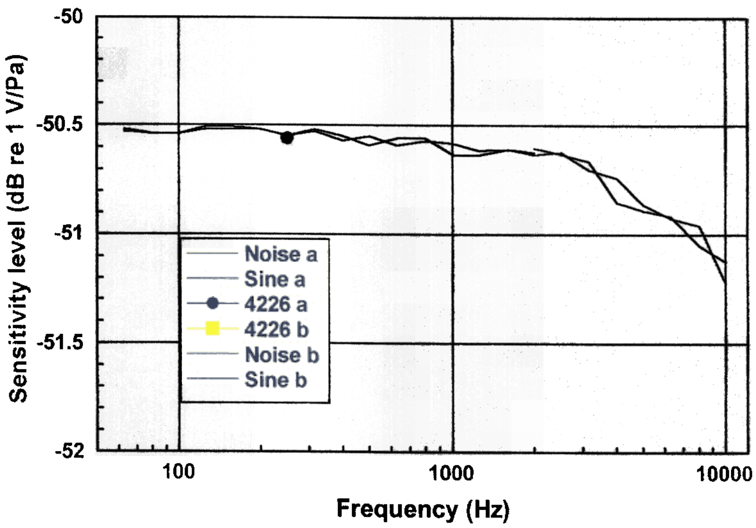

Figure 9 Pressure sensitivity level of microphone 4135 1680529 measured by comparison with a laboratory standard microphone

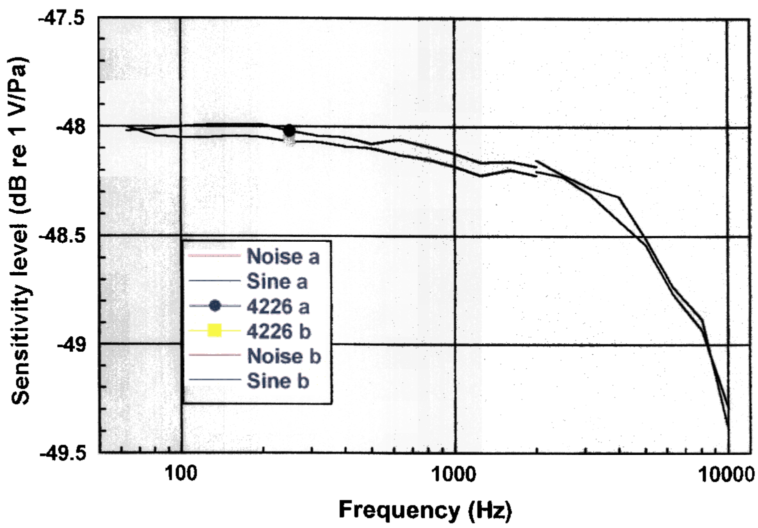

Figure 10 Pressure sensitivity level of microphone 4135 1901601 measured by comparison with a laboratory standard microphone

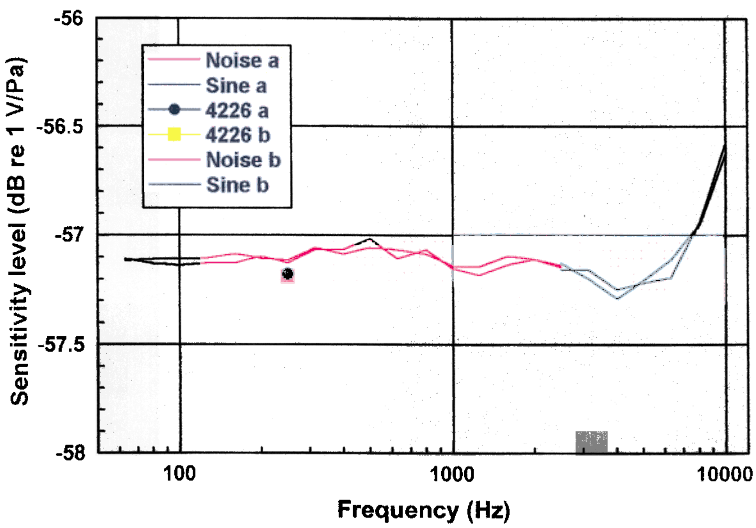

Figure 11 Pressure sensitivity level of microphone 4136 1756306 measured by comparison with a laboratory standard microphone

4 CONCLUSIONS

The best arrangement for the simultaneous comparison calibration of WS3 microphones proved to be one that is quite well defined and relatively simple to implement. **The WS3 microphone should have its grid removed and be brought face to face with a LS2 reference microphone so that its diaphragm is in the same plane as the front face of the LS2 microphone. The sound source should be arranged so that the field around the microphone is cylindrically symmetric.**

The arrangement works well because most of the boundaries of the acoustical space are well defined. Arrangements with more open boundaries could not be modelled so successfully. The method also benefits from not requiring any adaptor to be attached to the WS3 microphone (which could risk altering the sensitivity). Another benefit is that the reference microphone is a laboratory standard microphone and therefore can bring the lowest uncertainty to the method. If the method had required a WS2/WS3 comparison then the uncertainties would have been higher as the WS2 microphone would itself have needed to be calibrated against a LS2 microphone.

The method will now be refined and formalised before a routine service for the pressure calibration of WS3 microphones is made available at NPL. Part of this refinement will include a detailed analysis of the uncertainties. However initial indications are that the method as implemented at NPL should be able to offer uncertainties (at 95% confidence level) of about 0.1 dB below 1 kHz rising to 0.2 dB at 10 kHz.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry.

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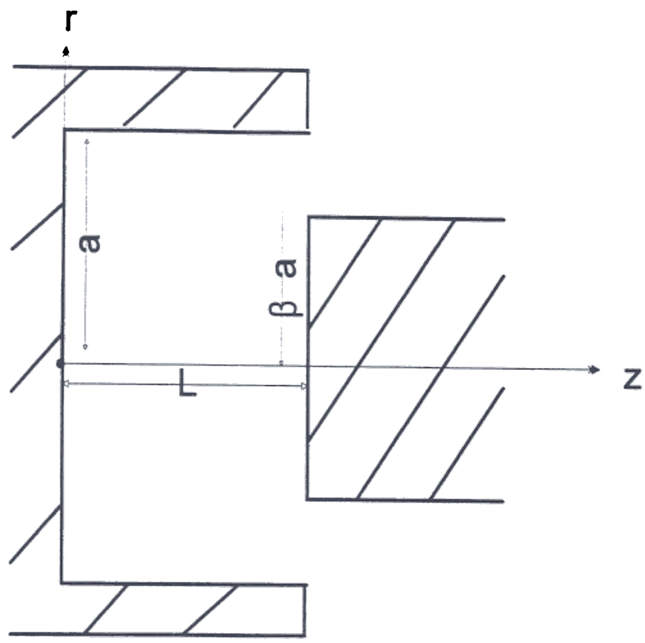
APPENDIX THE EFFECT OF PRESSURE NON-UNIFORMITY ON A COMPARISON CALIBRATION WHEN THE TEST AND REFERENCE MICROPHONES ARE OF DIFFERENT SIZES



Consider a cavity, as shown above, filled with a gas of density ρ and sound speed c. The laboratory standard microphone has a front cavity of radius a and a cavity depth of L. The external diameter of the smaller working standard microphone has a radius βa and is arranged so that its diaphragm is in the same plane as the front face of the laboratory standard microphone. All the solid boundaries are assumed to be rigid while the open boundary is assumed to be a constant volume velocity source.

Following the methods used in reference 3, the source is assumed to be circularly symmetric and is expanded in a Fourier-Bessel series as

$$u(r) = \sum D_n J_0(k_n r) e^{i\omega t}$$

where D_n are coefficients found from the orthogonal properties of the Bessel functions, k_n are the roots of $J_1(k_n)=0$, ω is the angular frequency and t is time.

Then the pressure at any point in the cavity is given by

$$p= \sum C_n \cosh(\mu_n z) J_0(k_n r/a)$$

where

$$C_n = D_n i\omega\rho / (\mu_n \sinh(\mu_n L))$$

and

$$\mu_n = \sqrt{((k_n/a)^2 - (\omega/c)^2)}$$

As an example consider a WS2P microphone being compared with a LS1P microphone at 10 kHz:

The roots of $J_1(k_n) = 0$ are given by:

$n := 1, 2 .. 15$

k_n
3.8317
7.0156
10.1735
13.3237
16.4706
19.6159
22.7601
25.9037
29.0468
32.1897
35.3323
38.4748
41.6171
44.7593
47.9015

$n := 16, 17 .. 50$

$k_n := (n + 0.25) \cdot \pi$

The other parameters are

$a := \frac{18.6 \cdot 10^{-3}}{2}$ m

$c := 345.9$ m/s

$L := 0.002$ m

$\rho := 1.2$ kg/m^3

$\omega := 2 \cdot \pi \cdot 10000$ rad/s

$\beta := \frac{12.7}{18.6}$

and as the source (u(r)) is assumed uniform then

$$D_0 := \frac{2}{a^2} \cdot \int_{\beta \cdot a}^{a} r \, dr$$

$n := 1, 2 .. 50$

$$D_n := \frac{2}{a^2 \cdot J0(k_n)^2} \cdot \int_{\beta \cdot a}^{a} r \cdot J0\left(\frac{k_n \cdot r}{a}\right) dr$$

$n := 0, \; .. \; 50$ $\qquad \mu_n := \sqrt{\left(\frac{k_n}{a}\right)^2 - \left(\frac{\omega}{c}\right)^2}$ $\qquad c_n := \frac{D_n \cdot i \cdot \omega \cdot \rho}{\mu_n \cdot \sinh(\mu_n \cdot L)}$

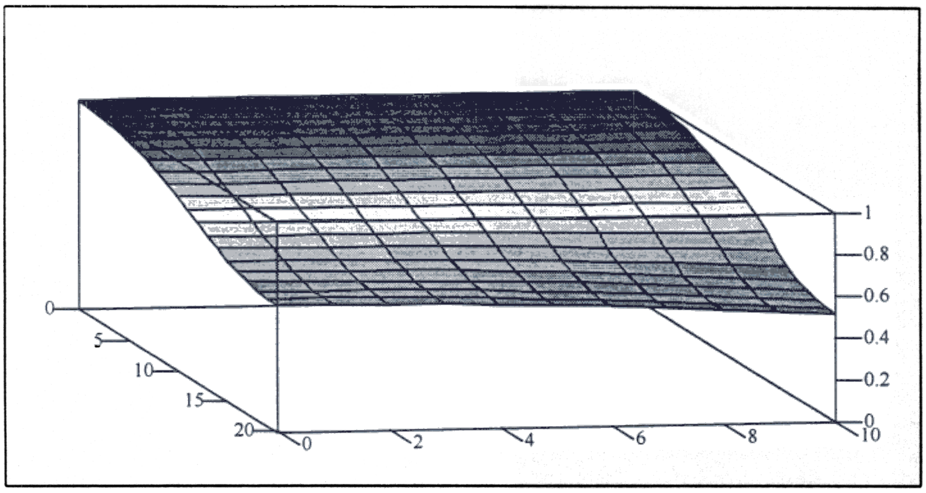
and finally

$$p(r,z) := \sum_n c_n \cdot \cosh(\mu_n \cdot z) \cdot J0\left(k_n \cdot \frac{r}{a}\right)$$

If the cavity is divided into elements (20 along the radius and 10 along the length) and the pressure at the centre of the laboratory standard microphone is used as a reference, then the pressure distribution in the cavity can be plotted as:

$s := 0, 1 .. 20 \quad q := 0, 1 .. 10$

$$ZZ_{s,q} := \left| \frac{p\left(s \cdot \frac{a}{20}, q \cdot \frac{L}{10}\right)}{p(0,0)} \right|$$



ZZ

Reference 4 gives the sensitivity of a condenser microphone as a function of radius across the diaphragm as

$$M(r,\omega,R,F) := 1 - \frac{J0\left(2.405 \cdot \frac{\omega}{2 \cdot \pi \cdot F} \cdot \frac{r}{R}\right)}{J0\left(2.405 \cdot \frac{\omega}{2 \cdot \pi \cdot F}\right)}$$

where R is the radius of the diaphragm and F is the resonance frequency of the microphone.

For the microphones in this example we will take

$F_{ls1p} := 8000$ Hz $\quad F_{ws2p} := 22000$ Hz

$R_{ls1p} := 0.00895$ m $\quad R_{ws2p} := 0.004475$ m

Therefore the ratio of the output of the LS1P microphone compared with the WS2P microphone if they had the same uniform sensitivity level would be

$$X := \frac{\int_0^{R_{ls1p}} M(r,\omega,R_{ls1p},F_{ls1p})\cdot p(r,0)\cdot r\,dr}{\int_0^{R_{ls1p}} M(r,\omega,R_{ls1p},F_{ls1p})\cdot r\,dr} \cdot \frac{\int_0^{R_{ws2p}} M(r,\omega,R_{ws2p},F_{ws2p})\cdot r\,dr}{\int_0^{R_{ws2p}} M(r,\omega,R_{ws2p},F_{ws2p})\cdot p(r,L)\cdot r\,dr}$$

So to compensate for this in the comparison calibration (assuming the laboratory standard microphone is the reference microphone) the sensitivity level of the working standard microphone should be increased by

$$20\cdot\log(X) = -1.1 \quad \text{dB}$$