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Methods for determining the pressure sensitivity of working standard microphones - a report on Euromet project A311

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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. In order to develop an agreed method for this calibration a Euromet[1] project was undertaken to investigate possible approaches and to suggest methods which could be standardised by the IEC. This is a report of that work.

[1]Euromet is an international organization of national metrology institutes of the States of the *European Free Trade Association* and the States of the European Communities.

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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.

Most commonly, a working standard microphone is calibrated by comparison with a laboratory standard microphone[2], the latter being a device capable of calibration by the primary method of reciprocity[3]. Recent intercomparisons and the publication of international Standards on the calibration of laboratory standard microphones have established good agreement between national standards laboratories for the primary standards. However an intercomparison of sound calibrators[4] exposed the problem of calibrating working standard microphones by demonstrating differences of up to 0.2 dB at 1 kHz between different laboratories. International agreement is now sought for the methods to be used for the calibration of these microphones. It was decided that this work should be done as a Euromet project in order that the different resources of several European standards laboratories could be applied to the task and a mutually acceptable solution could be found.

1.1 ORGANISATION OF THE PROJECT

In March 1993 Erling Frederiksen (Brüel & Kjær, Denmark), Dr Utz Richter (PTB), Knud Rasmussen (Danish Technical University) and myself met to discuss possible solutions and how the work could be shared.

NPL presented some measurements and a theoretical analysis of the effect of a grid on the pressure sensitivity of a microphone (see appendix A), and it was concluded that the pressure sensitivity of a microphone could not be determined without access to the diaphragm and that all the potential methods should recognise this.

Erling Frederiksen explained the design of the Brüel & Kjær type 4226 multifunction calibrator. The acoustical part of the device consists of a small coupler containing a feedback microphone, a low frequency piezo-ceramic sound source and a radial PVDF sound source. Brüel & Kjær volunteered to make some versions of this part containing just the radial source as a type of `active coupler' which would allow us to insert a laboratory standard microphone and a working standard microphone so that their diaphragms were face to face. Then they could be subject to identical sound pressures and so their sensitivities could be compared.

Utz Richter showed some cavities used to calibrate the non-standard microphones at 1 kHz in the sound calibrator intercomparison. It was discussed how some of them could be adapted to work at higher frequencies and PTB volunteered to develop this idea.

It was suggested that two microphones could be compared in a free-field if they were mounted face to face with their diaphragms close together. NPL volunteered to try this as the equipment they had for the calibration of sound intensity probes could be adapted for this purpose.

It was decided that each laboratory would also use the Brüel & Kjær prototype active coupler. NPL volunteered to distribute a set of microphones (a LS2P, a WS2P and a WS2F, with a calibrated LS2P as the reference microphone) to each participant so that calibrations could be compared between laboratories. A timetable for the project was agreed with targets set for presentations at the acoustics Euromet meetings in the summers of 1994 and 1995.

The microphones used in the project were:

Partner	Reference microphone	LS2P	WS2P	WS2F
NPL	4134M 982504	4134M 982508	4134 1743825	4188 1765030
DTU	4134M 982508	4134M 982477	4134 1743735	4188 1765031
PTB	4134M 982515	4134M 982546	4134 1743745	4188 1765032

1.2 CALIBRATION PRINCIPLES

The international Standard which gives specifications for working standard microphones[1] does not restrict their principle of operation. They need not be reciprocal transducers so a reciprocity method cannot be used to calibrate them. The Standard does restrict some of their dimensions (so that they can be used in sound calibrators) and, for microphones where the pressure sensitivity is required to be measured, it does require that any protection grid should be removable. The latter requirement is necessary because the definition of the pressure sensitivity of a microphone relies upon a sound pressure being *uniformly* applied over the exposed surface of the diaphragm. However, when the grid is removed the microphone need have no standard shape and this makes it difficult to support the microphone in any calibration device.

The principle of a comparison method is that when the reference microphone and the test microphone are exposed to the same sound pressure either simultaneously or sequentially, then the ratio of their pressure sensitivities is given by the ratio of their open-circuit outputs. The sensitivity of the test microphone can then be calculated from the sensitivity of the reference microphone. These measurements can be performed particularly rapidly if a wide band sound source is used and the outputs of the microphones are analysed in narrow bands.

In order for the two microphones to be simultaneously exposed to essentially the same sound pressure it is necessary for the two diaphragms to be separated by less than a twentieth of the wavelength at the highest frequency of interest. For frequencies up to 20 kHz this can be achieved by mounting the two microphones face to face separated by about 1 mm in either a coupler or jig. Couplers usually contain an integral sound source; in a jig, use is made of an external sound field.

In order for the two microphones to be sequentially exposed to essentially the same sound pressure it is necessary for either the exchange of microphones not to change the sound pressure significantly or for any change to be detected and corrected for. This can be achieved by incorporating a sound source, a monitor microphone and the test/reference microphone together in a coupler.

2 WORK AT NPL

2.1 INITIAL INVESTIGATIONS

For some years NPL had had a device for the sequential comparison calibration of microphones at 250 Hz. This was a conventional pistonphone with the addition of a WS3P microphone mounted flush with the inside wall of the cavity. This `monitor' microphone could be used to detect a change in sound pressure in the cavity due to a change of microphone. The device worked well for laboratory standard microphones but less well with working standard microphones. There was evidence that the change in sound pressure in the cavity did not necessarily follow the change in sound pressure behind a grid when microphones of one type were exchanged for those of another type. In one particular experiment it was possible to distinguish between two different types of WS1F microphone by their characteristic deviations in this device and to identify one microphone which was a hybrid consisting of the shell of one type and a diaphragm of the newer type!

Initial experiments with a simultaneous comparison method were done in a Brüel & Kjær type 3541 intensity calibrator. In this device two microphones are held close together and subjected to the same pink noise. Again the method worked well with laboratory standard microphones but had problems with working standard microphones above a few kHz. The problems were found to be due to the grid on the microphone (see Appendix A), but it was not possible to hold a working standard microphone in the device without its grid in place.

Another method of simultaneous comparison was developed where the two microphones were held in an intensity probe with their diaphragms very close together (any grid having been removed). The probe was then held in a free-field room and subjected to pink noise. This proved to be a satisfactory method but potentially very expensive if a free-field room was required.

The conclusions of the initial investigations were:

1) Working standard microphones must be calibrated without a protection grid in place in order to remove unpredictable grid effects.

2) Comparison methods where microphones of similar sizes are placed face-to-face, separated by a small distance give the lowest uncertainties.

3) Methods which use a pink noise source and third-octave analysis of the signals are practical and fast.

This provided the framework for the work done by NPL under the collaborative project.

2.2 CALIBRATION WITH THE BRÜEL & KJÆR ACTIVE COUPLER

Brüel & Kjær supplied a prototype of their active coupler consisting of a PVDF source and ports to accommodate two microphones face to face (see Figure 1). The device did not come with any adaptors to replace the grids on working standard microphones so these were developed at NPL. For the pre-circulation measurements we took a normal grid from a 4134 microphone, removed a disc of 11 mm diameter from the front face by spark erosion and used the remaining part to locate the microphone in the coupler (see Figure 2).

Nine microphones (3 type LS2P, 3 type WS2P, and 3 type WS2F) were calibrated at NPL by comparison with laboratory standard microphones type LS2P. The sound source was driven

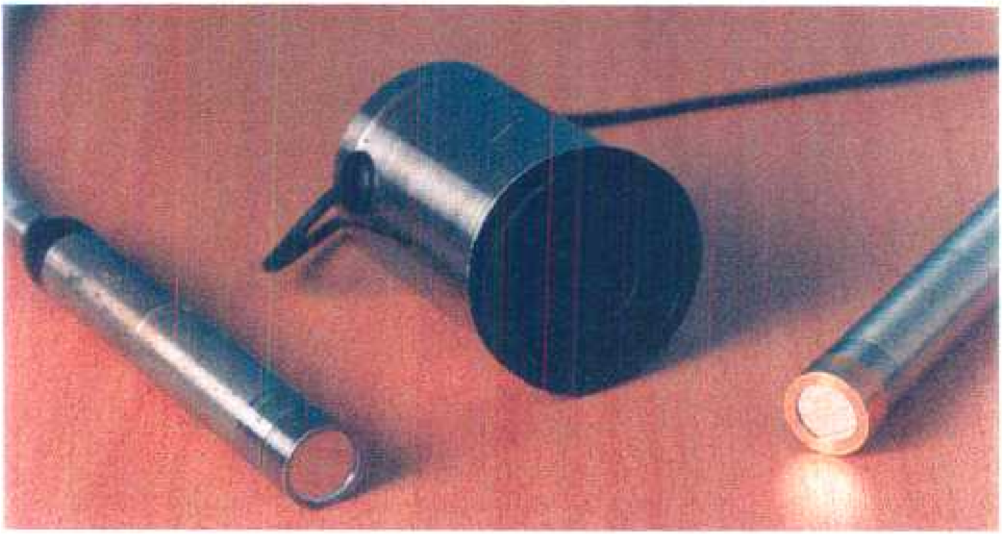

Figure 1 The B&K active coupler and the microphone adaptor used for the post-circulation measurements.

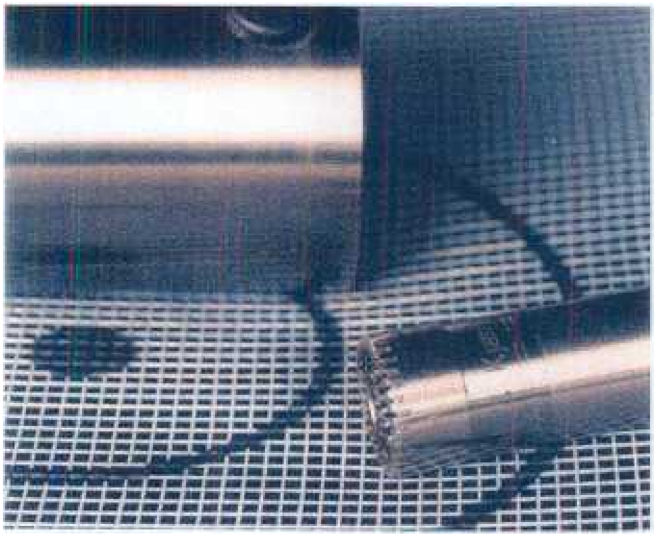

Figure 2 The microphone adaptor used for the pre-circulation measurements

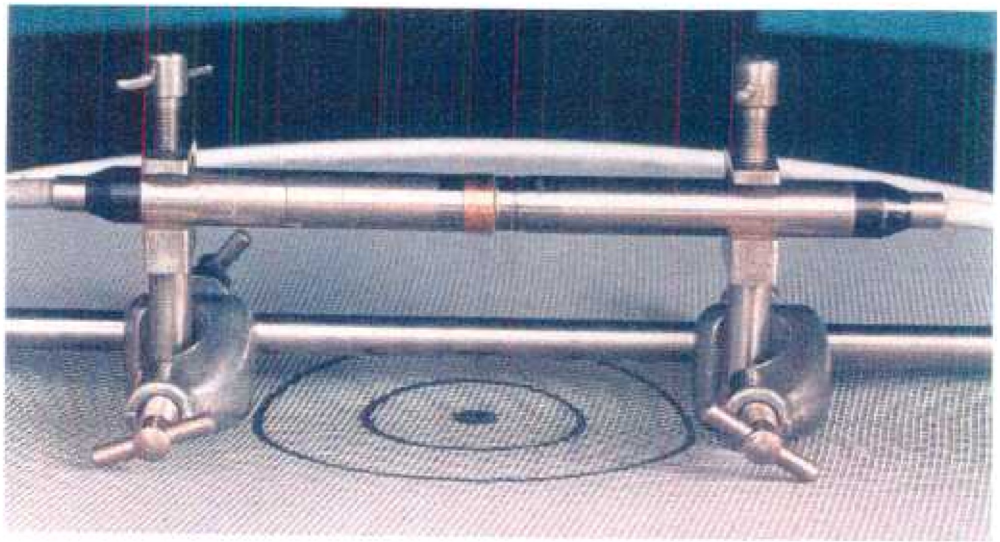

Figure 3 The jig mounted inside a B&K type 4222 Anechoic Test Chamber

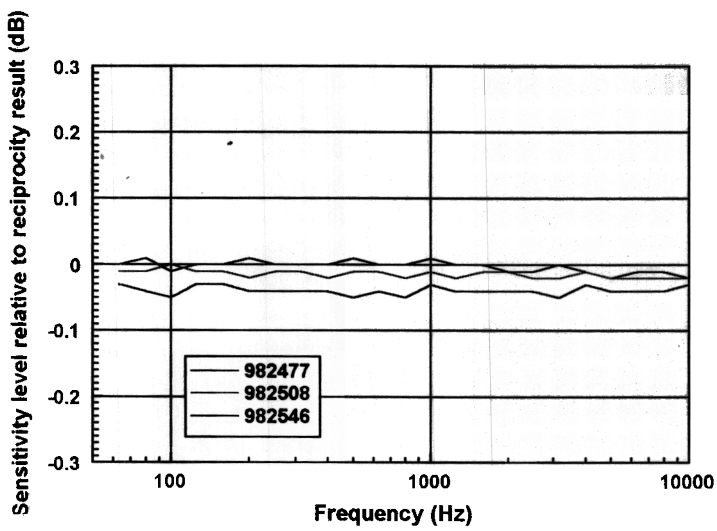

Figure 4 Results for microphones type 4134M in the active coupler relative to reciprocity results

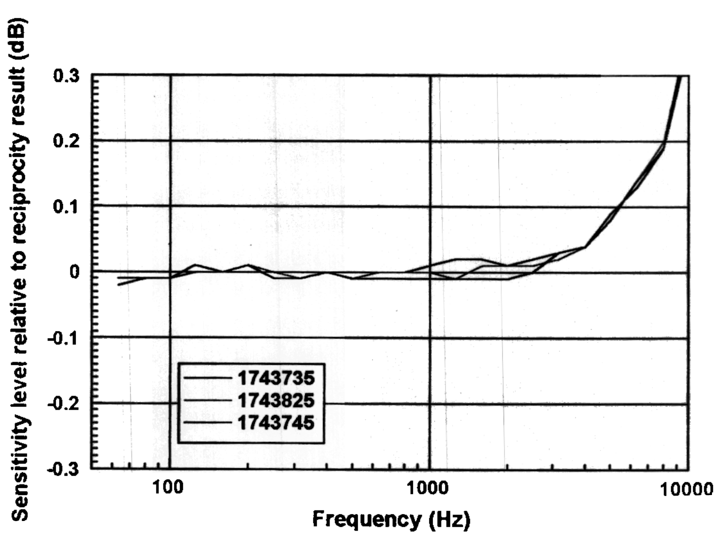

Figure 5 Pre-circulation results for microphones type 4134 in the active coupler relative to reciprocity results

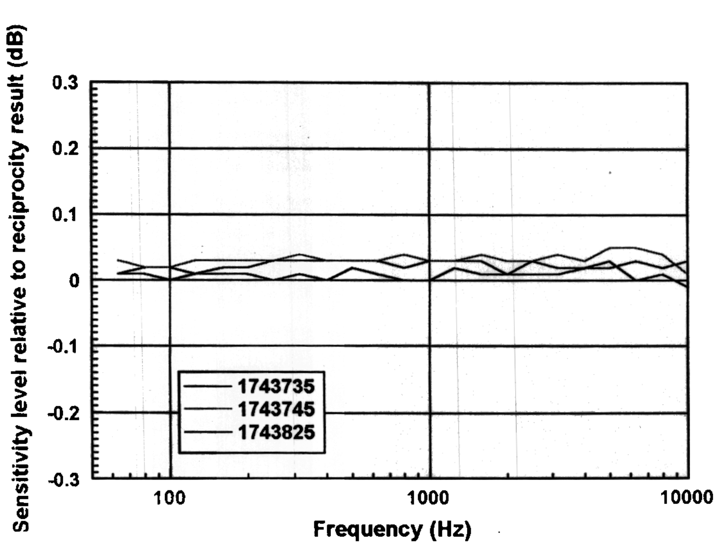

Figure 6 Post-circulation results for microphones type 4134 in the active coupler relative to reciprocity results

with pink noise (at approximately 60 V rms) and the microphone outputs were measured on a Norsonics 830 real time analyzer. During the measurements the microphones were swapped to eliminate any differences in the sound field or the gains of the pre-amplifiers and analyzer input channels.

Results of the calibrations, relative to the sensitivities determined by reciprocity, are shown in Figures 4 and 5. It was not possible to calibrate the WS2F microphones by reciprocity so these results are omitted.

While the method gave satisfactory results with the laboratory standard microphones, it can be seen that the adapted working standard microphones had a significant error above 4 kHz. It was thought that these deviations could be due to the complicated shape of the modified grid and the resulting small irregular volumes around the microphone diaphragm. Therefore, on the return of the microphones an adaptor ring (Brüel & Kjær type UA0825) was taken and the diameter of the opening was enlarged to 11 mm and this was used to locate the microphone in the coupler (see Figure 1).

The results that were then obtained are shown in Figure 6, confirming that it was the design of the adaptor that caused the problems at high frequencies.

2.3 CALIBRATION WITHOUT A COUPLER

The main obstacle to a comparison method for working standard microphones appeared to be supporting the microphone in a cavity without its protection grid in place. A radical solution to this problem was to remove the cavity. This is possible by mounting two microphones face to face, separated by a small distance, in a sound field. The two microphones would then respond to the same sound pressure, and the *pressure* sensitivity of the microphone could be determined. The arrangement for mounting the microphones is called a jig.

Figure 3 shows an arrangement used at NPL for this method. A B&K type 4222 Anechoic Test Chamber was used so that high sound pressure levels could be generated around the microphone without disturbing other users of the laboratory. The method was also implemented with the microphones held in an ordinary room with the noise being generated by a domestic loudspeaker. The results from this alternative arrangement were similar but the high noise levels required caused disturbance to other staff.

The nine microphones were again calibrated by comparison with laboratory standard microphones type LS2P. The sound source was driven with pink noise to generate a sound pressure level of approximately 74 dB in each third octave band and the microphone outputs were measured on a Norsonics 830 real time analyzer. During the measurements the microphones were swapped to eliminate any differences in the sound field or the gains of the pre-amplifiers and analyzer input channels.

Results of the calibrations, relative to the sensitivities determined by reciprocity, are shown in Figures 7 and 8. It was not possible to calibrate the WS2F microphones by reciprocity but the results of a calibration in a jig and a coupler are shown for one microphone relative to the mean value for the two methods in Figure 9.

Some of these results show a deviation at frequencies below 125 Hz and this is thought to be due to the microphone vent being exposed to the sound field. The size of the deviation varies

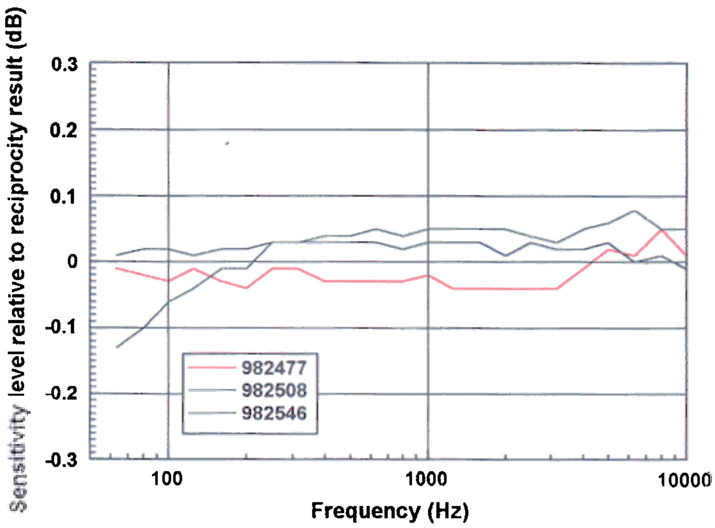

Figure 7 Results for microphones type 4134M in the jig relative to reciprocity results

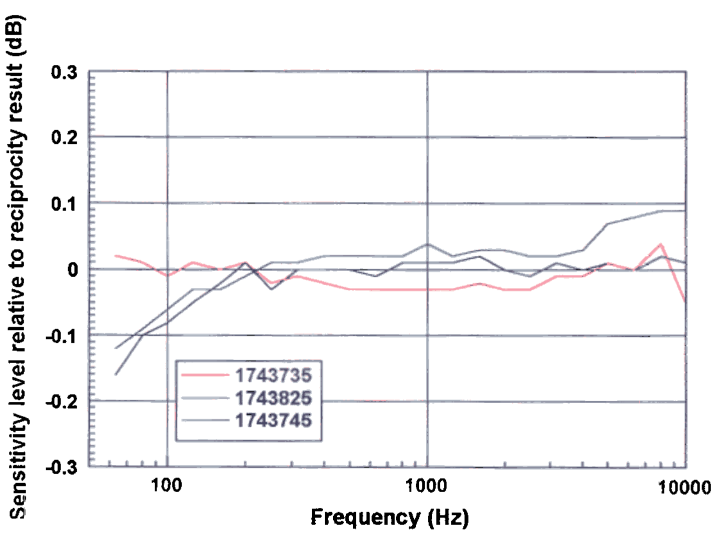

Figure 8 Pre-circulation results for microphones type 4134 in the jig relative to reciprocity results

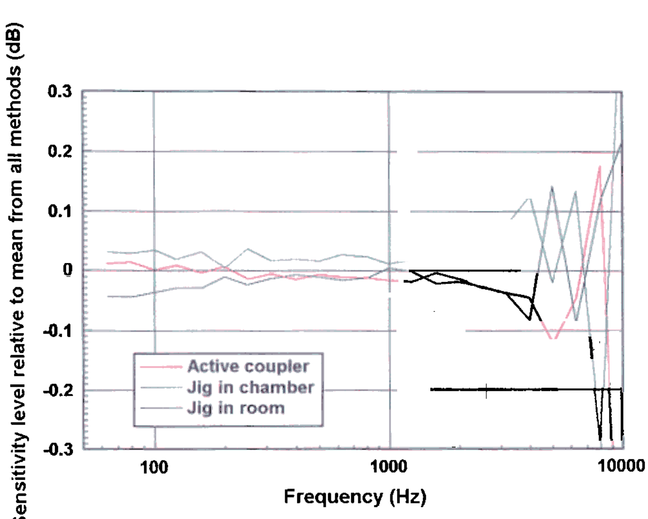

Figure 9 Results for a microphone type 4188 in the coupler and the jig relative to the mean sensitivity by those methods.

between microphones of the same type and no method could be found to eliminate this problem or to predict whether a given microphone would be affected.

2.4 UNCERTAINTIES

The work in this project concentrated on exploring different approaches rather than a detailed analysis of the uncertainties associated with any particular approach. Indeed, where different methods have been compared using the same reference microphones and measuring systems, many sources of uncertainty in an actual calibration have not been relevant. However, the dominant sources of uncertainty in an actual calibration will be those associated with the calibration of the reference microphone and the repeatability of the comparison measurements. The latter, which was typically better than 0.02 dB at NPL, can be minimised by careful handling and high signal levels.

One additional source of uncertainty is caused by the difference in acoustic impedance between the test and reference microphones. Appendix B gives a theoretical analysis of this problem and shows that the uncertainty can be less than 0.01 dB even when the two microphones have impedances at opposite extremes of the ranges allowed in IEC 1094.

Another source of uncertainty is introduced when a noise source and third octave analysis is used if the test and reference microphones have different frequency responses. The reciprocity calibration of the reference microphone is usually valid for a single frequency, rather than a third octave band of noise, and the comparison is therefore only valid when the test and reference microphones have the same relative responses across a third octave. Experimental determinations of the difference between calibrations using noise and those using single frequencies found no noticeable difference when the test and reference microphones were of the same type, but with a 4188 microphone compared with a 4180 microphone differences of 0.06 dB at 4 kHz, 0.13 dB at 5 kHz, 0.22 dB at 6.3 kHz, and 0.12 dB at 8 kHz were observed.

At a temperature or static pressure away from the reference conditions some uncertainties will arise if the test and reference microphones have different temperature and pressure coefficients. These uncertainties can be minimised by using a reference microphone of the same type as the test microphone or by performing the measurements close to reference conditions.

NPL are now preparing a routine procedure for the comparison calibration of WS2 microphones and the uncertainties associated with that procedure are being analysed in detail.

2.5 CONCLUSIONS

The following conclusions were drawn from the work at NPL:

- Working standard microphones must be calibrated without a protection grid in place in order to remove unpredictable grid effects.

- Simultaneous comparison calibrations using pink noise and third octave analysis are fast (3 repeats in 15 minutes) and can achieve an overall uncertainty of less than 0.1 dB up to 10 kHz.

- It is necessary to verify each combination of microphone type and calibration arrangement by comparing with different arrangements.

- It may be necessary to use two different arrangements to cover a full frequency range for some microphone types. For example, if a microphone demonstrates high frequency deviations in couplers and low frequency deviations in jigs then a full calibration can be achieved by using both methods.

3 WORK AT PTB

PTB were supplied with three test microphones and a reference microphone from NPL, and a B&K active coupler direct from Brüel & Kjær. Their task was to calibrate the test microphones by comparison with the reference microphone using both the B&K active coupler and a sequential method using the B&K type 4226 multi frequency calibrator. In addition, they developed a sequential method for LS1P microphones that will have particular relevance for the calibration of microphone systems associated with IEC 303 reference couplers and IEC 126 ear simulators.

3.1 FITTING ADAPTORS FOR THE WS2 MICROPHONES

The adaptors developed at NPL were not forwarded to PTB with the microphones. Initially, they tried to use a B&K type UA0825 adaptor ring but found that the sensitivity of the 4134 microphone changed by up to 0.07 dB depending on the force by which the adaptor ring was screwed on the microphone. This is a cause for concern because the manufacturer has designed the UA0825 to be compatible with the type 4134 microphone. Indeed, that microphone had been reciprocity calibrated at NPL using another UA0825 adaptor and no change in sensitivity had been observed. If we cannot rely on the UA0825 adaptors, then it may be that only microphones that are maintained in the LS configuration can be calibrated by reciprocity.

Because of this problem, PTB manufactured their own fitting adaptors having an outer diameter of 13.2 mm and a length of 6.5 mm and leaving free the surface of the diaphragm. With this fitting adaptor, some leakage remained between the central cavity in a coupler and air around the side of the microphones. The calibrations were then performed using both the fitting adaptor and the normal grids.

3.2 SIMULTANEOUS COMPARISON WITH THE B&K ACTIVE COUPLER

The three test microphones were calibrated by comparison with the reference microphone. The sound source was driven at 10 V by sinusoidal signals with frequencies in 1/3-octave steps between 63 Hz and 20 kHz. The outputs of the microphones were measured using the insert-voltage method. During the measurements, the microphones were swapped to eliminate any differences in the sound field. The results of these simultaneous comparisons, using fitting adaptors where necessary, are shown in Figures 10-12. The results for the LS2P microphone are plotted relative to the NPL reciprocity value but the results for the WS2 microphones are plotted relative to the mean of both methods used at PTB as the sensitivity of these microphones obviously changed before calibration at PTB, perhaps due to the use of the UA0825 adaptor. At 10 kHz, the results for the calibrations performed with normal grids fitted differed from those using the adaptors by 0.6 dB for the WS2P microphone and 0.5 dB for the WS2F microphone, thus confirming the initial conclusions drawn by NPL.

3.3 SEQUENTIAL COMPARISON USING THE B&K TYPE 4226

The B&K type 4226 multifrequency calibrator has a built-in control microphone which stabilizes the sound pressure level inside the coupler at 114 dB and is therefore a suitable coupler for a sequential comparison calibration. The sound source was driven at 1 V by sinusoidal signals with frequencies in 1/3-octave steps between 63 Hz and 16 kHz. The outputs of the microphones were measured using the insert voltage method. The results for these calibrations, using fitting adaptors where necessary, are also shown in Figures 10-12. At 4 kHz, the measurements were not stable, probably due to an instability of the control mechanism at that

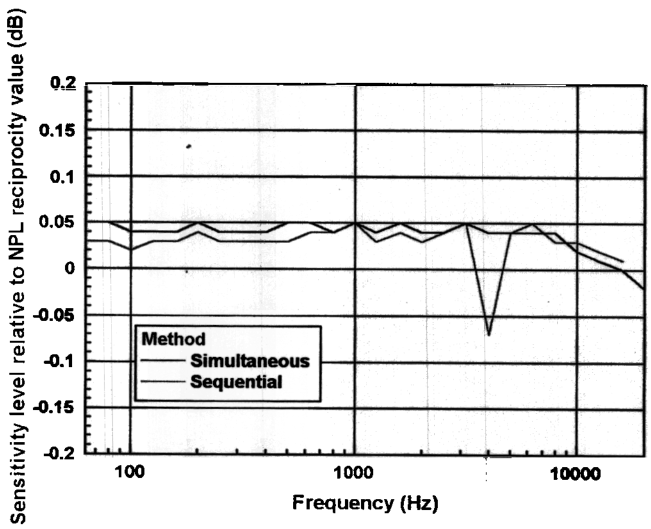

Figure 10 Results for microphone 4134M, 982546 at PTB, relative to the NPL reciprocity results

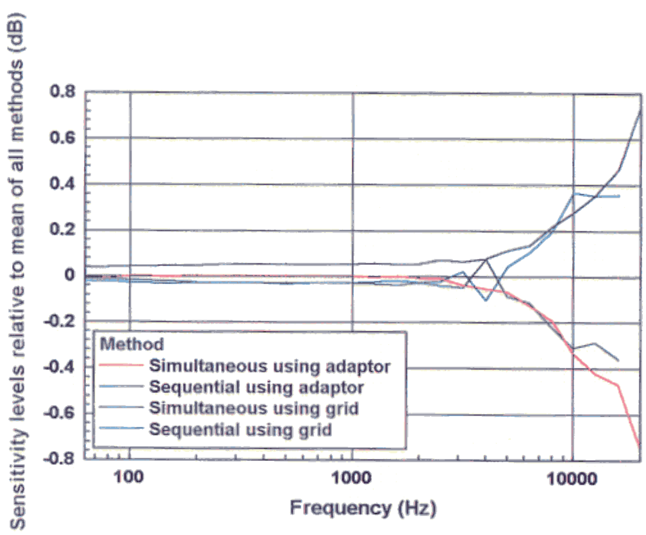

Figure 11 Results for microphone 4134, 1743745 at PTB, relative to the mean results at PTB.

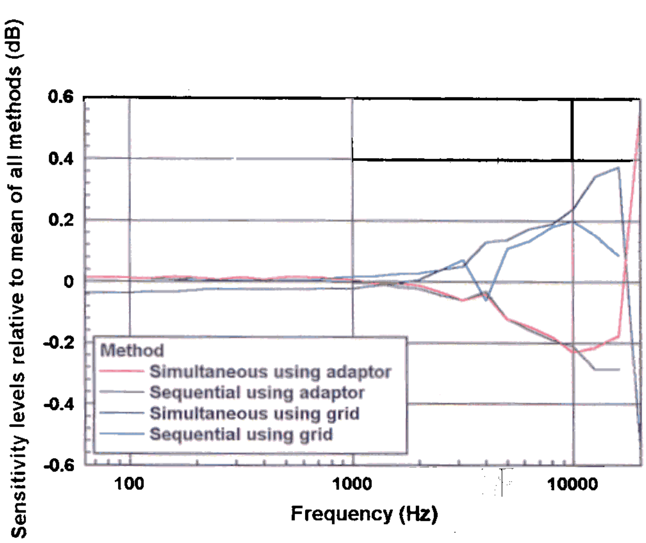

Figure 12 Results for microphone 4188, 1765032 at PTB, relative to the mean results at PTB.

frequency. The results for the calibrations performed with grids were in error by similar amounts to those found with the simultaneous method.

3.4 A SEQUENTIAL COMPARISON METHOD FOR WS1P MICROPHONES

Figures 13 and 14 show a coupler developed at PTB for the calibration of microphones type 4144. A 4144 microphone, used as the sound source, is screwed directly into the coupler without any grid or adaptor. A probe tube microphone is inserted from the side of the coupler so that the probe tip is two thirds of the distance along a radius from the wall, and is used to control the sound pressure in the coupler. The test and reference microphones are in turn adapted with the same adaptor ring (B&K type DB0111) and held in the coupler by a yoke and spring arrangement. The distance between the source diaphragm and test diaphragm is no more than 5 mm.

Six different microphones which had previously been calibrated by the reciprocity method were used to evaluate this coupler. Two of them (M1 and M2) were used as the reference microphones and the others (M3 to M6) were used as the test microphones. During one calibration the test and reference microphone were always measured with the same adaptor ring type DB0111. The microphone under test was compared with two reference microphones and the mean values of the resulting sensitivity levels were taken. This procedure reduces both the measurement uncertainty and the risk of false calibrations due to an unstable reference microphone.

The sensitivity level determined by this comparison method relative to the sensitivity level determined by reciprocity for each of the microphones is shown in Figure 15. The maximum difference found between reciprocity calibration and the comparison calibration was 0.04 dB from 125 Hz to 5 kHz and 0.11 dB at 6.3 kHz and 8 kHz. The repeatability of the comparison measurements was about 0.03 dB.

3.5 CONCLUSIONS

The results from the work at PTB demonstrate:

- The need to remove any grid and expose the diaphragm of the microphones in order to make measurements at high frequencies.

- That simultaneous and sequential methods can agree within 0.03 dB at frequencies up to 10 kHz but it is necessary to verify that the monitor mechanism in a sequential measurement is working correctly.

- A sequential comparison method for WS1P microphones can give an acceptable uncertainty in the calibration of microphone systems used in the IEC 303 reference coupler.

- At least two reference microphones should be used for a calibration so that any instability in them will be detected.

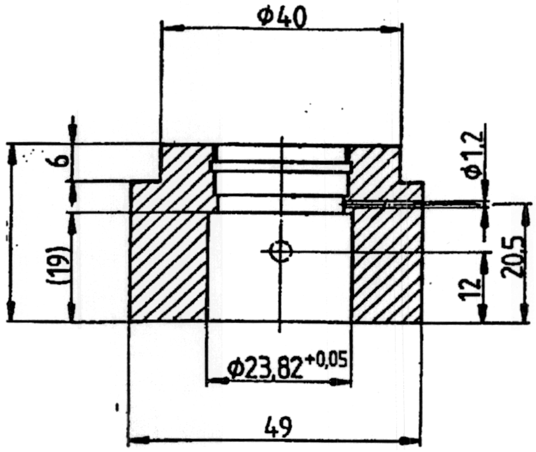

Figure 13 Sketch of the coupler developed at PTB for WS1P microphones (dimensions are in mm).

Figure 14 The coupler developed at PTB for WS1P microphones shown with microphones inserted.

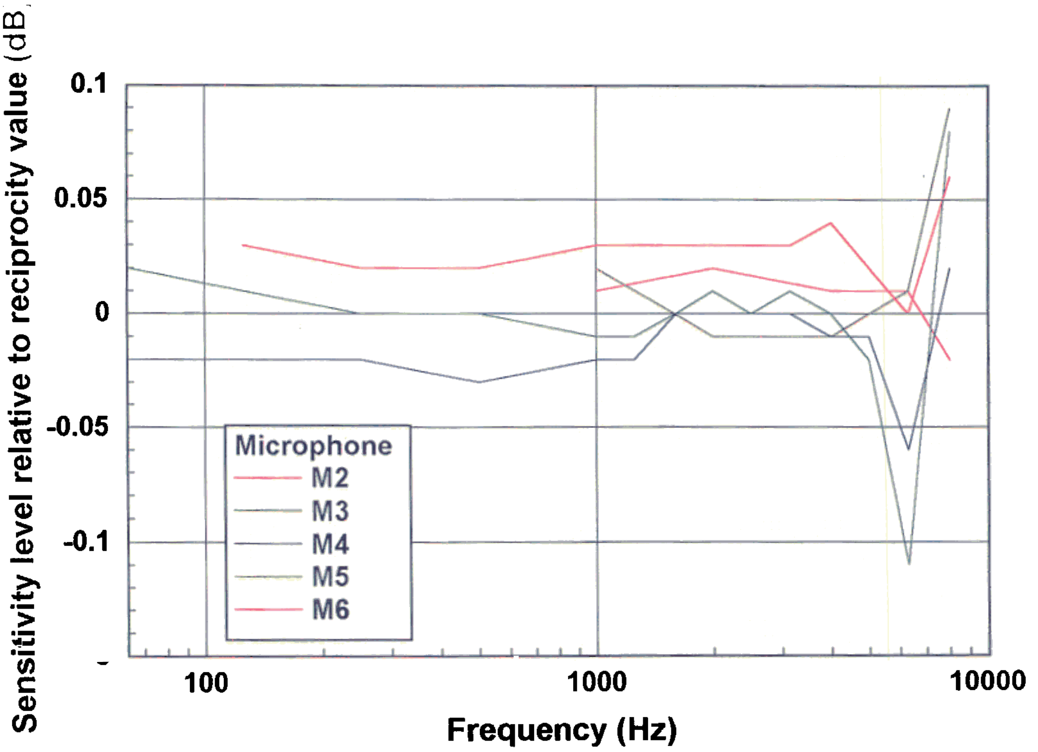

Figure 15 Results for five microphones (B&K type 4144) calibrated at PTB by comparsion, relative to the sensitivities determined by reciprocity at PTB.

4 WORK AT DTU

DTU were supplied with three test microphones and a reference microphone from NPL, and a B&K active coupler direct from Brüel & Kjær. Their task was to calibrate the test microphones by comparison with the reference microphone using the B&K active coupler, a coupler for simultaneous comparison calibrations developed at DTU, and a jig. In addition, measurements with pure tones and pseudo-random noise were compared. A full report[5] of the work at DTU is available and only summaries will be reproduced here.

4.1 THE MEASUREMENT METHOD

Whichever coupler/jig was used, the method of measuring the outputs of the microphones was the same: the two microphones were attached to B&K type 2645 pre-amplifiers which were connected to the two input channels of the DTU reciprocity calibration apparatus[6]. This only served as a two channel amplifier and allowed access to the insert voltage capabilities of the pre-amplifiers. For sinusoidal measurements, the sources were driven from a synthesizer and the voltages were measured with a DVM via a 1/3-octave filter. For pseudo-random noise measurements a B&K type 2032 was used as source and analyser, giving results in narrow bands (bandwidth 16 Hz or less below 10 kHz). In each case, the signals were measured as complex values, so that both the amplitude and phase sensitivity could be determined.

Initially, because an insert voltage method was being used, it was thought unnecessary to exchange the microphones. However it was discovered that there was significant difference between the two microphone positions in some couplers and the jig, and that in order to eliminate this asymmetry it was still necessary to exchange the microphones between the ports of the coupler.

4.2 COUPLERS/JIGS USED

In addition to the B&K active coupler, DTU made their own coupler and jig and made some measurements in a B&K type 3541 residual intensity testing device.

The coupler made at DTU was constructed in plexi-glass and consisted of a simple bore with two O-rings to seal the gap between the pre-amplifiers and the coupler. The O-rings were spaced 11 mm apart and the microphones were inserted so that the diaphragms are separated by about 1 mm. In the centre of the coupler, a small opening with a radius of about 1 mm and a length of about 2 mm lead to the front of a flush mounted microphone (B&K type 4144) which was used as the sound source.

The jig made at DTU was a simple symmetric fork which held the preamplifiers so that the microphones were face-to-face, separated by 1-1.5 mm. The sound source for the jig was a loudspeaker at a distance of 1 m in an ordinary room, so that the sound arrived at grazing incidence to the microphone diaphragms.

4.3 RESULTS

Measurements were performed both with and without protection grids. The results for the grid configuration confirmed the conclusions drawn at NPL and PTB. The results for the WS2P microphone without grid, but adapted with an adaptor type UA0825, are shown in Figure 16.

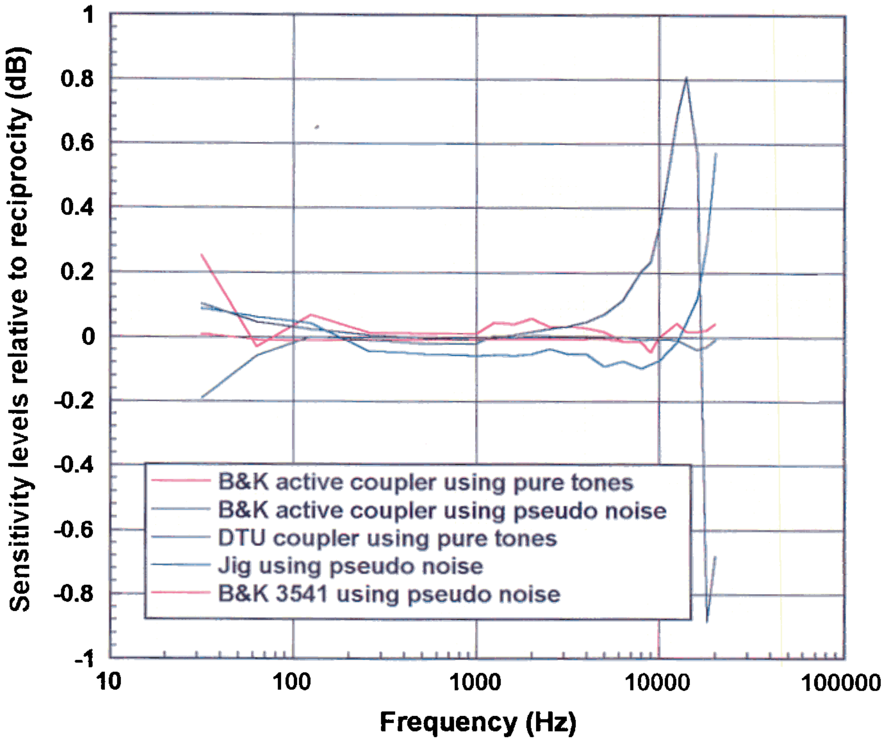

Figure 16 Results for microphone 4134, 1743735 with adaptor ring at DTU, relative to DTU reciprocity results

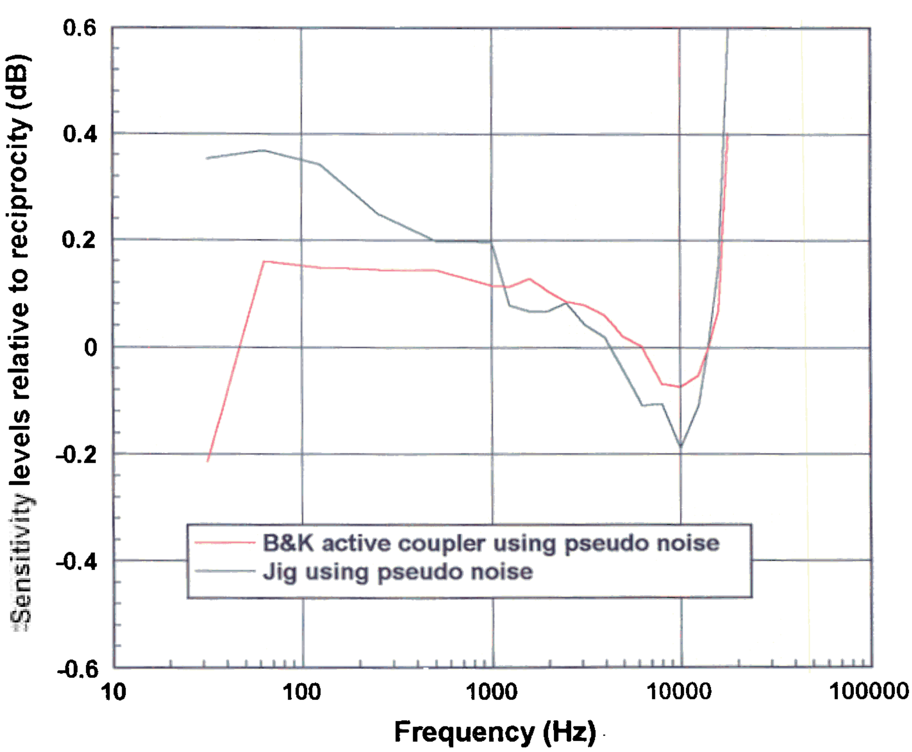

Figure 17 Results for microphone 4188, 1765031 at DTU, relative to DTU reciprocity results.

4.3.1 The B&K active coupler
Using a sinusoidal source, this coupler gave the best repeatability of all the methods. During the measurements, the driving voltage to the active coupler element was about 7 V varying with frequency in order to keep a constant sound pressure level in the coupler of about 90 dB re 20 μPa. However, the maximum driving voltage available was 14 V and below 125 Hz, this sound pressure level could not be achieved.

The pseudo-random noise signal consisted of 800 equally spaced frequencies and thus the available signal level at a single frequency was 800 times less than the level of the total signal. The voltage driving the sound source was 10 V and thus the signal level at the single frequencies was about 25-30 dB lower than when the sinusoidal signal was used. Below 250 Hz the signal level was further reduced by about 12 dB per octave due to the frequency response of the transducer element. The lower signal levels resulted in a worse repeatability than the sinusoidal case but the transducer can be driven at 70 V so the repeatability could be improved with suitable amplification.

4.3.2 The DTU Jig
The jig was only used with pseudo-random noise and the signals and analysing technique used were exactly the same as those for the active coupler. The overall signal level was slightly higher than during the coupler measurement and in particular the low-frequency level was increased due to the better low-frequency performance of the loudspeaker. Consequently, the repeatability was improved in places.

Above 12 kHz, the response of the loudspeaker falls off and the directivity properties are more pronounced. As a result, the exact positioning of the microphones becomes more critical. The angle of incidence of the sound also appears to become more important when the wavelength is comparable with the microphone diameters. There is no evidence in the results to indicate any influence from the room.

4.3.3 Other couplers
A few measurements were carried out with the DTU coupler using a pure tone signal. The repeatability was similar to that obtained with the active coupler. However, the absolute values of the measured differences deviate systematically from the true differences for frequencies above 5 kHz, due to the asymmetric sound field inside the coupler.

A single measurement was also carried out using the B&K type 3541 residual intensity testing device, but since the internal sound source in the calibrator only works up to about 5 kHz and the level of the sound signal is much lower than for the other couplers, this coupler was also surpassed by the active coupler.

4.3.4 Results for the WS2F microphone
The results for the WS2F microphone (a B&K type 4188) are shown in Figure 17. These results are shown relative to a reciprocity calibration at DTU. Because the 4188 cannot be adapted to the LS2 configuration, it was adapted with a cylindrical fitting adaptor and a PTFE washer was put on the mating face in the reciprocity coupler in an attempt to isolate the coupler volume from the volume in the adaptor. The results suggest that this attempt was unsuccessful: the two comparison methods agree with each other better than they agree with the reciprocity result which appears to have a frequency dependent error of approximately 0.15 dB per decade. This type of error in plane wave reciprocity calibrations is often caused by a leak between the coupler and the space around the microphone. The differences between the two comparison methods are compatible with the explanations already given for the WS2P microphone.

4.4 CONCLUSIONS

The investigations at DTU showed that the active coupler could be used to calibrate WS2 microphones with an uncertainty of 0.1 dB up to 8 kHz and with an uncertainty of less than 0.2 dB up to 20 kHz. Other arrangements were tried but found to be less versatile.

Perhaps the most important conclusion was that it is necessary to swap the microphones between ports to eliminate any asymmetry in the sound field.

5 DISCUSSION

5.1 COMPARISON OF RESULTS

Initially it was decided to have all the microphones supplied and calibrated by one laboratory so that simple comparisons could be made between different partners. However many of the microphones proved to be unstable and a different, less uniform, approach to the presentation of the results has had to be adopted.

Figures 18-20 show the history for some of the microphones. The measurements are at 250 Hz but may be by reciprocity, pistonphone, or comparison. (The change for 4134 1743825 does not appear because it was 0.8 dB.) The histories for the LS2P microphones are consistent with previous intercomparisons but those for the WS2P and WS2F are less stable. It may be that during the course of the experiments, the WS2 microphones were shocked by various adaptors and insertions into small cavities. It is recommended that, once an optimum procedure has been chosen, the stability of a group of WS2 microphones be monitored by that procedure to determine if the calibration method is causing any harm to the microphones.

5.2 RECOMMENDATIONS

The following recommendations can be made following the conclusions drawn at the various laboratories:

- If the pressure sensitivity of a microphone above 1 or 2 kHz is to be determined, then the microphone grid must be removed for the calibration.

- In simultaneous comparison calibrations it is necessary to swap the microphones between ports to eliminate any asymmetry in the sound field.

- Simultaneous comparison calibrations using pink noise and third octave analysis are fast with an acceptable uncertainty up to 20 kHz. The uncertainty may be improved by calibrating with pure-tones but with an increase in the time required for a full calibration.

- Sequential comparison calibrations can be as good as simultaneous comparison calibrations but are vulnerable to faults in the monitoring circuit.

- At least two reference microphones should be used for a calibration so that any instability in them will be detected.

- It is necessary to verify each calibration arrangement with a small sample of each microphone type by comparing with different arrangements.

- It may be necessary to use two different arrangements to cover a full frequency range for some microphone types.

- The B&K active coupler proved to be the best coupler in these investigations but it could be improved further by making it more symmetric (having the same holding arrangements at each end) and by the manufacturer supplying the necessary fitting adaptors for the microphones.

Once these methods have been implemented for WS2 microphones, then work should start on

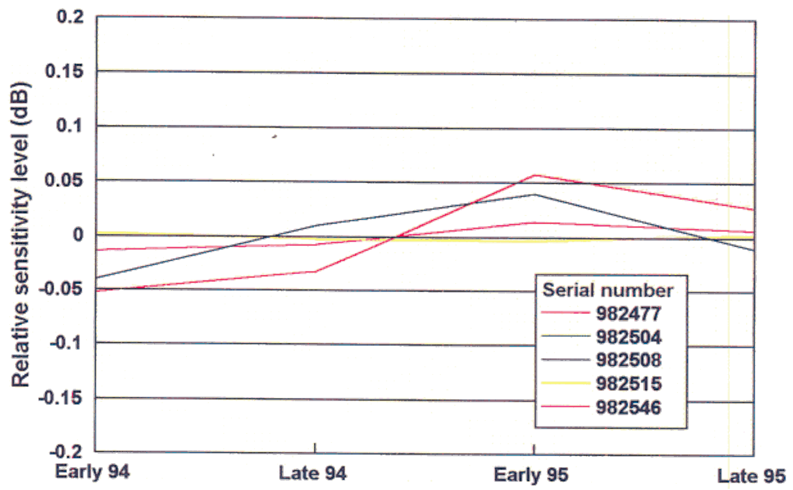

Figure 18 Change in sensitivity level with time for microphones type 4134M

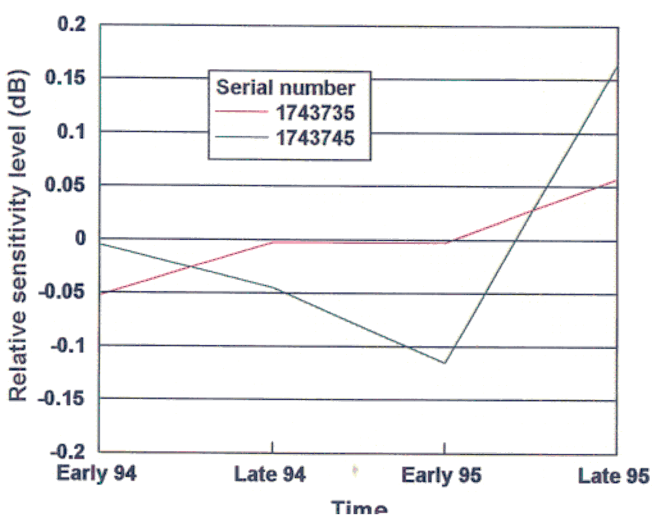

Figure 19 Change in sensitivity level with time for microphones type 4134

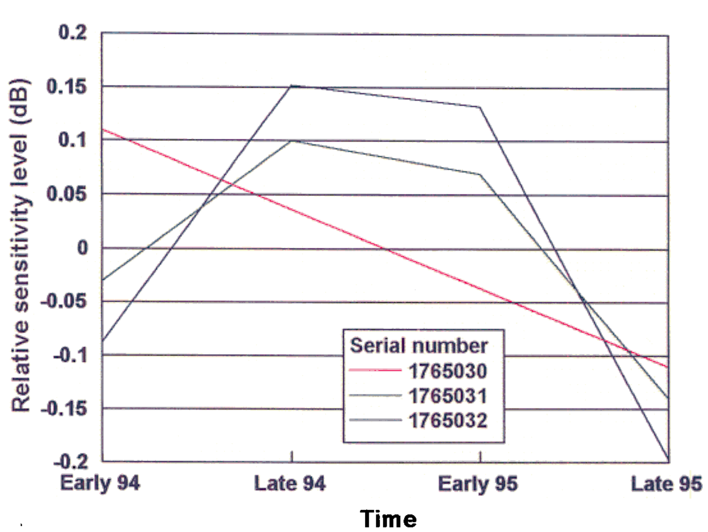

Figure 20 Change in sensitivity level with time for microphones type 4188

investigating the calibration of WS3 microphones by this method. The principles should be the same, but radial non-uniformity of the sound field is likely to cause higher uncertainties.

6 ACKNOWLEDGEMENTS

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APPENDIX A THE EFFECT OF A PROTECTION GRID ON THE OBSERVED PRESSURE SENSITIVITY

Although the pressure sensitivity is defined in terms of a pressure distributed uniformly over the diaphragm, there are many measurement situations where it is more practical to keep the protection grid in place. Using a simple model for two microphones in a small cavity it is possible to estimate the effect of the grid on the measured pressure.

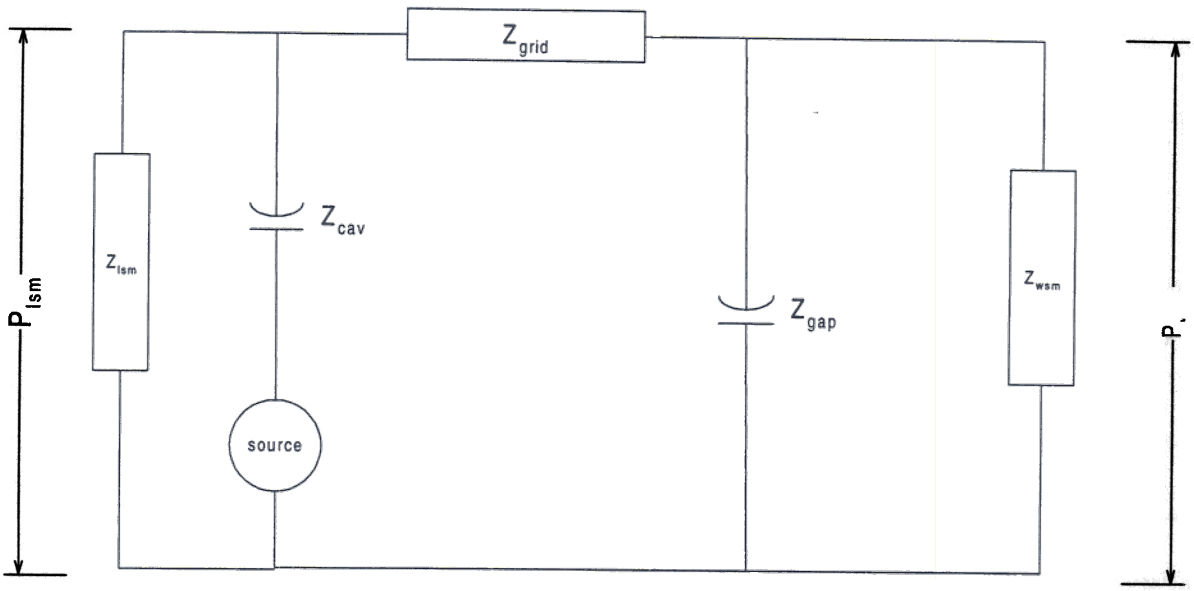


Figure A1 Equivalent circuit for a working standard microphone and a laboratory standard microphone in the same cavity.

Consider the equivalent circuit in Figure A1 which represents a laboratory standard microphone (of acoustical impedance Z_{lsm}) and a working standard microphone (of acoustical impedance Z_{wsm}) in a cavity (of acoustical impedance Z_{cav}). The cavity contains a source of sound. The grid of the working standard microphone is represented by the acoustical impedance Z_{grid}, and the air between the grid and the diaphragm is represented by the acoustical impedance Z_{gap}.

The ratio of the pressure at the diaphragm of the working standard microphone to the pressure at the diaphragm of the laboratory standard microphone is given by

$$\frac{p_{wsm}}{p_{lsm}} \quad \left(1+\frac{Z_{grid}}{Z_{gap}}+\frac{Z_{grid}}{Z_{wsm}}\right)^{-1}$$

For a Brüel & Kjær microphone type 4134 (a working standard microphone of type WS2P) the grid can be modelled as 108 holes of 1 mm diameter and 0.5 mm deep, with an air volume of 50 mm^3 between the grid and the diaphragm. This represents a grid with an open area of 62% of the cross section of the microphone. However, when this microphone is placed in a sound calibrator the open area reduces to about 8% as most of the apertures are around the edge of the grid and are obscured by the calibrator. It can then be modelled as 11 holes of 1 mm diameter and 0.5 mm deep, with an air volume of 100 mm^3 between the grid and the diaphragm. Table A1 shows the pressure ratio for these two cases.

Table A1 Increase in pressure at the diaphragm of a working standard microphone relative to the pressure outside the grid.

Frequency Hz	Pressure increase dB	
	Normal grid	Grid partly obscured by calibrator
250	0.000	0.001
500	0.000	0.004
1000	0.001	0.017
1250	0.002	0.026
1600	0.003	0.042
2000	0.005	0.064
2500	0.007	0.099
3150	0.011	0.156
4000	0.017	0.250
5000	0.026	0.389
6300	0.041	0.617
8000	0.065	1.001
10000	0.099	1.591

Seven WS2P microphones (Brüel & Kjær type 4134) were calibrated by comparison with a laboratory standard microphone in a B&K type 3541 intensity calibrator. They were calibrated both with their protection grids on and in the LS2P configuration. The mean difference between the sensitivity levels determined in the two configurations is shown in Figure A2. Also shown is the theoretical difference due to the presence of the grid when it is partly obscured by the calibrator. The agreement between the empirical and theoretical data is very good, demonstrating that the model given is sufficient for these microphones.

While a normal grid causes errors of less than 0.1 dB at frequencies below 10 kHz, a grid partly obscured by a sound calibrator can cause errors greater than 0.1 dB above 2.5 kHz. The first case may be acceptable in most measurement situations, but the error in a sound calibrator is unacceptable at any frequency above 1 kHz.

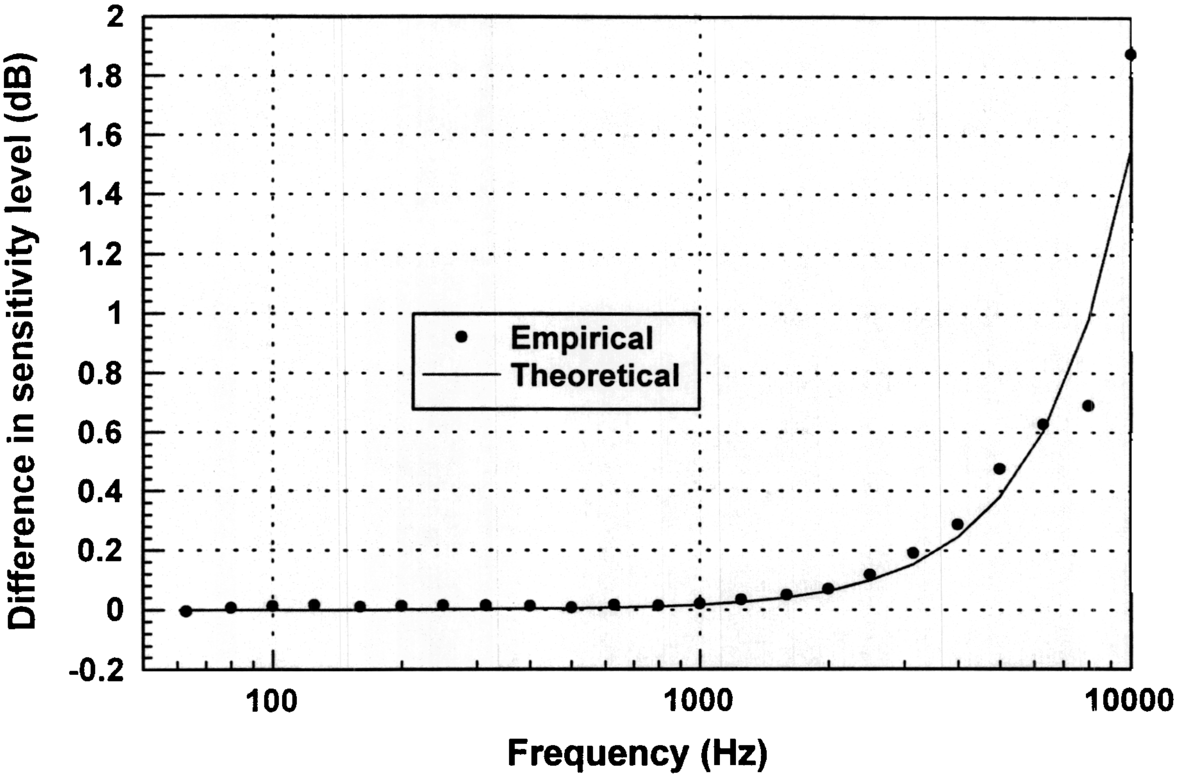
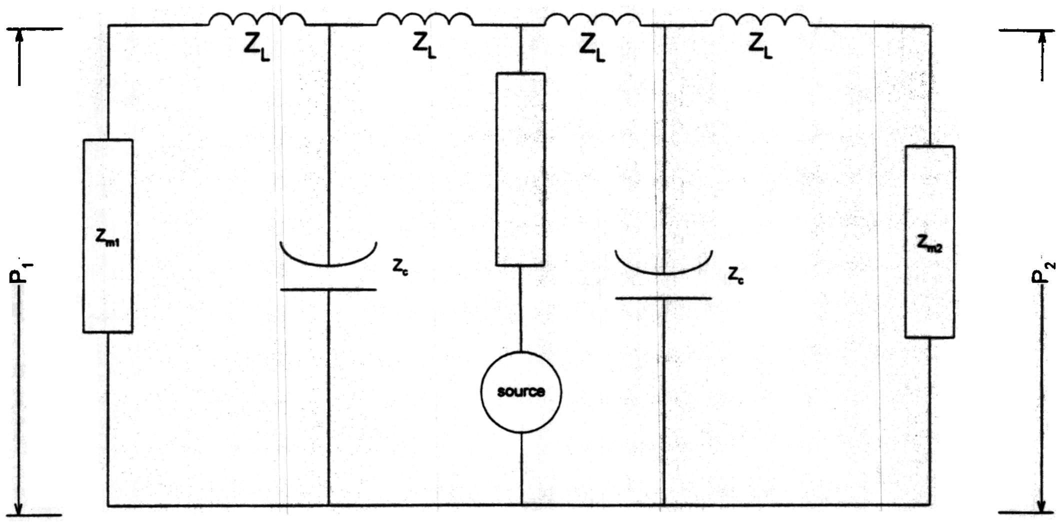


Figure A2 Difference in observed sensitivity level between a 4134 microphone in a WS2P configuration and in a LS2P configuration

APPENDIX B UNCERTAINTIES CAUSED BY DIFFERENCES IN ACOUSTIC IMPEDANCE BETWEEN THE TEST AND REFERENCE MICROPHONES



A symmetric coupler can be modelled by the above circuit. P_1 and P_2 are the sound pressures at the two microphones which have acoustic impedances Z_{m1} and Z_{m2}. The volume of the coupler is represented by the two Z_c elements and the mass of the air is represented by the four Z_L elements.

As an example, consider an LS2P microphone being compared with a high sensitivity WS2P microphone. Typical values for their acoustic impedance are given by:

$r_1 := 330\cdot 10^{6}$	N s m^{-5}	$r_2 := 7\cdot 10^{7}$	N s m^{-5}
$c := 48\cdot 10^{-15}$	N^{-1} m^{5}	$c_2 := 2.6\cdot 10^{-13}$	N^{-1} m^{5}
$m_1 := 1210$	kg m^{-4}	$m_2 := 820$	kg m^{-4}

$$Z_{m1}(w) := r_1 + w\cdot \ m + \frac{1}{i\cdot w\cdot c_1} \qquad Z_{m2}(w) \quad r_2 + w\cdot i\cdot m_2 + \frac{1}{i\cdot w\cdot c_2}$$

where ω is the angular frequency.

The density of the air is taken to be $\rho := 1.21$ kg m^{-3}

the ratio of principal specific heats to be κ 1.4

and the static pressure to be p_0 101325 Pa

For the coupler we assume a tube of length $L := .002$ m

and radius $r := 1.27 \cdot \frac{10^{-2}}{2}$ m

giving a volume of $v := \pi \cdot r^2 \cdot L$ $\quad v = 2.534 \cdot 10^{-7}$

The acoustic impedance of the volume on each side of the reference plane is

$$Z_c(w) := \frac{\kappa \cdot p_0}{i \cdot w \cdot \frac{v}{2}}$$

and the acoustic impedance of the mass elements can be approximated by

$$Z_L(w) := \frac{\left(\rho \cdot \frac{\frac{L}{4}}{\pi \cdot r^2}\right) \cdot i \cdot w}{3}$$

Then if we define

$$Z_{s1}(w) := \frac{Z_c(w) \cdot \left(Z_L(w) + Z_{m1}(w)\right)}{Z_c(w) + Z_L(w) + Z_{m1}(w)} \qquad Z_{s2}(w) := \frac{Z_c(w) \cdot \left(Z_L(w) + Z_{m2}(w)\right)}{Z_c(w) + Z_L(w) + Z_{m2}(w)}$$

and

$$Z_{o1}(w) := Z_L(w) + Z_{s1}(w) \qquad Z_{o2}(w) := Z_L(w) + Z_{s2}(w)$$

the ratio of the two sound pressures P_1/P_2 is given by

$$R(w) := \frac{Z_{s1}(w) \cdot Z_{m1}(w)}{Z_{o1}(w) \cdot \left(Z_L(w) + Z_{m1}(w)\right)} \cdot \frac{Z_{o2}(w) \cdot \left(Z_L(w) + Z_{m2}(w)\right)}{Z_{s2}(w) \cdot Z_{m2}(w)}$$

and the error in the sensitivity level will be given by

$$x(w) := 20 \cdot \log(|R(w)|)$$

Thus it is possible to plot the error in the determination of a sensitivity level over the frequency range

$f := 100, 200 .. 20000$ Hz