Proceedings of the Institute of Acoustics

STANDARDS FOR HYDROPHONE CALIBRATION IN THE UK

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1. INTRODUCTION

There exists a wide range of applications for the generation, detection and measurement of underwater acoustical signals at frequencies below 1 MHz. Whilst some of these applications are in the defence field, the scope is broadening considerably in civilian fields, for instance in geophysics and geology, hydrography, communications, marine biology, medicine and industrial processing. Requirements for acoustical calibrations are as varied as the applications. In some fields, calibrations are required for ensuring quality control during manufacture, and in others they are required to demonstrate compliance with specification standards, often to meet contractual obligations; these aspects are becoming of increasing importance in Europe with the development of the single European Market. In medical or occupational areas, calibrations may be important in ensuring that maximum acoustic exposure levels are not exceeded. For these various reasons, many companies have established their own calibration and measurement facilities. However, until now there has been no source of UK measurement standards to which these companies can turn for guidance, to provide traceability to primary standards and to provide the basis for international acceptability of their calibrations and measurements.

As a consequence, the National Physical Laboratory, NPL, has been coming under increasing pressure from private industry to provide traceable national standards at frequencies below 500 kHz. Prior to embarking on a programme of standards development, NPL organised a round-robin intercomparison of hydrophone calibrations in order to investigate current capabilities within the UK. The intercomparison involved ten participants, including several major civil and military establishments in the field as well as private companies and universities [1]. The results and conclusions of the intercomparison are briefly described in the first part of this paper.

NPL is now establishing a UK primary standards facility for the calibration of hydrophones, leading eventually to the launch of a new calibration service. Initially, this will be based on the free-field reciprocity method in the frequency range 10-500 kHz. However, the need for new initiatives in this field has already been recognised, both in the development of improved standards, and in the development of new high-frequency hydrophones for use as transfer standards. In addition, possibilities are being examined for extending downwards in frequency the operation of the existing primary standard laser interferometer used above 500 kHz, and extending upwards in frequency the existing air-borne acoustical standards via pistonphone techniques. Once standards are established, dissemination will ultimately be through the National Measurement Accreditation Service (NAMAS).

2. THE ROUND-ROBIN INTERCOMPARISON

2.1 Outline

The intercomparison involved the circulation of three different types of hydrophone to each of the ten participants in turn. The three hydrophones chosen were of a type commonly used for reference measurements: two were standard Brüel and Kjær hydrophones, one of type 8100 and the other of type 8103, and the third was a type F-42D from the Underwater Sound Reference Division (USRD) of the Naval Research Laboratory in Florida, USA (2). All three hydrophones are reversible devices having no in-built amplifier and could therefore be used as both transmitter and receiver. Each participant was asked to calibrate the devices using the method of their choice at 250 Hz and at selected frequencies in the range 1-500 kHz. After each participant had returned the hydrophones to NPL, a check was made on the stability of the hydrophones by use of a 250 Hz pistonphone calibrator which was calibrated with reference to air-borne acoustical standards. In addition, a check was made on the electrical impedance of the hydrophones.

2.2 The calibrations

The hydrophones were circulated with a procedure document which specified the preferred frequencies at which calibrations were to be made. The open-circuit voltage sensitivity of the hydrophones was requested and the hydrophone impedances were supplied by NPL to enable corrections to be made for the effects of amplifier loading. The participants were requested to make an assessment of the systematic uncertainties in their calibrations and to make at least four repeated measurements on each hydrophone so enabling a value for the random uncertainties to be determined. All uncertainties were requested at the 95% confidence level.

The most common method of calibration used by the participants was free-field reciprocity (3-6). In this absolute method, a sound source, the hydrophone to be calibrated, and a reversible transducer are paired off in three measurement arrangements. In the first two arrangements, the reversible transducer and the hydrophone are compared as receivers in the sound field produced by the source. In the third arrangement, the reversible transducer is used as a source and the hydrophone is exposed to the field produced by it. The sensitivity of the hydrophone (or the transmitting response of the source) can then be calculated from electrical measurements and from the appropriate reciprocity parameter, which relates the receiving sensitivity of the reversible transducer to its response as a source.

Instead of reciprocity, comparison methods of calibration were used by some participants. For example, a few participants used a technique where a standard source, previously calibrated by reciprocity, was used to provide a known sound field. Alternatively, a previously calibrated hydrophone was used, the hydrophone to be calibrated being compared to this standard hydrophone when placed at the same point in a sound field (6).

A few participants calibrated the hydrophones in large volumes of water such as a large reservoir or, in one case, a salt-water harbour. However, the majority of the participants performed the calibrations in laboratory tank facilities. These facilities can give rise to problems due to interfering reflections from the tank boundaries. Pulsed or gated techniques or the use of noise signals were used to overcome these problems, especially where the tank was not lined with an acoustic absorber (6).

2.3 Results and discussion

At the time of the intercomparison, extensive calibration facilities, such as a large tank, were not available at NPL. Consequently, NPL could only calibrate the hydrophones at 250 Hz using a pistonphone. This created a problem when comparing results since the "correct" values of sensitivity were not known. As a compromise, a grand mean of the results of all the participants was calculated at each frequency for each hydrophone. The results of each participant were then compared to the grand means.

Figures 1, 2 and 3 show for each hydrophone how the rms difference from the grand mean varies with frequency, averaged over all the participants. The graphs should reveal the frequency ranges where most difficulties were encountered during calibration.

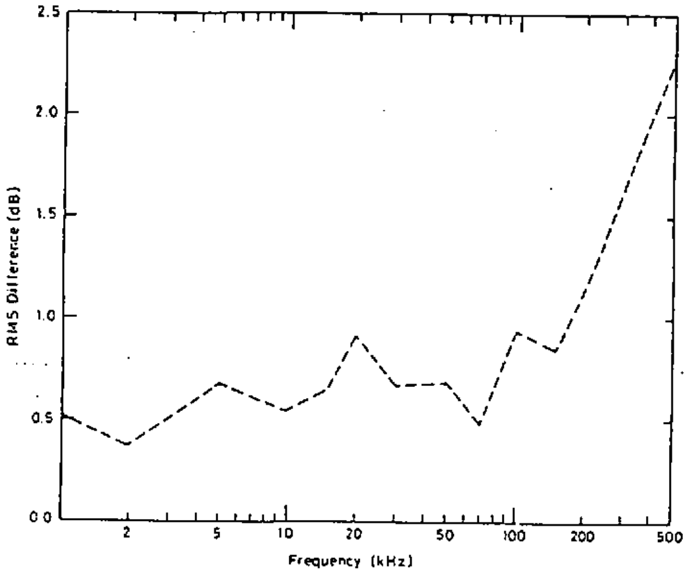

Figure 1 The rms difference from the grand mean for the B&K8100.

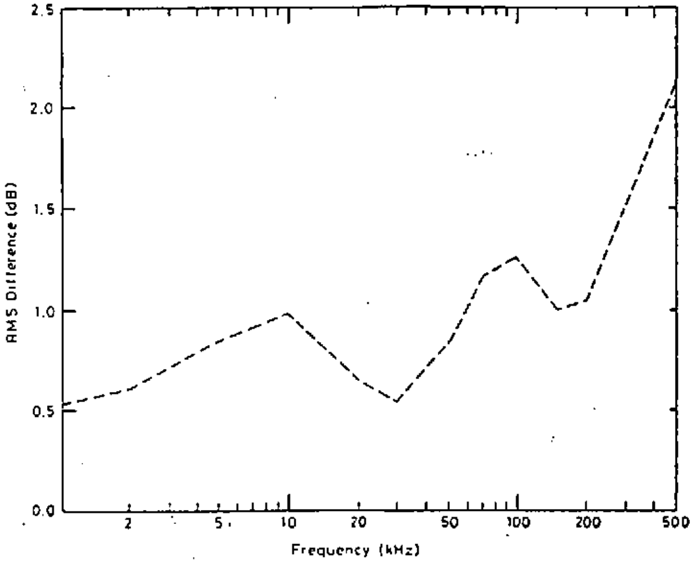

Figure 2 The rms difference from the grand mean for the B&K8103.

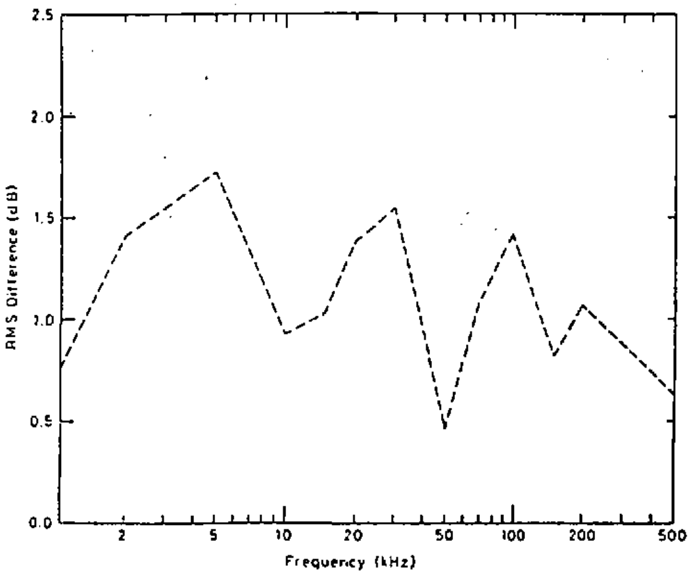

Figure 3 The rms difference from the grand mean for the Actran F-42D.

For the two Brüel and Kjær hydrophones (Figs. 1 and 2), the rms differences range from 0.5 to 1.0 dB at lower frequencies but above 50 kHz the differences increase rapidly to well over 2 dB at 500 kHz. This is perhaps not surprising for the B&K 8100 which has a frequency response which falls off rapidly above 100 kHz. The B&K 8103 has a higher frequency response and should be easier to calibrate at high frequencies but has a lower sensitivity which creates problems of poor signal-to-noise ratio. The relatively poor results demonstrate the increased difficulty experienced by participants when calibrating devices at these frequencies due to the greater directionality of the hydrophones. For the Actran F-42D (Fig. 3), the rms differences show a somewhat different behaviour. Firstly, they show a more erratic variation with frequency and secondly, the trend appears to be one of worse agreement at lower frequencies (below 10 kHz) and no increase above 100 kHz. The latter may be because of the higher frequency response of this device (it has a resonance above 150 kHz and still has a moderately high sensitivity at 200 kHz).

Whilst the results of some of the participants showed the same smooth frequency response as was obtained for the grand means with essentially only a systematic shift in level, some showed considerable "structure" with peak-to-peak variations of several decibels. Maximum differences from the grand means were frequently greater than 1 dB and sometimes greater than 3 dB. One probable explanation for the variation is interference effects from stray reflections and standing waves. Standing waves due to reflections from tank walls, the water surface or even between the transducer and hydrophone, are a considerable problem when continuous wave systems are used. One method of checking for this effect would be to perform meacurements at several different projector to receiver distances and to compare the results; in the absence of interference, the measured sensitivity should be independent of distance. Rarely, however, were different distances used between transmitter and receiver to test for interference effects.

Interference effects are most problematic at lower frequencies where the wavelength is relatively long. Even when using tone burst or gated techniques (which are essential when small tanks are used), reflections can be obtained from structures close to the hydrophones such as the hydrophone mounts. Frequently, the hydrophones are attached to poles and these poles are secured to right angled brackets. Reflections from these brackets, which are normally directly above the hydrophone, could be one of the reasons for the F-42D giving the most variable results of the three hydrophones since it was the only spherical hydrophone and it is more sensitive to such reflections. The F-42D also had problems with electrical noise which affected the results of several participants.

The hydrophones were usually aligned acoustically in the water after mounting. Ideally, this requires the hydrophone mount to have independent translation and rotation adjustments. However, in most cases, the mounting arrangements were quite crude. For example, rarely was a system described where the hydrophones could be rotated about their own axis of symmetry;

usually rotating the hydrophones produced some translation as well. In fact, due consideration was not always given to the alignment and mounting arrangements especially at frequencies above 100 kHz, where the hydrophone is at its most directional, and this is one potential source of error in the calibrations.

In general, the uncertainties (particularly the systematic) in the calibrations were not well assessed, though with some notable exceptions. Some participants simply quoted a figure, such as ±1 dB, and gave no justification for this figure in terms of assessment of possible sources of error. Others gave a breakdown of the systematic uncertainties but neglected the possible effects of interference and poor mounting arrangements which, though difficult effects to quantify, could make a significant contribution to the errors in the calibration. The random uncertainties were generally well assessed with the hydrophones being removed from the water between repeated measurements. The contributions to the overall uncertainties from random uncertainties were generally greater than those from systematic uncertainties. It should be noted that the differences from the grand mean frequently exceeded the quoted uncertainties demonstrating that the uncertainties were generally underestimated.

3. UK HYDROPHONE CALIBRATION STANDARDS FOR THE FUTURE

In the light of the results of the intercomparison, it has been decided that NPL will take a more active rôle in this area. Although not possessing a large tank of its own, NPL is fortunate to be situated adjacent to ARE, Teddington where there is a suitable tank which is at present under-used. The tank is lined with Fafnir absorbers so as to provide an anechoic environment. To begin with, NPL plan to use this facility to set up primary standards for calibrating hydrophones in the frequency range 10-500 kHz by the free-field reciprocity method. Eventually, this will lead to the provision of a calibration service for customers. Organisations wanting to offer their own services for the calibration of measuring hydrophones or the characterisation of acoustical transmitters and receivers may wish to have formal traceability to NPL. This will be achieved, as in other areas of measurement, through the accreditation of calibration and measurement laboratories by the National Measurement Accreditation Service (NAMAS).

At present, a laser interferometer is used at NPL to provide primary standards at frequencies above 500 kHz. The possibilities are being examined of extending these standards downwards in frequency and preliminary investigations suggest that it should be possible to extend interferometry down to 300 kHz or further. However, an additional problem for this frequency range is the lack of suitable transfer standards. Most of the available hydrophones, such as those used in the intercomparison, have a response which falls off above 150 kHz and the sensitivity of hydrophones designed for use in the medical diagnostic frequency range (>1 MHz) is generally too low to be useful. Consequently, it will be necessary to develop new hydrophones for the frequency range 100 kHz to 1 MHz. Ideally, a secondary standard should be stable, and possess high sensitivity, small size compared to the wavelength and a smooth frequency response. It may not be possible to achieve all these objectives in one device and one characteristic may have to be sacrificed, for example, small size. This would produce a directional hydrophone which, though overcoming some problems, would be more difficult to use. The above considerations will be the subject of further study.

At low frequencies where wavelengths are relatively long, pressure calibration techniques must be used, and NPL is fortunate in having an Acoustical Standards Section which has considerable experience of pistonphone techniques for airborne acoustical calibration. A start has been made using a commercially available Brüel and Kjær 4223 pistonphone operating at 250 Hz which can be used to calibrate Brüel and Kjær hydrophones. The pistonphone has an air-filled coupler which accepts the hydrophone together with a half-inch microphone. The microphone open-circuit output voltage is determined using a standard insert voltage technique (7) which enables the effect of the loading of the microphone preamplifier to be eliminated. The microphone is calibrated with reference to primary air-borne acoustical standards at NPL (7), thus enabling the sensitivity of the hydrophone to be determined by comparison. Corrections are made for deviations of ambient temperature and atmospheric pressure from standard conditions and stability of the microphone is checked using a B&K 4220 pistonphone which has also been calibrated at NPL.

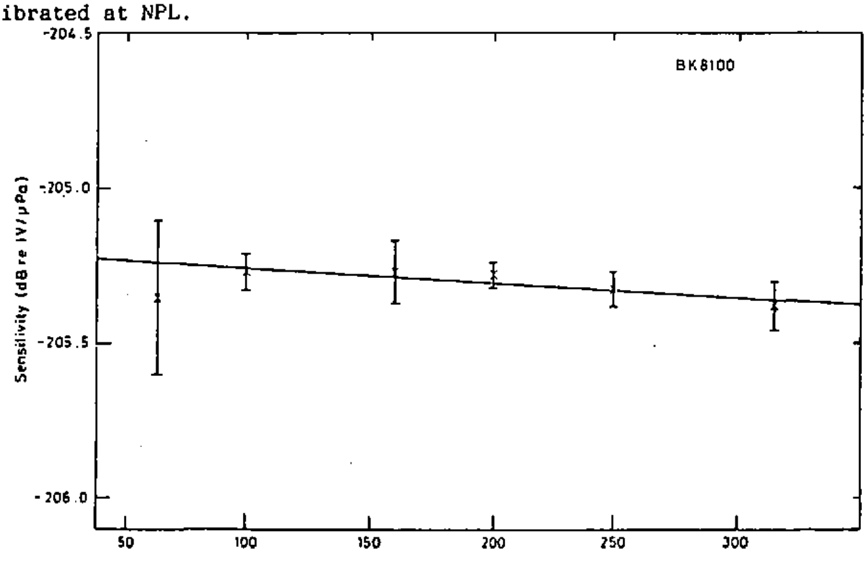

Figure 4 The sensitivity of a B&K 8100 hydrophone measured using a B&K 4223 pistonphone referenced to an NPL calibrated microphone. Error bars denote random uncertainties expressed at the 95% confidence level.

If the dc supply voltage to the pistonphone is varied, it is possible to alter the frequency of operation of the pistonphone over the range 50 to 320 Hz. Figure 4 shows the results of calibrations performed on a B&K 8100 hydrophone at frequencies between 60 and 315 Hz with the error bars denoting random uncertainties expressed at the 95% confidence level. A least squares fitted straight line has been drawn through the results which shows a slight negative gradient. This is not thought to be significant since there is no reason for the response of the hydrophone not to be completely flat over this frequency range.

4. SUMMARY

A national intercomparison of hydrophone calibration techniques has been conducted in the frequency range 250 Hz to 500 kHz. Three hydrophones were circulated to ten participating organisations. The laboratories employed a number of different calibration techniques in facilities ranging from small laboratory tanks to large volumes of water such as a reservoir and a salt-water harbour. To compare the results, reference values were determined by taking the grand mean of all the results at each frequency.

In almost every case, the maximum difference between a participant's results and the grand means exceeded the uncertainties (95% confidence level) for that particular participant. Maximum differences were frequently greater than 1 dB and sometimes greater than 3 dB. Clearly, the estimates of uncertainty were in many cases too optimistic. Only one of the participants was capable of producing a set of results which were consistent with overall uncertainties of ±1 dB (95% confidence level) or better. This situation should be of concern to those interested in the reliability of calibration results.

In the light of these findings, NPL is setting up a UK primary standards facility for the calibration of hydrophones, leading to the launch of a new calibration service. At first, this will be based on free-field reciprocity calibration in the frequency range 10-500 kHz. Other calibration methods will also be investigated, especially for frequencies outside this range, and new hydrophones may need to be developed for the frequency range 100 kHz to 1 MHz. In the long term, standards will be disseminated through the National Measurement Accreditation Service.

5. ACKNOWLEDGEMENTS

The authors wish to thank the participants in the intercomparison for their time and effort in calibrating the hydrophones, in many cases while under considerable pressure of other work, and for their many constructive comments both at the beginning and at the end of the exercise.

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