Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Validation of primary hydrophone calibrations by inter-laboratory comparisons and by independent calibration methods

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A description is presented of two approaches which may be used to validate primary calibration methods for hydrophones and transducers. Firstly, a comparison may be made with another independent absolute calibration method, preferably one based on a different physical principle (and therefore with few common sources of uncertainty). Secondly, an inter-laboratory comparison of calibrations may be undertaken between different institutes operating at a similar level. This paper describes the results of such exercises for free-field calibration of hydrophones in the range from 1 kHz to 500 kHz. Firstly, two independent calibration methods are compared: the three-transducer reciprocity method and a method based on optical interferometry. The differences observed in the results are typically less than 0.5 dB, which is of the same order as the overall uncertainties of each of the methods. Secondly, the results are shown of a recent international comparison of hydrophone calibrations involving institutes from Canada, China, Germany, Russia, South Africa, UK, and USA. Here, the agreement was generally within quoted uncertainties, the results generally lying within a ±0.5 dB band for frequencies up to 300 kHz. A discussion is given of the general sources of uncertainties in the calibrations.

1 Introduction

In metrology, it is important to be able to validate calibration methods to confirm the uncertainty assessment and to increase confidence in the method. This is particularly true for absolute methods that may be used as a primary standard. One method of validating a primary standard is to compare it to another independent absolute calibration method, preferably one based on a different physical principle (and therefore with few common sources of uncertainty). Another important way to validate an absolute calibration method is to compare with calibrations undertaken by equivalent laboratories in other countries.

This paper provides a brief description of both of these methodologies. Results are presented for a number of hydrophones calibrated using both the method of three-transducer spherical-wave reciprocity and by methods based on optical interferometry. In addition, results are presented from a recent international comparison of hydrophone calibrations undertaken under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration convened by the Bureau des Poids et Mesures, Paris.

2 Validation using independent calibration methods

At the UK National Physical Laboratory (NPL), several independent calibration methods are used as primary standards over different frequency ranges. In the frequency range 500 kHz to 20 MHz, the primary standard is realised using optical interferometry [1]; in the range from 1 kHz to 500 kHz, it is realised by the method of three-transducer spherical-wave reciprocity [2]. Although these are the defined ranges of the two primary standards, both methods can be used in the frequency range 200 kHz to 1 MHz, enabling a comparison to be undertaken between these two independent methods. In addition, NPL is working to devise a new calibration method as a future primary standard for the lower frequency range [3]. Using this method, a comparison is possible with the reciprocity method between 7 kHz and 600 kHz.

Primary calibration of hydrophones for frequencies greater than 500 kHz is achieved using an NPL laser interferometer [4,5]. In this method, the acoustic pressure is determined by measuring the displacement of an optically reflective and acoustically compliant membrane in the acoustic field. An ultrasonic transducer produces an acoustic field which the thin plastic membrane (the pellicle) follows. The pellicle, which is 5 μm thick and coated on one side with 25 nm of gold, reflects the optical beam of the laser interferometer. The displacement, a, of the pellicle is related to the output voltage, V_I , of a specially-designed Michelson homodyne interferometer using equation (1),

$$V_I = V_0 \sin(4\pi \mu\, a / \lambda) \qquad (1)$$

Where λ is the optical wavelength, V_0 is the reference voltage corresponding to the amplitude of the output signal when the displacement exceeds half the optical wavelength, and μ is the refractive index of the medium. The acoustic pressure, p, in the field is calculated from the measured displacement, from knowledge of the angular frequency, ω, water density, ρ, and speed of sound, c. The hydrophone under test is then substituted for the pellicle with the acoustic centre placed at the same point in the field that has been interrogated by the interferometer. The calibration is performed by measuring the hydrophone output voltage, V_H, corresponding to the known acoustic pressure. The hydrophone sensitivity, M_H, can therefore be obtained using equation (2).

$$M_H = \frac{V_H V_0}{V_I} \frac{2\mu}{\rho c f \lambda}. \qquad (2)$$

Advantages of this method are its direct traceability to length and its insensitivity to the properties of the ultrasonic field generated by the transducer. Using the laser interferometer, a reference hydrophone can be calibrated in the frequency range 200 kHz to 1 MHz with typical overall uncertainties (95% confidence level) of between ±0.3 and ±0.5 dB.

The primary method of calibrating hydrophones in the frequency range 1 kHz to 500 kHz is three-transducer spherical-wave reciprocity [2]. This method requires the use of three hydrophones, P (projector), T (transducer) and H (hydrophone under test), at least one of which must be a reciprocal transducer; that is, its transmitting and receiving sensitivities are related by a constant factor. The hydrophones are paired off in three measurement stages, with one device being used as a transmitter and the other as a receiver, separated by a distance, d, as shown in Fig. 1. For each pair of hydrophones, a measurement is made of the ratio of the voltage, e, across the terminals of the receiving device to the current, i, driving the transmitting device. Using the reciprocity principle as applied to the reciprocal hydrophone, the sensitivity of H (or in fact any one of the hydrophones) can be determined from the purely electrical measurements described above. For example, the sensitivity of H is given by:

$$M_H = \sqrt{J \frac{d_1 d_2}{d_3} \frac{Z_{PH} Z_{TH}}{Z_{PT}}} \quad (3)$$

where Z_{PH} is equal to e_{PH} / i_{PH} etc.

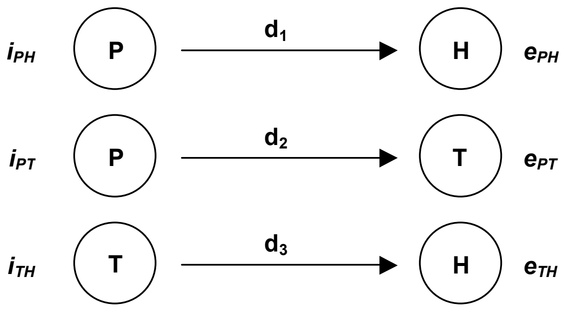

Fig. 1 Transducer arrangement for reciprocity measurements.

This method is well established [2] and is the NPL primary standard in the frequency range 1 kHz to 500 kHz with typical overall uncertainties (95% confidence level) of ±0.5 dB. In both the techniques described above, measurements were made in a laboratory tank using discrete-frequency tone-burst signals, with gating and time-windowing techniques employed to isolate reflections from boundaries. For reciprocity, the measurements were made in a tank of dimension 2.0 x 1.5 x 1.5 m, and for the interferometer, a tank of only 1.0 x 0.4 x 0.4 m was used.

Unfortunately, the homodyne interferometer described here is not suitable for measurement of displacement at lower kilohertz frequencies. This interferometer is limited to higher frequency measurements and its phase locked configuration also limits the displacements that may be conveniently measured to amplitudes of less than half the optical wavelength. Furthermore, the pellicle used for the measurements is housed in a metal ring with dimensions unsuitable for lower frequency use due to the presence of reflections. To measure the acoustic field in water at lower frequencies (down to 10 kHz) requires a different measurement arrangement and a different configuration of interferometer [3]. A comparison was performed between 7 kHz and 600 kHz of a reciprocity calibration and an optical calibration performed using a Doppler heterodyne velocity interferometer (commercially known as a vibrometer) and a long strip type pellicle [3]. These measurements were performed in the 2.0 x 1.5 x 1.5 m tank to allow a lower frequency calibration. The pellicle used was also thicker than with the higher frequency measurements. If the laser vibrometer measures the particle velocity, u, the hydrophone sensitivity is given by:

$$M_H = \frac{V_H}{\rho c u} \quad (4)$$

The following results show comparisons of hydrophone sensitivities obtained using optical methods and those obtained using reciprocity methods. Fig. 2 shows such a comparison between 200 kHz and 1100 kHz for a B&K8103 hydrophone and Fig. 3 shows a similar comparison for a GEC pvdf disc hydrophone between 300 kHz and 700 kHz. In both cases, the agreement is better than 0.5 dB across the calibrated frequency range, which is within the combined uncertainties of the methods The optical method does however, provide a more direct calibration method traceable to length. The optical method is also less reliant on the type of acoustic field and makes no assumptions about the reciprocal nature of the transducer.

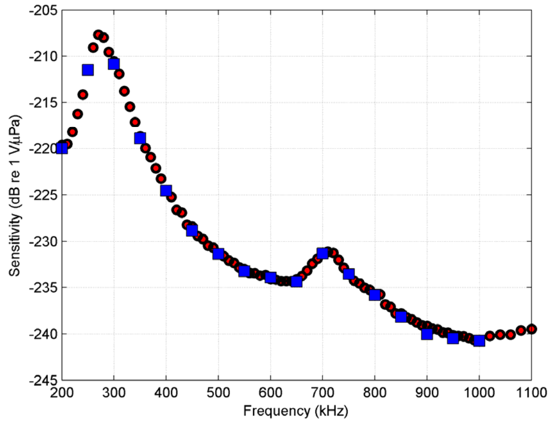

Fig. 2 B&K8103 by free-field reciprocity (squares) and HF optical interferometry (circles).

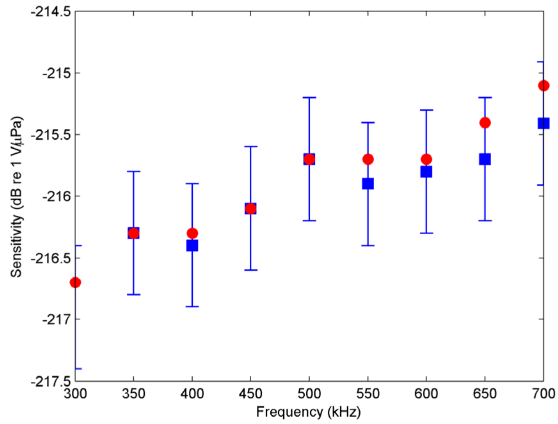

Fig. 3 GEC pvdf disc hydrophone by free-field reciprocity (squares) and HF optical interferometry (circles). The error bars denote the uncertainties for the reciprocity method expressed for a confidence level of 95%

Fig. 4 shows a reciprocity calibration of a TC4034 between 7 kHz and 600 kHz compared with a calibration over the same frequency range performed using the laser Doppler vibrometer and the long strip type pellicle. The optical method for the calibration of hydrophones below 500 kHz is being developed at NPL as a potential future primary standard to replace reciprocity. Work is on-going to overcome the light losses through the long optical path lengths in water and vibration modes across the pellicle. However, even with these issues, Fig. 4 shows very close agreement between the two methods with differences only exceeding 0.5 dB at lower frequencies where reflections from the pellicle mounting frame limited the free-field window. This method looks very promising as a future primary standard, capable of replacing reciprocity below 500 kHz, with potentially greater accuracy.

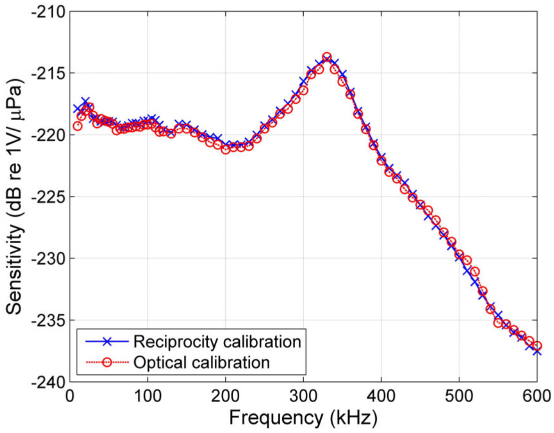

Fig. 4 Reson TC4034 by reciprocity and laser vibrometry.

3 Validation by inter-laboratory comparison

Another method to validate an absolute calibration method is to compare with calibrations undertaken by equivalent laboratories in other countries. An example of such an exercise is the Key Comparison for the primary free-field standards for sound in water at frequencies between 1 kHz and 500 kHz (comparison identifier: CCAUV.W-K1). This project was organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV) of the Comité International des Poids et Mesures (CIPM) as part of the requirements of the Mutual Recognition Arrangement [6]. The comparison had seven participating countries, each represented either by the respective National Metrology Institute (NMI), or by an organisation officially designated as representing the country for this exercise. These are listed in Table 1 along with their country

Institute name	**Country**	**Code**
NPL	U.K.	UK
WTD (PTB)	GERMANY	DE
USRD/NUWC	U.S.A.	US
VNIIFTRI	RUSSIA	RU
NIM	CHINA	CN
DRDC	CANADA	CA
CSIR	SOUTH AFRICA	ZA

Table 1: Participants in Key Comparison CCAUV.W-K1

The pilot laboratory for the project was the National Physical Laboratory (NPL), UK. NPL undertook the initial assessment and calibration of the hydrophones and performed checks on the hydrophone sensitivities between the calibrations by participants to ensure that the hydrophone sensitivities were stable. NPL prepared and circulated a protocol document describing the measurements required, with participants asked to assess uncertainties according to the ISO GUM [7]. The comparison was organised as a round-robin exercise with each participant asked to determine the free-field open-circuit voltage sensitivity of the same three hydrophones at selected frequencies in the range 1 kHz to 500 kHz. The hydrophones chosen for the comparison were: an H52 hydrophone manufactured by USRD-NUWC in the USA; a B&K8104 hydrophone manufactured by Brüel and Kjær in Denmark; and a TC4034 hydrophone manufactured by Reson in Denmark. The H52 was used for the frequency range 1 kHz to 100 kHz, the B&K8104 for the range 10 kHz to 150 kHz, and the TC4034 for 100 kHz to 500 kHz. Each participant calibrated the three hydrophones at approximately 40 discrete acoustic frequencies in the range 1 kHz to 500 kHz. The method of calibration used by participants was the method of three-transducer spherical-wave reciprocity [2]. Most commonly, participants used laboratory tank facilities, the largest being 15 x 7.5 x 7 m and the smallest dimension of any of the test tanks used being 4.5 m. One participant used an open-water facility on a lake, which had a water depth of 11 m, a laboratory platform being created using a pier or pontoon based structure from which transducers may be lowered into the water. For all participants, discrete-frequency tone-burst signals were employed, with reflections isolated from the direct-path signal by use of gating and time-windowing techniques

The results of the check calibrations undertaken by NPL to monitor the stability of the hydrophones showed that the hydrophones may be considered stable for the purposes of the comparison exercise. The maximum variation in the check calibrations at each frequency was generally within the Type A uncertainty of the NPL measurements, and although the deviation exceeded the Type A uncertainty at a few frequencies, this was not considered significant. There was some evidence that there may have been a gradual increase in the sensitivity of the H52 of 0.01 dB per month during the comparison, but no corrections were applied since this was considered a marginal variation.

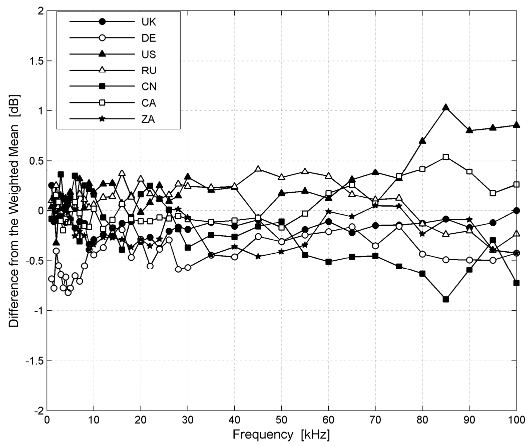

Fig. 5 The differences from the KCRV (weighted mean) for the H52 hydrophone.

The results provided by the participants were used to derive the Key Comparison Reference Values (KCRV) at each acoustic frequency using a weighted mean approach, with the analysis following the guidance provided by reference [8]. No results were classified as outliers, the chi-squared consistency check applied to the data demonstrating that the weighted mean was an acceptable model to use for this data set. The degree of equivalence of national measurement standards was then calculated from the differences of the participants' results from the KCRV. The results of the calibrations are presented in Fig. 5, Fig. 6 and Fig. 7 as differences from the KCRV. The agreement between the results was generally encouraging, with the calibration values reported by the laboratories agreeing within quoted uncertainties over the majority of the frequency range, and the results generally lying within a ±0.5 dB band for frequencies up to 300 kHz, a factor of two improvement on the spread of results obtained in the 1998 EUROMET comparison within Europe [9].

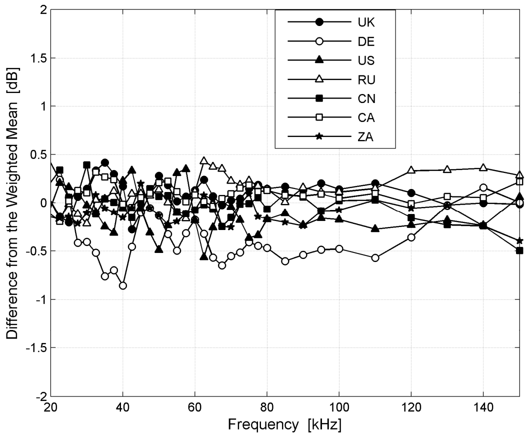

Fig. 6 The differences from the KCRV (weighted mean) for the B&K8104 hydrophone.

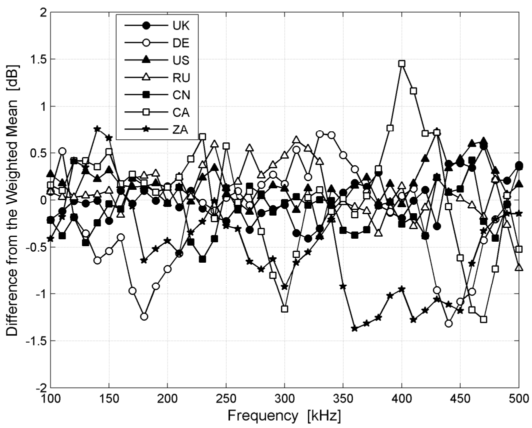

Fig. 7 The differences from the KCRV (weighted mean) for the TC4034 hydrophone.

Degrees of Equivalence (DOEs) were calculated from the differences of the participant results from the KCRV (see Figs 8, 9 and 10). In the regions of frequency overlaps where more than one hydrophone was calibrated at a particular frequency (a total of 18 of the 94 frequencies), the DOE data were combined to provide a single DOE value by use of a weighted mean approach with due consideration given to the correlation in the calibrations undertaken on the different hydrophones by the same participant [10,11]. The bilateral DOEs between participants were also calculated in a similar manner. Although the H52 hydrophone was calibrated over the frequency range 1 kHz to 100 kHz, the data for the frequency range 80 kHz to 100 kHz were not used to form the combined DOE value since the spread in the results for that hydrophone in that frequency range indicated that the results may have been of doubtful quality, this being close to the upper limit of the operating frequency range of the device.

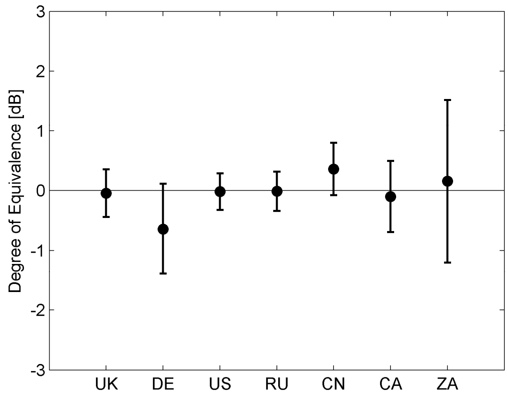

Fig. 8 Degrees of Equivalence for a frequency of 3 kHz, expanded uncertainties at coverage factor of k=2)

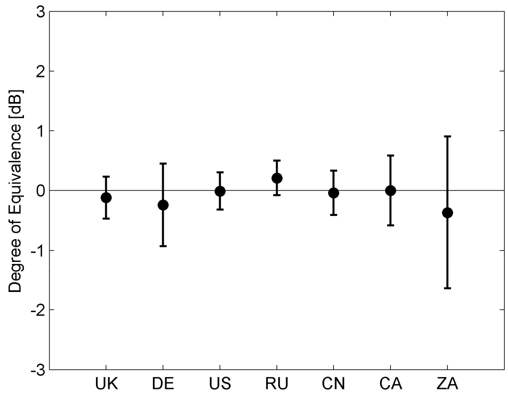

Fig. 9 Degrees of Equivalence for a frequency of 50Hz, expanded uncertainties at coverage factor of k=2)

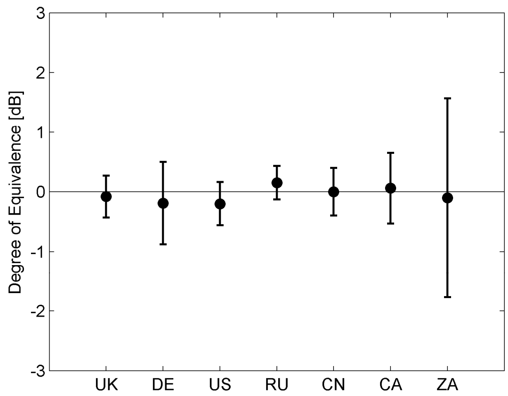

Fig. 10 Degrees of Equivalence for a frequency of 100Hz, expanded uncertainties at coverage factor of k=2)

For this comparison, the depths of immersion during calibrations by different participants ranged between 1.8 m to 4.0 m and the water temperatures ranged from 14.0 ºC to 21.1 ºC. For the range of depths employed by the participants in this comparison, it is highly unlikely that the depth variation has significantly influenced the results. However, the water temperature ranged over approximately 7 °C, and this could have an influence on the apparent agreement between results from different participants. Some data was available on the typical variation in response of the hydrophone models used here from measurements made at NPL [12] and at USRD [13], and extra measurements were made at NPL where necessary [4]. This evaluation showed that the maximum variation in the responses of the hydrophones caused by the variation in water temperature is of the order of only 0.2 dB for the H52 hydrophone, 0.25 dB for the TC4034 hydrophone, but is of the order of 0.5 dB for the B&K8104 hydrophone. However, it should be noted that although these data shown were derived from measurements of the same types of hydrophone, the devices tested were not the actual hydrophones used in the comparison. The consensus among the participants was to make no corrections to account for temperature variation, and therefore none were made. The final report and the data generated by the comparison have now been made available on the BIPM web-site at: www.kcdb.bipm.org/appendixB

4 Conclusion

This paper presented results of two approaches used to validate primary calibration methods for hydrophones and transducers. These were: (i) a comparison with another independent absolute calibration method based on a different physical principle; (ii) an inter-laboratory comparison of calibrations undertaken between different institutes. The results of these exercises have been presented for free-field calibration of hydrophones in the range from 1 kHz to 500 kHz. The two independent calibration methods compared were the three-transducer reciprocity method and a method based on optical interferometry. The differences observed in the results are typically less than 0.5 dB, which is of the same order as the overall uncertainties of each of the methods. Secondly, the results are shown of a recent international comparison of hydrophone calibrations involving institutes from Canada, China, Germany, Russia, South Africa, UK, and USA. Here, the agreement was generally within quoted uncertainties, the results generally lying within a ±0.5 dB band for frequencies up to 300 kHz. Some discussion was given of the general sources of uncertainties in the calibrations.

Acknowledgments

Regarding the Key Comparison, particular thanks should go to: Mr D. Krüger (WTD), Dr A. L. Van Buren, Dr J Zelesak and Mr R. Drake (USRD), Dr A. Enyakov and Dr A. Issaev (VNIIFTRI), Dr Zhu Houqing (NIM), Dr C. Purcell (DRDC), and Dr P. Botha (CSIR).

The authors would like to acknowledge the support of the National Measurement System Policy Unit of the UK Department for Innovation Universities and Skills.

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