A COMPARISON OF HYDROPHONE CALIBRATION BY FREE-FIELD RECIPROCITY AND BY OPTICAL INTERFEROMETRY IN THE FREQUENCY RANGE 200 kHz TO 1 MHz

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1. INTRODUCTION

In metrology, the primary standard is the most accurate implementation of an absolute calibration method, usually traceable as directly as possible to the primary standard base units. As the national standards laboratory for the UK, NPL has established two primary standard methods for the free-field calibration of hydrophones. In the frequency range 500 kHz to 20 MHz, the primary standard is realised using optical interferometry; in the range from 2 kHz to 500 kHz, it is realised by the method of three-transducer spherical-wave reciprocity. One of the most important methods of validating a primary standard is to compare with another independent absolute calibration method, preferably one based on a different physical principle (and therefore with few common sources of uncertainty). Although the ranges of the two primary standards are defined as above, 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.

2. METHODS

2.1 Optical interferometry

Primary calibration of hydrophones for frequencies greater than 500 kHz is achieved using the NPL laser interferometer. In this method, an ultrasonic transducer produces an acoustic field which is detected by a thin plastic membrane (the pellicle) which is 3.5 or 5 µm thick and coated on one side with 25 nm of gold. The pellicle reflects the optical beam but is effectively transparent to the acoustic beam so that it follows the motion of the wave. The displacement of the pellicle is determined using a specially-designed Michelson interferometer, the output of which, V_I, varies with displacement, a, according to the following relationship [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 $\lambda/2$, and μ is the refractive index of the medium. For small ultrasonic amplitudes (less than 5 nm), the output can be assumed to vary linearly with displacement ($\sin\theta \approx \theta$ for small θ). Assuming plane-wave conditions, the acoustic pressure in the field may be calculated from the measured displacement by multiplying by the angular frequency, water density and speed of sound. The hydrophone 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 hydrophone output voltage, V_H, corresponding to the known acoustic pressure is then measured, and the hydrophone sensitivity, M_H, calculated from:

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

where ρ is the water density, c is the speed of sound and f is the acoustic frequency.

Figure 1 shows a schematic diagram of the interferometer, the design being based on the original work of Drain, Speake and Moss [2], and subsequently refined by NPL [3]. The output of a 5 mW HeNe laser is split into the reference and signal beams by use of an electro-optic Pockels cell and a polarising beam splitter. The reference beam is turned back on its original path by use of the corner-cube reflector and the calcite prism, whereas the signal beam is reflected from the pellicle which follows the motion of the ultrasonic wave. The beams are recombined at the avalanche photodiode detectors and the difference in optical phase is detected by the interferometer circuitry. A number of quarter wave plates are used to effect necessary changes in polarisation and prevent light returning to the laser. A second polarising beam splitter at 45° permits interference between the signal and reference beams, providing two interference signals which differ in phase by π. The interferometer output is obtained by taking the difference between these signals, enabling common-mode rejection of fluctuations in light level occurring in both beams due to changes in laser power. A beam displacer (a rotatable glass block) and a translatable lens allow the positioning and focusing of the signal beam on the pellicle so that it may be aligned with the acoustic centre of the hydrophone. The acoustic source transducer (a plane-piston) is driven by tone-burst signals and time-windowing and gating techniques are employed to isolate boundary reflections, enabling measurements to be made at frequencies from 200 kHz to 20 MHz in the 1.0 x 0.4 x 0.4 m tank.

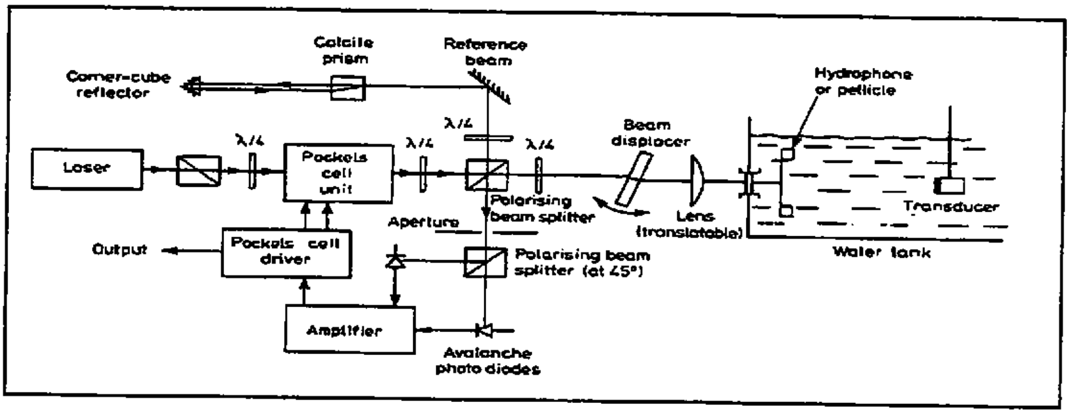

Figure 1 Schematic diagram of the NPL laser interferometer.

The interferometer is mounted on an optical table which is supported by air-operated anti-vibration mounts. However, even with this arrangement, environmental vibration still causes movements of the pellicle which although lower in frequency are much greater in amplitude than the ultrasonic displacement. This introduces changes of optical phase into the signal beam and generates spurious output signals in the interferometer. This problem is overcome by using a feedback system which compensates for the vibration by introducing equal phase changes to the reference beam by means of the Pockels cell. The feedback circuitry is designed to respond only to low frequency signals so that the ultrasonic displacement may still be detected at the interferometer output. The feedback circuit is adjusted to ensure that the interferometer is balanced in its most sensitive mode, where the output is linear for small displacements.

The reference voltage, V_0, provides a calibration of the interferometer which is necessary since the output depends on the intensity of light in the signal beam, which can vary if the pellicle moves due to environmental vibration in a direction perpendicular to the laser beam. It is desirable to measure both V_0 and V_I at the same instant, but in practice V_0 is measured just before and after the ultrasound is detected. To do this, the feedback circuit is disabled and the interferometer output is measured while simultaneously the Pockels cell is used to drive the interferometer over a complete interference fringe at a frequency of 2 kHz.

A thorough investigation of the uncertainties in the method has been undertaken [4] which identified a number of corrections which must be made to the measurements. The interferometer actually responds to changes in optical phase which are caused not just by the displacement of the pellicle but also by changes in refractive index of the water caused by the propagating acoustic wave. For a plane acoustic wave travelling in a direction parallel to the optical beam, this acousto-optic interaction may be accounted for simply by use of an effective refractive index in equations 1 and 2 (a value of approximately unity is used instead of the usual 1.332 for water) [4,5]. The frequency response of the diode/amplifier combination is also important since the reference voltage is measured at a frequency of 2 kHz, whereas the displacement is measured at high ultrasonic frequencies. The variation in interferometer response with frequency has been measured [6] and the data are used to correct the calibrations, the uncertainty on the correction being the largest single source of uncertainty in the method. Other corrections are made to account for the fact that the pellicle is not in fact acoustically transparent but reflects some of the ultrasound, and for the fact that the acoustic field is not in fact an ideal plane-wave, requiring a correction for the spatial-averaging effect of the hydrophone. As part of the validation of the calibration method, NPL took part in a European comparison of calibrations of miniature ultrasonic hydrophones organised under the auspices of the Commission of the European Communities, and achieved a mean difference from the overall grand means of only 0.2 dB [7].

Advantages of this method are its direct traceability to primary standards of length and its insensitivity to the properties of the ultrasonic field generated by the transducer. Using the interferometer, a reference hydrophone can be calibrated in the frequency range 200 kHz to 20 MHz with typical overall uncertainties (expressed for a confidence level of 95%) of between ±0.3 and ±0.5 dB depending on frequency and hydrophone properties.

2.2 Free-field reciprocity

The primary method of calibrating hydrophones in the frequency range 2 kHz to 500 kHz is three-transducer spherical-wave reciprocity (8). This method requires the use of three hydrophones, here labelled P, T and H, 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, at each of which one device is used as a transmitter and the other as a receiver [9].

For each pair of hydrophones, a measurement is made of the transfer impedance, Z, which is the ratio of the voltage, V, 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 any one of the hydrophones can be determined from the purely electrical measurements described above with traceability to standards of electrical measurement. The sensitivity, M_H, of the hydrophone H is given by:

$$M_H = \sqrt{J \frac{d_{PH}\, d_{TH}}{d_{PT}} \frac{Z_{PH}\, Z_{TH}}{Z_{PT}}} \qquad 3$$

where $Z_{PH} = V_H / I_P$ etc, d_{PH} is the hydrophone separation distance for the P to H measurement etc, and J is the reciprocity parameter which relates the transmitting and receiving sensitivities of the reciprocal transducer, T, and which for a spherically-spreading acoustic field is given by:

$$J = \frac{2 d_0}{\rho f} \qquad 4$$

where ρ is the water density, f is the acoustic frequency and d_0 is the reference distance used in the definition of the transmitting response of the hydrophones (usually defined as 1 m). Equation 3 can be simplified somewhat by keeping the separation distances the same for each set of measurements (so $d_{PH} = d_{PT} = d_{TH} = d$) and by keeping the current driving hydrophone P the same for P to H and P to T. If more than one device is reciprocal, for example hydrophone P, then a fourth measurement (T to P) may be made and the value of M_H calculated in two different ways, providing some redundancy in the calibration.

Free-field reciprocity calibrations at NPL are performed in either the 5 m deep by 5.5 m diameter test tank or, as was the case for the measurements reported here, in a smaller laboratory tank of dimension 2 x 1.5 x 1.5 m [10]. Both these test tanks have the advantage of having precision positioning systems which enable the hydrophones to be accurately positioned and manipulated. Calibrations are performed in accordance with IEC 565 [8] using discrete-frequency tone-burst signals, with gating and time-windowing techniques employed to isolate reflections from boundaries. The drive current is measured using a calibrated current probe (25-turn transformer) with the voltage obtained from the probe attenuated by a calibrated attenuator to equalise the voltage with that obtained from the receiving hydrophone. Both voltages are digitised using a signal analyser (12-bit ADC sampling at 10 MHz) and transferred to a computer controller where measurements are made on the steady-state part of the tone-burst signal. As is the case for the interferometer, calibrations are controlled automatically by computer software via an IEEE 488 interface. Where relevant, equipment is calibrated periodically by a UKAS laboratory.

Care has been taken to design the experimental procedure to achieve low measurement uncertainties, for example the use of the same equipment chain (eg preamplifier, filter, digitiser) for all voltage measurements eliminates the need for an absolute calibration of these items since only voltage ratios are required. Similarly, the use of a calibrated attenuator to equalise the voltages reduces any problem from nonlinearity of measurement equipment. In addition, a number of checks are built in to the procedure, providing quantitative indicators of the measurement accuracy which then feed directly into the calculation of measurement uncertainty. For example, a reciprocity-check is performed at each frequency of measurement (if P and T are reciprocal, $Z_{PT} = Z_{TP}$) to assess the validity of the assumption of reciprocal behaviour. The degree to which the transfer impedances differ is then used as the contribution from this source to the overall uncertainty budget. Similarly, an assumption of a spherical-wave field has been made which is tested by making repeated measurements at different separation distances (for spherical-spreading, the product of Z and d is a constant). Again the deviation from the ideal behaviour is quantified and forms the appropriate contribution to the uncertainty budget. At NPL, a calibration is derived from the mean of at least four independent sets of measurements, each at a different separation distance and with the hydrophones remounted between sets. The remounting of the hydrophones allows the effect of slight differences in factors such as mounting and orientation to influence the results. The random uncertainty calculated from the repeated measurements then provides a measure of the sensitivity of the calibration to these effects. In general, the hydrophone to be calibrated is designated as H in the calibration, and the hydrophones chosen as P and T are NPL reference hydrophones which have a stable calibration history. Comparison of the calibration results for these devices with the expected values provides yet another check on the accuracy of the calibration.

To validate the calibration method, NPL took part in a European comparison of calibrations of reference hydrophones in the range 10-315 kHz organised under the auspices of the Commission of the European Communities, and achieved a mean difference from the overall grand mean averaged over all frequencies and hydrophones of only 0.3 dB [10]. This method has now been established as the NPL primary standard in the frequency range 2 kHz to 500 kHz with typical overall uncertainties (95% confidence level) of ±0.5 dB.

3. EXPERIMENTAL COMPARISON

To compare the two calibration methods, both were used to calibrate three reference hydrophones. The first was a Brüel & Kjær 8103 hydrophone which has a cylindrical element roughly 6 mm diameter and 8 mm long and which has resonances at frequencies of approximately 125 kHz, 275 kHz and 710 kHz. Using the interferometer, calibrations were undertaken at frequencies from 200 kHz to 1 MHz at intervals of 10 kHz. For comparison, calibrations were also undertaken by the free-field reciprocity method in the same frequency range but at intervals of 50 kHz. For the reciprocity calibrations, the B&K 8103 was used as the reciprocal transducer, T, with two Reson TC4034 hydrophones used as P and H. The elements of the TC4034's are 6.35 mm diameter spheres with resonance frequencies of 350 kHz. For both methods, the hydrophone was mounted in a hollow free-flooding Aluminium tube, the internal diameter of which matched that of the hydrophone body.

In addition, a GEC-Marconi sonar hydrophone (type Y-33-7638) was used for comparison purposes. This hydrophone is a piston design, 25 mm diameter and made from layered pvdf mounted on a brass backing. This hydrophone exhibits no strong resonances in the range 100 kHz to 1 MHz but is quite directional, with a -6 dB beamwidth of less than 1.5° at 1 MHz. To aid alignment, the hydrophone was mounted on a 10 cm diameter perspex disc which fitted into the same mount as for the pellicle. The hydrophone could then be tilted in the mount about two orthogonal axes in the plane of the perspex disc. A similar mounting arrangement was used for the reciprocity calibrations, with the GEC hydrophone used as H, and a Reson TC 4034 and B&K 8103 used as P and T respectively. Calibrations were performed at 50 kHz intervals in the range 300 kHz to 1 MHz using both methods.

Finally, a Reson TC 4035 hydrophone was calibrated. This hydrophone has a 1.5 mm diameter, 1.5 mm long cylindrical element with a resonance frequency at about 700 kHz. A miniature preamplifier using surface mounted components is integrated into the body of the hydrophone and provides an impedance buffer and a gain of 10 dB. This hydrophone was developed jointly by the Reson A/S, the University of Bath (Department of Physics) and NPL during a project which was part funded by the European Commission [12]. The hydrophone was calibrated using the interferometer from 300 kHz to 900 kHz at intervals of 10 kHz, and by the reciprocity method between 300 kHz and 800 kHz at 50 kHz intervals (the same two hydrophones being used as P and T as for the GEC sonar hydrophone).

4. RESULTS AND DISCUSSION

Figure 2 gives the results of the calibration of a Brüel & Kjær 8103 hydrophone by the methods of interferometry and reciprocity. The resonances in the hydrophone response at 275 kHz and 710 kHz are clearly seen in the interferometer results since these have a greater resolution (10 kHz intervals). Also shown in the figure are the differences between the results. As can be seen, except for the values at 900 kHz, the differences are 0.4 dB or less (overall mean difference is +0.21 dB) which is considerably less than the combined uncertainties of the two methods.

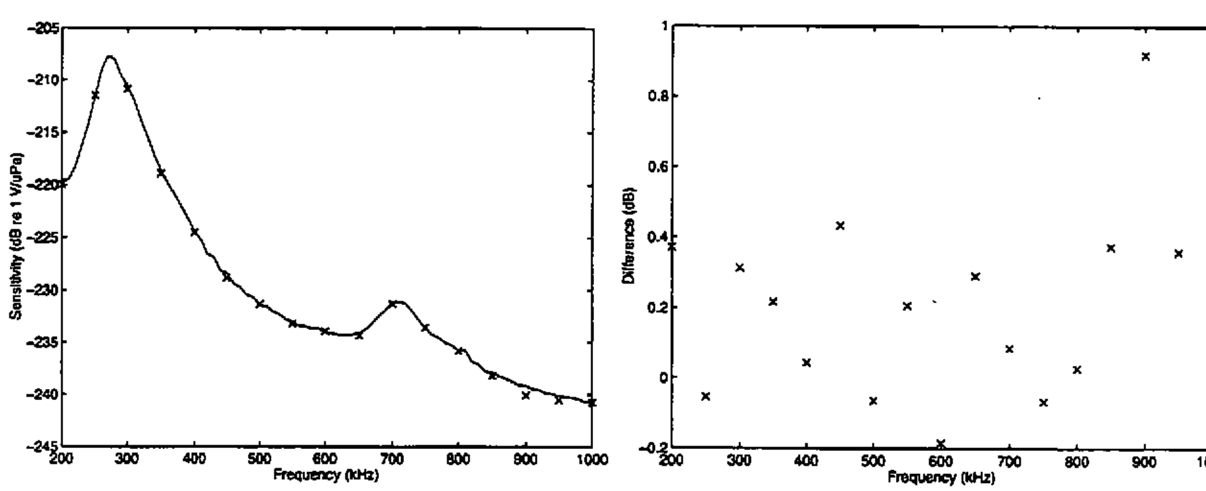

Figure 2 Left: results of calibration of a B&K8103 hydrophone by interferometry (solid line) and reciprocity (x); Right: the difference between the results of the two methods (interferometry minus reciprocity).

COMPARISON BETWEEN RECIPROCITY AND INTERFEROMETRY

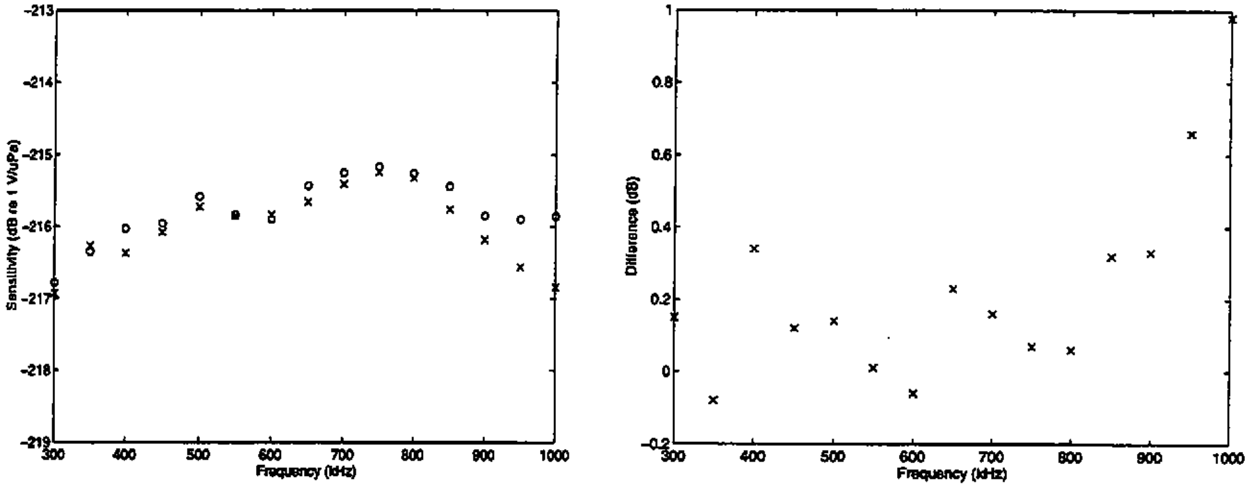

Figure 3 Left: results of calibration of a GEC 25 mm pvdf sonar hydrophone by interferometry (x) and reciprocity (o); Right: the difference between the results of the two methods (interferometry minus reciprocity).

Figure 3 shows the results for the GEC pvdf sonar hydrophone. Once again, the results are in good agreement with similar differences to those shown for the B&K 8103, and a similar trend of worsening agreement at the highest frequencies. The mean difference for this hydrophone is +0.22 dB in the range 300 kHz to 1 MHz. Figure 4 shows the results for the TC 4035 hydrophone presented in the same manner. Agreement is once again well within the combined uncertainties, with the mean difference for this hydrophone being +0.46 dB in the range 300 to 750 kHz.

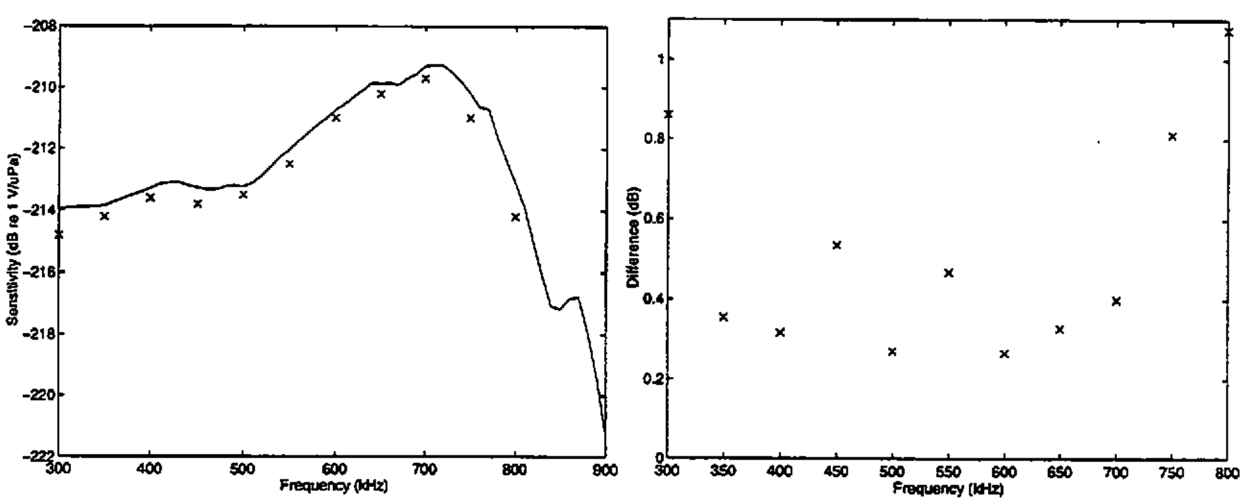

Figure 4 Left: results of calibration of a Reson TC 4035 hydrophone by interferometry (x) and reciprocity (solid line); Right: the difference between the results of the two methods (interferometry minus reciprocity).

It is believed that the reciprocity values are the main source of the increased discrepancies at the higher frequencies since the hydrophones are becoming increasingly directional and much less sensitive, especially when used as projectors. To obtain measurable signal levels during reciprocity calibrations at such high frequencies it is necessary to drive the hydrophones quite hard. This can cause the hydrophones to behave non-reciprocally and can cause electrical measurement problems due to the high attenuation values required for equalisation. It is possible to improve the accuracy at high frequencies by using small piston transducers as P and T in calibrations but this was not done for the work reported here.

Conversely, the interferometer results become less accurate at lower frequencies, mainly due to the restrictions on the echo-free time available for calibrations in the small interferometer tank, which increases the problems from acoustic reflections and the lack of steady-state conditions. The reflections from the pellicle mounting ring arrive only 33 μs after the direct path signal, giving about 6 cycles at 200 kHz. Any turn-on transients caused by resonances in either the source transducer or the hydrophone reduces the available steady-state signal even further. In general, the results from the interferometer tend to be slightly higher than those from free-field reciprocity.

5. CONCLUSION

The two primary standard methods for the free-field calibration of hydrophones at NPL have been compared by calibration of two reference hydrophones using both methods in the frequency range 200 kHz to 1 MHz. In general, agreement is 0.4 dB or better except at the highest frequencies where the accuracy of the reciprocity calibrations is questionable. This is well within the combined uncertainties of the methods, and provides independent validation for the primary standards.

6. ACKNOWLEDGEMENTS

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