Proceedings of the Institute of Acoustics

RECIPROCITY CALIBRATIONS AT LOUGHBOROUGH UNIVERSITY

L A A Warnes & W Wood

Dept. of Electronic & Electrical Engineering, Loughborough University, Leics. LE11 3TU.

1. INTRODUCTION

The National Physical Laboratory not long ago published a report on a hydrophone calibration round robin, which indicates disturbingly large differences in the receiver sensitivities of standard hydrophones reported by the participants[1]. Table 1 summarizes the results, while some are given in more detail in Table 2. The tables show that differences from the overall mean of the ten laboratories (the grand mean) of ±1 dB were routine, but much larger differences arose. One may presume that the participants took more care than they would normally, and the high standard of hydrophone construction - resulting in little directionality over a wide frequency range - should have produced calibrations in much greater accord. Various methods were used in the calibrations, but the method used at Loughborough for all the measurements was reciprocity, which appears to have given better than average results and a random error consistent with the estimated systematic error. This paper therefore looks critically at the method of reciprocity calibration to assess the sources of error and the range of frequencies over which it may be applied in test tanks.

2. ASSESSMENT OF PRIMA FACIE ERRORS

The reciprocity calibration[2] is an absolute method which is in principle simple to perform and with care can achieve accuracies of the order of ±0.3 dB (corresponding to ±3½% in voltage terms). In a laboratory test tank the lower limit of frequency is about 5 kHz, while with suitable projectors and hydrophones, this sort of accuracy is probably attainable at up to 500 kHz - possibly even to higher frequencies. In normal circumstances the intensity of sound from a projector falls as the inverse square of the range - so-called spherical spreading and in this case the reciprocity formula may be written

$$M_H = \sqrt{([2/\rho f I]|V_H V_H'/V_T|)} \qquad (1)$$

where M_H is the receiver sensitivity in V/Pa, V_H is the open-circuit voltage at the hydrophone terminals when placed one meter from a projector driven by a current of I A at a frequency f Hz. V_T is the open-circuit voltage produced at the terminals of a reciprocal transducer in the same sound field as that which gave V_H. V_H' is the open-circuit voltage of the hydrophone placed one meter from the reciprocal transducer when it is driven with the same current, I, at the same frequency, f. ρ is the density of the medium. Usually placing the receivers exactly 1 m from the sources is inconvenient and spherical spreading being implicit in equation (1), no further harm is done in rewriting it as

$$M_H = \surd([2/\rho f][V_H r_H V_H' r_H' / V_T r_T]) \qquad (2)$$

where r_H, r_H' and r_T are the distances between sources and receivers in m. Equation (2) contains nine quantities to be measured, though ρ is usually looked up in tables after the water temperature is measured. The error involved in taking ρ as 1000 kg/m^3 is no more than 0.01 dB for a laboratory tank filled with tap water and left for a week or two. f is measurable to a better accuracy than this, and so can be discounted as a source of error. r_H etc can be measured with a tape measure or ruler, but it is necessary to orientate the supports carrying the projectors and hydrophones with some accuracy, unless the measurement is made under water. A more convenient way is to time the passage of the sound pulse. The speed of sound in air-free tap water is virtually the same as that in pure water and depends only on temperature, changing by about +3.5 m/s/K (+0.2%/K) at about 15°C. The timing may be done on an oscilloscope, along with the voltage measurements while pulses must in any event be used for measurements in a test tank. The accuracy of this method of measuring distances is ±0.6%.

Voltage measurement is very important and an accurate oscilloscope calibration is essential over all the voltage and frequency ranges used. The easiest way to do this is to use a sine-wave source and AC voltmeter. The estimated accuracy of this measurement, with pulse heights on the oscilloscope screen of at least 50 mm, is ±0.6%. The current into the projector is measured by a series resistor. Non-inductively wound, precision resistors are not as suitable as cheap metal-film resistors because of their greater inductance. Typical inductance values are 0.75 μH for a 10 Ω precision resistor and 0.04 μH for a 2.2 Ω metal film resistor. At 200 kHz the reactive components amount to 9.3% and 2.3% of the respective impedances, both negligible, but above about 400 kHz the reactance of the precision resistor may be significant.

Taken together the errors involved in using equation (2) are three voltage errors and three range errors and a single current error, all of magnitude 0.6%. Assuming ρ and f to be free from significant error we find the RMS error to be $\surd(7 \times 0.6^2) = 1.6\%$, which is equivalent to an error of only 0.07 dB in M_H. Yet the random error in determining M_H appears to be on average ±0.3 dB: why is this?

3. THE MAJOR CAUSES OF ERROR

Apart from non-quantifiable sources of error which lie outside the scope of this paper (e.g. bubbles clinging to the transducer surface), the possible

RECIPROCITY CALIBRATIONS AT LOUGHBOROUGH UNIVERSITY

causes may be listed

(1) Errors due to directionality in the transducers' beam patterns.
(2) Errors caused by pulse shape irregularities.
(3) Errors of omission, such as using an uncalibrated amplifier, using an extension cable of "negligible" length or not taking the water temperature.

Of these, (1) is most important at high frequencies while (2) is usually considered to be more important at low frequencies, so that these together may be responsible for the just-discernible minimum in random error which occurs at 50 kHz in table 2. At Loughborough we carry out reciprocity calibrations in the range from 5 kHz to 200 kHz using 25 mm diameter ball hydrophones which are resonant at about 70 kHz. Their beam patterns are reasonably omnidirectional, with fluctuations of about ±2 dB at 200 kHz in the horizontal plane, and rather better than this at lower frequencies; as a result the orientation of the hydrophone is not very critical. To be sure, the receiving face of the hydrophone still needs to be marked, but an orientational error of 10° ought not to produce an error of more than 0.2 dB. Unfortunately hydrophones with cylindrical active elements are often used, such as the B & K 8100 and 8103 types. In the former of these the element is about 20 mm in height, so the beam pattern formula

$$B(\vartheta) = \sin([\pi d/\lambda]\sin\vartheta)/([\pi d/\lambda]\sin\vartheta) \qquad (3)$$

leads to the conclusion that the vertical orientation must be within $\pm 3^\circ$ to give a response not more than 0.3 dB down from the maximum at 200 kHz. This is fairly hard to achieve and it is considered that this was the most important source of error in the calibrations carried out at Loughborough on the B & K 8100 hydrophone. The position is better with the B & K 8103 hydrophone in this regard, since its element is only 8 mm high, so that the vertical orientation required for the response to be within 0.3 dB of the maximum at 200 kHz is only $\pm 8^\circ$. Despite this, the random uncertainty of the calibrations for the 8103 was larger than for the 8100, probably because the horizontal beam pattern was less uniform, though it may be that the lower sensitivity over most of its range contributed: however, the smallest voltage measured was 0.16 mV at 200 kHz and that was from the B & K 8100, yet this measurement had one of the smallest random errors (0.1 dB). In order to use the reciprocity method at 500 kHz with the B & K 8103 type of hydrophone it will be necessary to construct a rig for the purpose in which the hydrophone can be mounted with vertical alignment errors of $< 3^\circ$. Since the active element must be at some distance from any rigid support, this requirement is not easy to satisfy. Though the Actran F-42D ball hydrophone appeared to be reasonably omnidirectional below its resonant frequency, the larger errors at 150 and 200 kHz indicate problems with beam patterns at these frequencies - problems which do not affect the 25 mm ball hydrophones used as transmitter and reciprocal transducer in the measurements at Loughborough.

RECIPROCITY CALIBRATIONS AT LOUGHBOROUGH UNIVERSITY

We now consider the problem of pulse measurement. The tank at Loughborough is not of ideally size, being only 2 m deep. Normally hydrophones are positioned at 1 m depth and the round-robin reciprocity measurements were carried out at 1.4 m range. The bottom and surface reflections are very strong and travel a distance of $2\sqrt{(0.7^2 + 1^2)} = 2.44$ m, so they arrive about 1.04/1476 s, or about 700 μs after the first part of the received pulse. This is the longest useable pulse for this range. Multipath effects can be checked for easily enough by examining the stability of the pulse to changes in frequency. Multipaths cause rapid variations in amplitude which should be absent from the direct-path signal. Less-detectable interference effects occur when there are reflections from the mounting apparatus. These are weak effects usually, since the acoustic impedances of the plastics used for mountings are not far from that of water. However, unless the mounting is physically rather small they will be present. They may be detected by either repeating the measurements at two or more different ranges or by making measurements at closely-spaced frequencies. In the latter case a regular ripple superimposed on the steady trend of the measurements leads to the diagnosis of mounting reflections. At Loughborough the hydrophones were taped by the cable, just before it entered the protective stalk-moulding of the active element, to thin-walled plastic tubing about 15 mm OD. This arrangement did not appear to produce marked reflections.

That the first part of the pulse can be very irregular is well known. It is chiefly because the projector-receiver combination consists essentially of series resonant circuits which are being driven off resonance. As a rule of thumb, a resonant circuit subjected to pulse excitation takes about Q cycles of the resonant frequency to settle to its steady-state response. The 25 mm diameter ball hydrophones used at Loughborough appear to have Qs of 4 or 5 and resonant frequencies around 70 kHz, so any transient effects on the pulse shape are of about 70 μs duration: there is plenty of time left during which the pulse amplitude is constant. The pulse-shape problem appears to be worse at low frequencies for two reasons: first, because there are not many cycles to look at, and when the first one or two are distorted, it seems risky to rely on the few remaining. One can only take courage and trust they will be sufficient. The second reason is related to the resonant frequency. In order to get larger pulse amplitudes one may decide to employ projectors which resonate at lower frequencies - at Loughborough we have used 75 mm diameter ball hydrophones which resonate at 27 kHz, and the pulse shape at 5 kHz is very poor simply because Q cycles at 27 kHz lasts 2½ times as long as Q cycles at 70 kHz. There are transducers which have rather high Qs - perhaps as high as 40 - and these are difficult to measure accurately in a shallow tank. Reverberations can be minimized by operating with low pulse repetition rates and well away from the side walls. Low-frequency noise can also be a problem with an inadequate experimental set up, but even with the best technique and equipment some transducers are much worse than others, and should not be used in hydrophone calibration.

Coming to the third possible explanation for inaccurate results, there is an important correction which must be made to the sensitivity of a hydrophone when its cable length is changed. When a charge amplifier is used with the hydrophone the correction is the capacitance ratio[3]

$$V_o/V_o' = (C_h+C_c+C_a)/C_h \tag{4}$$

where V_o is the open-circuit voltage of the hydrophone without extension cable and V_o' is the voltage from the hydrophone with the extension cable, while C_h is the static capacitance of the hydrophone, C_c is the capacitance of the extension cable and C_a is the parallel input capacitance of the amplifier. For example, suppose the hydrophone's static capacitance is 8 nF, the coaxial extension cable is 6 m long and has a capacitance of 0.65 nF, while the amplifier has a parallel input capacitance of 20 pF; then the correction is +8.4% or 0.7 dB. If a charge amplifier is not used then the correction becomes

$$V_o/V_o' = (Z_h+Z_{ca})/Z_{ca} \tag{5}$$

Where Z_h is the hydrophone impedance and Z_{ca} is the impedance of the cable and amplifier. If the latter is of good quality, then the combination of cable and amplifier amounts to just the cable capacitance and the correction is then

$$V_o/V_o' = (Z_h+Z_c)/Z_c \tag{6}$$

where $Z_c = -j/\omega C_c$. The impedance of the hydrophone must then be measured at each frequency used in calibration; alternatively, the hydrophone's equivalent circuit can be used with SPICE[4] to compute the corrected voltages. This correction can be substantial: with the 25 mm ball hydrophones and an extension cable of 7 m of 50 Ω coax, the correction at 90 kHz amounted to 14%, or 1.1 dB. With small hydrophones like the B & K 8103 the correction is significant- even with only 2 m of coaxial extension cable it amounted to 0.6 dB - though in this case the correction up to 150 kHz could be made using equation (4).

The water temperature is important because M_H is sensitive to temperature, and if the temperature range over which the hydrophone is used is appreciable, this must be allowed for. For example, a typical change in sensitivity is 0.04 dB/K, so a deviation of 10°C from the calibration temperature could lead to an error of 0.4 dB.

In conclusion, the overwhelming source of error in the reciprocity calibration - other than human error - appears to be the directional nature of the transducer's response, which can only be overcome by better constructional techniques on the part of the manufacturers or by using purpose-built mountings and taking exceptional care in using them. If high quality ball hydrophones resonant at about 200 kHz can be made, and with adequate care in their use, the reciprocity technique may be expected to produce calibrations within ±0.3 dB at all frequencies from 5 kHz to 500 kHz.

4. TABLES OF RESULTS

Table 1

Summary of Results of Round Robin Measurements

Type of Hydrophone	Maximum[a] Difference	RMS[a] Difference	Random[b] Error	Estimated[c] Uncertainty
BK 8100[d]	-4.0	0.9	0.3	0.6
BK 8103[e]	+3.1	1.0	0.3	0.6
F-42D[f]	-4.3	1.2	0.3	0.3

Notes: All figures in dB

[a]From grand mean of 10 labs

[b]Mean for repeated measurements made at LUT

[c]For measurements made at LUT

[d]21 mm OD cylindrical hydrophone

[e]9.5 mm OD cylindrical hydrophone

[f]20 mm OD ball hydrophone

Table 2

Comparison of Measurements on 3 Standard Hydrophones

Freq. (kHz)	Type	Grand[a] Mean	Manuf.[b] Calib.	Measured[c] Response	Random[d] Error	System.[e] Error
10	BK 8103	-211.3	-211.5	-210.7	0.2	0.3
	BK 8100	-205.0	-205.0	-204.9	0.3	0.2
	F-42D	-208.2	-208.7	-208.1	0.1	0.2
15	BK 8103	-211.3	-212.3	-210.9	0.2	0.3
	BK 8100	-205.2	-205.5	-204.9	0.4	0.2
	F-42D	-208.1	-208.9	-207.9	0.2	0.2
20	BK 8103	-211.7	-213.0	-211.3	0.2	0.3
	BK 8100	-205.6	-205.3	-205.5	0.3	0.2
	F-42D	-208.9	-209.2	-208.7	0.1	0.2
30	BK 8103	-212.1	-212.4	-211.9	0.2	0.3
	BK 8100	-205.7	-206.2	-206.0	0.2	0.2
	F-42D	-210.1	-210.0	-210.3	0.2	0.2
50	BK 8103	-213.0	-212.6	-212.9	0.2	0.4
	BK 8100	-202.5	-203.3	-202.9	0.1	0.2
	F-42D	-210.5	-210.6	-210.2	0.1	0.2
70	BK 8103	-213.3	-214.1	-213.3	0.2	0.4
	BK 8100	-203.8	-203.9	-203.5	0.3	0.3
	F-42D	-211.3	-211.3	-211.3	0.2	0.2
100	BK 8103	-210.8	-212.6	-209.8	0.4	0.5
	BK 8100	-210.2	-210.3	-209.4	0.3	0.3
	F-42D	-212.0	-212.3	-211.4	0.3	0.3
150	BK 8103	-213.9	-215.9	-213.3	0.4	0.7
	BK 8100	-218.7	-219.9	-218.8	0.3	0.4
	F-42D	-204.0	-204.0	-203.9	0.6	0.4
200	BK 8103	-222.2	-221.4	-221.7	0.4	0.8
	BK 8100	-228.2	-228.3	-229.0	0.1	0.5
	F-42D	-214.2	-	-214.7	0.5	0.4

Notes: Responses in dB re 1V/μPa

[a]Average of 10 laboratories

[b]Receiver response given by manufacturers

[c]Reciprocity measurement at Loughborough

[d]σ_{n-1} of measurements at Loughborough (4 readings)

[e]Estimated systematic error at Loughborough

5. REFERENCES

[1] S P Robinson, R C Preston & D R Bacon, 'A National Intercomparison of Hydrophone calibration Methods' NPL Acoustics Report Ac 116, (1988)

[2] R J Urick, '*The Principles of Underwater Sound*' pp 46–48, 2nd Edn., McGraw-Hill (1975)

[3] Brüel & Kjær, Instruction Manual for Hydrophone Types 8100, 8101, 8103, 8104, (1983)

[4] P W Tuinenga, '*SPICE: A Guide to Circuit Simulation & Analysis Using PSpice*', Prentice Hall, (1988)