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Phase calibration of hydrophones by the free-field reciprocity method in the frequency range 10 kHz to 400 kHz

Gary Hayman, Stephen P Robinson

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National Physical Laboratory | Hampton Road | Teddington | Middlesex | United Kingdom | TW11 0LW

Switchboard 020 8977 3222 | **NPL Helpline** 020 8943 6880 | **Fax** 020 8943 6458 | **www.npl.co.uk**

Phase calibration of hydrophones by the free-field reciprocity method in the frequency range 10 kHz to 400 kHz

by

Gary Hayman, Stephen P Robinson

ABSTRACT

In this report, a description is given of work carried out at the National Physical Laboratory to investigate phase response calibration of hydrophones by the free-field reciprocity method. A co-linear arrangement of hydrophones, based on the method of Luker and Van Buren, is used in order to eliminate some of the difficulties in the measurement of the device separation and the speed of sound in water. The experimental implementation of this method in the NPL open tank facility is described, along with the use of a laser alignment system to accurately set the position of the central hydrophone. The results of calibrations of three hydrophones are presented and these are compared to phase response measurements, performed on the same three hydrophones, using an optical vibrometry method, at Hangzhou Applied Acoustic Research Institute (HAARI) in China. Agreement between the two methods is shown to be generally good, with typical differences of less than 8° throughout the majority of the frequency range. However, the Type A uncertainty for the reciprocity measurements is relatively large at higher frequencies, with 95% confidence level uncertainties reaching 30° at 400 kHz. The major sources of error in the reciprocity method as implemented are discussed, along with possible explanations for some of the disagreements seen when the results are compared to calibrations by the optical method.

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National Physical Laboratory
Teddington, Middlesex TW11 0LW

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1. INTRODUCTION

To ensure faithful recording of acoustic pressure signals in water it is necessary to know the complex sensitivity of the hydrophone. This means that the phase response as well as the magnitude response is required. At frequencies very much below resonance frequency, an invariant hydrophone response may be assumed, but at frequencies close to resonance this is no longer true. This has significant consequences when using a hydrophone to measure a broadband acoustic field, i.e. one containing a broad range of frequencies such as an impulsive sound (e.g. a short pulse or “click”). If the hydrophone phase response is not flat, phase delays may be introduced into the different frequency components of the signal, leading to distortions in the appearance of the time-domain waveform. For high fidelity reproduction of the acoustic signal, either a hydrophone with a flat response must be used or the measured signal must be corrected using deconvolution techniques. For the latter case, the hydrophone sensitivity must be known in terms of its complex-valued response (magnitude and phase), and hence the phase response must be measured.

Phase response is also important for beam forming in arrays, where differences in inter-element phase response can lead to errors. Generally, only relative phase response measurements are required to compare the individual elements of an array, but often a “gold standard” hydrophone is kept, against which other elements are compared. In such cases, an absolute phase calibration method will be required to measure the response of the gold standard and monitor any changes over time.

Phase calibration of hydrophones is rarely attempted compared to magnitude response. This may be because there are a number of experimental difficulties which limit the accuracy. In the measurement of phase, the determination of the separation between the acoustic transducers becomes particularly important, since any error in the measurement of distance will correspond to an increasing fraction of an acoustic wavelength as the frequency increases. This will result in a correspondingly greater error in the measured phase at higher frequencies. The positioning of transducers in large test tanks and open water sites to the accuracy required to perform reasonable phase measurements is not a trivial problem. However, there are a number of methods described in the literature [1-6]. In particular, the method of Luker and Van Buren [2] involves a procedure which is designed to overcome the difficulties in measuring the separation distances and determining the speed of sound in water. This method has been adopted for the work described in this report.

This report is organised as follows. First, a description is given of the method used, which is based on that of Luker and Van Buren. In the next section, the experimental implementation of this method is described. In Section 4, the results of the experiments are presented and compared to measurements performed at another institute (Hangzhou Applied Acoustic Research Institute in China). A discussion is then given of the major sources of error in the method as implemented. Finally, conclusions are presented and recommendations for improvements are made.

2. METHODOLOGY

The free-field sensitivity of a hydrophone can be determined by the method of three-transducer spherical-wave reciprocity. The phase angle of the free-field sensitivity can also be determined if one extends the measurements to include phase [1]. All of the pressures, input currents, output voltages, transfer impedances, transmitting responses, and free-field sensitivities are now complex; they include both amplitude and phase. For example, the pressure produced by the projector P at the hydrophone H becomes:

$$p = \exp\left[jk\left(d_0 - d_1\right)\right]\frac{S_{\mathrm{P}} I_{\mathrm{P}}}{d_1} \tag{2.1}$$

where the distance d_1 is measured from the reference centre of the projector to the reference centre of the hydrophone. The wavenumber $k = 2\pi f / c$, where c is the speed of sound in the surrounding medium. The reference distance d_0 used in the definition of the transmitting response is equal to 1 m.

The complex transfer impedance Z_{PH} is given by:

$$Z_{\mathrm{PH}} = \exp\left[jk\left(d_0 - d_1\right)\right]\frac{M_{\mathrm{H}} S_{\mathrm{P}}}{d_1} \tag{2.2}$$

Similarly for the transfer impedances Z_{PT} and Z_{TH}:

$$Z_{\mathrm{PT}} = \exp\left[jk\left(d_0 - d_2\right)\right]\frac{M_{\mathrm{T}} S_{\mathrm{P}}}{d_2} \tag{2.3}$$

$$Z_{\mathrm{TH}} = \exp\left[jk\left(d_0 - d_3\right)\right]\frac{M_{\mathrm{H}} S_{\mathrm{T}}}{d_3} \tag{2.4}$$

where d_2 is the distance between the references centres of P and T and d_3 is the distance between the reference centres of T and H.

Equations (2.2) to (2.4) can be combined to give:

$$\frac{Z_{\mathrm{PT}} Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}} = \exp\left[jk\left(d_0 + d_1 - d_2 - d_3\right)\right]\frac{M_{\mathrm{T}} S_{\mathrm{T}} d_1}{d_2 d_3} \tag{2.5}$$

Using the complex spherical wave reciprocity parameter one obtains:

$$\frac{M_{\mathrm{T}}}{S_{\mathrm{T}}} = \frac{2}{j\rho f}\exp\left(jkd_0\right) \tag{2.6}$$

Expressions for the free-field sensitivity and transmitting response of T result from combining equations (2.5) and (2.6):

$$M_{\mathrm{T}} = \sqrt{\frac{2 d_2 d_3}{j\rho f d_1}\exp\left[jk\left(d_2 + d_3 - d_1\right)\right]\frac{Z_{\mathrm{PT}} Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}}} \tag{2.7}$$

$$S_{\mathrm{T}} = \sqrt{\frac{j\rho f d_2 d_3}{2d_1} \exp\left[jk\left(d_2 + d_3 - d_1 - 2d_0\right)\right] \frac{Z_{\mathrm{PT}} Z_{\mathrm{TH}}}{Z_{\mathrm{PH}}}} \qquad (2.8)$$

One can use equations (2.4) and (2.8) to derive the following expression for the complex free-field sensitivity of the hydrophone H.

$$M_{\mathrm{H}} = \sqrt{\frac{2d_1 d_3}{j\rho f d_2} \exp\left[jk\left(d_1 + d_3 - d_2\right)\right] \frac{Z_{\mathrm{PH}} Z_{\mathrm{TH}}}{Z_{\mathrm{PT}}}} \qquad (2.9)$$

The difficulty of determining the phase of M_{H} by this method lies in accurately determining both the sound speed and the measurement distances d_1, d_2 and d_3. For example, at 100 kHz in water, an error of only 1.0 mm in any one of the distances gives a phase error of about 12°. However, this difficulty can be avoided by positioning the three transducers P, H and T in a straight line with H located between P and T [2], as shown in Fig. 2.1. This assures that $d_2 = d_1 + d_3$. Then equation (2.9) simplifies to:

$$M_{\mathrm{H}} = \sqrt{\frac{2d_1 d_3}{j\rho f d_2} \frac{Z_{\mathrm{PH}} Z_{\mathrm{TH}}}{Z_{\mathrm{PT}}}} \qquad (2.10)$$

Since the distances and sound speed do not appear explicitly in a phase term in equation (2.10), the accuracy of the calculated phase of M_{H} is only limited by accuracy of the phase measurements of the voltages and currents and by positioning.

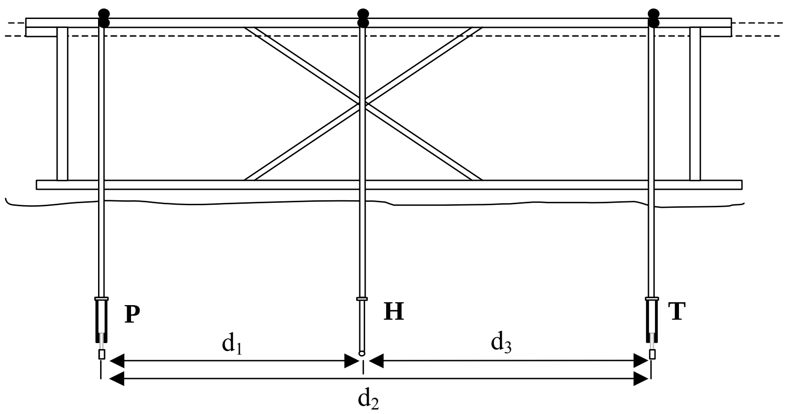

Fig. 2.1: Co-linear arrangement for three-transducer reciprocity which utilises a projector P and reciprocal transducer T to calibrate hydrophone H.

The logistics for making the measurements are as follows:

1. The transducers are mounted as shown in Fig. 2.1 with their reference centres separated by the distances d_1, d_2 and d_3, where $d_3 = d_2 - d_1$. Their reference directions are aligned with P pointing toward H and T. The complex transfer impedance Z_{PH} is determined from the input current to P and the output voltage from H.

2. The hydrophone H with its mount is removed. The complex transfer impedance Z_{PT} is determined from the input current to P and the output voltage from T.

3. The hydrophone H with its mount is replaced and rotated about its reference centre so that it now points toward T and the distance d_3 is maintained between the reference centres of H and T. The complex transfer impedance Z_{TH} is determined from the input current to T and the output voltage from H.

One now calculates the magnitude and phase angle of the free field sensitivity of the hydrophone from equation (2.10) using the measured transfer impedances. The resulting sensitivity is representative of both the hydrophone and its mount. Ideally, the calibration should be performed using the same mount that will support the hydrophone when it is used for field measurements.

3. EXPERIMENTAL IMPLEMENTATION

Measurements to determine the phase angle of the free-field sensitivity of a hydrophone by the method described in Section 2 were performed in the NPL small open-tank facility. This is shown in Fig. 3.1 and consists of a 2 x 1.5 x 1.5 m GRP tank with a two-carriage positioning system having XYZ and θZ motion with 10 µm and 0.01° resolution respectively.

Fig. 3.1: NPL small open-tank facility

With only two carriages available, it was necessary to devise a method of mounting a third transducer in order to achieve the co-linear arrangement described in Section 2. This was accomplished by placing a steel beam across the top of the tank to which a transducer mounting pole could be attached, the top of which can be seen in Fig. 3.1 just beyond the far carriage. The hydrophone H was mounted to the far carriage, which was positioned centrally in the tank, and the transducer T mounted on the near carriage set to give a T to H separation of 0.5 m. The projector P was mounted to the pole attached to the beam and this was also positioned to give a P to H separation of 0.5 m. All three devices were set to the same depth of 0.8 m and aligned visually using the viewing window, which can be seen in the end of the tank in Fig. 3.1. Fig. 3.2 shows the co-linear arrangement of devices as viewed through the window. In this photograph, the outer P and T devices are both Reson TC4034 hydrophones and the centrally-mounted H is a B&K 8103 hydrophone.

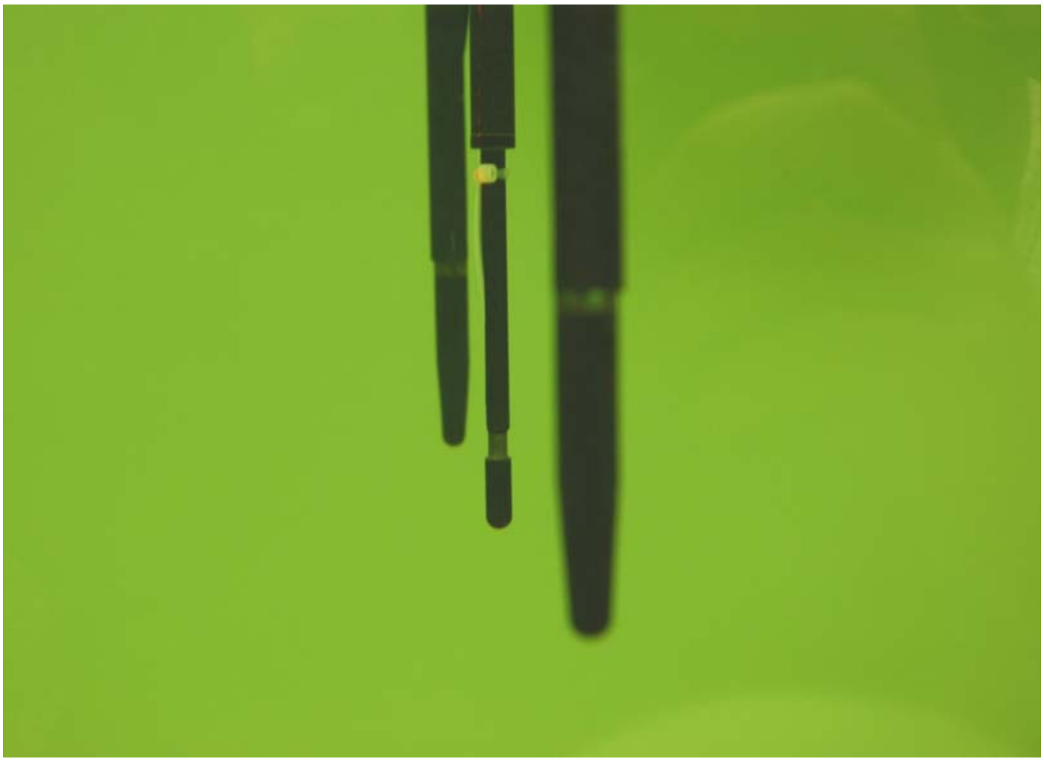

Fig. 3.2: Co-linear arrangement of devices as viewed through the window in the end of the tank.

In order to achieve an accurate phase calibration of H by the method described in Section 2, it is a requirement that the sum of the P to H and T to H separations, measured centre-to-centre, is equal to the P to T separation. It is therefore vital that there is no translation of H when it is rotated between the P to H and T to H measurements. To ensure that this was the case, a laser alignment system was used to check the position of H before and after rotation. This consisted of a laser module and adjustable mounting bracket which was clamped to the side of the tank in line with the hydrophone H. This arrangement is shown in Fig. 3.3. The laser was set to produce a vertical line focussed at the hydrophone and positioned so that the front edge of the hydrophone just touched the beam. The small tank positioning system has manual joystick control and this enables very fine movements of the X-axis position of H in increments down to 10 µm. In order to accurately set the position of H prior to each P to H and T to H measurement, the carriage was first moved back so that the laser beam no longer impinged on the hydrophone. The carriage was then moved forward slowly until the beam could just be seen as a faint vertical line on the front face of the hydrophone when viewed through the window in the front of the tank. If the carriage was moved forward too far the line became brighter and began to move towards the side of the hydrophone. Fig. 3.4 shows the vertical laser alignment beam on the hydrophone as viewed through the tank window.

Fig. 3.3: Laser alignment module and adjustable mounting bracket clamped to the side of the tank.

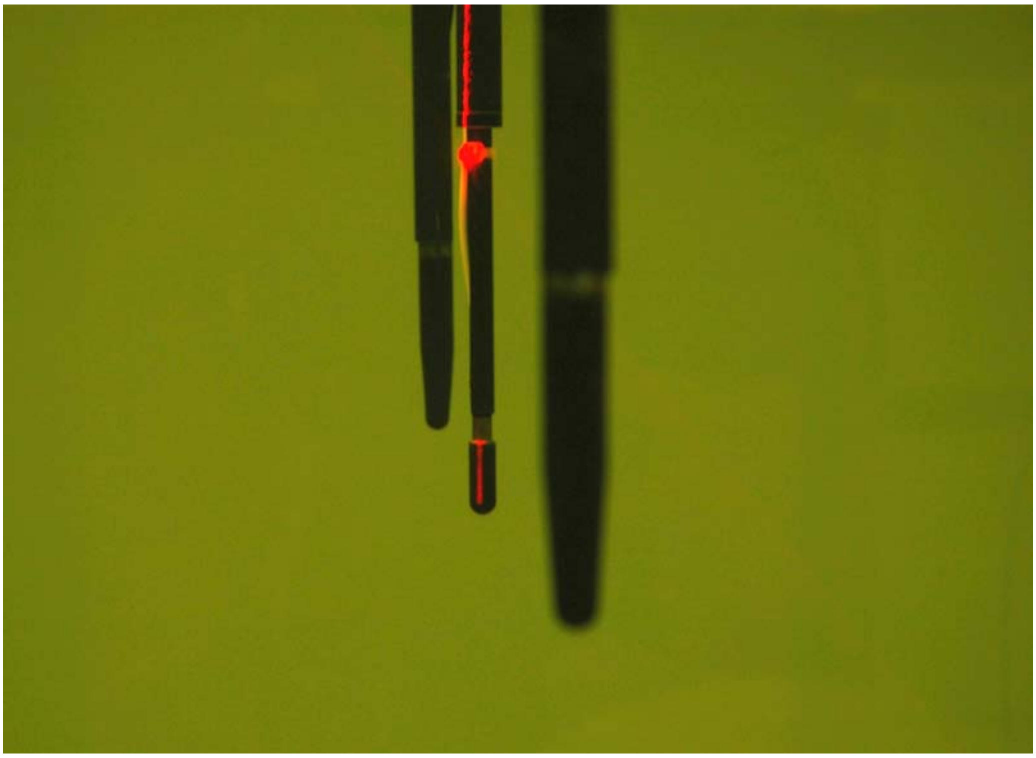

Fig. 3.4: View of the laser alignment beam as seen through the window in the front of the tank.

A schematic of the equipment used to perform the measurements is shown in Fig. 3.5. A function generator was used to produce a sinusoidal tone burst signal at the frequency of interest. This was fed to a power amplifier to drive the projector via a current probe used to monitor the drive current. The measuring instrument was an Agilent 89410A Vector Signal Analyzer, and a switching unit enabled a single channel to be used to measure both the voltage from the hydrophone and the projector drive current. The signals were conditioned using a preamplifier and one octave band pass filter prior to measurement. Additionally, a calibrated attenuator was used to reduce the drive current signal to a similar level to that of the hydrophone receive voltage in order to minimise any linearity issues in the measuring instrumentation.

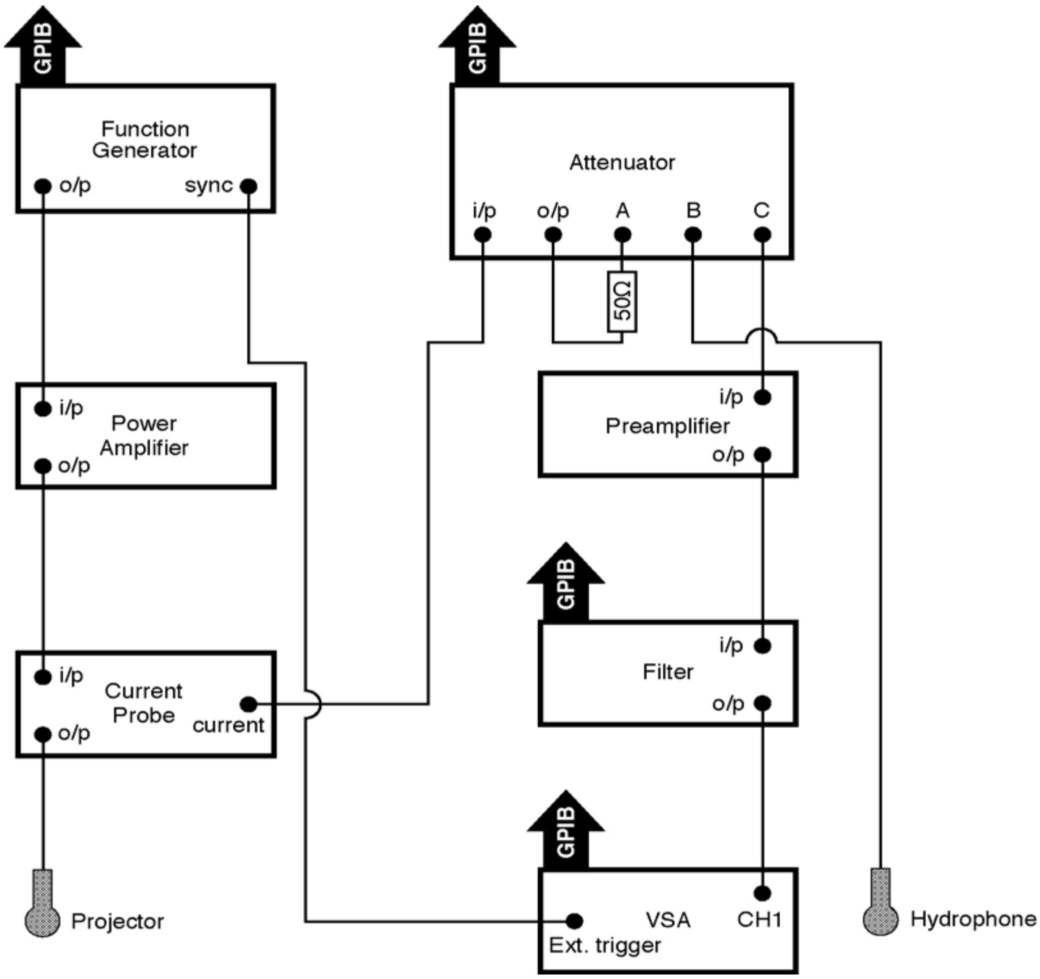

Fig. 3.5: Schematic of the equipment used to perform the phase measurements.

The drive current and hydrophone voltage signals were both measured via the preamplifier and filter, so any phase delay introduced by these instruments will cancel when the phase difference between the signals is considered. This is not the case with the current probe and attenuator, which could potentially introduce errors into the measurement of the phase of the drive current. In order to assess these potential errors, the phase difference between the output and input of each of these instruments was measured. Over the frequency range of interest, the error in the phase of the signal produced by each instrument was found to be typically less than 2°. Also, for most frequencies, the sign of the error was different for each of the instruments, and hence there will be some degree of cancellation in the error produced in the phase of the drive current. From equation (2.10), the error introduced in the calculated phase angle of the sensitivity of the hydrophone by such an error in the drive current phase measurement will be typically less than 1°. This was considered to be negligible in relation to the overall measurement uncertainties.

A PC running NPL written software was used to control the function generator, attenuator, filter and vector signal analyzer via a GPIB interface. At each frequency, the drive current and receive voltage signals were captured by the vector signal analyzer. The windowed, steady state portion of the time waveform was transferred from the analyzer to the PC where a software algorithm performed a discrete Fourier transform on the signal [7], calculating both the amplitude and phase of the spectral component at the acoustic frequency.

A potential source of error in the measurements was the possibility of movement in the position of the projector P. As described above, P was mounted to a beam placed across the top of the tank, so the position of the device was potentially less stable than that of T and H, which were fixed to the carriages of the positioning system. In order to assess the stability of the position of P, the phase of the P to T transfer impedance was compared between measurement runs. The differences were found to be small, typically less than 5° at 100 kHz, implying a minimal change in the position of P during the course of the measurements.

4. RESULTS

Measurements of the phase angle of the free-field sensitivity of the following three hydrophones were made using the method and procedures described above:

Brüel & Kjær 8104	S/N: 1757063
Brüel & Kjær 8103	S/N: 1785461
Reson TC4034	S/N: 0902100

The B&K 8104 was calibrated over the frequency range 10 kHz to 150 kHz, the B&K 8103 over the range 100 kHz to 400 kHz and the Reson TC4034 over both frequency ranges. For the lower frequency range, an ITC1042 transducer was used as P and a Brüel & Kjær 8100 hydrophone as T. For the higher frequency range, two further Reson TC4034 hydrophones were used as P and T.

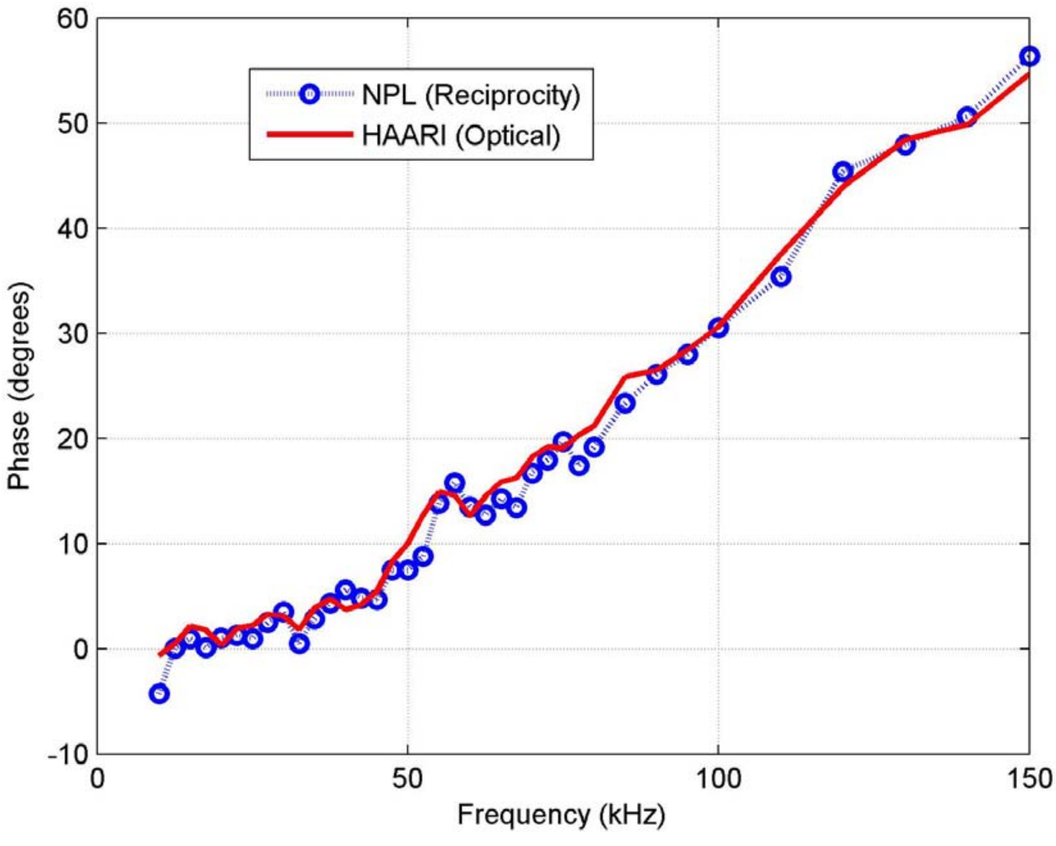

Fig. 4.1: Phase response of the Reson TC4034 hydrophone measured over the frequency range 10 kHz to 150 kHz.

The same three hydrophones had previously been calibrated for their phase response over the same frequency ranges at Hangzhou Applied Acoustic Research Institute (HAARI) in China. The method used by HAARI was an optical calibration system, which used a Laser Doppler Vibrometer to measure the particle velocity at the hydrophone location [6]. This gave the opportunity to compare the results for the phase response of the hydrophones, measured in two separate laboratories by two completely independent methods, based on different physical principles and with few common sources of error.

Fig. 4.1 shows the phase response of the Reson TC4034 hydrophone measured over the frequency range 10 kHz to 150 kHz. The results of both the reciprocity method measured at NPL and the optical method measured at HAARI are shown, and it can be seen that there is good agreement throughout the frequency range. Both sets of measurement data display a small peak in the response just below 60 kHz and a small dip at around 35 kHz. There is a discrepancy at 10 kHz, the lowest frequency, which is due to poor signal-to-noise during the reciprocity measurement. The ITC 1042 used as P and the B&K 8100 used as T have peak transmitting responses at approximately 80 kHz and 90 kHz respectively. These both fall off at a rate of around 12 dB per octave as the frequency decreases and this, in combination with the relatively low sensitivity of the Reson TC4034 hydrophone, leads to poor signal levels at the bottom end of the frequency range.

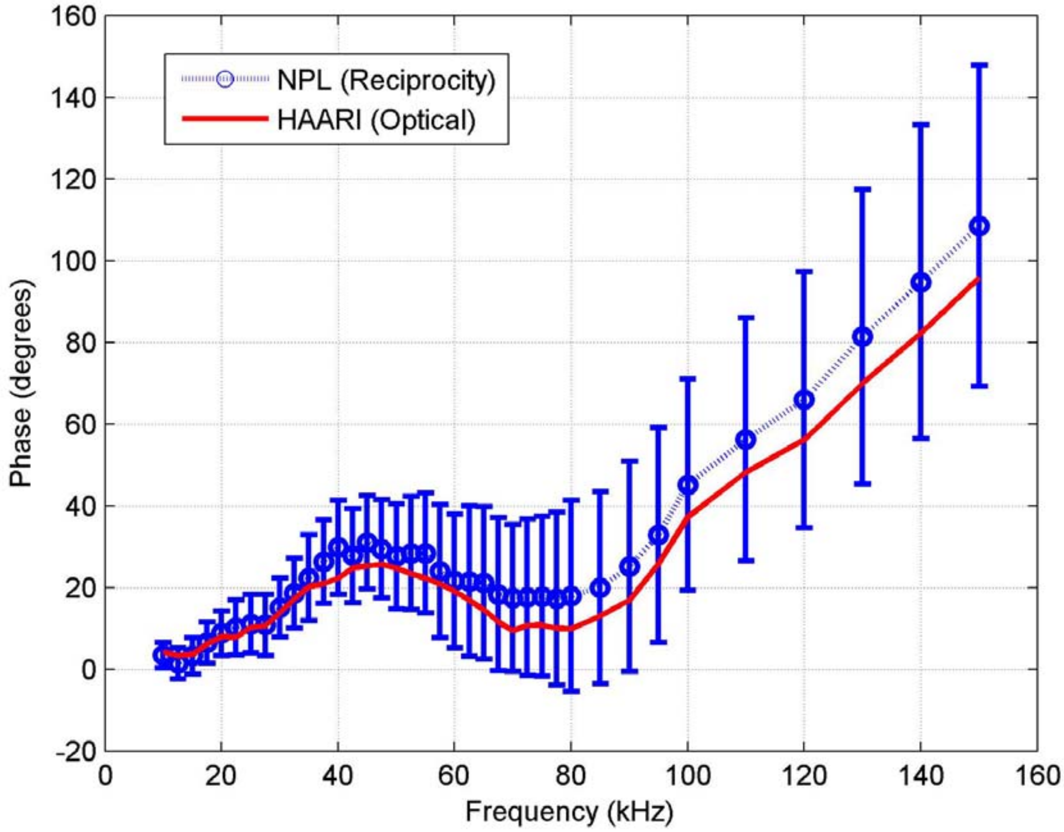

Fig. 4.2: Phase response of the Brüel & Kjær 8104 hydrophone measured over the frequency range 10 kHz to 150 kHz.

The results of the phase response measurements for the Brüel & Kjær 8104 hydrophone, measured over the frequency range 10 kHz to 150 kHz, are shown in Fig. 4.2. Again, the results of both the reciprocity method measured at NPL and the optical method measured at HAARI are shown. The reciprocity results are the average of four sets of measurements and the error bars indicate the Type A uncertainty for a 95% confidence level. Although there is a reasonable agreement between the two sets of results, there is a slight phase ramp in the reciprocity results relative to the optical measurements. This is indicative of a small, systematic positioning error when the Brüel & Kjær 8104 hydrophone is rotated between the P to H and T to H measurements.

Fig. 4.3 shows the phase response results for the Reson TC4034 hydrophone measured over the higher frequency range: 100 kHz to 400 kHz. This time, the reciprocity results are the average of six sets of measurements, with the error bars again indicating the Type A uncertainty for a 95% confidence level. The agreement between the reciprocity and the optical measurements is, once again, very good at the majority of the frequencies measured. A comparison with Fig. 4.1 will show that there is also good agreement between the reciprocity measurements in the 100 kHz to 150 kHz overlap region of the two calibrations. As described at the beginning of this section, the measurements for the two frequency ranges were made using different types of devices for P and T, giving further confidence in the measurement results in this overlap region.

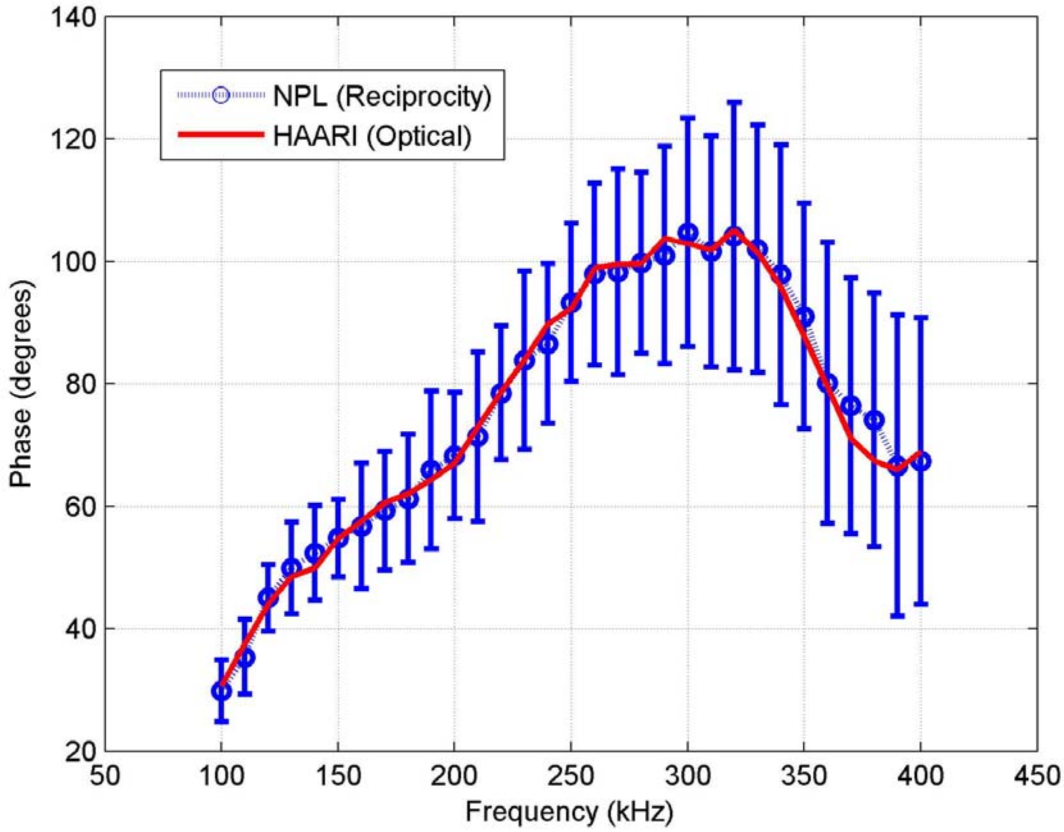

Fig. 4.3: Phase response of the Reson TC4034 hydrophone measured over the frequency range 100 kHz to 400 kHz.

The results presented in Fig. 4.4 show the phase response of the Brüel & Kjær 8103 hydrophone measured over the frequency range 100 kHz to 400 kHz. Four measurement runs were performed using the reciprocity method, and the average is displayed along with error bars indicating the Type A uncertainty for a 95% confidence level. The measurements made by the reciprocity method at NPL are compared to those made using the optical method at HAARI. While the agreement between the two methods is good, the response around the 250 kHz peak in the reciprocity results appears slightly higher and shifted down in frequency when compared to the optical measurement results. Previous work on the variation of hydrophone characteristics with temperature has shown that the Brüel & Kjær 8103 exhibits significant changes in electrical impedance and sensitivity as the temperature varies [8-10]. This is particularly noticeable around this length mode resonance, where the peak in the conductance displays a change in height, along with a shift in frequency, as the temperature varies. It is therefore probable that this slight disagreement between the two methods is due to a difference in the temperature of the water in the tanks used for the measurements.

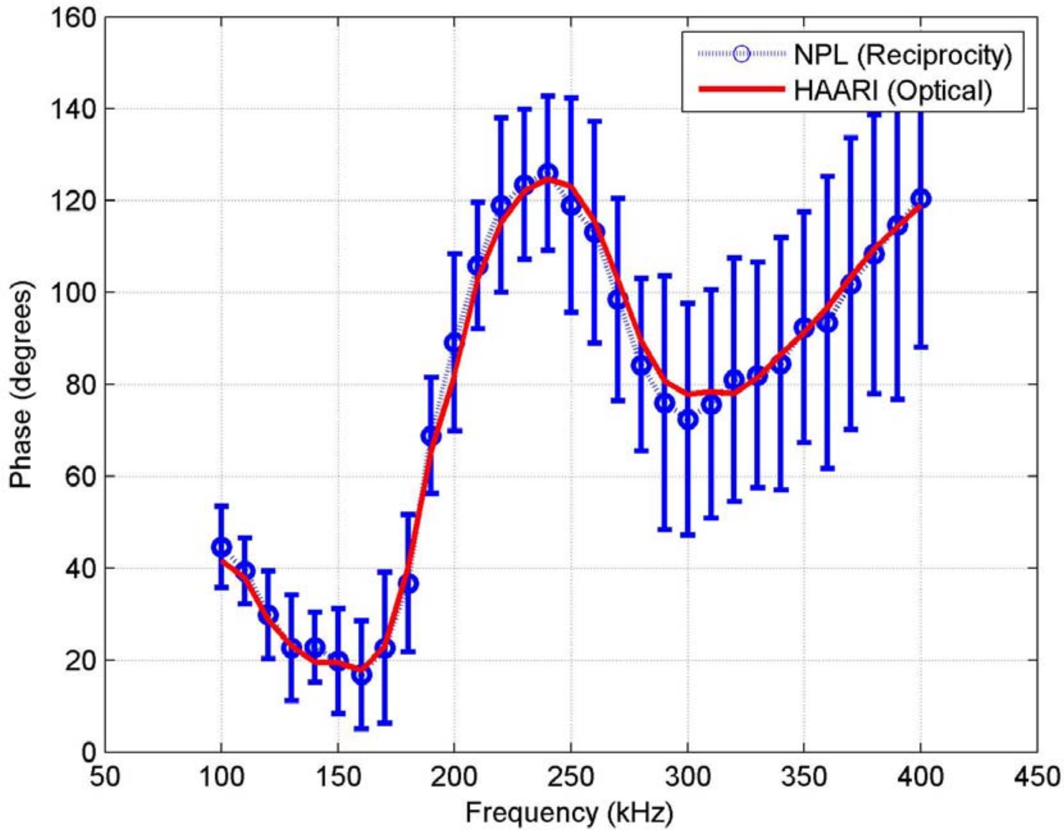

Fig. 4.4: Phase response of the Brüel & Kjær 8103 hydrophone measured over the frequency range 100 kHz to 400 kHz.

It will be observed that although the reciprocity results presented above are the average of between four and six measurement runs, the error bars are relatively large, indicating a significant variation between individual data sets. The error bars also increase in size with frequency and this would suggest a variation in the positioning of H between measurement runs. Any error in positioning is a greater proportion of a wavelength as the frequency increases and will appear as a correspondingly larger error in the resulting phase measurement. The effects of positioning errors during the measurements are discussed in further detail in the following section.

5. DISCUSSION

The results presented in the previous section have shown that while it is possible to achieve accurate measurements of the phase response of a hydrophone using the reciprocity method, the positioning of the hydrophone is critical to the accuracy of the measurements. As seen in Section 2, the co-linear mounting arrangement used for this method eliminates some potential sources of error, such as the measurement of the separation of the devices and the determination of the speed of sound in the water. However, the largest source of uncertainty remains the stability of the position of H as it is rotated between the P to H and T to H measurements. The hydrophones used in these experiments are cylindrical or spherical devices with thick cables attached to the end of long mounting poles, and so to maintain the X-axis position of the hydrophone to the required accuracy as it is rotated through 180° is not a trivial feat.

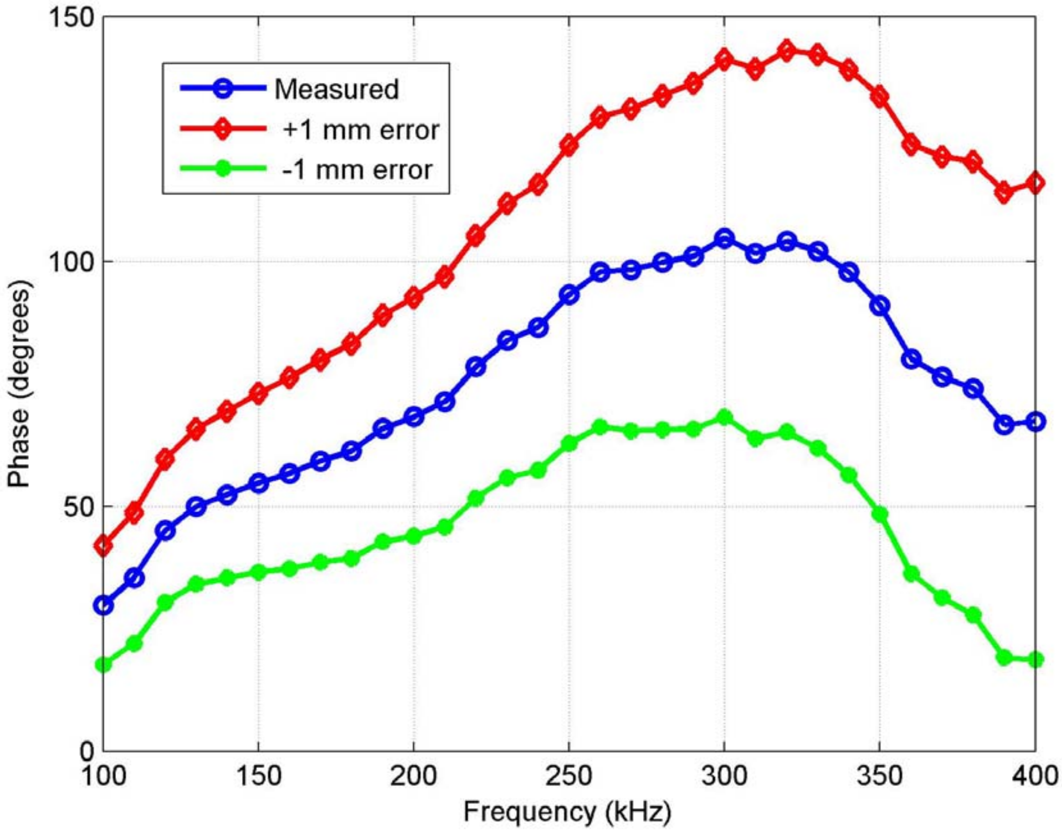

Fig. 5.1: The effect on the Reson TC4034 phase response of an overall 1 mm error in the positioning of the hydrophone when rotated between the P to H and T to H measurements.

For illustration, Fig. 5.1 shows the phase response data for the Reson TC4034 hydrophone (as presented in the previous section) along with the effect on this data of an overall 1 mm movement in the X-axis position of the hydrophone as it is rotated. If the hydrophone position is actually 0.5 mm closer than expected to both P and T for the P to H and T to H stages of the measurement, the effect is to superimpose a positive phase ramp on the measured data. A positioning error whereby the hydrophone is 0.5 mm further away from both P and T than expected will introduce a negative phase ramp. It can be seen that at 400 kHz, the highest frequency of measurement in these experiments, a movement of only 1 mm in the X-axis position of H as it is rotated will cause an error in the phase response of almost 50°. It is estimated that, by using the laser alignment system described in Section 3, it is possible to maintain the position of the hydrophone to within ± 0.3 mm.

From the results shown in Fig. 4.1, it can be seen that over the frequency range 10 kHz to 150 kHz the phase response of the Reson TC4034 hydrophone exhibits a steady increase with frequency. Taking into account what has been said above, it could therefore reasonably be suggested that this may not be the genuine response of the hydrophone, but instead an artefact due to a positioning error during the measurement, especially when one considers that ultrasonic membrane hydrophones exhibit a much flatter phase response [3-5].

Fig. 5.2: X-ray radiograph of the Reson TC4034 hydrophone showing the small spherical element.

The X-ray radiograph of the Reson TC4034 shown in Fig. 5.2 confirms that this hydrophone has a small spherical element, the diameter of which has been estimated to be around 6 mm. For frequencies below the resonance frequency, it is possible to calculate the theoretical phase for an ideal, infinitely rigid, spherical hydrophone as follows [2]

$$\phi = ka - \tan^{-1}(ka) \tag{5.1}$$

where a is the radius of the spherical element. The wavenumber $k = 2\pi f / c$, where f is the frequency and c is the speed of sound in the surrounding medium.

The theoretical phase response curves for three spherical hydrophones with element diameters of 6 mm, 9 mm and 12 mm have been plotted in Fig. 5.3. These have been calculated over the frequency range 2.5 kHz to 200 kHz in the same frequency steps as the measured data i.e. 2.5 kHz up to 80 kHz, 5 kHz from 80 kHz to 100 kHz and 10 kHz thereafter. It can be seen that the increase in the phase response with frequency follows a similar pattern to that of the measured data in Fig. 4.1.

The reason for the increase in the phase response with frequency for the hydrophones used in these experiments is related to the fact that they have active elements of finite size. All distances are measured from the reference centre of the device and for spherical and cylindrical hydrophones this is generally taken to be the geometric centre. However, an electrical signal will appear at the end of the hydrophone cable when an acoustic signal first impinges on the hydrophone. The electrical signal will therefore appear to arrive before the acoustic signal by an amount related to the radius of the device. At low frequencies, where the wavelengths are larger, the effect on the phase response of the hydrophone is small. But as the frequency increases this difference is greater in relation to the wavelength, and so the phase response increases, causing the acoustic centre of the device to appear to move as the frequency changes. With thin membrane hydrophones, the thickness is generally small in relation to the wavelengths of the signals used and so this is not an issue. However, this apparent movement of the acoustic centre with frequency is also observed in microphone calibration [11].

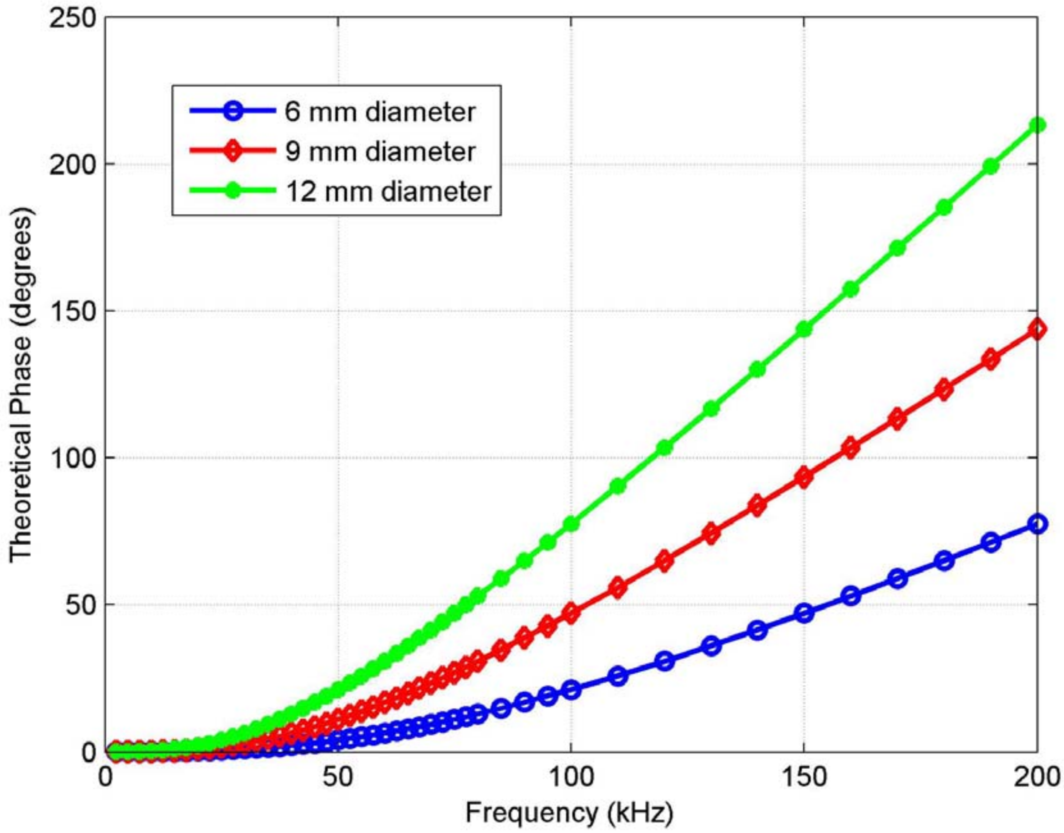

Fig. 5.3: Theoretical phase response calculated for hydrophones with spherical elements of 6, 9 and 12 mm diameter.

The results presented in Section 4 for the Brüel & Kjær 8104 hydrophone (see Fig. 4.2) show a difference between the NPL reciprocity measurements and the optical measurements from HAARI. While the difference is within the uncertainties indicated by the error bars, there is an increase with frequency which would suggest a possible positioning error. In order to investigate this further, signal waveforms before and after rotation of the hydrophone were compared. After the completion of the P to H stage of the measurements, the tone burst waveform at 150 kHz was captured. The hydrophone was then rotated through 180° and re-positioned using the laser alignment system ready for the T to H stage of the measurements. A second 150 kHz tone burst waveform was captured with P once again transmitting to H. If there has been no change in the X-axis position of the hydrophone, it would be expected that the arrival times of the two waveforms would be the same. However, from Fig. 5.4 it can be seen that there is a difference in the arrival times of the two waveforms. (The difference in amplitude is due to the directional properties of the hydrophone.)

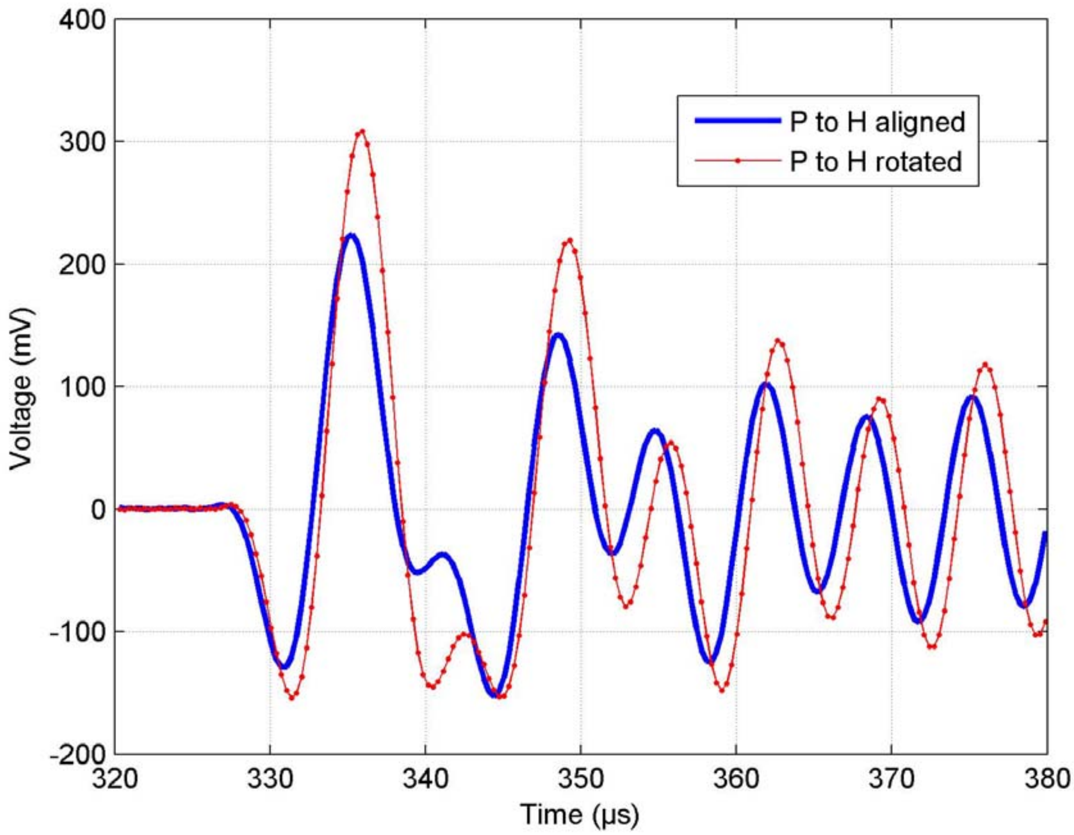

Fig. 5.4: Initial cycles of 150 kHz tone burst waveform received by the Brüel & Kjær 8104 hydrophone showing the change in arrival time as the hydrophone is rotated through 180°.

An X-ray radiograph of the hydrophone explains the reason for this waveform shift. In the side-on view of the device in Fig. 5.5, the 0° reference direction of the hydrophone is towards the top of the X-ray radiograph. The four cylindrical elements are to the right and it can be seen that the top three are slightly offset towards the reference direction. This means that, although the X-axis position of the hydrophone remained fixed for both the P to H and T to H stages of the measurements (to within the accuracy of the laser alignment), the elements were slightly closer than expected to both P and T for the respective measurements. The criterion that $d_2 = d_1 + d_3$, necessary for an accurate measurement by this method, is therefore not met and a ramp is superimposed on the resulting phase response.

Fig. 5.5: X-ray radiograph of the Brüel & Kjær 8104 hydrophone showing the front to back offset in the elements.

For comparison, the similarly captured waveforms for the Reson TC4034 hydrophone are shown in Fig. 5.6. Again, the waveforms are 150 kHz tone burst signals transmitted from the ITC 1042 transducer (P) to the Reson TC4034 before and after rotation and re-alignment of the hydrophone. It can be seen that there is a minimal change in the arrival time of the signal, indicating that the spherical element is co-axial with the hydrophone body.

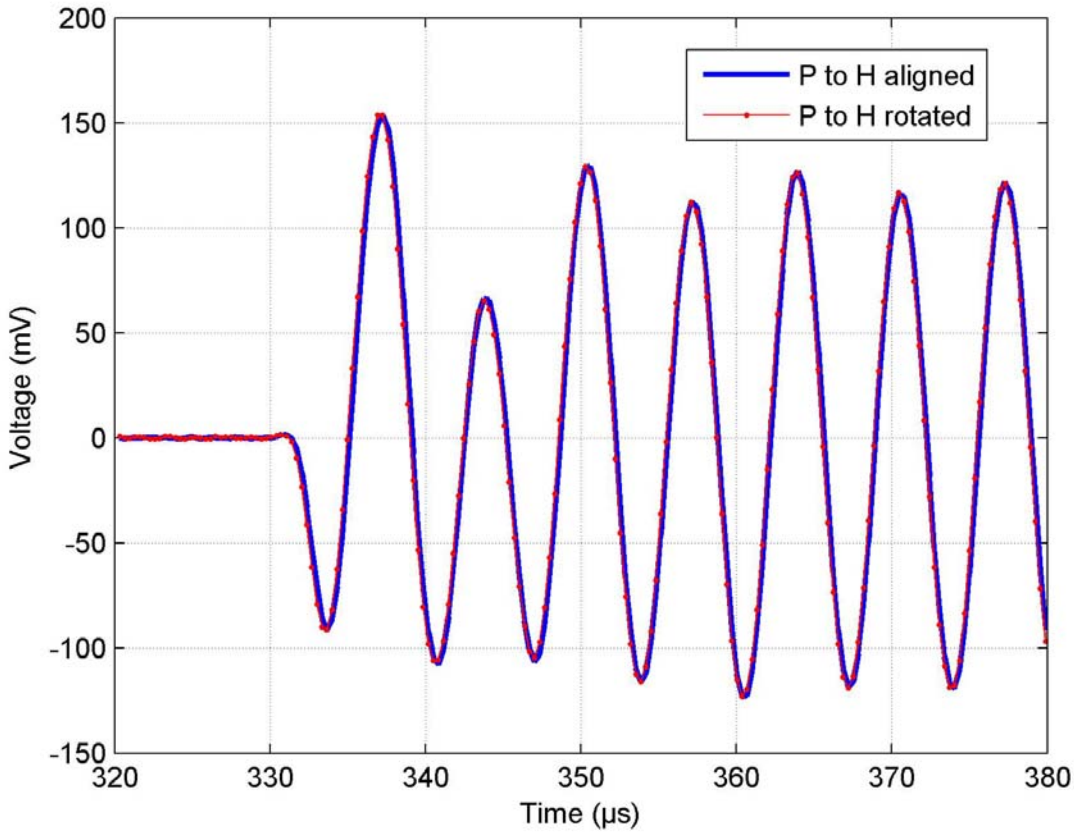

Fig. 5.6: Initial cycles of 150 kHz tone burst waveform received by the Reson TC4034 hydrophone showing minimal change in arrival time as the hydrophone is rotated through 180°.

6. CONCLUSIONS

6.1 SUMMARY

A description has been given of the work undertaken at the National Physical Laboratory to implement phase response calibration of hydrophones using the reciprocity method. In order to overcome some of the experimental difficulties which limit the accuracy of phase measurements, a co-linear arrangement of hydrophones, based on the method of Luker and Van Buren [2], was employed.

Experimental measurements of phase response, covering the frequency range 10 kHz to 400 kHz, have been made for three hydrophones: a Brüel & Kjær 8104, a Brüel & Kjær 8103 and a Reson TC4034. The NPL small open tank facility with precision positioning system was used for the measurements, and the use of a laser alignment system enabled the central hydrophone to be rotated through 180° without significant translation of the device in the X-axis.

The results of the measurements have been presented and compared to phase response calibrations of the same three hydrophones, performed using an optical method, by Hangzhou Applied Acoustic Research Institute (HAARI) in China [6]. Agreement between the two methods has been shown to be good, although the Type A uncertainty for the reciprocity measurements was relatively large at higher frequencies.

The major sources of error in the method as implemented have been discussed, along with possible explanations for some of the disagreements seen when the results have been compared to calibrations by the optical method.

6.2 RECOMMENDATIONS

The co-linear mounting arrangement used in these experiments eliminates some of the potential errors associated with the measurement of transducer separation and determination of the speed of sound in water. However, the degree to which the X-axis position of the central hydrophone can be maintained as it is rotated between the outer transducers limits the accuracy of the method. It has been shown that a small change in the position of the hydrophone can introduce a relatively large error in the phase response, especially at higher frequencies.

The optical method of phase response measurement employed at HAARI [6] uses a Laser Doppler Vibrometer and a pellicle (thin reflective membrane) mounted in the tank to measure the particle velocity in the acoustic field. The pellicle is then replaced by the hydrophone, with its reference centre at the location of the particle velocity measurement, and the hydrophone output measured. While the initial positioning of the hydrophone will have an effect on the accuracy of the calibration, the hydrophone remains stationary throughout the measurement and so changes in position due to rotation are not an issue. Installed in the wall of the tank at HAARI is an optical magnifier with a crosshair in the viewfinder, and it is estimated that this enables the hydrophone to be positioned at the same location as the pellicle to within 0.05 mm. A positioning error of this magnitude equates to an uncertainty of only 4.8° in the phase measurement at 400 kHz.

While it has been possible to achieve reasonable results using the reciprocity method in these experiments, there can be significant variation between measurement runs, and the problem of maintaining the position of the central hydrophone to the required accuracy remains an issue. The optical method requires no rotation of the hydrophone and the alignment method employed by HAARI achieves a positional accuracy which results in low measurement uncertainties. In conclusion, for future work on the measurement of the phase response of hydrophones, the optical method appears to have the potential to achieve more consistent results and lower measurement uncertainties than the reciprocity method.

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