Phase calibration of hydrophones: heterodyne time-delay spectrometry and broadband pulse technique using an optical reference hydrophone

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2004 J. Phys.: Conf. Ser. 1 14
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Abstract. Two hydrophone calibration techniques are presented which provide amplitude and phase of hydrophone sensitivity. Heterodyne time-delay spectrometry can be applied in the frequency range from 0.5 to 50 MHz to all common hydrophones but needs a standard to obtain absolute values. A pulse technique between 1 and 70 MHz allows exploiting of an optical multilayer hydrophone as a phase standard. In combination with HTDS, a calibration service is established that covers the complete spectrum of common piezoelectric and optical hydrophones for absolute amplitude and phase calibration. The measured complex frequency responses form the basis of deconvolution procedures suitable for the correction of measurements of, for example, the output of ultrasound diagnostic machines.

1. Introduction

Ultrasound plays an important role in many fields of medicine. The detection of the sound field pressure applied is often a crucial point, especially if the acoustic output of a diagnostic or therapeutic machine is to be determined for declaration purposes. Precise and reliable measurements are, however, impeded by the non-ideal transfer characteristic of the detection line with the hydrophone as the most important unit. In the case of a broadband measurement, for example of high-frequency or nonlinearly distorted waveforms, a non-ideal hydrophone characteristic may seriously influence the measurement. Deconvolution procedures can be applied for data correction requiring that the complex sensitivity of the hydrophone be determined.

To date, primary and secondary calibration methods provide the amplitude of the hydrophone frequency response. In this contribution, two quite distinct techniques are presented for the determination of both, amplitude and phase of the hydrophone frequency response. First, heterodyne time-delay spectrometry (HTDS) is exploited to obtain results with quasi-continuous frequency dependence [1]. This technique can be applied to all common hydrophone types. Since it is a secondary calibration method it provides values related to a standard hydrophone and a phase standard is required to obtain ‘absolute’ phase frequency response values.¹

An optical multilayer hydrophone [2, 3] shows an excellent flat amplitude frequency response at least up to 75 MHz. This flat amplitude response is expected to be accompanied by a just as flat phase

¹ Note that ‘absolute’ phase values do not exist in general because phase is defined as the difference between two angle values of a field vector.
response and the optical hydrophone is suitable for being used as the required phase standard. Because of acoustic multi-reflections in the glass substrate of the optical hydrophone, the direct use by the HTDS-technique would require an impractically small resolution bandwidth to ensure free-field conditions. Short broad-band pulses enable a much simpler possibility of avoiding signal disturbances and a substitution calibration using pulses from a focusing transducer was realised. To obtain a wide bandwidth, sharp focusing in connection with nonlinear sound propagation was applied which limits the technique to small-diameter hydrophones ($\Phi \leq 0.2\) mm). Together with HTDS-technique a calibration service is, however, established that covers the complete spectrum of common piezoelectric and optical hydrophones.

2. Calibration techniques

Time-delay spectrometry exploits the finite propagation time of ultrasound in a medium to ensure free-field conditions during calibration [4-7]. The pressure wave emitted by the transducer takes some time to reach the hydrophone and the instantaneous frequency of the received signal is shifted by

$$\Delta f = \frac{f_{\text{Stop}} - f_{\text{Start}}}{t_s} \frac{l}{c},$$

with respect to the frequency of the transmitting voltage applied to the transducer during a sweep between $f_{\text{Start}}$ and $f_{\text{Stop}}$. $t_s$ in eq. (1) is the sweep time, $l$ the distance between hydrophone and transducer and $c$ the velocity of sound in the medium. If the analyser unit used for both, generating the transmitting voltage and detecting the hydrophone signal, can operate a frequency offset between the two signals, a narrow IF filter selects the length of the signal path of the sound. If the frequency offset is set to $\Delta$, the direct path between transmitter and hydrophone is chosen and, for example, reverberation from the tank walls is filtered out.

![Set-up of HTDS measurement](figure1.png)

**Figure 1.** Set-up of HTDS measurement, Synth: synthesiser, 1:1: power divider, $f_{LO}$: local oscillator frequency, $\Delta$: frequency shift, $M_1$, $M_2$: mixer, T: transducer, H: hydrophone, NetwA: network analyser.

For a complex transfer function measurement, coherent detection of the receiving signal is required, so a network analyser (HP 8753 ET, Agilent, Palo Alto, CA) was used (figure 1). To ensure a fixed phase relation between transmitting and receiving signal, a heterodyne scheme with a separate
mixer $M_1$ (figure 1) closing the necessary phase locked loop (heterodyne time-delay spectrometry HTDS [1]) was used. The network analyser was operated in the frequency offset mode and the local oscillator frequency was set to $f_{LO} = 50$ MHz. A second mixer $M_2$ provided the transmitting signal fed into the transducer, and the hydrophone is connected to the receiving port B detecting the ratio B/A. Two measurements, one with the standard hydrophone and one with the hydrophone to be calibrated, are carried out under equal excitation conditions and the hydrophones frequency response is obtained by comparison of the results.

The optical multilayer hydrophone (figure 2) comprises a glass substrate covered with dielectric optical coatings [2, 3]. These coatings form a micro-interferometer of which the optical reflectance is very sensitive to changes in the thickness and the optical index of the layers. If the sound wave hits the hydrophone, the sound pressure deforms the layers and the optical reflectance change is measured by a simple detection scheme consisting of He-Ne laser, two lenses and a photodetector. The substrate is obliquely illuminated to match the optical resonance, i.e. the working wavelength of the sensor to the laser wavelength.

The optical multilayer hydrophone was excited by short nonlinearly distorted sound wave pulses generated by a focussing transducer (Deutsch GmbH, $\varnothing = 12$ mm, nominal focal length 50 mm) driven by a fast electrical pulse generator [8]. The photodetector output voltage was proportional to the sound pressure and the signal was acquired by a sampling oscilloscope and stored in a computer. An FFT-procedure in the computer provided the frequency spectrum of the signal. The measurement was repeated under different matching conditions between the transducer and the generator slightly shifting the fundamental and harmonic frequencies of the pulses to cover the complete frequency range with high signal strength. The frequency response is obtained again by two measurements, the first with the optical hydrophone as standard and the second with the hydrophone to be calibrated.

3. Results
Several hydrophones were calibrated using both techniques. Fig. 3 shows the results of HTDS for two membrane hydrophones of 1 mm diameter and 25 µm layer thickness in comparison with values of two different techniques, interferometry and standard TDS (amplitude values only). The sensitivity amplitude of the bilaminar device shows a steeper increase than that of the coplanar device because of

![Figure 2. Set-up of the optical multilayer hydrophone, $d_i$: layer thickness, $n_i$: optical index of $i$-layer.](image-url)
the lower resonance frequency. This variation in amplitude is accompanied by a monotone phase change as expected from the acoustic resonance in the PVDF layer.

Figure 3. Amplitude (left) and phase (right) of sensitivity of two membrane hydrophones (∅ 1mm, layer thickness 25 µm) and comparison with results of other techniques (amplitude values only).

In the second example, a needle-type hydrophone with a strongly irregular frequency response was calibrated by HTDS and by the optical pulse technique. Fig. 4 shows amplitude and phase of the sensitivity obtained with both, the HTDS and the pulse techniques. A bilaminar membrane hydrophone (∅ 0.2 mm) and the optical multilayer hydrophone, respectively, served as a reference in the amplitude measurement. Both phase results relate to the membrane hydrophone for comparison.

Figure 4. Amplitude (left) and phase (right) of sensitivity of a needle-type hydrophone (∅ 0.2 mm) obtained with HTDS and pulse technique using the optical hydrophone.

Although there is very good agreement between the results of both calibration techniques, an additional independent validation for the phase values would improve the credibility of the method. The comparison with a theoretical model requires ‘absolute’ phase values, i.e. values that are related to a constant phase reference. The optical hydrophone provides a flat phase response and a membrane hydrophone is used as transfer standard. In the first step, the transfer standard was calibrated using the pulse technique and the optical hydrophone as reference in amplitude and phase. In the second step, any other hydrophone could be calibrated by HTDS using the transfer standard as a reference. Fig. 5 shows the results for two membrane hydrophones (bilaminar: ∅ 1 mm, coplanar: ∅ 0.5 mm). The coplanar device, in particular, shows excellent agreement with the results of a hydrophone model [9].
4. Discussion and Conclusions

The amplitude and phase of hydrophone sensitivity could be obtained by two different techniques, heterodyne time-delay spectrometry and a pulse technique in connection with an optical multilayer hydrophone. Up to a frequency of 20 MHz, the agreement between the two methods is excellent, at higher frequencies it is still good and the differences lie well below the uncertainties.

The agreement of the ‘absolute’ phase values with theoretical results is surprisingly good although the bilaminar device shows significant differences at frequencies higher than 20 MHz. These differences seem, however, to be due to inappropriate model parameters because of the manufacturing spread of the hydrophones.

The uncertainties depend strongly on the hydrophone and measurement conditions. No general values can be given and as an example table 1 summarises the values for the HTDS-measurement in figure 4. Note that the amplitude uncertainties contain a contribution for the primary calibration but the phase values do not.

**Table 1.** Uncertainties (k=2) for the measurement in figure 4 as an example, confidence level 95%.

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - 5 MHz</td>
<td>13.4%</td>
<td>15.9°</td>
</tr>
<tr>
<td>5 - 12 MHz</td>
<td>10.5%</td>
<td>8.8°</td>
</tr>
<tr>
<td>12 - 20 MHz</td>
<td>10.0%</td>
<td>13.0°</td>
</tr>
<tr>
<td>20 - 30 MHz</td>
<td>10.4%</td>
<td>19.1°</td>
</tr>
<tr>
<td>30 - 40 MHz</td>
<td>11.5%</td>
<td>25.0°</td>
</tr>
<tr>
<td>40 - 50 MHz</td>
<td>20.8%</td>
<td></td>
</tr>
</tbody>
</table>

The hydrophone calibration techniques presented provide amplitude and phase of hydrophone sensitivity in the frequency range from 0.5 to 50 MHz for the HTDS and 1 to 70 MHz for pulse technique. The measured complex frequency responses form the basis of deconvolution procedures suitable for the correction of measurements of, for example, the output of ultrasound diagnostic
machines [8]. Although both techniques are secondary calibration techniques which require a primary calibrated standard to obtain absolute values, the phase response of the optical multilayer hydrophone should be flat up to 70 MHz and it can be used as a phase standard. The pulse technique, which should only be applied to small diameter hydrophones, allows calibrating secondary transfer standards that can be used in HTDS. In combination with HTDS, a calibration service is established that covers the complete spectrum of common piezoelectric and optical hydrophones.

5. References