HETERODYNE AND TIME-GATED TIME-DELAY SPECTROMETRY FOR AMPLITUDE AND PHASE CALIBRATION OF HYDROPHONES

Ch. Koch, V. Wilkens
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
ultrasonics@ptb.de

Abstract

The determination of amplitude and phase of the hydrophone sensitivity using two techniques based on time-delay spectrometry is presented. The frequency range in which the technique can be applied is from 1 MHz to 50 MHz. The agreement with the results obtained by alternative calibration techniques is excellent, which emphasises the correct working of this coherent technique.

Introduction

Calibrated hydrophones form the basis of the precise and reliable measurement of medical and technical ultrasonic fields. To date, primary and secondary calibration methods provide the amplitude of the hydrophone frequency response. The result of an ultrasound measurement is always determined by the transfer characteristic of the detection line with the hydrophone as the most important unit. In the case of a broad-band measurement, for example of high-frequency or nonlinear distorted waveforms, a non-ideal hydrophone characteristic may seriously influence the measurement. Correct results can be obtained by deconvolution of the measured waveforms using the complex transfer function of the detection line. This procedure requires determining the phase response of the hydrophone.

Recently a calibration method based on time-delay spectrometry (TDS) has been presented that provides both, amplitude and phase response of hydrophones [1]. In the present paper additional measurement examples are given so that a comparison with other calibration techniques can be made. To validate the phase measurement capabilities, a calibration method using short pulses from a focussing transducer was applied [2] and good agreement was found in a wide frequency range.

Since TDS is a secondary calibration technique, a standard hydrophone having undergone a primary calibration is necessary for absolute values to be obtained. Unlike for the amplitude, a standard for the phase is not available to date and in the present work an optical multilayer hydrophone [3] was used for this purpose. It has an extremely flat amplitude frequency response [4], and keeping in mind the Kramers-Kronig relations, it can be assumed that the phase is just as constant over a wide frequency range as the amplitude. With the aid of this standard, 'absolute' phase responses could be obtained and they were compared to the results of a theoretical model.

Calibration techniques and set-up

Time-delay spectrometry exploits the finite propagation time of ultrasound in a medium to ensure free-field conditions during calibration [5-8]. 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

$$\Delta = \frac{f_{\mathrm{Stop}} - f_{\mathrm{Start}}}{t_{\mathrm{S}}} \frac{l}{c}, \tag{1}$$

with respect to the frequency of the transmitting voltage applied to the transducer during a sweep between f_{Start} and f_{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 Δ, the direct path between transmitter and hydrophone is chosen and for example, reverberation from the tank walls is filtered out.

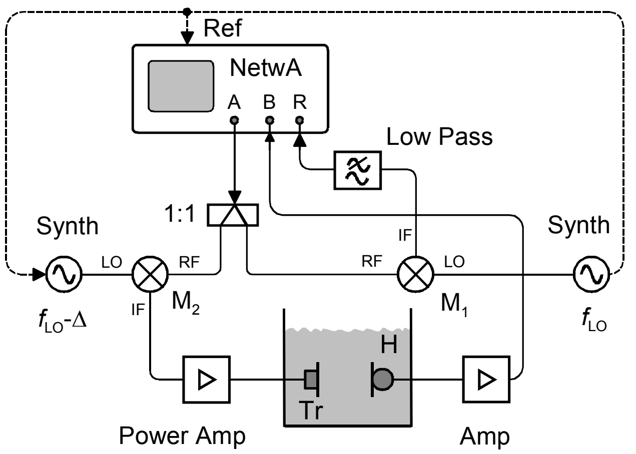

Figure 1: Set-up of HTDS measurement, Synth: synthesiser, 1:1: power divider, f_{LO}: local oscillator frequency, Δ: frequency shift, M_1, M_2: mixer, T: transducer, H: hydrophone, NetA: network analyser.

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 (Fig. 1). To ensure a fixed phase relation between transmitting and receiving signal, a heterodyne scheme with a separate mixer M_1 (Fig. 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.

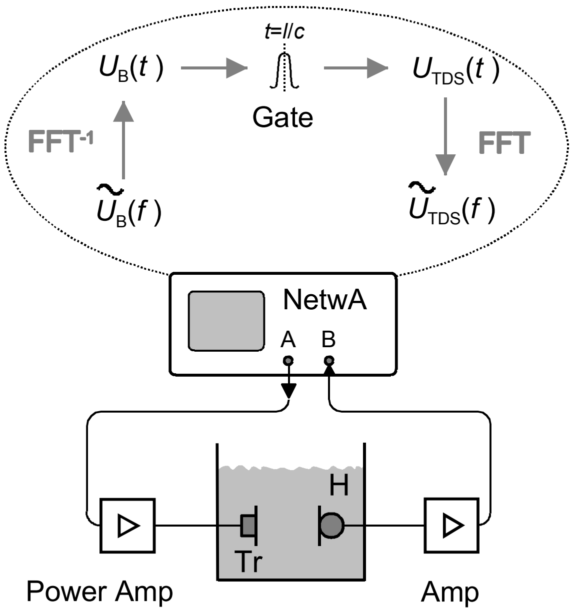

Figure 2: Set-up of GTDS measurement, NetA: network analyser, U_B: voltage measured at port B, FFT: fast Fourier transform, U_{TDS}: TDS signal.

The method described relies on the separation of unwanted signals from the measurement information in the frequency domain. On the other hand, coherent detection of TDS signals is also possible if the signals are distinguished in the time domain by their propagation time (gated time-delay spectrometry GTDS). In a first step, the frequency response of the transducer-hydrophone transmission line is determined and the transducer is excited by a continuously swept voltage with a frequency increasing from f_{Start} to f_{Stop} (Fig. 2). Then the frequency dependent signal voltage acquired by port B is converted to the time domain by an inverse FFT algorithm. The direct sound as well as reverberation signals and other disturbances are represented as signals on the time scale appearing at their individual propagation times. Now a gate is set to time position $t' = c/l$, and all unwanted signal contributions are cancelled out. Finally, an FFT algorithm provides the free-field frequency response.

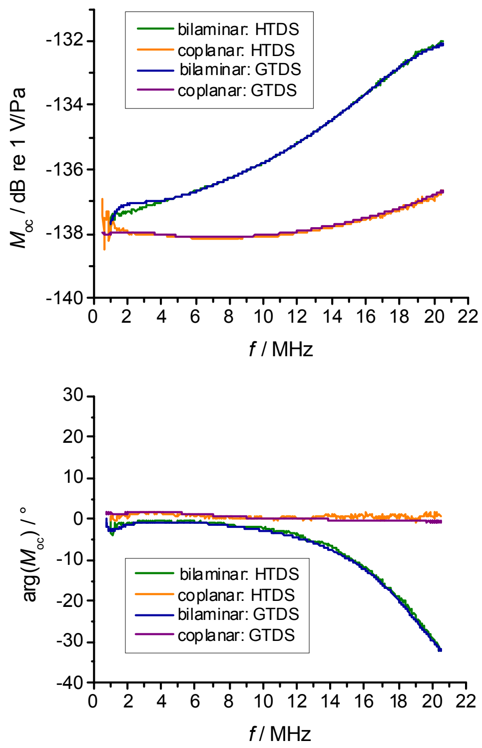

Figure 3: Amplitude and phase of sensitivity for two membrane hydrophones with GTDS and HTDS, plane source transducer

The results obtained with the coherent TDS-techniques were compared to those of alternative calibration techniques. Optical interferometry can be used for reliable primary calibration of standard hydrophones [9]. Because of both, the long time a measurement cycle takes and the long working distances between transducer and laser measurement point, it provides only amplitude information although, in general, a phase measurement is possible. To compare the coherent TDS phase results to an independent method, a calibration technique using broad-band pulses from a focussing transducer (Karl Deutsch GmbH, Hürth, ∅ 12 mm, $f_L = 50$ mm) as acoustic stimulation was developed and an amplitude and a phase calibration with wide frequency range could be realised at least for hydrophones with comparably small active diameters [2]. By this technique the recently developed optical multilayer hydrophone [3, 4] could be utilized as a phase reference. Its working principle is based on the measurement of optical reflectance changes caused by sound induced deformations of dielectric optical layers acting as micro-interferometers. Since optical detection allows wide bandwidth detection and because of the small thickness of the sensing element ($d \approx 1.9$ µm), an extremely flat amplitude and phase frequency response is found.

Results

The first measurements were carried out in the common frequency range between 1 and 20 MHz. A bilaminar membrane hydrophone with a PVDF layer thickness of 25 µm (∅ 1 mm) and a coplanar device of the same layer thickness and diameter were calibrated using the two coherent TDS techniques (Fig. 3). The sensitivity amplitude of the bilaminar device shows a steeper increase than that of the coplanar device because of 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.

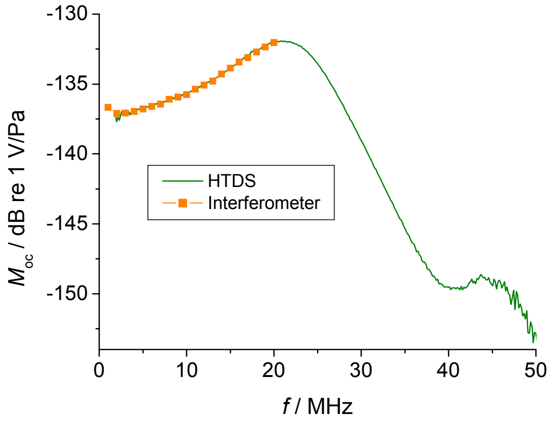

Figure 4: Amplitude of sensitivity of a membrane hydrophone (25 µm layer thickness) with HTDS and interferometry, focussing source transducer

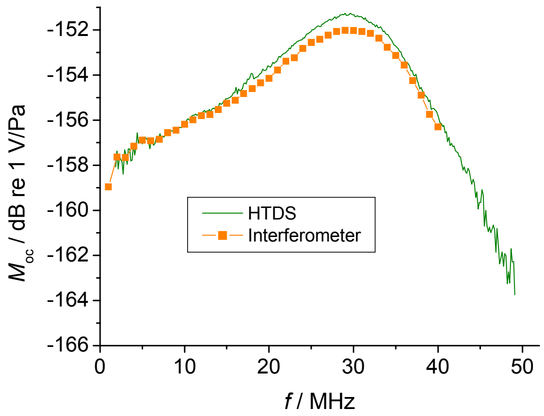

Figure 5: Amplitude of sensitivity of a membrane hydrophone (15 µm layer thickness) with HTDS and interferometry, focussing source transducer

In a measurement similar to that shown in Fig. 3, the agreement between coherent and conventional TDS techniques was excellent [1]. To compare with other techniques, Figs. 4 and 5 depict two additional examples with respect to optical interferometry. The results for the bilaminar device used in Fig. 3 is plotted in Fig. 4 up to a frequency of 50 MHz together with interferometer results which are in excellent agreement. The comparison of the results for another bilaminar device (∅ 0.2 mm) with a layer thickness of 15 µm shows differences around the acoustic resonance. The reason for this deviation is not yet clear but the difference is much smaller than the measurement uncertainty.

To validate the phase measurements, a test hydrophone of the needle type with a strongly irregular frequency response was used to check the procedures against a coarse example. Fig. 6 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, respetively served as a reference in the amplitude measurement. Both phase results relate to the membrane hydrophone for comparison. 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.

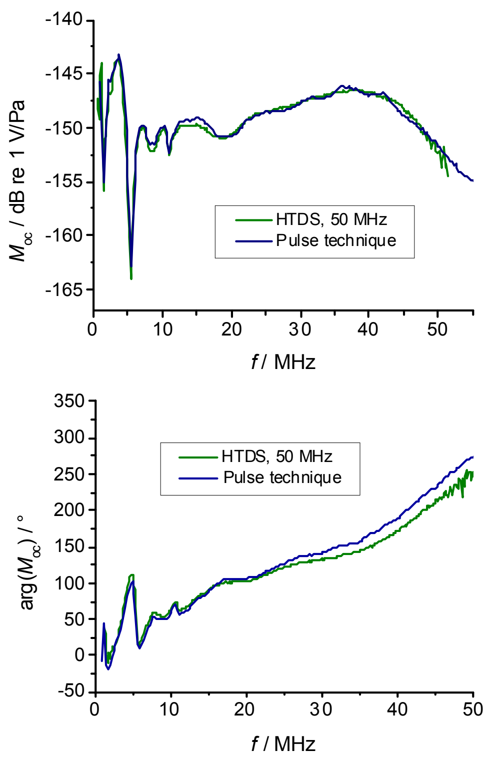

Figure 5: Amplitude and phase of sensitivity of a needle hydrophone (∅ 0.2 mm) with HTDS and pulse technique

The optical multilayer hydrophone was exploited as a phase reference and ‘absolute’ phase responses could be obtained (Fig. 7) for two membrane hydrophones without built-in amplifier and with a layer thickness of 25 µm (bilaminar, ∅ 1 mm, coplanar ∅ 0.5 mm). The coplanar device, in particular, shows excellent agreement with the results of a hydrophone model [9].

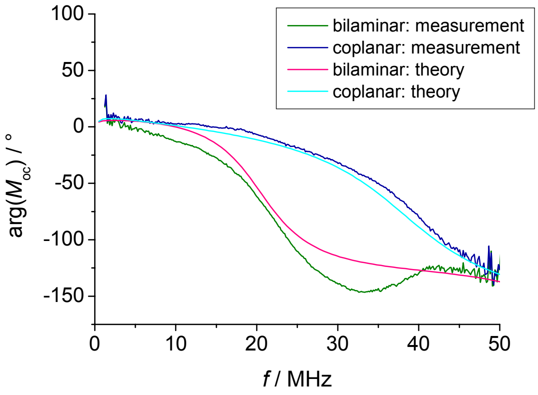

Figure 7: 'Absolute' phase of sensitivity of two membrane hydrophone (25 µm layer thickness) with HTDS and theory

Discussion and conclusions

The agreement of the 'absolute' phase values with theoretical results is surprisingly good although the 25 µm 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.

Although the acoustic distance between hydrophone and transmitter is adjusted with an uncertainty of ±2 ns, a small phase offset linearly increasing with frequency cannot be avoided [1]. This phase offset does not hinder a deconvolution procedure but to compare the phase values a correction was applied. For this purpose, the phase data were differentiated with respect to frequency f and linearly fitted (function type: $A \times f + B$). Finally, the values $B \times f$ were subtracted from the non-differentiated phase values for correction.

The uncertainties depend strongly on the hydrophone and measurement conditions. No general values can be given and as an example Tab. 1 summarises the values for the measurement in Fig. 6. Note that the amplitude uncertainties contain a contribution for the primary calibration but the phase values do not.

Frequency range	Measurement	
	Amplitude	Phase
2 - 5 MHz	13.4%	15.9°
5 - 12 MHz	10.5%	8.8°
12 - 20 MHz	10.0%	13.0°
20 - 30 MHz	10.4%	19.1°
30 - 40 MHz	11.5%	25.0°
40 - 50 MHz	20.8%	

Table 1: Uncertainties (k=2) for the measurement in Fig. 6 as an example, confidence level 95%.

The amplitude and phase of the hydrophone sensitivity could be obtained by two techniques based on time-delay spectrometry. The frequency range in which the technique can be applied extends from 1 MHz to 50 MHz at the moment. The agreement with the results of alternative calibration techniques is excellent, which emphasises both the correct working of coherent TDS and the reliability of the other calibration techniques used by the laboratory.

References

[1] C. Koch, "Amplitude and Phase Calibration of Hydrophones by Heterodyne and Time-Gated Time-Delay Spectrometry," IEEE Trans. UFFC 50, 344-348, 2003.

[2] V. Wilkens, Ch. Koch, W. Molkenstruck, "Frequency response of a fiber-optic dielectric multilayer hydrophone," Proceedings IEEE Ultrasonics Symposium 2000, S. 1113-1116.

[3] V. Wilkens, Ch. Koch, "Optical multilayer detection array for fast ultrasonic field mapping," Opt. Lett. 24, 1026-28, 1999.

[4] V. Wilkens, "Characterisation of an optical multilayer hydrophone with constant frequency response in the range from 1 to 75 MHz," J. Ac. Soc. Am. 113, 1431-1438, 2003.

[5] R. C. Heyser, "Acoustical measurements by time delay spectrometry," J. Audio Engr. Soc. 15, pp. 370-382, 1967.

[6] G. Ludwig, K. Brendel, "Calibration of hydrophones based on reciprocity and time delay spectrometry," IEEE Trans. UFFC vol. 35, pp. 168-174, 1988.

[7] P. C. Pedersen, P. A. Lewin, L. Bjørnø, "Application of time-delay spectrometry for calibration of ultrasonic transducers," IEEE Trans UFFC 35, 185-205, 1988.

[8] P.M. Gammell, G.R. Harris, "Time delay spectrometry for hydrophone calibrations below 1 MHz," J. Acoust. Soc. Am. 106, L41, 1999.

[9] Ch. Koch, W. Molkenstruck, "Primary calibration of hydrophones with extended frequency range 1 - 70 MHz using optical interferometry," IEEE Trans. UFFC 46, 1303-1314, 1999.