Broadband amplitude and phase calibration of hydrophones and impulse deconvolution within diagnostic ultrasound exposimetry

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Introduction

For precise and reliable measurements of medical and technical ultrasound fields calibrated hydrophones are required. To process the results of exposure measurements with calibrated hydrophones, it has become a standard practice to use the voltage-pressure transfer factor M at the acoustic working frequency f_{awf} of the device under test rather than the broadband frequency dependent transfer function $M(f)$ of the hydrophone. This is a consistent approach only if the ultrasonic field is of narrow bandwidth, or if the hydrophone provides a sufficiently flat frequency response covering the whole frequency range of interest.

An alternative to the demand for a flat frequency response for exposure measurements on diagnostic ultrasound equipment may be an adequate correction procedure. Correct pressure waveforms $p(t)$ and the respective standard pulse parameters can be obtained for broadband pulses by deconvolution of the voltage-time signals $u(t)$ with the non-ideal impulse response $m(t)$ of the hydrophone. In contrast to the usual conversion method, the transfer function has to be known here in amplitude and phase, and this data has to cover the whole frequency range where a significant content of the voltage spectrum $U(f)$ is expected.

Broadband Calibration Technique

A simple method for amplitude and phase calibration that has previously been used to determine the complex frequency responses of fiber-optic hydrophones [1] is applied to the calibration of piezoelectric ultrasonic hydrophones. An optical multilayer hydrophone [2] is used as a reference receiver in a secondary calibration technique. Due to its flat constant amplitude frequency response in a very broad frequency range from 1 to 75 MHz, the system is expected to provide also a flat phase response, and it is used here as a primary phase standard.

The calibration method is based on the successive measurement of broadband nonlinearly distorted pulses of a focusing source transducer (Karl Deutsch GmbH, acoustic focusing, frequency range: 3-12 MHz, diameter: 12 mm, nominal focal length: 50 mm) driven by a pulse generator (peak voltage: 350 V, rise time measured with 50 Ω load: 18 ns) with the reference and the hydrophone to be calibrated using the same excitation conditions (Figure 1). The frequency spectra of the pulses are calculated by numerical Fourier transformation of the time waveforms. Due to the short excitation voltage pulse and the nonlinear propagation of the sound wave producing higher harmonics, the broad frequency range from 1 up to 70 MHz is covered using this transducer-pulse generator combination. The complex-valued frequency response of the hydrophone under test is obtained by division of the respective frequency spectra with high frequency resolution in a broad frequency range.

The calibration result obtained for a bilaminar membrane hydrophone with a nominal diameter of 0.2 mm and a PVDF thickness of 2 × 15 µm is depicted in Figure 2. The amplitude response increases monotonously up to the thickness mode resonance at ~31 MHz and decreases at higher frequencies. Very good agreement is found with results of a primary interferometric calibration [3] at discrete frequencies in the range from 1 to 40 MHz.

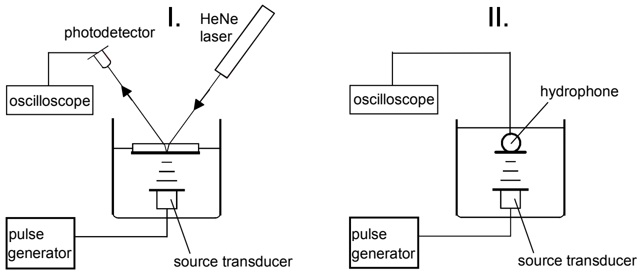

Figure 1: Hydrophone substitution calibration procedure; I. measurement of a broadband focused ultrasound pulse with the optical reference hydrophone, II. measurement with the hydrophone to be calibrated after topping up the water tank.

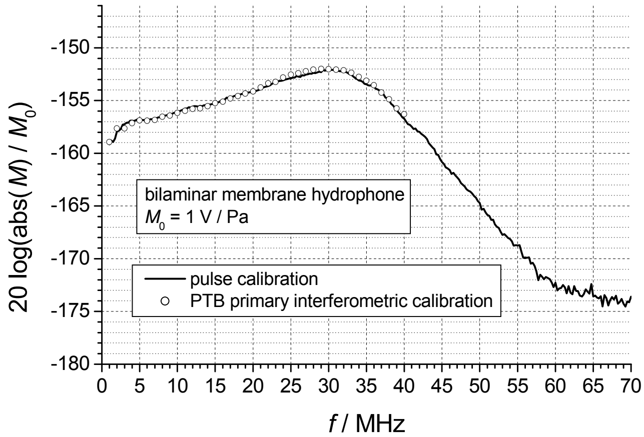

Figure 2: Amplitude response of a PVDF bilaminar membrane hydrophone with 15 µm layer thickness; comparison of results obtained by broadband pulse calibration and primary interferometric calibration.

The second calibration example relates to a needle-type PVDF hydrophone with a nominal diameter of the sensing element of 0.2 mm, an outer diameter of the needle of 0.5 mm, and a foil thickness of 9 µm. This sample shows very strong variations in the amplitude response in the frequency range from 1 to 20 MHz and the thickness mode resonance peak can be observed at ~38 MHz (Figure 3). However, this hydrophone is expected to provide limited results for exposure measurements, but here it confirms the high frequency resolution and broadband capabilities of the calibration method investigated.

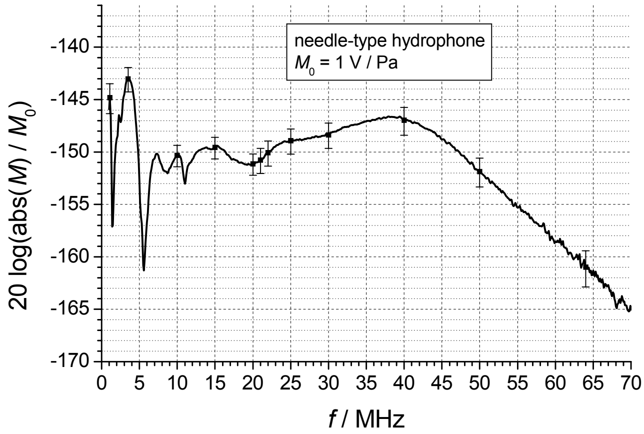

Figure 3: Amplitude response of a PVDF needle-type hydrophone with 9 µm layer thickness obtained by broadband pulse calibration (uncertainties displayed relate to 95% confidence level).

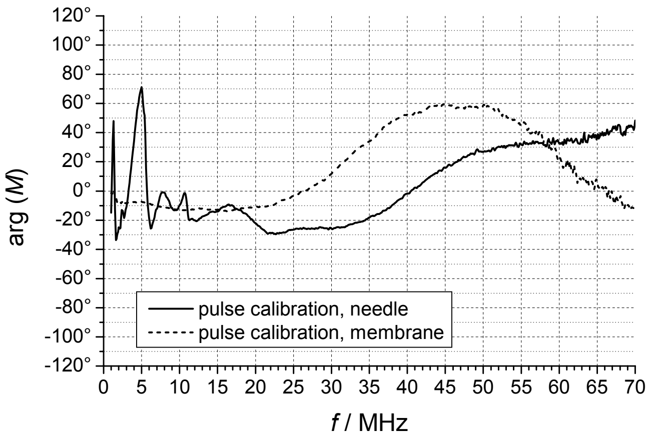

Figure 4: Phase responses of the needle-type and the membrane hydrophone as determined by broadband pulse calibration using the optical multilayer hydrophone as the reference.

Figure 4 shows the phase responses of both the membrane and the needle-type hydrophone. For the membrane hydrophone the phase response is flat up to ~22 MHz and shows some variation at higher frequencies with the first inflection point at the resonance peak frequency of the amplitude response. Similar to the respective amplitude response variations, the phase response for the needle-type hydrophone shows strong variations in the frequency range from 1 to 20 MHz and smoother changes at higher frequencies.

Improved Exposimetry

Exposure measurements were performed on a commercial diagnostic ultrasound machine to investigate the applicability and relevance of the broadband complex-valued hydrophone calibration data obtained. The pressure-time waveforms obtained for M-mode operation of the diagnostic machine as measured with the membrane hydrophone are shown in Figure 5. Both voltage to pressure conversion methods were applied: A) common conversion using the factor $M(f_{awf})$, and B) deconvolution of the voltage-time signals $u(t)$ performed in the frequency domain using the complex-valued broadband transfer function $M(f)$:

$$p(t) = \mathcal{F}^{-1}\left(\mathcal{F}(u(t))/M(f)\right), \qquad (1)$$

where $\mathcal{F}$ denotes Fourier transformation. Due to the transfer function increasing with increasing frequency up to the thickness mode resonance, the positive peak pressure value $p_+ = \text{maximum}\{p(t)\}$ is strongly overestimated and the rarefactional peak pressure $p_- = \text{minimum}\{p(t)\}$ slightly underestimated when using conversion method A) in comparison to the results obtained by conversion method B). Here the oscillations in the decreasing parts of the positive voltage peaks are corrected very well, and a much more reasonable pressure waveform is obtained because the weighting effect of the hydrophone frequency response described above is numerically compensated.

In the exemplar measurements performed with the membrane hydrophone for various parameter settings of the diagnostic ultrasound machine, p_+ was overestimated by up to ~50%, p_- was underestimated by up to ~11%, and the pulse intensity integral *PII* (cf. Figure 5) was overestimated by up to ~28% when using conversion method A) in comparison to the broadband evaluation method B).

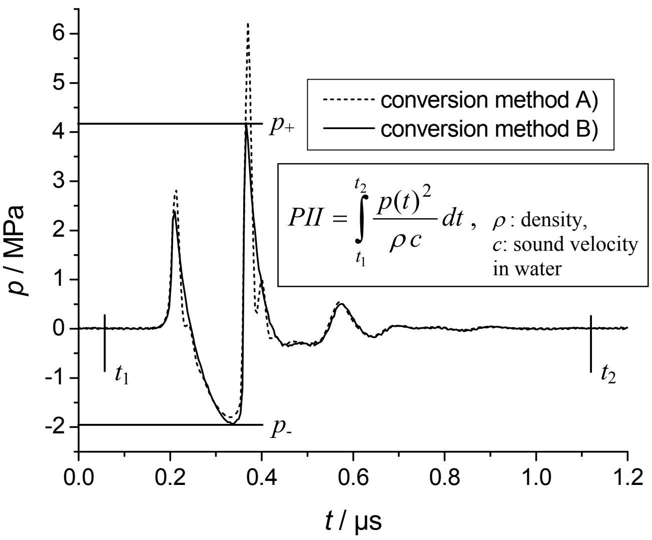

Figure 5: M-mode pressure-time waveform produced by a commercial diagnostic ultrasound machine (z = 30 mm) measured by a membrane hydrophone, voltage-to-pressure conversion as commonly applied using $M(f_{awf})$ (A), and using the broadband complex-valued frequency response $M(f)$ as determined by pulse calibration (B); insert: definition of *PII*.

References

[1] V. Wilkens, C. Koch, and W. Molkenstruck, "Frequency response of a fiber-optic dielectric multilayer hydrophone," *Proc. of the 2000 IEEE Ultrasonics Symp.*, San Juan, Puerto Rico (2000) 1113-1116.

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

[3] C. Koch and W. Molkenstruck, "Primary calibration of hydrophones with extended frequency range 1 to 70 MHz using optical interferometry," IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 46, 1303-1314 (1999).