Time delay spectrometry for hydrophone calibrations below 1 MHz

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Abstract: Knowing the response of miniature ultrasonic hydrophones at frequencies below 1 MHz is important for assessing the accuracy of acoustic pressure pulse measurements in medical ultrasound applications. Therefore, a time delay spectrometry (TDS) system was developed as an efficient means to measure hydrophone sensitivity in this frequency range. In TDS a swept-frequency signal is transmitted. A tracking receiver distinguishes arrivals with different propagation delays by their frequency offset relative to the signal being transmitted, thus eliminating spurious signals such as those reflected from the water surface or tank walls. Two piezoelectric ceramic source transducers were used: a standard planar disk and a disk with varying thickness to broaden the thickness-resonance. This latter design was preferred for its more uniform response without significant sensitivity loss. TDS is not an absolute method, but it was demonstrated to provide efficient, accurate calibrations via comparison with a reference hydrophone using a substitution technique.

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Introduction

Miniature ultrasonic hydrophones are the primary measurement devices used to characterize the acoustic pressure fields produced by medical diagnostic ultrasound transducers. Because of the broadband nature of the pressure pulses, particularly when distorted by nonlinear propagation effects in water as commonly observed, it is important that the hydrophone's response be known over a wide range of frequencies extending down to approximately 100 kHz.[1] However, at present, hydrophone sensitivities below 1 MHz are rarely reported because of the lack of suitable calibration techniques. In this regard, three-transducer reciprocity and laser interferometry have been used in this frequency range, but these are time-consuming single-frequency techniques.[2,3] A method employing broadband, plane-wave pulses of known spectral content also has been used successfully, but the sensitivity of this method is low because of the unfocused, nonresonant operation of the source transducer.[4]

A calibration procedure that overcomes both of these deficiencies involves the swept-frequency technique known as time delay spectrometry or TDS. [5-7] However, in the past TDS has been used for hydrophone calibrations only at frequencies above 1-2 MHz. Therefore, a calibration system based on TDS, but designed to operate at frequencies from approximately 100 kHz to 2 MHz, was successfully developed and tested, and the results are presented herein. In this approach, the digitized TDS response of a "reference" hydrophone, i.e., one having a known frequency response, was subtracted (on a dB scale) from the response of a "test" hydrophone to be calibrated. This procedure results in an efficient method of producing sensitivity plots over the entire frequency range.

In the following sections, a description is given of the TDS swept-frequency generation system, the source transducers used to create the broadband calibration field, and the reference and test hydrophones. Then calibration plots are presented, including a comparison with single-frequency sensitivity measurements performed at a national measurement laboratory using the methods of Refs. 2 and 3.

TDS system

The basics of TDS, including its signal-to-noise enhancement (compared to a broadband pulse) and immunity to multipath interference effects, have been described elsewhere (see Refs. 5-7 and references therein). In the implementation used here, the source transducer is excited with a sine wave signal whose frequency is swept linearly with time. At any instant, signals from paths with different propagation times or time delays will have different frequencies when they arrive at the receiving transducer. The frequency difference between any two signals is equal to the difference in their propagation times or time delays multiplied by the sweep rate (in frequency per unit time). A narrow-band tracking filter passes only those signals that fall within the time-delay window around the desired time delay. The width of this time delay window is equal to the bandwidth of the tracking filter divided by the sweep rate. Because the frequency is swept linearly with time, the tracking filter follows the transmitted signal with a constant frequency offset. Because of this constant frequency offset, the tracking filter can be implemented by heterodyning the received signal with the transmitted signal frequency and using a fixed-frequency filter.

A tracking receiver with a -3 dB bandwidth of 300 Hz was used. For the frequency sweep rate of 20 MHz/s, this bandwidth provides a 3-dB temporal resolution of 15 µs, which yields a measured -3 dB full-width frequency resolution of 32 kHz. Although the source was swept from 0–2 MHz, only the portion between 100 kHz and 1.9 MHz was used for data. This is due to limitations of this particular implementation: at the end of the sweep the transmitted and received signals were not simultaneously available to heterodyne, and there were start-up transients at the beginning of the sweep.

For all measurements, the source transducers were driven with a swept frequency source of 50 ohms impedance, which was specified to provide an output of 200 mW into a 50-ohm load. This level, which could have been increased by at least an order of magnitude, was found to be sufficient for these experiments. The voltage sensitivity of the TDS system was measured by connecting the tracking receiver to a calibrated CW source instead of the hydrophone output.

Measurements were made in a 40x40x62-cm tank filled with distilled, degassed, room-temperature water. The direction of the ultrasound beam was along the 62-cm tank dimension, and the back of the tank was lined with an acoustically absorbing rubber sheet.

Source transducers and hydrophones

The main factor that determines the usable frequency range for calibration is the bandwidth of the source transducer. In this study, two different transducers were used: a 3.8 cm diameter, plane ceramic disk with a thickness-resonance frequency of 500 kHz (Model V389, Panametrics, Waltham, MA) and a 2.5 cm diameter, plano-concave, broadband ceramic disk fabricated by Gerald Posakony of the Battelle Pacific Northwest National Laboratory. Posakony used the design of Vopilkin et al.,[8] a design that also has been used in a medical imager based on TDS.[7] The nonuniform thickness of the plano-concave transducer acted to broaden the usual thickness-resonance behavior. The plane surface was in contact with the water; the concave surface was spherical and the thickest and thinnest dimensions were 1.37 mm and 0.25 mm, respectively. (This transducer was a split disk originally designed for transmit-receive use, but in the present work the two halves were connected electrically in parallel for transmit-only operation.) The back surfaces of both transducers were acoustically damped.

Two commercial hydrophones having piezoelectric polyvinylidene fluoride as the active element were used: a bilaminar spot-poled membrane hydrophone for the reference device (Model 804, Perceptron, Hatboro, PA) and a needle-type for the test hydrophone (Model HPM1/1, Precision Acoustics, Dorchester, England).[4] The geometrical diameters of the piezoelectrically active regions were 0.4 mm and 1.0 mm for the membrane and needle, respectively. The needle hydrophone included an integral preamplifier. An external broadband amplifier having 40 dB gain was used with the membrane hydrophone (Model 5676, Panametrics).

TDS calibration via substitution

For the substitution calibration procedure, both hydrophones were placed at the same location in the ultrasound field, and their responses were measured. The test hydrophone sensitivity, $M_t(f)$, at frequency f, is

$$M_t(f) = M_r(f) \bullet S_t(f,z)/S_r(f,z) \;\; \mathrm{V/Pa}, \qquad (1)$$

where $M_r(f)$ is the reference hydrophone sensitivity, and $S_t(f,z)$ and $S_r(f,z)$ are the measured test and reference hydrophone responses at point z on the source transducer axis.

Equation (1) was evaluated (in dB) using the needle and membrane hydrophones as the test and reference hydrophones, respectively. The membrane hydrophone was chosen as the reference because membrane hydrophones have been shown to have a flat, uniform response (within the measurement uncertainty of approximately ±1 dB) over the frequency range of interest.[3,4] Therefore, $M_r(f)$ can be treated as a constant whose value was determined as follows: An independent calibration of the needle hydrophone used had been performed previously at discrete frequencies from 100 kHz to 1 MHz in 100 kHz steps (National Physical Laboratory, UK), so a separate comparison of the two hydrophone outputs was made at 1 MHz, from which $M_r(1\ \mathrm{MHz})$ was found to be 1.4 V/MPa (at amplifier output). This value was taken as the membrane (reference) sensitivity $M_r(f)$ in Eq. (1) over the measured frequency range. In addition, errors introduced by spatial averaging over the hydrophone's active surfaces were negligible, because the measured -6 dB beamwidths for the planar transducer at 1.5 MHz and the plano-concave transducer at 1.9 MHz were both 1 cm or greater.

Selection of distance z entails a trade-off, in that z should be chosen large enough to avoid significant near-field effects at the highest frequency of interest, but small enough to maintain useful pressure amplitudes at the lower frequencies. Regarding the latter, a decrease in frequency places a given axial position farther beyond the last axial maximum, causing a corresponding drop in the pressure amplitude. For the planar transducer, a measurement distance of 25 cm was chosen, which, based on planar piston behavior, is at the last axial maximum at 1 MHz. For the plano-concave transducer, measurements were made at four source-to-hydrophone distances to investigate potential near/far-field effects: z = 11, 17, 21, and 25 cm. At 1 MHz the 11-cm distance is at the last axial maximum for an ideal planar piston transducer having the same diameter as the plano-concave transducer.

Results and discussion

As stated previously, the usable frequency range for calibration is determined primarily by the bandwidth of the source transducer. Therefore, first the TDS system was used with the membrane hydrophone to measure the transmit spectrum $T(f,z) = Sr(f,z)/Mr(f)$. The results for both source transducers when driven by the 200 mW, 50-ohm source described above are plotted in Fig. 1 from 100 kHz to 1.9 MHz. The peak pressures were between 30 kPa and 100 kPa, levels at which nonlinear effects are negligible for these calibration measurements. The acoustic output of the 500 kHz planar transducer shows a transmit spectrum that peaks at the fundamental (approximately 500 kHz) and third harmonic. It has a sharp minimum at the second harmonic, as expected for a simple thickness-mode resonance. The responses of the plano-concave transducer at all four distances are similar but decrease with increasing distance.

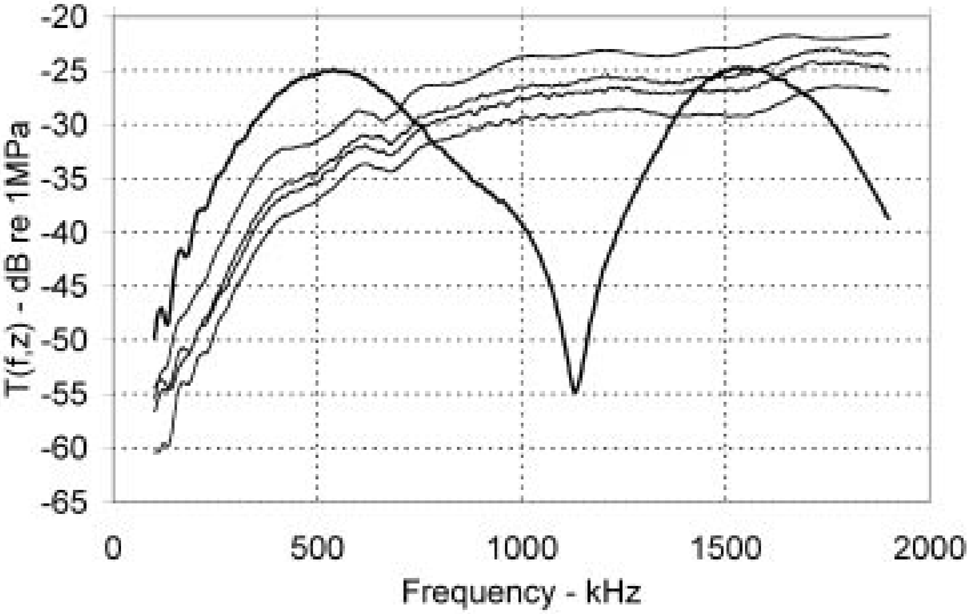

Fig.1. Pressure response, T(f,z), vs frequency for the 500 kHz planar source transducer at z = 25 cm (heavy line), and for the plano-concave source transducer at, top to bottom, z = 11, 17, 21, and 25 cm.

Figure 2 shows the results of using the plano-concave transducer to calibrate the needle hydrophone via substitution. As described above, for each of the four calibrations, the acoustic pressure was measured with the membrane hydrophone, as shown in Fig. 1. Then the needle hydrophone was substituted at the same location, and its response was recorded and divided (subtracted on a dB scale) by the acoustic pressure to produce the absolute response of the needle hydrophone. The measurements from z = 17 cm to 25 cm are within 1 dB of each other for all frequencies above 300 kHz and within 2 dB down to 100 kHz. For frequencies below 1 MHz, the measurements at all four distances agree within 3 dB. At frequencies above 1 MHz only the response at the 11 cm distance, which is in the near field, differs significantly from the others. The data at 17 cm show no appreciable deviation from 21 cm and 25 cm even though this distance is at the edge of the far field at 2 MHz. It should be remembered that this transducer is considerably apodized compared to the true planar transducer.

Figure 3 compares the substitution calibrations of the needle hydrophone using both the planar and plano-concave transducers at 25 cm. At most frequencies these two calibrations agree within 1 dB. The anomalous peak in the calibration using the planar transducer occurs at the second harmonic of the source transducer, where its response is a minimum. The 2 dB difference of the planar transducer at 1.9 MHz probably is due to the proximity of the measurement point to the last axial minimum in the near field. Also plotted in Fig. 3 are the individual calibration

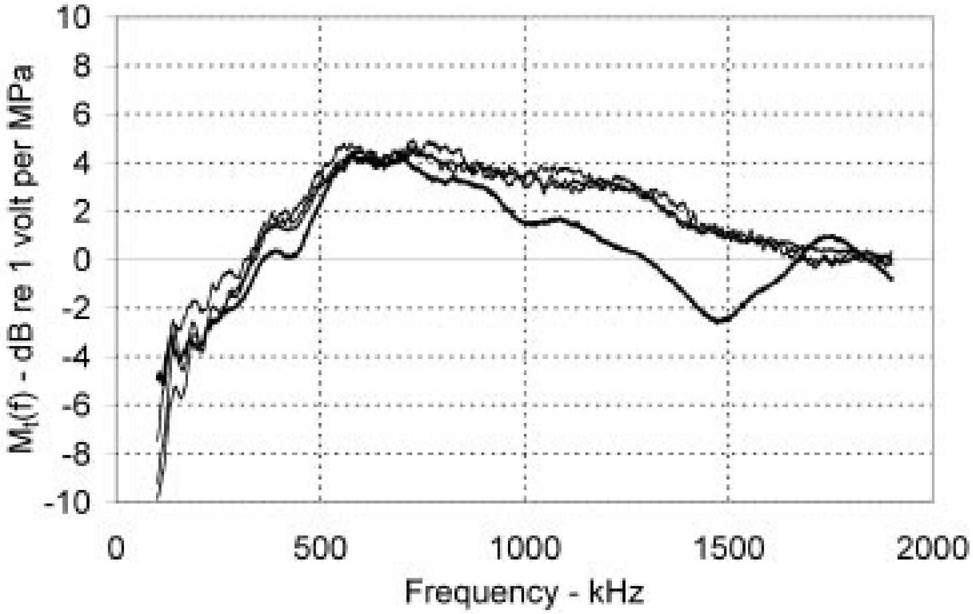

Fig. 2. Substitution calibration plots for needle hydrophone at z = 11, 17, 21, and 25 cm. The response at 11 cm (heavy line) differs significantly from the others.

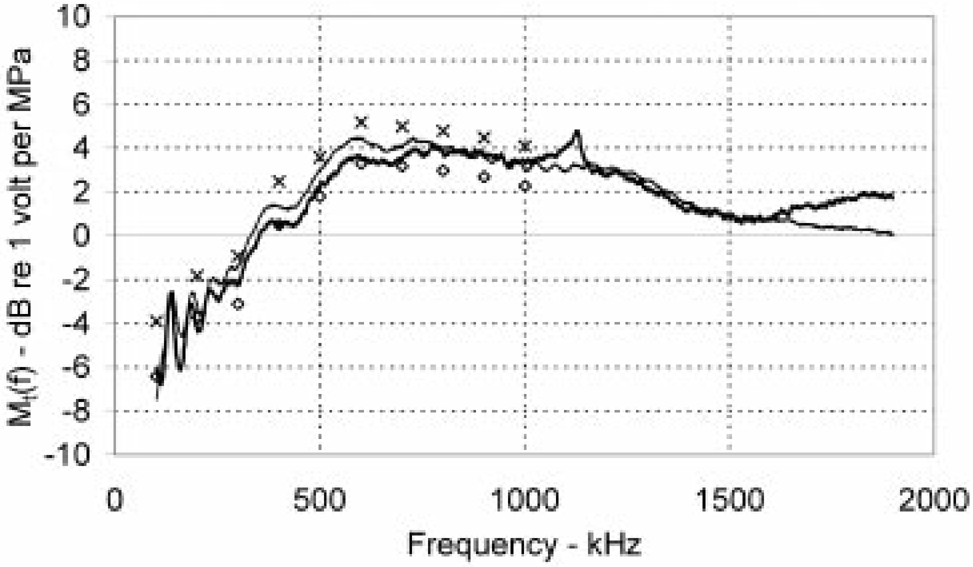

Fig. 3. Substitution calibration plots for needle hydrophone at z = 25 cm using both source transducers and upper and lower 95% confidence limit pairs for ten independent, single-frequency calibration measurements. Heavy line: planar transducer; light line: plano-concave transducer.

points for the needle. These ten data pairs represent the upper and lower 95% confidence limits for the independent, single-frequency sensitivity measurements described previously. The TDS calibration plots generally fall within these limits. The oscillations below 300 kHz were present in the membrane but not the needle response. This effect does not appear to be the case with all membrane hydrophones and is being investigated.

Conclusions

The TDS system described was shown to be a useful tool for substitution calibration methods in the 100 kHz to 2 MHz frequency range. It gives, in a single, rapid swept-frequency measurement, the data over the entire range, while excluding spurious signals and providing an improved signal-to-noise ratio compared to broadband pulse calibration techniques. To utilize the ability of TDS to furnish a calibration over a wide frequency range in one measurement for each source-receiver combination, it is desirable to have a broadband source transducer. In this regard, the plano-concave transducer was demonstrated to be a useful source because its response does not have the minimum at twice the fundamental frequency that is characteristic of a constant-thickness transducer.

References

[1] G.R. Harris, "Are current hydrophone low frequency response standards acceptable for measuring mechanical/cavitation indices?," Ultrasonics **34**, 649-654 (1996).

[2] S.P. Robinson and G.R. Dore', "Uncertainties in the calibration of hydrophones at NPL by the three-transducer spherical-wave reciprocity method in the frequency range 10 kHz to 500 kHz," NPL Report RSA(EXT)0054, National Physical Laboratory, Teddington, Middlesex, UK (November 1994).

[3] S.P. Robinson, "A comparison of the frequency response of membrane and needle probe PVDF hydrophones," in D. Evans and K. Martin, eds., *Physics in Medical Ultrasound II* (York, UK: Institute of Physical Sciences in Medicine, 1988) pp. 79-86.

[4] G.R. Harris and P.M. Gammell, “Sensitivity measurements of piezoelectric polymer hydrophones from 0.2-2 MHz using a broadband pulse technique,” J. Acoust. Soc. Am. **105**, 725-731 (1999).

[5] R.C. Heyser, “Acoustical measurements by time delay spectrometry,” J. Audio Eng. Soc., **15**, 370-382 (1967).

[6] P. Pedersen, P.A. Lewin, and L. Bjorno, “Application of time delay spectrometry for calibration of ultrasonic transducers,” IEEE Trans. Ultrason. Ferroelec. Freq. Contr. **35**, 185-205 (1988).

[7] R.C. Heyser, J.D. Hestenes, J.A. Rooney, P.M. Gammell, and D.H. Le Croissette, “Medical ultrasound imager based on time delay spectrometry,” Ultrasonics **27**, 31-39 (1989).

[8] W. Sachse and N.N. Hsu, “Ultrasonic transducers for materials testing and their characterization,” in Physical Acoustics, Vol. XIV, edited by W.P. Mason and R.N. Thurston (Academic Press, New York, 1979) pp. 304-305.

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