Two efficient methods for measuring hydrophone frequency response in the 100 kHz to 2 MHz range

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Abstract. As new medical applications of ultrasound emerge with operating frequencies in the hundreds of kilohertz to low megahertz region, it becomes more important to have convenient calibration methods for hydrophones in this frequency range. Furthermore, short diagnostic ultrasound pulses affected by finite amplitude distortion require that the hydrophone frequency response be known well below the center frequency. National standards laboratories can provide accurate calibration data at these frequencies, but the two methods now employed, laser interferometry and three-transducer reciprocity, are both single-frequency techniques, and they can be time-consuming procedures. Therefore, two efficient methods for generating a wideband acoustic pressure spectrum have been implemented to cover this frequency range. In one method a high-voltage pulse generator was used to excite a thick piezoelectric ceramic disk, producing a plane-wave acoustic pressure transient <1 µs in duration with peak amplitude of about 40 kPa. In the other technique, time delay spectrometry (TDS), a purpose-built 1-3 piezoelectric composite source transducer weakly focused at 20 cm was swept over the 0-2 MHz range. Its transmitting voltage response at 1 MHz was 11 kPa/V. The broadband pulse technique has the advantage of being simpler to implement, but TDS has a much greater signal-to-noise ratio because of the frequency-swept narrowband filter employed.

1. Introduction

Ultrasound is being used clinically and for biomedical research over several decades of frequency. For greater penetration or to enhance cavitation, lower frequencies typically are used, and established or investigational applications at the low end include high intensity focused ultrasound surgery [1],[2], extracorporeal shock wave therapy for urological and orthopedic applications [3],[4], bone sonometry for diagnosing osteoporosis [5], and ultrasound-assisted gene transfection and drug delivery [2],[6],[7].

Miniature ultrasonic hydrophones are the primary means used to map the ultrasonic pressure fields and record the temporal waveforms. Methods for extending the calibration range of hydrophones to 60-70 MHz have been developed, but the region below 2 MHz has received less consideration. This range is important not only for the applications just mentioned, but also because short ultrasound pulses affected by finite amplitude distortion, such as encountered in diagnostic imaging and Doppler systems, require that the hydrophone frequency response be known well below the center frequency [8].

Local laboratories seldom have facilities for calibrations below 1-2 MHz. The two techniques used at national measurement laboratories, three-transducer reciprocity and laser interferometry, are capable of performing the necessary calibrations, but they are discrete-frequency techniques, so characterizing a hydrophone over a range of frequencies is a time-consuming procedure. Therefore, means were investigated for rapid calibration of hydrophones in...
this frequency range, and two techniques were implemented, one employing a swept-frequency signal, and the other involving the time-domain measurement of a broadband pulse. A comparison calibration using four piezoelectric polymer hydrophones was employed to compare the methods over the range from 100 kHz to 2 MHz.

2. Methods

2.1 Comparison Calibration

In a calibration by comparison, a “reference” hydrophone with known sensitivity vs. frequency $M_R(f)$ and a “test” hydrophone with unknown sensitivity $M_T(f)$ are placed one after the other at the same point in an acoustic field of a source transducer. Then $M_T(f)$ is found from the relationship,

$$M_T(f) = M_R(f) \frac{H_T(f, z)}{H_R(f, z)}$$

where $H_T(f, z)$ and $H_R(f, z)$ are the measured voltage responses of the test and reference hydrophones, both located at distance $z$ along the source transducer axis. The two main components for producing the acoustic field are the source transducer and broadband generating electronics, each of which are discussed for the two techniques following a description of the hydrophones.

2.2 Hydrophones

Four piezoelectric polymer hydrophones were used. Two were needle designs with sensitive diameters of 0.2 mm and 0.6 mm, designated N0.2 and N0.6. N0.2 had an integral preamplifier. The other two were spot-poled membrane hydrophones with sensitive diameters of 0.4 mm and 1.0 mm (M0.4 and M1.0). M0.4 was bilaminar, with two layers of 25 µm-thick film, and M1.0 contained a single-layer of rubber-backed, 25 µm-thick film. M1.0 had an integral preamplifier, and M0.4 had a preamplifier attached via a 15 cm cable.

The bilaminar membrane hydrophone M0.4 was used as the reference hydrophone, having been calibrated by a national standards laboratory (UK National Physical Laboratory) at 18 discrete frequencies from 300 kHz to 2 MHz at 100 kHz intervals. All points fell within a sensitivity range of 12.3±0.6 nV/Pa, and the overall uncertainty was specified as ±8% at the 95% confidence level. Using these 18 points, a linear fit of sensitivity vs. frequency was calculated and used for $M_R(f)$ in equation (1) (correlation coefficient $R = 0.92$). An adjustment to $M_R(f)$ was then made to account for the roll-off below 300 kHz due to the single-pole, high-pass response of the attached preamplifier, which had a -3 dB frequency of 32 kHz. The correction was small, being about 0.5% at 300 kHz and 5% at 100 kHz. The resulting $M_R(f)$ was used in equation (1) for both the swept-frequency and broadband pulse techniques.

2.3 Swept-frequency technique

The swept-frequency technique used is known as time delay spectrometry (TDS), and the TDS system employed is described in [9]. In this technique a transducer is driven with a signal whose frequency is swept linearly in time. As a result, at a particular time the received frequency differs from the transmitted frequency by the TDS offset frequency $\Delta f = S\tau$, where $S$ is the TDS sweep rate and $\tau$ is the ultrasonic delay time. For these experiments the sweep rate was 20 Hz/µs, giving $\Delta f = 2$ kHz for a time delay of 100 µs. The receiver circuitry incorporates a “tracking filter” that tracks the transmitted frequency with an appropriate preset time delay. Stray signals with other than the desired path length (and therefore time delay) are discriminated against by this tracking filter.

The width of the tracking filter’s time acceptance window ($\Delta t$) is determined by the quotient of the resolution bandwidth setting of the tracking filter ($B$) and $S$. With the tracking filter’s bandwidth set to 300 Hz, a sweep rate of 20 Hz/µs provided a time acceptance window of $\Delta t = B/S = 15$ µs. Because the receiver uses such a narrow band filter, considerable improvement in signal-to-noise ratio (SNR) is realized compared to pulsed techniques. For additional improvement of the SNR, the log-magnitude signal provided by the TDS system was averaged by the data acquisition system (DSA602A, Tektronix, Beaverton, OR). Sixty four averages of the 1024-point waveforms (spectra) were recorded.
This system uses a logarithmic detector with a dynamic range of 60 dB, providing a direct readout of the response in dB. The spectral response of the hydrophone under test, $H_{f}(f, z)$, is immediately available in real time for display and recording. The measurement distance $z = z_{m}$ from the transducer to the hydrophone was fixed at 15 cm by setting the offset of the tracking filter for the desired time delay of $\tau = 100 \mu$s (assuming a sound speed in water of 1.5 mm/$\mu$s), and then adjusting the transducer-to-hydrophone distance to maximize the measured spectral response.

A key element of a swept-frequency technique is a transmitting transducer with sufficient transmit response over the frequency range of interest. In this regard, two 1-3 piezoelectric composite transducers were developed (transducer fabrication and poling: Smart Material Corp., Sarasota, FL; transducer assembly, UTX, Inc., Holmes, NY) [10]. In both designs the back face of the 4-cm diameter transducers was made spherically concave to disperse the thickness mode resonance, and the 1-3 composite material appeared to reduce unwanted lateral modes and provided a closer impedance match to water. The transducers differed in that one had a flat front face, whereas the other was weakly focused (20-cm radius of curvature), resulting in practical source-to-hydrophone working distances of 35 cm and 15 cm, respectively [10]. For the results reported here the focused transducer was used.

All measurements were made in deionized water at a temperature of $21.5 \pm 1.5 ^\circ C$. A 40 dB external amplifier (Model 5676, Panametrics, Waltham, MA) was used between the hydrophones (some of which incorporated a preamplifier as described in Sec. 2.2) and the input to the TDS system. The output of the sweeping generator directly drove the transmitting transducer. At the maximum output setting (23 dBm) a swept frequency sine wave was produced with an open circuit amplitude of 8.9 V peak in series with a source impedance of 50 $\Omega$. The resulting transmitting voltage response was 11 kPa/V at 1 MHz (see figure 9 in [10]), which was adequate to produce a useful signal with the least sensitive hydrophone (the reference bilaminar membrane). For some of the other hydrophones a lower drive level was used, determined by the precision attenuators of the source. $H_{f}(f, z_{m})$ was adjusted to account for these different drive levels. The precision (repeatability) of this technique was evaluated by taking four independent measurements (two from each of two operators) for each hydrophone. All the data were analyzed using MATLAB (The MathWorks, Natick, MA).

2.4 Broadband pulse technique

The details of this technique as implemented by the authors are described in [11]. Briefly, a piezoelectric ceramic transducer 6.35 cm in diameter and 2.54 cm thick was excited with a high-voltage pulse whose duration was short (<1 $\mu$s) compared to the transit time through the transducer (>5 $\mu$s). For points in the field close to the transducer and near its axis, the plane wave pulse radiated from the front face can be isolated in time from the pulses originating from the back face, as well as from the edge- and head-wave components emanating from the transducer perimeter. One difference from the approach in [11] is that in the present study a comparison calibration was performed instead of using the theoretical transient response of the transmitting transducer.

The high-voltage pulse generator was purpose-built for these measurements, and was operated with a peak voltage across the transmitting transducer of 1700 V [12]. The rise time and half-amplitude pulse duration were approximately 80 ns and 400 ns, respectively.

Measurements were performed in distilled water having a temperature of $21.5 \pm 1.5 ^\circ C$. The same external 40 dB hydrophone amplifier that was used in the TDS measurements was used here as well. The hydrophone waveform recording device (Tektronix DSA602A) was triggered simultaneously with the pulse generator. The reference and test hydrophones were positioned at an axial distance corresponding to a propagation delay of 33.5 $\mu$s, or approximately 5.0 cm. The hydrophones were centered on the axis by maximizing the edge- and head-wave pulses, which arrive in phase for a circular source transducer.

512 data points were recorded over a 5 $\mu$s temporal window. Because the transmitting transducer is neither focused nor operated in a resonance mode, the pressure amplitude is small (about 40 kPa peak), so 512 averages were taken of all waveforms to improve the SNR.

Before being fast Fourier transformed (FFT) to obtain $H_{f}(f, z_{m})$ and $H_{p}(f, z_{m})$ for equation (1), the waveforms were shifted vertically to remove any DC offset and multiplied by a raised-cosine window function to eliminate truncation effects in the FFT. Then they were zero-filled for
a total of 4096 points. The resulting frequency resolution was 24.4 kHz. As with the TDS measurements, four repeat measurements were made, and the four FFT amplitude spectra were averaged. Again, all data were processed using MATLAB.

3. Results and Discussion
The sensitivities for the four hydrophones are given in figure 1. The plot for the reference hydrophone, M0.4, is the same for both techniques, as mentioned previously, and is essentially a straight line fit to the single-frequency calibration data, except for the slight low-frequency roll-off beginning about 300 kHz. The other plots are for the three test hydrophones, the dotted and dashed lines being for the TDS and broadband pulse calibration techniques, respectively. The solid line represents smoothed TDS spectra as discussed next.

Figure 1. Sensitivity plots for the four hydrophones.

Low-frequency fluctuations were observed in all three TDS test hydrophone results, presumably because of the better frequency resolution of the TDS technique. Actually, these fluctuations are a characteristic of the reference hydrophone, as seen in figure 2, in which each hydrophone’s TDS response is plotted from 0.1-0.4 MHz in dB relative to its overall maximum value in the 0.1-2 MHz range. Thus, because the fluctuations occurred in $H_R(f, z_m)$ but not in $M(f)$ or $H_T(f, z_m)$, they appear in all plots of $H_T(f)$ via equation 1. It is tempting to attribute these low-frequency variations to the membrane structure, and to conclude that they are not noticeable in hydrophone M1.0 because this membrane is rubber-backed. However, this phenomenon would need further study to support such speculation. It is doubtful that their presence would lead to significant error in any practical measurement situation. Because these fluctuations in $H_T(f)$ were artifacts of the computational process, these spectra were smoothed with a 20-point running average (solid lines in figure 1). (It is noted that using a TDS filter bandwidth of $B = 100$ Hz, resulting in $\Delta t = 5$ µs, would also smooth these fluctuations because of the poorer frequency resolution).

To assess the measurement precision of each technique, the Type A uncertainty, $u_A(f) = S_x(f) / n^{0.5}$, and the corresponding uncertainty at the 95% confidence level, $t_{0.975}[u_A(f)]$, were found vs. frequency, where $S_x(f)$ is the standard deviation, and, with $n = 4$ measurements, $t_{0.975} = 3.18$ [13]. For the TDS measurements, $u_A(f)$ was computed using the four measured $H_T$ spectra. For the broadband pulse measurements, $u_A(f)$ was computed using the four $H_T$ amplitude spectra calculated via FFT. The results, plotted as a percent relative to the mean, $\overline{\tau}\ (f)$, are shown in figure 3. Each plot compares the random uncertainty of the two methods for each of the four hydrophones. For

Figure 2. TDS spectra illustrating low-frequency fluctuations in $H_R$ (M0.4, solid line) compared to $H_T$ for test hydrophones (top to bottom, M1.0, N0.6, N0.2 – dotted lines).
the TDS technique, the values for all four hydrophones are generally less than 5% except close to 100 kHz. For the broadband pulse technique, the random uncertainty increases for the two less sensitive hydrophones, N0.6 and M0.4, particularly at low frequencies. The least sensitive hydrophone, M0.4, shows the greatest uncertainty and most variation for the broadband pulse technique, which is not surprising given the inherently smaller SNR for this calibration method.

Figure 3. Plots of the random uncertainty at the 95% confidence level, \( t_{0.975}[\hat{U}_A(f)] \), for the four repeat measurements for each hydrophone, expressed relative to the mean \( \bar{U}(f) \) in percent. TDS - Solid line; broadband pulse – dashed line.

Figure 4. Plots of independent calibration data from NPL for hydrophone N0.2, along with the TDS (smoothed) and broadband pulse sensitivity spectra.

To evaluate the techniques in an absolute sense, independent calibration data for hydrophone N0.2 were compared to the TDS and broadband pulse calibration spectra for this hydrophone. Figure 4 shows these spectra along with 20 discrete calibration points from 100 kHz to 2 MHz at 100 kHz intervals obtained from a national standards laboratory (UK National Physical Laboratory). The error bars for the discrete calibration data also are shown. For the TDS sensitivity spectrum (smoothed) the average difference from the reference data was -9%, and the maximum difference was -20%, occurring at 400 kHz. For the broadband pulse plot these values were -10% for the average difference and 35% for the maximum difference at 100 kHz. Given the random uncertainties in figure 3 and the overall uncertainty for M0.4, there would appear to be little if any statistical difference between the discrete and broadband calibration data. However, there does appear to be a negative bias in the TDS and broadband pulse spectra compared to the discrete data, possibly due to a decrease in the absolute sensitivity of the needle hydrophone over the eight months since its calibration.

4. Conclusions
Each of the two broadband methods studied, TDS and broadband pulse, was successfully employed in the calibration of miniature hydrophones over the 100 kHz to 2 MHz frequency range. Both measurement methods can be used in conjunction with a reference hydrophone for comparison calibrations at a finer frequency resolution than would be practical with the standardized single-frequency techniques. They also can be used for fast and convenient spot checks of hydrophone sensitivity from 0.1-2 MHz.

In the broadband pulse technique, errors due to incorrect hydrophone positioning or spatial averaging are minimized due to the plane wave nature of the pulses generated. However, in practice unambiguous positioning of the reference and test hydrophones at the same point in the ultrasound field was straightforward in both techniques. For less sensitive hydrophones (M less than approximately 50 nV/Pa), TDS appeared to have the advantage in terms of measurement precision. On the other hand, the broadband pulse technique is easier and less costly to implement,
given the relative simplicity of the pulse generator [12] and transmitting transducer [11] compared to the TDS system electronics [9] and transducer [10].

Note: The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the U.S. Food and Drug Administration.

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