BEYOND 40 MHZ FRONTIER: A NEW CHALLENGE FOR ULTRASOUND METROLOGY

PETER A. LEWIN*, SUMET UMCHID*, ALEXANDER SUTIN** and ARMEN SARVAZYAN**

*The School of Biomedical Engineering, Science and Health Systems and
Department of Electrical and Computer Engineering, Drexel University,
Philadelphia, PA 19104, USA
** Artann Laboratories, Lambertville, 08530 NJ, USA
E-mail: lewin@ece.drexel.edu

Abstract - Several techniques that are suitable for calibration of ultrasound hydrophones in the frequency range beyond 20 MHz are briefly reviewed. Attention is largely focused on substitution techniques because in contrast to the primary methods they are not as laborious and can be carried out relatively quickly. The techniques discussed include two acoustic procedures using swept frequency systems, an approach based on nonlinear propagation of acoustic waves in water medium, an acousto-optic technique that employs fiber optic sensors and a novel technique that is based on Time Reversed Acoustic (TRA) approach. It is shown that these techniques are capable of extending the frequency range in which the hydrophones can be calibrated up to 100 MHz. The importance of spatial averaging correction and its impact on the acoustic output measurements is also pointed out.

1. Introduction

There is a growing interest in calibration of wideband hydrophone probes at the frequencies exceeding 20 MHz. An increasing number of diagnostic ultrasound scanners operate at frequencies close to 15 MHz and the requirements for hydrophone bandwidth as specified in [1, 2] render the usual 1-20 MHz calibration inadequate. This paper discusses several techniques that are suitable for calibration of ultrasound hydrophone probes in the frequency range beyond 20 MHz. Attention is largely focused on substitution techniques because in contrast to the primary calibration methods they are not as laborious and can be carried out relatively quickly. The techniques discussed include two acoustic procedures using swept frequency systems, an approach based on nonlinear propagation of acoustic waves in water medium, an acousto-optic technique that employs fiber optic sensors and only very recently tested promising technique that is based on Time Reversed Acoustic (TRA) approach. It is shown that these techniques are capable of providing the hydrophone's frequency response up to 100 MHz. The importance of spatial averaging correction and its impact on the acoustic output measurements is also pointed out.

2. Substitution techniques

A convenient summary of principles of primary calibration techniques such as reciprocity and laser interferometry displacement measurements can be found in [3]. In contrast to primary or absolute calibration methods such as acoustic force, reciprocity or optic interferometry [3], the substitution (secondary) technique requires the existence of a previously calibrated hydrophone probe. Once such a probe is available the absolute sensitivity of the unknown hydrophone (in terms of V/Pa) can be readily determined. This is done by performing two measurements. In the first one the calibrated probe is immersed in the plane wave acoustic field and the open circuit voltage (with a specified electric load) generated at the probe's terminal is recorded. This voltage can be measured at discrete frequencies or as a continuous function of frequency when using e.g. swept systems such as those described below. The obtained magnitude frequency spectrum is stored in a digital memory included in one of the instruments constituting the measurement system and subsequently the identical measurement procedure is repeated with the unknown probe brought into the very same position in the acoustic field. The product of the ratio of the voltages measured (strictly speaking, that of the unknown probe over the known one) and the absolute sensitivity of the previously calibrated probe yields the absolute sensitivity of the hydrophone being calibrated.

One of the most effective secondary calibration methods employs linear frequency sweep and is based on the Time Delay Spectrometry (TDS). The TDS was initially implemented in the frequency range 1-10MHz [4]. It was gradually extended down to approximately 100 kHz [5, 6] and at present it is routinely used to provide calibration data up to 40 MHz. The TDS approach, originally conceived by Heyser in the early seventies for testing of loudspeakers in air [7] offers a rapid, practically continuous frequency calibration of the hydrophone probes and allows high frequency response of the probes to be determined without the need to employ nonlinear acoustic wave propagation and associated generation of harmonics.

An example of a hydrophone frequency response, which demonstrates one of the advantages of using the swept frequency methods is shown in Fig.1. It is clear that the TDS approach used here is particularly useful in identifying rapid variations in the hydrophone's sensitivity caused by the spurious mechanical resonances. Such resonances may be undetectable when the calibration is performed at discrete (often carried out at 1 or 2 MHz) intervals.
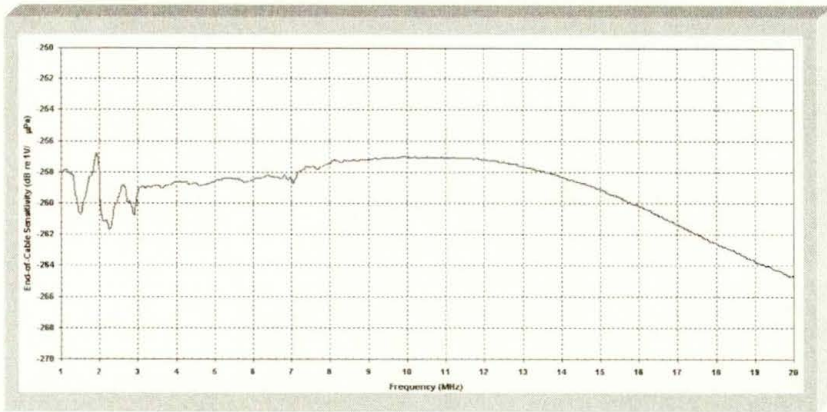
Figure. 1. An example of a hydrophone frequency response (of a hydrophone afflicted by spurious mechanical resonances) demonstrating one of the advantages of using the Time Delay Spectrometry (TDS) calibration method.

The upper frequency limit of the Time Delay Spectrometry technique was recently extended [8] by additional 20 MHz, so the hydrophones could be calibrated up to 60 MHz. This extension was achieved using Time Gating Frequency Analysis (TGFA) approach. The TGFA could be considered as a time domain implementation of the TDS technique. Similarly to TDS, the TGFA uses a linearly swept frequency source excitation signal and establishes free field environment in reverberating water tank. However, instead of introducing a frequency shift to account for the wave propagation delay between the acoustic source and the hydrophone, the TGFA method transforms the measured signal from the frequency to time domain using inverse fast Fourier transform (IFFT). The time gate and its delay are adjustable electronically and applied to ensure that only the direct signal produced by the wideband acoustic source is measured by the hydrophone and the undesirable echoes are minimized or rejected. The time domain signal received within the gate is then FFT back transferred into the frequency domain. The measurement procedure is carried out initially for the previously calibrated hydrophone probe and then for the unknown one. In this way, two frequency responses are obtained. Again, the product of the ratio of these two responses and the absolute sensitivity of the reference hydrophone yields the absolute sensitivity of the probe under test. Fig. 2 shows an example of such calibration. There, end-of-cable sensitivity of a 150 microns needle hydrophone is shown. The hydrophone was calibrated up to 60 MHz using the TGFA technique. A 500 microns diameter co-planar membrane hydrophone calibrated by NPL, UK was used here as a reference.

Both TDS and TGFA approaches, when carefully implemented, can provide overall calibration uncertainty to within +/- 1 dB and +/- 1.5 dB, at 40MHz and 60 MHz, respectively. This uncertainty is primarily governed by the uncertainty of the reference hydrophones.
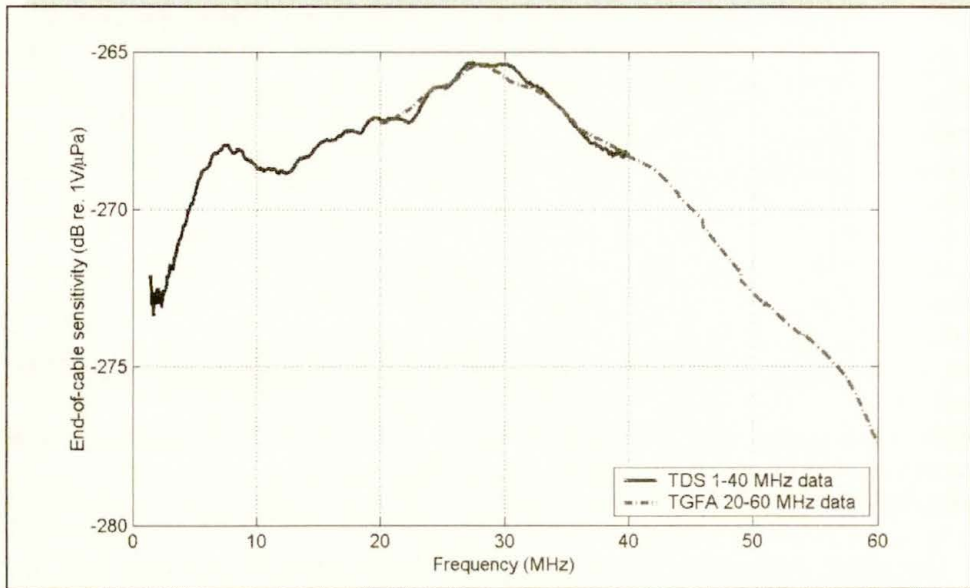
Figure 2. TGFA calibration example of the 150 microns diameter hydrophone. A 500 microns diameter co-planar membrane hydrophone calibrated by NPL, UK was used as a reference. For comparison, the results obtained using the Time Delay Spectrometry (TDS) are also shown. See text for further details. After [8].

3. Nonlinear calibration technique

In its simplest implementation, the utilization of nonlinear wave propagation provides yet another desirable and independent enhancement of the ultrasound hydrophone calibration bandwidth. In principle, the upper frequency when using nonlinear procedure is determined by the signal-to-noise ratio of the measured signal corresponding to the pressure amplitude of the highest harmonic produced by the (shocked) acoustic source. The absolute pressure amplitudes at different harmonics generated by the source can be predicted by an appropriate nonlinear wave propagation model [9, 10] that includes all medium losses and spatial averaging corrections. The details of the recently employed nonlinear calibration technique can be found in [8]. By comparing the amplitudes of the predicted spectrum of the pressure-time waveform to those actually measured by the hydrophone immersed in the field produced by the 10 MHz source used here, the sensitivity of the hydrophone probe was determined at 10 MHz intervals, up to 100 MHz (see Fig.3). The 10 MHz interval resolution could be improved by using several acoustic sources operating at different center frequencies or by using a more versatile, wideband source, that could be activated with the excitation signal wobbling around the center frequency.
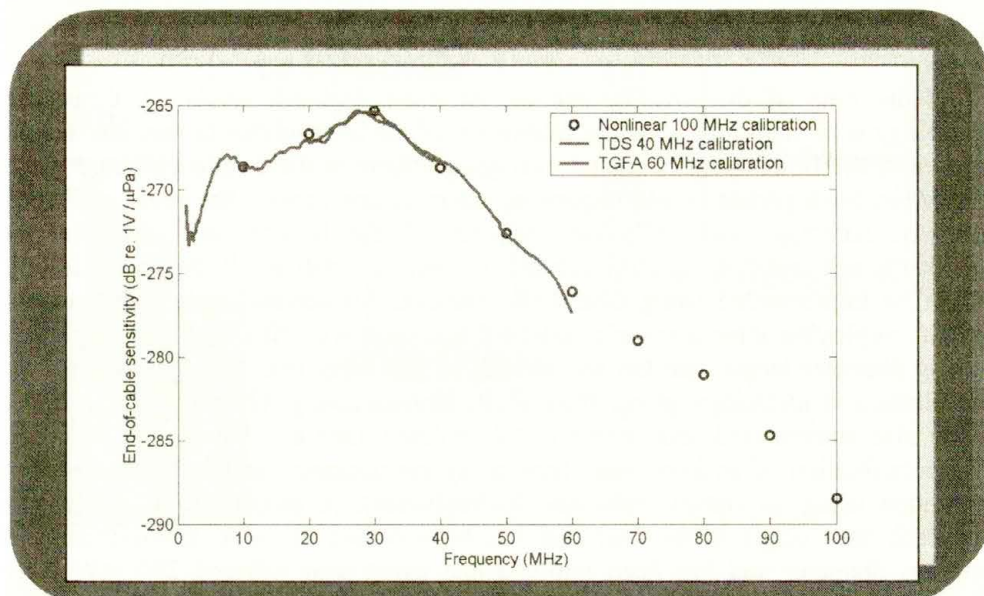
Figure 3. An example of the high frequency hydrophone calibration obtained utilizing the nonlinear wave propagation effects. A 500 microns diameter co-planar membrane hydrophone calibrated by NPL, UK was used as a reference. For comparison, the results obtained using the Time Delay Spectrometry (TDS) and Time Gating Frequency Analysis TGFA are also shown. After [8].

4. Finite aperture effects

The ideal ultrasound hydrophone probe should behave as a point receiver to eliminate any disturbance of the sampled or probed field, however, all of the hydrophones available in practice exhibit finite aperture that imposes certain limitations on the calibration techniques described above. Particularly, the spatial averaging effects have to be accounted for when the calibration is carried out in focused fields and when the reference hydrophone diameter differs from that of the calibrated hydrophone [11]. Ignoring the spatial averaging effects can lead to underestimation of acoustic output parameters used to compare the safety indicators associated with different diagnostic ultrasound imaging systems. A discrepancy of up to 40% in determination of Pulse Intensity Integral (PII) using the pressure-time waveform measured by, respectively, 200 and 500 micron diameter hydrophone probes was reported in [11]. One way to minimize the effects of spatial averaging is to take advantage of acousto-optic techniques and fiber optic sensors described in the next section.

5. Acousto-optic calibration

At the time of this writing one of the most desirable goals of ultrasound metrology is to obtain the absolute calibration of the hydrophone probes that would be free of the finite aperture spatial averaging effects in the frequency range up to 100 MHz. Such probes would require an effective aperture on the order of 7 or 8 microns. Although such effective diameter of the hydrophone probe is not practically achievable using conventional piezoelectric polymer hydrophone design, it can be implemented using fiber optic sensors. An acousto-optic measurement system employing interferometric approach and used with fiber optic hydrophones having diameter larger than the wavelength at 100 MHz was already proposed by the ultrasound metrology group from PTB, Braunschweig, Germany and is most likely also summarized somewhere in this volume, (see e.g. Koch and Wilkens, Phase calibration of hydrophones: time delay spectrometry and broad band-pulse technique using an optical reference hydrophones). A modification of the this approach uses single mode fiber that has been etched down to approximately 8 microns diameter and has been implemented using near infrared 250 mW laser source. In the initial experiments the fiber optic (FO) hydrophone probe was immersed in the nonlinear field (see above) and the magnitude spectrum received by the probe was compared with the one predicted using the nonlinear propagation model [10]. The preliminary experiments indicated FO probe's sensitivity on the order of -310 dB re 1V/microPa, which, in general, is insufficient in measurement practice and efforts are underway to boost this value.

6. Time Reversed Acoustics calibration

In addition to optimizing acousto-optic calibration methods and fiber optic hydrophone measurement arrangement, recently, a new calibration approach based on Time Reversed Acoustics (TRA) [12-16] was developed. Briefly, the TRA method provides an elegant and effective way of spatial and temporal concentration of acoustic energy. Although the TRA calibration requires also a reference hydrophone it can be carried out swiftly in small arbitrarily shaped reverberating containers and, due to the focusing properties of TRA, does not require the two, reference and unknown, hydrophone probes to be positioned in exactly the same point in the acoustic field, the TRA system provides focusing to the hydrophone and the amplitude of the focused signal does not change even for a significant change in the hydrophone position. Fig. 4 shows the experimental set-up using a water tank with an acoustic source made of PZT ceramic disk glued to an aluminum cylinder resonator.
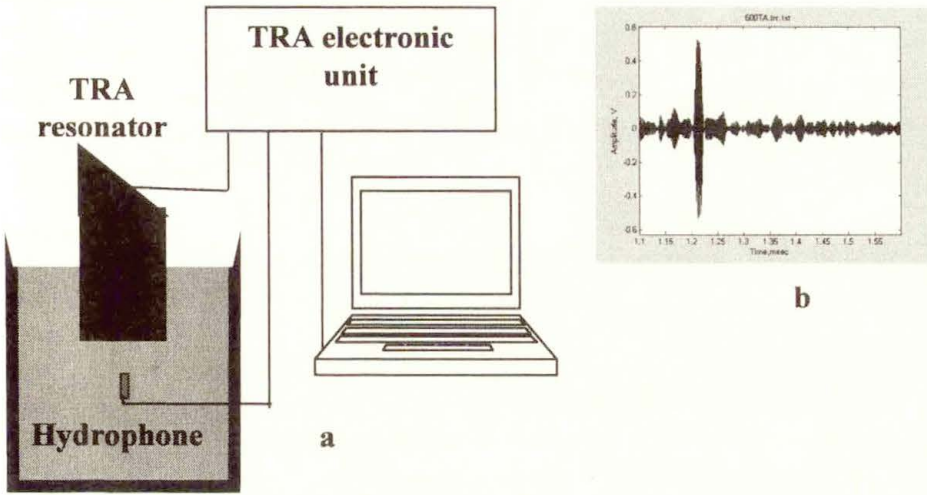
Figure 4. Time Reversed Acoustics (TRA) measurement arrangement (a) and example of the TRA focused signal (b).

The heart of the system is the TRA electronics that controls the calibration procedure. The calibration is conducted in the following way. First, an electrical RF pulse is applied to the PZT transducer, which radiates ultrasonic energy into the resonator; the resonator reradiates the long reverberation signal into water tank. Next, this reverberation signal is recorded by the hydrophone, time reversed, conditioned (i.e. amplified and normalized), applied again to the PZT source and the TRA focused signal is once more recorded by the hydrophone. An example of the received TRA signal is shown in Fig.4b. The amplitude of the focused signals obtained from the reference and tested hydrophones at different frequencies are compared and eventually the absolute sensitivity of the unknown hydrophone is determined in the way similar to the one described above for other methods of calibration by substitution.

A comparison of the sensitivity obtained using the Time Delay Spectrometry and the Time Reversed Acoustics approaches is shown in Fig. 5. The measurement bandwidth was limited to frequencies in the range from 250 kHz to about 1.5 MHz. This relatively low frequency bandwidth was due to limited frequency responses of the PZT disks available for the experiments. The bandwidth can be extended by using wideband PZT sources.
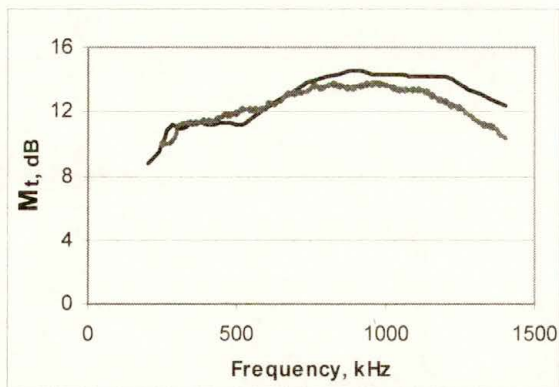
Figure 5. A comparison of the relative sensitivity M, obtained using the Time Delay Spectrometry and Time Reversed Acoustics approaches. TDS: top line at 1.3 MHz, TRA: bottom line at 1.3 MHz.

As it can be seen from Fig. 5, at this time the agreement is far from being satisfactory and the reason for the up to 2 dB discrepancy is not fully understood. However, to the best of the authors' knowledge the data of Fig. 5 represent the results of the very first efforts to apply the TRA to calibration of hydrophones. Also, an initial examination of the results indicates that the measurement uncertainty and the frequency range of the TRA approach depends on the appropriate design of the phase inverter, associated power amplifier characteristics, such as linearity, and the achievable signal-to-noise ratio. Currently, in addition to examining the reason for the calibration discrepancy observed and establishing the fundamental limitations of the TRA approach in ultrasound hydrophone probe calibration, the TRA bandwidth is being extended. As already noted – due to the self-focusing provided by emitting time reversed signal - the hydrophones can be positioned arbitrarily in the water container and the method holds promise to provide yet another effective tool of hydrophone calibration.

7. Conclusions

Currently used primary and secondary calibration methods of ultrasound hydrophone probes were summarized. It was demonstrated that when carefully executed the methods could successfully provide calibration data up to 100 MHz. The overall uncertainty of the calibration depended on the frequency range and the specific method used. Usually, the uncertainty increased with increasing frequency. The most likely future technologies for calibration and sensing of acoustic fields were also discussed. A novel application of the Time Reversed Acoustics was presented and it was shown that the method, when fully developed could provide yet additional effective and swift way of calibration of hydrophone probes' by substitution in reflective environment. Future research priorities were also briefly outlined and it was indicated that the high frequency calibration in the vicinity of 100 MHz would require the use of acousto-optic methods. Moreover, in order to

minimize the measurement errors caused by the finite aperture of the currently available polymer hydrophone probes the development of fiber optic probes will be needed. Such probes, as noted above, can have effective aperture on the order of 8 microns that practically eliminates the need for spatial averaging corrections when sampling 100 MHz fields. Also, it could be expected that the fiber optic hydrophones would exhibit a zero phase shift in the wide bandwidth.

Acknowledgements

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