Wideband Spherically Focused PVDF Acoustic Sources for Calibration of Ultrasound Hydrophone Probes

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***Abstract*—Several broadband sources have been developed for the purpose of calibrating hydrophones. The specific configuration described is intended for the calibration of hydrophones in a frequency range of 1 to 40 MHz. All devices used 25 μm film of PVDF bonded to a matched backing. Two had radii of curvatures (ROC) of 25.4 and 127 mm with f numbers of 3.8 and 19, respectively. Their active element diameter was 0.26 in (6.60 mm). The active diameter of the third source used was 25 mm, and it had an ROC of 254 mm and an f number of 10. The use of a focused element minimized frequency-dependent diffraction effects, resulting in a smooth variation of acoustic pressure at the focus from 1 to 40 MHz. Also, using a focused PVDF source permitted calibrations above 20 MHz without resorting to harmonic generation via nonlinear propagation.**

I. Introduction

Modern medical imaging equipment now is using ultrasound frequencies as high as 40 MHz. All clinically employed imaging equipment requires characterization in terms of its acoustic output and display of mechanical and thermal indices [1]. According to the recently published AIUM/NEMA standards and FDA guidelines [2], [3], it is recommended that ultrasound hydrophone probes be calibrated to eight times the center frequency of the imaging transducer or at least as high as 40 MHz. These upper frequency limits have been introduced to take into account nonlinear propagation phenomena, which lead to the presence of harmonics in the pressure-time waveform generated in the examined tissue. Typically, the hydrophone probes used in ultrasound exposimetry measurements have a calibrated frequency range of 1 to 20 MHz. This is partly due to the fact that the calibration procedures beyond 20 MHz are extremely time-consuming and difficult to implement. Also, conventional PZT ceramic sources become fairly inefficient at such high frequencies [4], and, consequently, maintenance of adequate signal-to-noise ratio during calibration is difficult.

This paper describes very wideband piezoelectric PVDF polymer acoustic sources, that operate in the frequency range from 1 to 40 MHz. The properties of a wideband, plane piston-like design PVDF polymer sources were described in [4]. In contrast, this paper describes the design, construction, and performance of focused PVDF sources, especially developed to optimize hydrophone calibration procedures in the frequency range up to 40 MHz. Although the sources described in this work can be used at frequencies beyond 40 MHz, this frequency is the upper cut-off frequency of the spectrum analyzer used here.

In the next section, the construction of the focused wideband PVDF sources is described. In Section III, the advantages and fundamental design limitations of a focused source are discussed. Section IV contains a brief outline of the measurement arrangement used and the results of the sensitivity calibrations of selected PVDF hydrophone probes in the frequency range from 1 to 40 MHz. It is shown that the PVDF sources developed, when used in a swept-frequency calibration system, offer a rapid, virtually continuous frequency determination of the sensitivity of the hydrophone probes versus frequency. The sources have a signal-to-noise ratio better than 30 dB at relatively low excitation voltages. In the measurements carried out here, the maximum excitation voltage was approximately $10V_{pp}$ to maximize the long-term stability of the sources. The design described also may be well suited for calibration of hydrophones used in nonlinear propagation measurement because high voltage excitation of the PVDF will lead to generation of harmonics.

The concept of using a focusing source for hydrophone calibration has been suggested in [5]–[9]. For example, Lum *et al.* [5], [6] describe a nonlinear procedure carried out at discrete frequencies based on producing a distorted pressure-time waveform with high harmonic content. This method was used to estimate frequency response, bandwidth, and angular response of high frequency hydrophones. Also, an interferometric procedure reported in [8] utilized focused transducers and harmonic generation via nonlinear propagation. Recently, Bleeker and Lewin [9] proposed a novel calibration technique for miniature ultrasound hydrophone probes using the KZK time domain finite difference approach. The method also requires the use of a focused source for generation of harmonics. In this context, it is worthwhile to note that the use of time delay spectrometry (TDS) [10], [11] with a wideband, spherically focused source makes it possible to perform high frequency hydrophone calibration without resorting to nonlinear phenomena.

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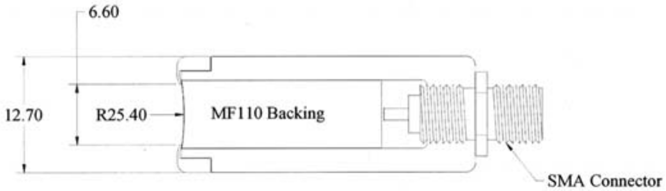

Fig. 1. Schematic construction of the focused polymer source with focal number 4. Two similar sources with f numbers 10 and 20 also were used (dimensions in mm).

II. Design Details

Wideband PVDF transmitters already have been designed and tested by Lewin and Schafer [4], who showed that the plane PVDF transducer was capable of operating up to 40 MHz. However, focused transducer construction offers several advantages in comparison with the unfocused plane piston design tested in [4]. Focusing improves hydrophone signal-to-noise ratio and, providing the measurements are made in the focal plane, offers plane wave conditions at the measurement site. Furthermore, it minimizes diffraction effects, which is especially advantageous when used over a wide frequency range. This feature makes it particularly useful as a source in swept frequency hydrophone calibrations based on the use of the TDS.

Three sources with focal numbers of approximately 4, 10, and 20 were used to obtain the results presented. (The actual values were 3.84, 10.16, and 19.24.) The influence of f number on the calibration procedure is discussed in the next section. The construction of the sources was identical to that shown schematically in Fig. 1 (f number, 4). The piezoelectric element made from 25 μ PVDF film was bonded to a concave-shaped backing material (Ecosorb MF110; Emerson Cummings, Canton, MA) with an ROC of 1.00 in or 2.54 cm. The f number 20 source had an ROC of 12.7 cm (5 in) and a diameter equal to 6.6 mm. The f number 10 source had an ROC of 254 mm (10 in) and a diameter equal to 25 mm. The frequency response of the 25-μ film depends heavily on the acoustic impedance of the backing [4]. In the design tested here, the acoustic impedance of the backing was 4.20×10^6 Ns/m^3, closely matched to the PVDF film, thereby ensuring the useable bandwidth beyond 40 MHz. The useable frequency range of 25-μ film may be as high as 70 MHz as it will become half wave resonant at around 45 MHz. A thin layer of parylene was applied to protect the transducers from the ravages of clean, deionized water.

The polymer material comes prepoled by corona discharge and is not electroded by the manufacturer. Front electrical contact is made using an evaporated gold film with a 2000-Åthickness, which creates the outer electrode. The backing is metalized prior to assembly and functions as the back electrode. The housing comprises a copper-plated phenolic, and electrical termination is accomplished either by using the SMA connector, as shown in Fig. 1, or by providing direct connection to a RG174 coax cable terminated by a BNC connector. The evaporated film thickness has been found to have significant effects on acoustic performance above 100 MHz.

III. Benefits of Using a Focused Source

When an unfocused plane piston source is used, the ratio of transmit voltage to acoustic pressure at any point is typically a complicated function of frequency because of diffraction effects. Specifically, the pressure at any point in the field is [12]:

$$p(r,\theta,t) = j \cdot \frac{\rho_0 c U_0 k}{2\pi} \int_S \frac{e^{j(\omega t - kr')}}{r'} \cdot dS \qquad (1)$$

where ρ_0 is the density of the fluid in front of the transducer, r$'$ is the distance from a given dS on the source surface S to the point in the field of interest, c is the plane wave acoustic velocity in this fluid, U_0 is the normal velocity of the source surface (assumed constant over the aperture), and k is $2\pi/\lambda$ where λ is the acoustic wavelength in the fluid.

Using (1) to approximate the field of a focusing source, it is observed that when the point of interest is at the center of curvature of a spherically focused source, r$'$ becomes a constant with respect to dS, and the integral's frequency dependence is only due to propagation delays. Ultimately, this means that there is no frequency dependence caused by diffraction at the center of curvature.

A transfer function free of diffraction effects can simplify calibration procedures, and focusing enhances the hydrophone signal-to-noise ratio during measurements. Eq. (2) shows that such a function can be implemented by using a focused source [13]:

$$p(0,D) = \frac{-jka^2}{2D} p_0 \exp(jkD) \qquad (2)$$

where p_0 is $\rho_0 c_0 u_0$ and D is the focal length or ROC of the source. At the focal length or center of curvature, pressure is linearly dependent on frequency and does not contain the multiple nulls of an unfocused beam.

The lateral–3-dB beamwidth at the focal distance or in the focal plane is approximately equal to the product of wavelength and focal number, f_n [13, eq.(25)]. Large f number sources are preferable because the larger the f number, the wider the lateral beamwidth. This is important because the beamwidth should encompass the effective aperture of the measured hydrophone at the highest frequency of interest to avoid rapid spatial variations in pressure over the hydrophone element. Fortunately, large f number devices are easier to build than more tightly focused devices. Also, it is possible to do calibrations deeper than the focus to achieve a more spatially uniform field when working with larger aperture hydrophones.

To minimize the spatial averaging error, ideally the–1-dB lateral beamwidth at the highest frequency of interest should be larger than or equal to the effective diameter

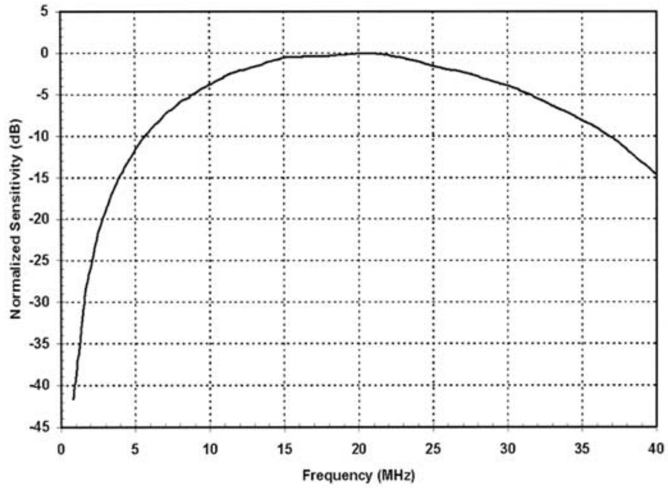

Fig. 2. Combined normalized frequency response of a 0.5-mm diameter coplanar-shielded membrane hydrophone and wideband focused PVDF (source f number, 20).

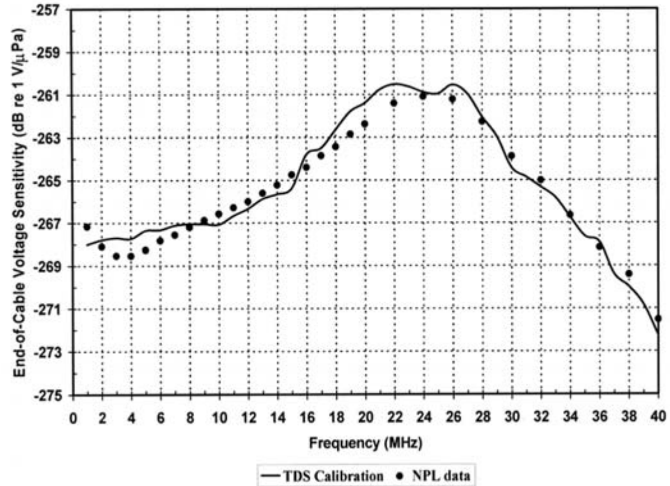

Fig. 3. Frequency response of a 0.5-mm diameter bilaminar PVDF membrane hydrophone. · = NPL data; ——— = this work (continuous TDS calibration).

of the hydrophone. The lateral–1-dB beamwidth of the focal number 20 source at 40 MHz was measured to be 0.51 mm. The measurement was done with a PVDF needle hydrophone with an effective diameter of 150 μ. This is in agreement with theoretical calculations obtained using the Jinc function [13, eq.(24)].

Frequency response measurements on the focused sources were carried out using the TDS technique, the details of which can be found in [10], [11]. The signal was swept in the frequency range 1 to 40 MHz, and the hydrophone was positioned in the focal region. The TDS parameters were adjusted so that a reflection-free environment was ensured [10], [11]. The measurements were carried out in a water tank with dimensions of approximately $75 \times 45 \times 60$ cm in degassed and deionized water.

IV. Results

Fig. 2 shows the normalized combined frequency responses of a single-layer, 25-μ thick PVDF membrane hydrophone with an active electrode diameter of 0.5 mm (coplanar-shielded design; GEC-Marconi, UK) and the spherically focused PVDF source ($f_n = 20$). As expected, the acoustic output of the focused source was adequate for calibration of the hydrophones in the frequency range from 1 to 40 MHz. It should be noted that the combined frequency responses include several effects. These are a) the effect of the frequency response of the hydrophone probe, b) the effective diameter of the hydrophone probe, and c) the frequency-dependent loading effects of the power amplifier (here an ENI 240L, Rochester, NY) used to drive the focused source. As mentioned, the maximum driving voltage was approximately 10 V_{pp} to maximize long-term stability of the source.

A. Examples of Hydrophone Calibrations

Fig. 3 shows the calibration results for a 0.5-mm diameter, bilaminar (50-μ thick) PVDF membrane hydrophone (GEC-Marconi, UK). The continuous frequency response of the bilaminar membrane hydrophone was obtained with TDS/reciprocity calibration [10], [11] (solid line). The plot with discrete calibration points was provided by a national reference laboratory (National Physical Laboratory, UK). This plot is in excellent agreement with the TDS/reciprocity data. The largest discrepancy of about 1.3 dB is observed at approximately 20 MHz.

Fig. 4 shows the calibration results of a 150-μ nominal diameter needle PVDF hydrophone (Specialty Engineering Associates, Soquel, CA) with a built-in preamplifier in the frequency range from 1 to 40 MHz. The hydrophone was calibrated using the TDS substitution technique and the focused PVDF source ($f_n = 20$). In this calibration, a 25-μ coplanar shielded PVDF membrane hydrophone (GEC-Marconi, UK) served as a reference hydrophone. All measurements were repeated four times in 48-h intervals to minimize the overall uncertainty. In the low frequency range, the effect of a spurious resonance is visible [14], but the hydrophone's frequency response is essentially flat and uniform beyond 8 MHz.

A new type of hydrophone is currently under development to minimize the effects of spurious resonances such as those observed in the low megahertz range (Fig. 4). This new device is basically a membrane style hydrophone built on the end of an ellipsoid of lossy epoxy [15]. The active element in the device is defined by the end of an axial wire, which is perpendicular to the 12-μ copolymer film bonded to the tip of the device. This configuration has the advantage of minimal shunt capacitance, excellent shielding, and reduction of spurious artifacts in the frequency response caused by surface waves because any surface waves generated by incident ultrasound propagate

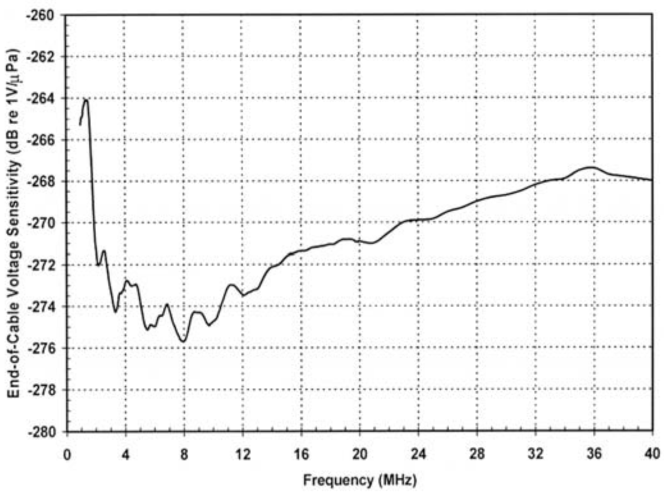

Fig. 4. Frequency response of a 150-μ effective diameter Specialty Engineering Associates needle PVDF hydrophone with a built-in preamplifier.

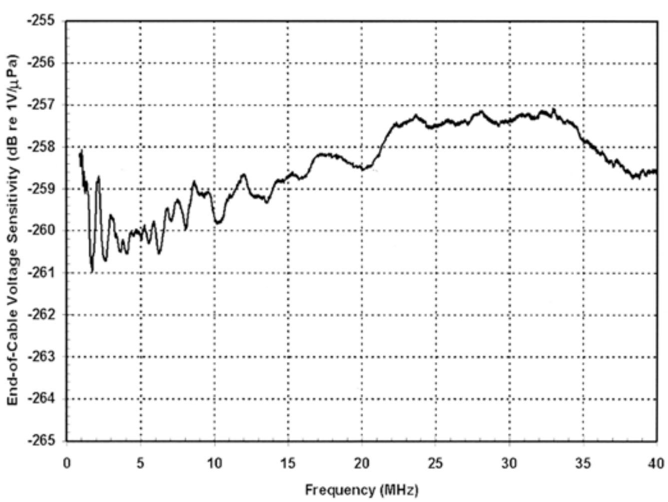

Fig. 5. Frequency response of a new 130-μ effective diameter "Golden Lipstick" hydrophone (Specialty Engineering Associates, Soquel, CA) as measured using focused PVDF source ($f_n = 20$).

around the elliptical cross section without reflection. The shielding currently in use is an evaporated gold film over the front end of the device. This gives the device the appearance of being a "golden lipstick," and, hence, it is referred to as the "GL" model. Active element sizes as small as 25 μm have been tested; typical active element sizes are 400 μm; larger apertures are available. A calibration of one of the recently manufactured GL devices with an effective diameter of 130 μ is shown in Fig. 5 and indicates that the hydrophone sensitivity varies no more than +/−2 dB from 1 to 40 MHz.

V. Discussion and Conclusions

The results presented here indicate that the new spherically focused PVDF sources produce an acoustically useful output in the frequency range 1 to 40 MHz. By weakly focusing the sources, it was possible to minimize the diffraction effects, which degrade the performance of plane piston sources in the near field. By combining the features of PVDF films and a weakly focused aperture, it is possible to obtain a smooth frequency response and a reasonable pressure level useful for the broadband calibration of hydrophones.

The purpose of this work was to demonstrate that wideband focused sources provide a useful tool for calibration of ultrasonic hydrophone probes at frequencies beyond 20 MHz without resorting to nonlinear phenomena. Focused sources require a much smaller water path to the hydrophone than unfocused ones. This is advantageous because with a plane source, it is difficult to maintain adequate hydrophone signal-to-noise ratio. With increasing frequency for a given source aperture, the near/far field transition distance increases, and there is also excessive attenuation of the signal because of water absorption. In the measurements reported here, hydrophone S/N ratio was typically higher than 30 dB in the frequency range from 1 to 40 MHz.

However, the finite aperture of the hydrophone imposes certain limitations on the calibration procedure described. When a finite size hydrophone is placed at the focal point of a focused source, diffraction in reception occurs because, in the geometrical focal plane of a focused source, the focused lateral beam profile is governed by a Jinc function [13], [16]. This means that the average pressure received over the hydrophone front face will vary with frequency, acoustic velocity, and the f number of the focused source. Hence, the task in designing a source for hydrophone calibration is either to minimize the effects of diffraction or to know exactly what they are and correct the received hydrophone signal for these known effects. As already mentioned, to minimize the effects of diffraction, the calibration performed with different effective diameter hydrophone probes was carried out with the focused source having an f number of 20.

Theoretical prediction of diffraction effects for an unfocused, plane piston source was recently discussed in [17]. The development of a theory for hydrophone reception at the focal point of a focused source is beyond the scope of this paper. In the approach presented here, the effects of diffraction were minimized by performing the hydrophone calibration using an appropriate focal number and effective hydrophone aperture. However, the diffraction model applicable to focused source is under development [18], and the experimental data obtained with different f number sources and different hydrophone apertures will be used to validate the model.

The focused sources feature robust design, excellent stability over time (better than +/ − 1 dB at 40 MHz), and are well suited for a rapid calibration technique based on swept signal excitation. Furthermore, the PVDF sources described previously, when driven at sufficiently high excitation voltage, can generate harmonics and may be applicable to the calibration of hydrophones used for nonlinear propagation phenomena measurements [5]. Currently, efforts are being directed toward extending the applicability of the focused sources to produce acoustically useful output in the frequency range up to 100 MHz and investigating the possibility of calibrating the sources in terms of Pa/V using interferometric approaches [8].

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