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Considerations for Choosing Sensitive Element Size for Needle and Fiber-Optic Hydrophones II: Experimental Validation of Spatial Averaging Model

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Abstract

Acoustic pressure can be measured with a hydrophone. Hydrophone measurements can underestimate incident acoustic pressure due to spatial averaging effects across the hydrophone sensitive element. The spatial averaging filter for a nonlinear focused beam is a low-pass filter that decreases monotonically from 1 to 0 as frequency increases from 0 to infinity. Experiments were performed to test an analytic model for the spatial averaging filter. Nonlinear pressure tone bursts were generated by three source transducers with driving frequencies ranging from 2.5 MHz to 6 MHz, diameters ranging from 19 mm to 64 mm, and focal lengths ranging from 38 mm to 89 mm. The nonlinear pressure fields were measured using four needle hydrophones with nominal geometrical sensitive element diameters of 200, 400, 600, and 1000 μm . The average root-mean-square difference (RMSD) between theoretical and experimental spatial averaging filters was $5.8 \pm 2.6\%$.

Keywords

Acoustic output measurement; hydrophone; needle; fiber optic; spatial averaging; spatiotemporal transfer function

I. Introduction

Needle and fiber-optic hydrophones are widely utilized in medical ultrasound and nondestructive evaluation to measure acoustic pressure with high spatial resolution [1–10]. Like most measurement devices, hydrophones produce distorted versions of the signals they are intended to measure. Hydrophone distortion is mainly due to two factors: frequency-dependent sensitivity and spatial averaging across the finite sensitive element. Both forms of distortion tend to increase with signal nonlinearity because nonlinear signals have broad frequency bands spanned by multiple harmonics of the fundamental frequency. Nonlinearity

affects spatial averaging because as harmonic frequency increases, harmonic beam width decreases, and the potential for harmonic spatial averaging increases.

Previously, a model was developed for predicting distortion of nonlinear ultrasound signals by needle and reflectance-based fiber-optic hydrophones [11]. The model was based on a spatiotemporal representation of ultrasound signals involving nonlinear theory for spectral characteristics [12] and Gaussian radial pressure distributions within the spatial extent of the hydrophone sensitive element [13–15]. The spatiotemporal representation was validated using high-resolution (85 μm) hydrophone measurements in focal planes of three source transducers. The model was based on a rigid piston (RP) model [16, 17] for hydrophone response. The RP model has been shown to be accurate for predicting sensitivity of needle hydrophones in the low frequency range [18, 19] and reflectance-based fiber-optic hydrophones over a broader frequency range [19]. The RP model has also been shown to be accurate for predicting directivity and frequency-dependent effective sensitive element size of needle [20] and reflectance-based fiber-optic [21] hydrophones. The objective of the present paper is to provide experimental validation for the model prediction of spatial averaging component of distortion.

The hydrophone spatiotemporal response, $H_p(f)$, is assumed to be separable into a product of spatial and temporal factors.

$$H_p(f) = M_L(f)S_p(f) \quad (1)$$

where f is frequency, $M_L(f)$ is the loaded sensitivity of the hydrophone, defined as the frequency-domain voltage output response $V(f)$ to normally-incident input plane pressure wave $P_{NP}(f)$

$$M_L(f) = \frac{V(f)}{P_{NP}(f)} \quad (2)$$

and $S_p(f)$ is a filter that accounts for spatial averaging. The subscript p is a reminder that a function depends on the particular pressure field distribution $p(r, f)$ incident upon the hydrophone and r is the radial coordinate. The separability assumption was shown to be valid for a wide variety of transducers and hydrophones [11]. The effects of $M_L(f)$ on pressure measurements has already been investigated extensively [19, 22–28].

The objective of the present paper is to provide experimental validation for the theoretical model for $S_p(f)$. Seven nonlinear test signals with frequencies ranging from 2.5 to 6 MHz were generated using circular, concave transducers that produced focused beams. Each nonlinear test signal was measured with four different hydrophones with nominal geometrical sensitive element diameters of 200, 400, 600, and 1000 μm . Experimental spatial averaging filters were computed from this dataset and compared with theoretical forms.

II. Methods

A. Spatial Averaging Filter

The reduction in measured pressure due to spatial averaging across the hydrophone sensitive element is given by the integral of the pressure wave divided by the effective area of the sensitive element [29–33]. When the effective hydrophone sensitive element radius a_{eff} depends on frequency, a spatial averaging filter may be written as [11]

$$S_p(f) = \frac{\int_0^{2\pi} \int_0^{a_{eff}(f)} p(r, f) r dr d\theta}{\pi a_{eff}^2(f)} \quad (3)$$

Harmonic pressure fields and frequency-dependent hydrophone effective sensitive element radii may be computed according to the model described previously [11].

It is assumed that the harmonic radial profiles are Gaussian within the spatial extent of the hydrophone sensitive element. It can be shown that for Gaussian harmonic beams,

$$S_p(f) = \frac{1}{\Omega_n^2(f)} [1 - e^{-\Omega_n^2(f)}] \quad (4)$$

Where

$$\Omega_n^2(f) = \frac{a_{eff}^2(f)}{2\sigma_n^2} \quad (5)$$

and the radial profile of each harmonic component of the nonlinear beam is given by

$$w_n(r) = \exp(ig_n r^2) \exp\left[-\frac{r^2}{2\sigma_n^2}\right] \quad (6)$$

where n is the harmonic number [11]. The coefficient g_n is related to the rate of phase change with radial coordinate. The full width half maximum (FWHM) of each harmonic component is $\sigma_n 2\sqrt{2\ln 2}$. A form for σ_1 in the focal plane of a circular focused piston transducer under classic-jinc-fundamental (CJF) conditions may be found by minimizing the mean-square difference between the magnitudes of (6) and the classic diffraction theoretical form over the half width half maximum (HWHM) of the beam [34], which results in $\sigma_1 = 1.93 D / (k_I a_s)$ in the focal plane, where D = focal length, $k_I = 2\pi / \lambda_1$, λ_1 is the wavelength of the fundamental component of the beam, and a_s is the radius of the source [11]. The harmonic beam width parameter may be extended to higher harmonics by postulating that $\sigma_n = \sigma_1 / n^q$ [11, 13–15, 35, 36]. It was shown in the previous paper [11] that the power law form was valid for six circular focused transducer geometries provided that the nonlinear propagation parameter [37] $\sigma_m < 2.4$, which corresponded approximately and conservatively to the local distortion parameter [38] $\sigma_q < 3$ and the spectral index SI (the fraction of energy

contained in harmonics above the fundamental) [39] values < 0.4 . In this range of SI values, q mostly falls in the range between 0.6 and 0.8 [11].

The formula for the frequency-dependent effective sensitive element radius for an RP hydrophone was [11]

$$\frac{a_{eff} - a_g}{a_g} = A e^{-Bka_g} \quad (7)$$

where a_g is the geometrical radius of the hydrophone sensitive element. The coefficients A and B depend weakly on the effective range of angle θ in the angular spectrum of the beam. A varies from 1.81 ($|\theta| < 10^\circ$) to 2.13 ($|\theta| < 90^\circ$). B varies from 1.07 ($|\theta| < 10^\circ$) to 0.94 ($|\theta| < 90^\circ$). The values chosen were $A = 1.85$ and $B = 1.05$, corresponding to $|\theta| < 30^\circ$ [11].

B. Substitution Experiment

If the pressure field incident upon a hydrophone has a spectrum, $P_p(f)$, then the hydrophone output voltage may be expressed as

$$V_p(f) = M_L(f) S_p(f) P_p(f) \quad (8)$$

Substitution experiments were conducted in which each of four hydrophones was exposed to the same nonlinear tone burst with spectrum $P_p(f)$ for each of 7 tone burst signals. For any pair of hydrophones (that may be labeled 1 and 2) measuring the same tone burst signal,

$$S_{p2}(f) = \frac{V_{p2}(f)/M_{L2}(f)}{V_{p1}(f)/M_{L1}(f)} S_{p1}(f) \quad (9)$$

The quotients of functions in the numerator and denominator, $V_{p1}(f)/M_{L1}(f)$ may be regarded as voltage spectra that have been deconvolved for hydrophone sensitivities [40]. Hydrophone 1 (the reference hydrophone) was always the hydrophone with the smallest geometrical sensitive element diameter, 200 μm (HNC-0200, Onda Corp., Sunnyvale, CA), and therefore the smallest spatial averaging effect. The spatial averaging filter $S_{p2}(f)$ for Hydrophone 2 was evaluated from (8) as follows. Voltage response $V_{p1}(t)$ was measured by using Hydrophone 1 to receive a nonlinear tone burst pressure wave at the focal point of a circular focused transducer (*i.e.*, radius of curvature of the transducer surface). Voltage response $V_{p2}(t)$ was measured by replacing Hydrophone 1 with Hydrophone 2 and repeating the measurement. Spectra of time domain voltage responses $V_{p1}(f)$ and $V_{p2}(f)$ were estimated using the Fast Fourier Transform (FFT). Complete, rectangular-windowed tone bursts (rather than windowed intervals from the middle) were analyzed. Sensitivities $M_{L1}(f)$ and $M_{L2}(f)$ were measured from 1 MHz to 40 MHz using time delay spectrometry [41] for the following hydrophones: Onda HNC-0200, Onda HNA-0400, and Force Technology Institute (FTI, Bondby, DK) custom hydrophone (referred to here as DAN-0600 (see Table I). Sensitivity for the Onda HNP-1000 was taken from the manufacturer specification from 1 MHz to 20 MHz. For frequencies between 20 MHz and 30 MHz, the HNP-1000 manufacturer-specified sensitivity was linearly extrapolated. The theoretical spatial averaging filter $S_{p1}(f)$ for Hydrophone 1 was computed from (4) assuming CJF conditions

and $q = 0.8$. The measured spatial averaging filter $S_p(\chi, f)$, for Hydrophone 2 computed from (8) could then be compared with the theoretical spatial averaging filter for Hydrophone 2 computed from (4).

In order to isolate variations due to spatial averaging effects, each empirical frequency-dependent spatial averaging filter function was scaled so that its average value over the range of harmonic frequencies measured was equal to the average value of the theoretical spatial averaging filter over the same range of frequencies. This eliminated discrepancies due to uncertainties in sensitivity magnitude, which has been reported to be on the order of ten percent [29]. There are many sources of uncertainty in hydrophone sensitivity including initial calibration uncertainty, dependence of sensitivity with temperature, and drift over time.

Theoretical predictions of spatial averaging filters required knowledge of geometrical sensitive element sizes of hydrophones to be used as inputs to the RP model [16, 17]. Two experimental methods were used to estimate geometrical sensitive element sizes: RP-model fits to sensitivity measurements [19] and RP-model fits to directivity measurements [20]. For each hydrophone, the mean of these two estimates was used as an input (a_g) in (7) to compute frequency-dependent effective sensitive element radius (a_{eff}) to be used in (4) to obtain the theoretical spatial averaging filter.

Sensitivity-based geometrical sensitive element size estimates for three hydrophones (HNC-0200, HNA-0400, DAN-0600), were determined by fitting sensitivity measurements to theoretical RP sensitivities with geometrical sensitive element size as an adjustable fitting parameter as previously reported [19]. This resulted in geometrical sensitive element diameters of 176 μm , 308 μm , and 584 μm as opposed to the nominal values of 200 μm , 400 μm , and 600 μm (see Table I). For the fourth hydrophone (HNP-1000), the nominal geometrical sensitive element diameter (1000 μm) was assumed for the following reasoning. The basic structure of RP sensitivity is a high-pass filter for frequencies up to $k_{max} a_g = 2.4$ or, equivalently, $f_{max} = 2.4 c / (\pi d_g)$ followed by relatively uniform behavior for frequencies above f_{max} [16, 18, 19]. Values of f_{max} corresponding to $d_g = 200, 400, 600$, and 1000 μm are 5.6, 2.8, 1.9 and 1.1 MHz. Empirical sensitivity data were only available for frequencies above 1 MHz. Therefore, the available sensitivity data for the HNP-1000 sampled only the relatively uniform portion of the sensitivity, making a curve-fit impractical.

Directivity-based geometrical sensitive element size estimates for all four hydrophones were determined by fitting directivity measurements to theoretical RP directivities with geometrical sensitive element size as an adjustable fitting parameter as previously reported [20]. For each hydrophone, this process was repeated for directivity measurements obtained at 1, 2, 3, 4, 6, 8 and 10 MHz, and the resulting geometrical sensitive element diameter estimates were averaged. This resulted in geometrical sensitive element diameters of 200 μm , 360 μm , 563 μm , and 966 μm as opposed to the nominal values of 200 μm , 400 μm , 600 μm , and 1000 μm (see Table I).

C. Experimental Methods

Table II lists the transducers used. The exponent q was estimated by fitting half-width HWHM to a power law proportional to $1/n^q$ as described previously [11].

A Tektronix (Beaverton, OR) AFG 3102 function generator was used to generate tone bursts containing 6-10 cycles of the driving frequency. Each source transducer was driven at its center frequency and perhaps one or two additional frequencies off resonance to expand the parameter space for the measurements. The output of the function generator was connected to an Amplifier Research (Souderton, PA) 150A 100B 150 Watt power amplifier. The output of the power amplifier was connected to the source transducer.

Each tone burst beam was measured at the transducer focal point using each of four hydrophones. Table I lists the four hydrophones. They included two ceramic hydrophones and two polymer (PVDF) hydrophones. The Onda HNA-0400 hydrophone is designed to accommodate therapeutic levels of acoustic output [4]. The hydrophones span a wide range of sensitive element diameters, from 200 to 1000 μm .

The nonlinearity metrics were $\sigma_m \sigma 0.7$, $\sigma_q < 0.9$, and $SI < 0.1$. The nonlinearity was high enough to ensure multiple detectable harmonics but low enough to prevent 1) significant risk of damage to hydrophones and 2) compromised measurements due to cavitation.

III. Results

Fig. 1 shows a tone burst from the Blatek transducer driven at 3.5 MHz and measured in the focal plane using the Onda HNC-0200 hydrophone. Fig. 2 shows the spectrum of this signal. The nonlinear nature of this signal results in peaks in spectrum at harmonics equal to integer multiples of the fundamental frequency at 3.5 MHz.

Figs 3–5 show measured and theoretical spatial averaging filters for the three source transducers driven with 2-3 function generator frequencies and measured with 3 hydrophones (HNA-0400, DAN-0600, and HNP-1000), always using the HNC-0200 as the reference. The theoretical spatial averaging filters are based on (20) (S_{Gaussian}) and (30) ($S_{\text{Quadratic}}$) in [11]. The vertical dashed lines denote the maximum frequencies of validity predicted by (33) in [11] for the spatial averaging filter derived from the quadratic model for harmonic radial profiles (30). S_{Gaussian} and $S_{\text{Quadratic}}$ in Figs 3–5 correspond to their counterparts in Figs 12 and 14 in [11].

As illustrated in Fig. 2, harmonic strength, and therefore signal-to-noise ratio (SNR), decreased with harmonic number. In Figs 3–5, only harmonics with adequate SNR are plotted. Although Fig. 2 shows 8 discernible harmonics for the HNC-0200 (and Blatek source transducer), the other hydrophones usually had fewer discernible harmonics because of increased spatial averaging reduction associated with larger sensitive element diameters. The Blatek transducer was less responsive at 2.5 MHz than at 3.5 MHz or 4.5 MHz, so fewer harmonics are plotted in the top row of Fig. 3 than in the lower two rows. The last three harmonics in the lower row of Fig. 4 appear relatively flat with frequency, perhaps due to diminished SNR.

The individual panels in Figs. 3–5 show that the spatial averaging filter is always a monotonically decreasing function of harmonic frequency. As hydrophone geometrical sensitive element diameter increases (moving from left panels toward right panels), spatial averaging filter magnitudes decrease as expected. The average root-mean-square differences (RMSD) between theoretical (S_{Gaussian}) and experimental spatial averaging filters were $6.0 \pm 3.0\%$ (Blatek), $5.7\% \pm 2.3\%$ (Panametrics 3.5 MHz) and $5.7\% \pm 2.4\%$ (Panametrics 5 MHz). The average RMSD for the three transducers combined was $5.8 \pm 2.6\%$.

Both models—without (S_{Gaussian}) and with ($S_{\text{Quadratic}}$) the quadratic approximation—are in good agreement for low harmonic number(s), with the number of harmonics in agreement varying from 1 to 5 depending on the transducer, driving frequency, and hydrophone geometrical sensitive element diameter. When the two models diverge from each other at higher harmonic numbers, the model without the quadratic approximation (S_{Gaussian}) is more consistent with the measurements.

IV. Discussion

Hydrophone measurements can underestimate incident acoustic pressure due to spatial averaging effects across the hydrophone sensitive element. This can be a concern for nonlinear fields with multiple harmonics, which are characterized by harmonic beam widths decreasing as harmonic number increases. Experiments were performed to test a theoretical model for the spatial averaging filter. Nonlinear pressure fields were generated by three source transducers in tone burst mode and measured using four needle hydrophones with nominal geometrical sensitive element diameters of 200, 400, 600, and 1000 μm . The average root-mean-square difference (RMSD) between theoretical and experimental spatial averaging filters was $5.8 \pm 2.6\%$.

The theoretical spatial averaging filter has been validated for a certain set of experimental conditions: 1) driving fundamental frequencies ranging from 2.6 MHz to 6 MHz, 2) transducer diameters ranging from 19 mm to 64 mm, 3) focal lengths ranging from 38 mm to 89 mm, 4) f-numbers ranging from 1.4 to 2.0, 5) $\sigma_m < 0.7$, $\sigma_q < 0.9$, $SI < 0.1$, and 6) harmonic numbers up to 6. These conditions are relevant to many nonlinear signals found in diagnostic ultrasound. Further experiments are required to expand the experimental parameter space for validation including smaller f-numbers, shorter pulses (such as those found in diagnostic B and M mode signals), higher nonlinearity and therefore larger numbers of harmonics (such as those found in HITU applications). Verification over a wider parameter space, including HITU applications, was considered by simulation previously [11]. The sensitivity deconvolutions performed in this study required knowledge of hydrophone sensitivities for frequencies up to about 30 MHz. Experimental studies with larger numbers of harmonics will require hydrophone sensitivity calibration to higher frequencies. This underscores the need for hydrophone sensitivity calibrations up to 40 MHz and beyond [22, 40, 42–47]. While the experiments here were performed with RP hydrophones, the spatial averaging analysis likely applies to non-RP hydrophones as well provided that spatial averaging filters are computed from spectra that are properly deconvolved for frequency-dependent sensitivity (which could be RP or non-RP, depending on the hydrophone).

The close agreement between theoretical and experimental spatial averaging filters supports many simplifying assumptions in the derivation of the analytic form for the spatial averaging filter, at least for the range of experimental conditions considered here. These assumptions include 1) hydrophone spatiotemporal response is separable into the product of a frequency-dependent sensitivity and a spatial averaging filter, 2) needle hydrophones can be accurately modeled as rigid pistons, 3) spatial averaging effects can be accurately modeled by integrating the magnitude of the beam over an effective sensitive element area, 4) nonlinear beams may be accurately modeled as having Gaussian radial profiles for harmonics (within the spatial extent of the hydrophone sensitive element) with beam widths falling off with harmonic number n as a power law $1/n^2$, and 5) the radial profile for the fundamental component of the nonlinear beam can be accurately approximated from the classic jinc diffraction pattern.

Previously, the spatial averaging correction method recommended by IEC 62127-1 Annex E [48] was extended to accommodate nonlinear beams with multiple harmonics [11]. The present paper provides experimental validation for this extension for numbers of harmonics ranging from 1 to 5, with the number of harmonics in agreement varying from 1 to 5 depending on the transducer, driving frequency, and hydrophone sensitive element diameter. The IEC 62127-1 Annex E approach, when extended to harmonics, requires that the harmonic beam profile may be accurately approximated as a parabola over the sensitive element of the hydrophone. This approximation gets weaker as harmonic number increases and harmonic beam width decreases. It should be noted that the IEC 62127-1 Annex E approach is based on the groundbreaking work of Preston *et al.* [29], which considered linear signals and was published before the dramatic rise in nonlinear applications that has transpired in recent decades. Preston *et al.* could not have reasonably been expected to anticipate the extent of the need for spatial averaging corrections for nonlinear beams that exists today.

Many papers have considered deconvolution of hydrophone sensitivity [22–27, 40] or corrections for spatial averaging [29–33, 49–54] but not both. The present paper and its companion paper [11] provide a comprehensive inverse-filtering framework to make both frequency-dependent corrections for RP hydrophones for all harmonics in nonlinear signals. The relative importance of the two distortions is illustrated in frequency domain for a variety of experimental parameter combinations in the Graphical Guide presented previously [11]. The relative importance of the two distortions for time domain metrics such as peak compressional pressure (p_+), peak rarefactional pressure (p_-) and pulse intensity integral (p_{ii}) is more complicated because it depends greatly on the spectrum of the incident pressure wave. The distorting effect of frequency-dependent sensitivity on time domain metrics has been investigated previously for SI up to 0.22 and pulse duration ranging from 1.5 to 7 cycles [19]. The distortion effects on p_+ and p_{ii} increase with SI and is maximum when d_g/λ_I is near 0.1 – 0.25 for pulse durations of 1.5 – 7 cycles [19]. The distorting effect on p_- is maximum when d_g/λ_I is near 0.6 for short pulses (1.5 cycles) and 0.4 for longer pulses (2.5 – 7 cycles) for SI up to 0.22 [19].

V. Conclusion

This paper provides experimental validation for a theoretical model for spatial averaging effects for nonlinear beams measured with hydrophones. Spatial averaging effects are characterized by a spatial averaging filter, which is a low-pass filter that decreases monotonically from 1 to 0 as frequency increases from 0 to infinity. The experiments considered moderately nonlinear beams. The experimental validation complements previous simulation verification that extended to a wider parameter space that included HITU applications.

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Biography

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REFERENCES

- [1]. Harris GR, "Progress in medical ultrasound exposimetry," IEEE Trans Ultrason Ferroelectr Freq Control, vol. 52, no. 5, pp. 717–36, 5 2005. [PubMed: 16048175]
- [2]. Szabo TL, Diagnostic Ultrasound Imaging: Inside Out, Second ed. Oxford, UK: Elsevier, 2014.
- [3]. Hynynen K et al., "500-element ultrasound phased array system for noninvasive focal surgery of the brain: a preliminary rabbit study with ex vivo human skulls," Magn Reson Med, vol. 52, no. 1, pp. 100–7, 7 2004. [PubMed: 15236372]
- [4]. Zanelli CI and Howard SM, "A robust hydrophone for HIFU metrology," (in English), Therapeutic Ultrasound, vol. 829, pp. 618–+, 2006.
- [5]. Canney MS, Bailey MR, Crum LA, Khokhlova VA, and Sapozhnikov OA, "Acoustic characterization of high intensity focused ultrasound fields: A combined measurement and modeling approach," (in English), J. Acoust. Soc. Am, vol. 124, no. 4, pp. 2406–2420, 10 2008. [PubMed: 19062878]
- [6]. Maxwell AD et al., "Cavitation clouds created by shock scattering from bubbles during histotripsy," (in English), J. Acoust. Soc. Am, vol. 130, no. 4, pp. 1888–1898, 10 2011. [PubMed: 21973343]
- [7]. Konofagou EE, "Optimization of the ultrasound-induced blood-brain barrier opening," Theranostics, vol. 2, no. 12, pp. 1223–37, 2012. [PubMed: 23382778]
- [8]. Kreider W et al., "Characterization of a Multi-Element Clinical HIFU System Using Acoustic Holography and Nonlinear Modeling," (in English), IEEE Trans Ultrason Ferroelectr Freq Control, vol. 60, no. 8, pp. 1683–1698, 8 2013. [PubMed: 25004539]
- [9]. Robertson JL, Cox BT, Jaros J, and Treeby BE, "Accurate simulation of transcranial ultrasound propagation for ultrasonic neuromodulation and stimulation," J Acoust Soc Am, vol. 141, no. 3, p. 1726, 3 2017. [PubMed: 28372121]
- [10]. Gopinath R. Broadband Fiber Optic Hydrophone Sensors for Sub-Millimeter Ultrasound Resolutions," (in English); 2008 International Topical Meetings on Microwave Photonics and 2008 Asia-Pacific Microwave Photonics Conference; 2008. 271
- [11]. Wear KA, "Considerations for choosing sensitive element size for needle and fiber-optic hydrophones I: Theory and graphical guide," IEEE Trans Ultrason Ferroelectr Freq Control, p. submitted, 2018.
- [12]. Blackstock DT, "Connection between the Fay and Fubini solutions for plane sound waves of finite amplitude," J. Acoust. Soc. Am, vol. 14, no. 2, pp. 1019–1026, 1966.
- [13]. Du G and Breazeale MA, "Harmonic distortion of a finite amplitude Gaussian beam in a fluid," J Acoust Soc Am, vol. 80, no. 1, pp. 212–216, 1986.
- [14]. Soneson JE and Myers MR, "Gaussian representation of high-intensity focused ultrasound beams," J Acoust Soc Am, vol. 122, no. 5, pp. 2526–31, 11 2007. [PubMed: 18189543]
- [15]. Hamilton MF and Blackstock DT, Nonlinear Acoustics. San Diego, CA: Academic Press, 1998.
- [16]. Jones DS, "The Scattering of a Scalar Wave by a Semi-Infinite Rod of Circular Cross Section," (in English), Philosophical Transactions of the Royal Society of London Series a-Mathematical and Physical Sciences, vol. 247, no. 934, pp. 499–528, 1955.
- [17]. Krucker JF, Eisenberg A, Krix M, Lotsch R, Pessel M, and Trier HG, "Rigid piston approximation for computing the transfer function and angular response of a fiber-optic hydrophone," (in English), J. Acoust. Soc. Am, vol. 107, no. 4, pp. 1994–2003, 4 2000. [PubMed: 10790026]
- [18]. Harris GR and Gammell PM, "Sensitivity measurements of piezoelectric polymer hydrophones from 0.2–2 MHz using a broadband-pulse technique," (in English), Journal of the Acoustical Society of America, vol. 105, no. 2, pp. 725–731, 2 1999.
- [19]. Wear KA, Liu Y, and Harris GR, "Pressure pulse distortion by needle and fiber-optic hydrophones due to nonuniform sensitivity," IEEE Trans Ultrason Ferroelectr. Freq Control, vol. 65, no. 2, pp. 137–148, 2018. [PubMed: 29389648]
- [20]. Wear KA, Baker C, and Miloro P, "Directivity and Frequency-Dependent Effective Sensitive Element Size of Needle Hydrophones: Predictions from Four Theoretical Forms Compared with

- Measurements,” *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 65, no. 10, pp. 1781–1788, 2018. [PubMed: 30010557]
- [21]. Wear KA and Howard SM, “Directivity and frequency-dependent effective sensitive element size of a reflectance-based fiber optic hydrophone: predictions from theoretical models compared with measurements,” *IEEE Trans Ultrason Ferroelectr Freq Control*, no. in press, 2018.
- [22]. Wilkens V and Koch C, “Amplitude and phase calibration of hydrophones up to 70 MHz using broadband pulse excitation and an optical reference hydrophone,” (in English), *J. Acoust. Soc. Am*, vol. 115, no. 6, pp. 2892–2903, 6 2004.
- [23]. Hurrell A, “Voltage to Pressure Conversion: Are you getting “phased” by the problem,” (in English), *AMUM 2004: Advanced Metrology for Ultrasound in Medicine 2004*, vol. 1, pp. 57–62, 2004.
- [24]. Wear KA, Liu YB, Gammell PM, Maruvada S, and Harris GR, “Correction for Frequency-Dependent Hydrophone Response to Nonlinear Pressure Waves Using Complex Deconvolution and Rarefactional Filtering: Application With Fiber Optic Hydrophones,” (in English), *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 62, no. 1, pp. 152–164, 1 2015. [PubMed: 25585399]
- [25]. Eichstadt S, Wilkens V, Dienstfrey A, Hale P, Hughes B, and Jarvis C, “On challenges in the uncertainty evaluation for time-dependent measurements,” (in English), *Metrologia*, vol. 53, no. 4, pp. S125–S135, 8 2016.
- [26]. Eichstadt S and Wilkens V, “GUM2DFT-a software tool for uncertainty evaluation of transient signals in the frequency domain,” (in English), *Meas. Sci. Tech*, vol. 27, no. 5, 5 2016.
- [27]. Eichstadt S and Wilkens V, “Evaluation of uncertainty for regularized deconvolution: A case study in hydrophone measurements,” (in English), *J. Acoust. Soc. Am*, vol. 141, no. 6, pp. 4155–4167, 6 2017. [PubMed: 28618819]
- [28]. Hurrell AM and Rajagopal S, “The Practicalities of Obtaining and Using Hydrophone Calibration Data to Derive Pressure Waveforms,” (in English), *IEEE Trans. Ultrason., Ferroelectr. Freq. Control*, vol. 64, no. 1, pp. 126–140, 1 2017. [PubMed: 27479961]
- [29]. Preston RC, Bacon DR, and Smith RA, “Calibration of medical ultrasonic equipment-procedures and accuracy assessment,” *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 35, no. 2, pp. 110–21, 1988. [PubMed: 18290137]
- [30]. Zeqiri B and Bond AD, “The Influence of Wave-Form Distortion on Hydrophone Spatial-Averaging Corrections - Theory and Measurement,” (in English), *J. Acoust. Soc. Am*, vol. 92, no. 4, pp. 1809–1821, 10 1992.
- [31]. Radulescu EG, Lewin PA, Goldstein A, and Nowicki A, “Hydrophone spatial averaging corrections from 1 to 40 MHz,” (in English), *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 48, no. 6, pp. 1575–1580, 11 2001. [PubMed: 11800120]
- [32]. Radulescu EG, Lewin PA, and Nowicki A, “1-60 MHz measurements in focused acoustic fields using spatial averaging corrections,” *Ultrasonics*, vol. 40, no. 1-8, pp. 497–501, 5 2002. [PubMed: 12159990]
- [33]. Cooling MP, Humphrey VF, and Wilkens V, “Hydrophone area-averaging correction factors in nonlinearly generated ultrasonic beams,” *J. Phys. Conf. Series, Adv. Metro for Ultrasound in Med*, vol. 279, pp. 1–6, 2011.
- [34]. Lucas BG and Muir TG, “The field of a focusing source,” *J. Acoust. Soc. Am*, vol. 72, no. 4, pp. 1289–1296, 1982.
- [35]. Reilly CR and Parker KJ, “Finite-amplitude effects on ultrasound beam patterns in attenuating media,” *J Acoust Soc Am*, vol. 86, no. 6, pp. 2339–48, 12 1989. [PubMed: 2600313]
- [36]. Ward B, Baker AC, and Humphrey VF, “Nonlinear propagation applied to the improvement of resolution in diagnostic medical ultrasound,” *J Acoust Soc Am*, vol. 101, no. 1, pp. 143–54, 1 1997. [PubMed: 9000731]
- [37]. Bacon DR, “Finite-Amplitude Distortion of the Pulsed Fields Used in Diagnostic Ultrasound,” (in English), *Ultrasound in Medicine and Biology*, vol. 10, no. 2, pp. 189–195, 1984. [PubMed: 6390897]
- [38]. Duncan T, Humphrey VF, and Duck FA, “A numerical comparison of nonlinear indicators for diagnostic ultrasound fields,” *Proceedings World Congress of Ultrasonics*, pp. 85–88, 2003.

- [39]. Duck FA, "Estimating in situ exposure in the presence of acoustic nonlinearity," J Ultrasound Med, vol. 18, no. 1, pp. 43–53, 1 1999. [PubMed: 9952079]
- [40]. Wear KA, Gammell PM, Maruvada S, Liu Y, and Harris GR, "Improved measurement of acoustic output using complex deconvolution of hydrophone sensitivity," IEEE Trans Ultrason Ferroelectr Freq Control, vol. 61, no. 1, pp. 62–75, 1 2014. [PubMed: 24402896]
- [41]. Wear KA, Gammell PM, Maruvada S, Liu Y, and Harris GR, "Time-delay spectrometry measurement of magnitude and phase of hydrophone response," IEEE Trans Ultrason Ferroelectr Freq Control, vol. 58, no. 11, pp. 2325–33, 11 2011. [PubMed: 22083766]
- [42]. Esward TJ and Robinson SP, "Extending the frequency range of the National Physical Laboratory primary standard laser interferometer for hydrophone calibrations to 80 MHz," IEEE Trans Ultrason Ferroelectr Freq Control, vol. 46, no. 3, pp. 737–44, 1999. [PubMed: 18238474]
- [43]. Selfridge A and Lewin PA, "Wideband spherically focused PVDF acoustic sources for calibration of ultrasound hydrophone probes," (in English), IEEE Trans Ultrason Ferroelectr Freq Control, vol. 47, no. 6, pp. 1372–1376, 11 2000. [PubMed: 18238683]
- [44]. Wilkens V, "Characterization of an optical multilayer hydrophone with constant frequency response in the range from 1 to 75 MHz," (in English), Journal of the Acoustical Society of America, vol. 113, no. 3, pp. 1431–1438, 3 2003. [PubMed: 12656378]
- [45]. Radulescu EG, Lewin PA, Wojcik J, and Nowicki A, "Calibration of ultrasonic hydrophone probes up to 100 MHz using time gating frequency analysis and finite amplitude waves," (in English), Ultrasonics, vol. 41, no. 4, pp. 247–254, 6 2003. [PubMed: 12782255]
- [46]. Bloomfield PE and Lewin PA, "Determination of Ultrasound Hydrophone Phase From Fourier-Hilbert Transformed 1 to 40 MHz Time Delay Spectrometry Amplitude," (in English), IEEE Trans. Ultrason. Ferroelectr., Freq. Control, vol. 61, no. 4, pp. 662–672, 4 2014.
- [47]. Weber M and Wilkens V, "Using a heterodyne vibrometer in combination with pulse excitation for primary calibration of ultrasonic hydrophones in amplitude and phase," (in English), Metrologia, vol. 54, no. 4, pp. 432–444, 8 2017.
- [48]. IEC 62127-1 Ultrasonics – Hydrophones – Part 1: Measurement and characterization of medical ultrasonic fields up to 40 MHz, 2013.
- [49]. Beissner K, "Maximum hydrophone size in ultrasonic field measurements," Acustica, vol. 59, pp. 61–66, 1985.
- [50]. Smith RA, "Are hydrophones of diameter 0.5 mm small enough to characterise diagnostic ultrasound equipment?," Phys Med Biol, vol. 34, no. 11, pp. 1593–607, 11 1989. [PubMed: 2685834]
- [51]. Boutkadjirt T and Reibold R, "Improvement of the lateral resolution of finite-size hydrophones by deconvolution," Ultrasonics, vol. 38, no. 1-8, pp. 745–8, 3 2000. [PubMed: 10829764]
- [52]. Boutkadjirt T and Reibold R, "Reconstruction of ultrasonic fields by deconvolving the hydrophone aperture effects. I. Theory and simulation," Ultrasonics, vol. 39, no. 9, pp. 631–9, 8 2002. [PubMed: 12206630]
- [53]. Boutkadjirt T and Reibold R, "Reconstruction of ultrasonic fields by deconvolving the hydrophone aperture effects. II. Experiment," Ultrasonics, vol. 39, no. 9, pp. 641–8, 8 2002. [PubMed: 12206631]
- [54]. Radulescu EG, Lewin PA, Nowicki A, and Berger WA, "Hydrophones' effective diameter measurements as a quasi-continuous function of frequency," (in English), Ultrasonics, vol. 41, no. 8, pp. 635–641, 11 2003. [PubMed: 14585475]

Fig. 1.
Tone burst from the Blatek transducer measured using the Onda HNC-0200 hydrophone.

Fig. 2.
Spectrum of tone burst from the Blatek transducer measured using the Onda HNC-0200 hydrophone.

Fig. 3.

Theoretical and experimental spatial averaging filters for the Blatek 3.5 MHz resonant frequency source transducer for 3 hydrophones and 3 driving frequencies. The theoretical spatial averaging filters are based on (20) (S_{Gaussian}) and (30) ($S_{\text{Quadratic}}$) in [11]. The vertical dotted lines denote the maximum frequencies of validity predicted by (33) in [11] for the spatial averaging filter derived from the quadratic model for harmonic radial profiles predicted by (30) in [11]. S_{Gaussian} and $S_{\text{Quadratic}}$ correspond to their counterparts in Figs. 12 and 14 in [11].

Fig. 4.

Theoretical and experimental spatial averaging filters for the Panametrics 3.5 MHz resonant frequency source transducer for 3 hydrophones and 2 driving frequencies. The theoretical spatial averaging filters are based on (20) (S_{Gaussian}) and (30) ($S_{\text{Quadratic}}$) in [11]. The vertical dotted lines denote the maximum frequencies of validity predicted by (33) in [11] for the spatial averaging filter derived from the quadratic model for harmonic radial profiles predicted by (30) in [11]. S_{Gaussian} and $S_{\text{Quadratic}}$ correspond to their counterparts in Figs. 12 and 14 in [11].

Fig. 5.

Theoretical and experimental spatial averaging filters for the Panametrics 5 MHz resonant frequency source transducer for 3 hydrophones and 2 driving frequencies. The theoretical spatial averaging filters are based on (20) (S_{Gaussian}) and (30) ($S_{\text{Quadratic}}$) in [11]. The vertical dotted lines denote the maximum frequencies of validity predicted by (33) in [11] for the spatial averaging filter derived from the quadratic model for harmonic radial profiles predicted by (30) in [11]. S_{Gaussian} and $S_{\text{Quadratic}}$ correspond to their counterparts in Figs. 12 and 14 in [11].

TABLE I**HYDROPHONES**

Hydrophone	Type	Geometrical Sensitive Element Diameter d_g (μm)			
		Nom	Sens	Dir	Mean
Onda HNC-0200	Ceramic	200	176	200 $\pm$ 20	188
Onda HNA-0400	Ceramic	400	308	360 $\pm$ 26	334
FTIDAN-0600	PVDF	600	584	563 $\pm$ 48	574
Onda HNP-1000	PVDF	1000	1000	966 $\pm$ 47	983

Nom: nominal. Sen: RP-model sensitivity fit. Dir: RP-model directivity fit (means and standard deviations). Mean: mean of sensitivity and directivity fits.

TABLE II

TRANSDUCERS

Manufacturer	Center Frequency (MHz)	Diameter (mm)	Focal Length (mm)	Driving Frequency (MHz)	q
Blatek (State College, PA)	3.5	63.5	88.9	2.5	0.80 ± 0.09
				3.5	0.84 ± 0.05
				4.5	0.77 ± 0.07
Panametrics (Waltham, MA)	3.5	19.1	38.1	3.5	0.76 ± 0.02
				4.5	-
Panametrics	5	19.1	38.1	5	0.79 ± 0.09
				6	-