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Correction for Spatial Averaging Artifacts in Hydrophone Measurements of High Intensity Therapeutic Ultrasound: An Inverse Filter Approach

Keith A. Wear [Senior Member IEEE],

Center for Devices and Radiological Health, Food and Drug Administration, Silver Spring, MD, 20993 USA

Samuel M. Howard

Onda Corporation, Sunnyvale, CA 94089

Abstract

High-intensity therapeutic ultrasound (HITU) pressure is often measured using a hydrophone. HITU pressure waves typically contain multiple harmonics due to nonlinear propagation. As harmonic frequency increases, harmonic beam width decreases. For sufficiently high harmonic frequency, beam width may become comparable to the hydrophone effective sensitive element diameter, resulting in signal reduction due to spatial averaging. An analytic formula for a hydrophone spatial averaging filter for beams with Gaussian harmonic radial profiles was tested on HITU pressure signals generated by three transducers (1.45 MHz, F/1; 1.53 MHz, F/1.5; 3.91 MHz, F/1) with focal pressures up to 48 MPa. The HITU signals were measured using fiber-optic and needle hydrophones (nominal geometrical sensitive element diameters: 100 μm and 400 μm). Harmonic radial profiles were measured with transverse scans in the focal plane using the fiber-optic hydrophone. Harmonic radial profiles were accurately approximated by Gaussian functions with root-mean-square (RMS) differences between transverse scans and Gaussian fits less than 9% for frequencies up to approximately 50 MHz. The Gaussian harmonic beam width parameter σ_n varied with harmonic number n according to a power law, $\sigma_n = \sigma_1/n^q$ where $0.5 < q < 0.6$. RMS differences between experimental and theoretical spatial averaging filters were $11\% \pm 1\%$ (1.45 MHz), $8\% \pm 1\%$ (1.53 MHz), and $4\% \pm 1\%$ (3.91 MHz). For the two more highly focused (F/1) transducers, the effect of spatial averaging was to underestimate peak compressional pressure (pcp), peak rarefactional pressure (prp), and pulse intensity integral (pii) by (mean $\pm$ standard deviation) (pcp: $4.9\% \pm 0.5\%$, prp: $0.4\% \pm 0.2\%$ pii: $2.9\% \pm 1.0\%$) and (pcp: $28.3\% \pm 9.6\%$ prp: $6.0\% \pm 2.4\%$ pii: $24.3\% \pm 6.7\%$) for the 100 μm and 400 μm diameter hydrophones respectively. These errors can be suppressed by application of the inverse spatial averaging filter.

Keywords

Acoustic output measurement; high intensity therapeutic ultrasound; hydrophone; needle; fiber optic; spatial averaging; spatiotemporal transfer function

I. INTRODUCTION

High intensity therapeutic ultrasound (HITU) is a minimally-invasive technology for treatment of cancer [1–6], uterine fibroids [7], brain disorders [3, 8–10], and other conditions [11–19]. It is essential to accurately measure acoustic output of HITU devices in order to ensure that they deliver appropriate dose to targeted tissues. Characterization of HITU systems is challenging because standardized methods for HITU dose measurements do not exist yet and high intensities of ultrasound can damage common measurement devices or render them ineffective [20, 21]. To address this challenge, the International Electrotechnical Commission recently initiated an effort to draft a technical specification on measurement of ultrasound at high pressure therapeutic levels (IEC/TS 62937) [22].

Acoustic dose is often characterized by acoustic power, which is typically measured using a radiation force balance [23, 24], and acoustic pressure, which is typically measured using a hydrophone [25, 26]. Reflectance-based fiber-optic hydrophones are often used to characterize HITU and lithotripsy pressure fields because they have high spatial resolution (on the order of 100 μm or less) and can withstand very high pressures (up to 70 MPa and beyond) [12, 27–37]. Robust needle [38] and membrane [20, 39] hydrophones have also been developed for HITU applications.

Hydrophones can distort pressure signals due to 1) frequency-dependent sensitivity and 2) spatial averaging across the finite sensitive element. These forms of distortion are relevant to HITU signals, which can be highly nonlinear and can therefore have very broad bandwidths due to the presence of multiple harmonics [28, 29, 40–43]. Nonlinearity affects spatial averaging because as harmonic frequency increases, harmonic beam width decreases [40, 44–49] and the potential for harmonic spatial averaging increases [50, 51].

The distorting effects of frequency-dependent sensitivity can be suppressed by performing sensitivity deconvolution of hydrophone measurements [27–30, 52–61]. Recently, an inverse-filter method for correction for spatial averaging artifacts in nonlinear ultrasound signals was derived and validated for signals in the diagnostic pressure range [50, 51]. The objective of the present paper is to extend that validation to HITU pressure signals.

II. METHODS

A. Hydrophone Response Model

The hydrophone spatiotemporal response, $H_p(f)$, is modeled as the 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 ratio of the frequency-domain voltage output response $U(f)$ to a normally-incident input plane pressure wave $P_{\text{NP}}(f)$

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

and $S_p(f)$ is a filter that accounts for spatial averaging. The subscript p is a reminder that the function depends on the particular pressure field distribution incident upon the hydrophone. The separability assumption was previously shown to be valid for a wide variety of transducers and hydrophones [50, 51].

B. Spatial Averaging Filter

The frequency-dependent voltage output of a hydrophone is proportional to the integral of the complex pressure field incident upon its sensitive element. The ratio of this integral to the area of the sensitive element quantifies the effects of spatial averaging [62–66]. The numerator and denominator of the ratio should be calculated based on the hydrophone *effective* sensitive element radius $a_{\text{eff}}(f)$, which is a function of frequency and can differ from the *geometrical* radius, a_g [50]. Functional forms for $a_{\text{eff}}(f)$ have been reported for needle and fiber optic hydrophones [50, 67, 68]. The spatial averaging filter may be written as [50]

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

where r is the radial coordinate and $p(r, f)$ is the pressure distribution normalized to its maximum (axial) value. (Previous publications neglected to specify that $p(r, f)$ in this formula should be normalized [50, 51], although this should have been apparent to most readers anyway. Otherwise the formula would predict the average pressure across the sensitive element instead of the dimensionless spatial averaging filter.) In this investigation, harmonic components of ultrasound beams are assumed to have Gaussian radial profiles. (This assumption has been validated previously for low-intensity nonlinear pressure fields [50] and will be tested experimentally for high-intensity pressure fields in the present paper.) For Gaussian harmonic beams, it can be shown that the spatial averaging filter is given by [50],

$$S_p(nf_1) = \frac{1}{\Omega_n^2} \left[1 - e^{-\Omega_n^2} \right], \quad (4)$$

where

$$\Omega_n^2 = \frac{a_{\text{eff}}^2(nf_1)}{2\sigma_n^2}, \quad (5)$$

$f = nf_1$, f_1 is the fundamental frequency, n is the harmonic number [50] and the radial profile of each harmonic component of the nonlinear beam is given by

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

The coefficient g_n is related to the rate of phase change with the radial coordinate. The full width half maximum (FWHM) of each harmonic component is $\sigma_n 2\sqrt{2\ln 2}$.

The spatial averaging filter requires knowledge of the harmonic beam width parameter σ_n for all harmonics of significant amplitude in the beam. Ideally, these could be measured from a high-resolution lateral hydrophone scan of the pressure field in the focal plane. If the data are analyzed in frequency domain, then σ_n may be measured for each individual harmonic.

If lateral scan data are not available, σ_1 may sometimes be modelled based on simulation [41] or diffraction theory. If the diffraction pattern for the fundamental frequency is the same as the low-amplitude case (so-called “classic-jinc-fundamental” or CJF condition [50]), then σ_1 for a circular focused piston transducer in the focal plane may be found by minimizing the mean-square difference between the magnitudes of (6) and the classic theoretical diffraction pattern over the half width half maximum (HWHM) of the beam [69], which results in $\sigma_1 = 1.93 D / (k_1 a_s)$, where D = focal length. $k_1 = 2\pi / \lambda_1$, λ_1 is the wavelength of the fundamental component of the beam, and a_s is the radius of the source [50]. The CJF approximation will be tested in the present investigation of HITU signals.

The dependence of σ_n on σ_1 and n may sometimes be accurately approximated as a power law, $\sigma_n = \sigma_1 / n^q$ [40, 44, 45, 47, 48, 50]. Simulation analysis has suggested that the power law approximation is accurate for transducers with center frequencies between 1 MHz and 5 MHz and f-numbers between 1.4 and 2.5 provided that σ_m (the nonlinear propagation parameter [70], not to be confused with σ_n) < 2.4 , which corresponds approximately and conservatively to σ_q (the local distortion parameter [71]) < 3.0 or the spectral index SI (the fraction of signal power in frequencies above the fundamental lobe [72]) < 0.4 [50]. This power law approximation will be tested in the present investigation of HITU signals.

A formula for the frequency-dependent effective sensitive element size [50], which is required for (5), can be derived from a rigid piston model [73, 74] that has been previously validated for sensitivity [75, 76] and directivity [67] of needle hydrophones and sensitivity [76] and directivity [68] of fiber optic hydrophones.

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

The coefficients A and B depend weakly on the effective range of angle θ in the angular spectrum of the beam [50]. 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 ($|\theta| < 90^\circ$) [50]. The values chosen for the present investigation were $A = 1.85$ and $B = 1.05$, corresponding to $|\theta| < 30^\circ$. This formula applies to needle hydrophones and reflectance-based fiber optic hydrophones that measure changes in a fluid refractive index caused by pressure changes [27, 30, 31, 68, 77, 78]. It does not apply to

fiber optic displacement sensors [79], Fabry-Perot interferometric fiber optic hydrophones [57, 80–83], other Fabry-Perot sensors [84, 85], or other fiber optic designs [86–88].

C. 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

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

The same spectrum $P_p(f)$ may be measured using two different hydrophones (here labeled 1 and 2). If (8) is rewritten for each hydrophone by adding a subscript 1 or 2 to $U_p(f)$, $M_L(f)$, and $S_p(f)$ and then the ratio of the two equations is taken, the pressure spectrum $P_p(f)$ (same for both measurements) will cancel out and the following substitution formula may be obtained [51],

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

The quotients of functions in the numerator and denominator, $U_{p1}(f) / M_{L1}(f)$, may be regarded as voltage spectra that have been deconvolved for hydrophone sensitivities [56].

In order to isolate the effects of spatial averaging, each frequency-dependent spatial averaging filter function was scaled so that its average value was equal to the average value of the theoretical spatial averaging filter over the range of harmonic frequencies measured. This eliminated discrepancies due to uncertainties in sensitivity magnitude, which have been reported to be on the order of ten percent [62]. There are many sources of uncertainty in hydrophone sensitivity including initial calibration uncertainty, dependence of sensitivity with temperature, and sensitivity drift over time [61].

D. Experimental Methods

Table I lists the hydrophones used. Hydrophone 1 (the reference hydrophone) was a fiber optic hydrophone (HFO, Onda, Sunnyvale, CA), with a nominal geometrical sensitive element diameter of 100 μm [30]. Hydrophone 2 was a robust needle hydrophone (HNA-0400, Onda) designed to withstand and measure high pressures, with a nominal geometrical sensitive element diameter of 400 μm [38].

Table II lists the transducers used. Sources were driven in tone bursts with a 100 Hz repetition rate (10 msec repetition period) through an Agilent (Santa Clara, CA) HP3314A function generator into an ENI (Rochester, NY) 240L amplifier. Waveforms were acquired using an Agilent 5012A digital storage oscilloscope after ringing-up to steady-state conditions. Data acquisition times were 5 - 10 μs .

After alignment of the beam, the depth of the maximum pulse-pressure-squared was found, and transverse scans were conducted in horizontal and vertical directions. Radiofrequency (RF) data were stored at every scan point and post-processed afterward. HFO signals were averaged in order to improve signal-to-noise ratio (SNR). The numbers of averages were 64

(1.45 MHz), 128 (1.53 MHz), and 32 (3.91 MHz). For the HNA-0400 measurements, an Onda AH2020 (1.45 MHz) or Onda AH2010 (1.53 MHz and 3.91 MHz) preamplifier was used.

The HNA-0400 spatial averaging filter $S_{p2}(f)$ was evaluated from (9) as follows. The HFO was used to measure voltage response $U_{p1}(t)$ from a nonlinear tone burst pressure wave at the focal point of the transducer. Voltage response $U_{p2}(t)$ was measured by replacing the HFO with the HNA-0400 and repeating the measurement. Windowed steady-state signals (excluding ring-up and ring-down portions) were analyzed. Spectra of time-domain voltage responses $U_{p1}(f)$ and $U_{p2}(f)$ were estimated using the Fast Fourier Transform (FFT). Sensitivities $M_{L1}(f)$ and $M_{L2}(f)$ in (9) were provided by the manufacturer. Sensitivities for needle [75, 76] and fiber optic [76] hydrophones have been shown to be accurately predicted by the rigid piston model [73, 74]. The sensitivity deconvolution bandwidth was limited by the maximum frequency for which the HNA-0400 sensitivity was calibrated, which was 60 MHz. Spatial averaging filters were computed up to a maximum frequency that varied between 43 MHz and 55 MHz among the three source transducers, depending on SNR.

For the HFO, the sensitivity was deconvolved as previously reported [30]. Briefly, a static (no sound on) measurement of HFO output was used to determine the small-disturbance relationship between HFO output and pressure (with knowledge of known properties of the water and fiber). Next, the slight nonlinearity in the dependence of the HFO output on pressure (on the order of 10% at 50 MPa and due to the nonlinear properties of water) was corrected for. This dependence was based on standard tables for water, assuming no significant frequency dependence. Finally, the frequency-dependent diffraction of the sound wave at the tip was corrected via deconvolution, using a diffraction kernel derived via Finite Element Analysis [30], calculated over the electronic bandwidth of the HFO, which was 150 MHz. When the Nyquist frequency (*i.e.*, half of the sampling frequency) exceeded 150 MHz, the deconvolution kernel was extended by assuming it is constant between 150 MHz and the Nyquist frequency.

Harmonic beam width parameters σ_n were measured from FFTs of transverse scans using the HFO fiber optic hydrophone. The exponent q was estimated by fitting harmonic FWHM to a power law function of harmonic number n that was proportional to $1/n^q$ as described previously [50].

E. Data Analysis

Effective radii of transducers were determined by fitting the focal plane diffraction pattern (measured with the HFO) for the first harmonic to a theoretical $2J_1(x) / x$ function where $J_1()$ is a Bessel function of the first kind, $x = k_1 a_s r / D$, $k_1 = 2\pi/\lambda_1$, λ_1 = fundamental wavelength, a_s = effective radius of transducer (adjustable fitting parameter), r = radial coordinate, and D = focal length [69]. More sophisticated transducer geometric modeling is possible if an axial scan [28, 42, 89] (instead of or in addition to a lateral scan) or a two-dimensional planar scan [29, 34, 90, 91] is available. While other methods evaluate effective radius in the linear regime, the present method evaluated effective radius in the nonlinear regime. Therefore, effective radius in the present context may incorporate effects of nonlinear propagation.

Nonlinearity of axial signals was characterized by the nonlinear propagation parameter σ_m [70], the local distortion parameter σ_q [71], and the spectral index SI [72]. Note that σ_m is approximately equal to σ_q when the local area factor F_a (square root of the ratio of the source aperture area to beam area) is between 2 and 12. Numerical analysis suggests that σ_m and σ_q have high correlations with energy transfer from the fundamental to higher harmonics [71]. SI is the fraction of the power spectrum contained in frequencies above the fundamental frequency [72, 92].

The effects of spatial averaging corrections on time-domain signals were investigated as follows. The spatial averaging correction was achieved by 1) applying an FFT to the voltage signals, 2) multiplying by the inverse of the spatial averaging filter (4), and 3) applying an inverse FFT. The HNA-0400 inverse spatial averaging filter was multiplied by a tenth-order Butterworth low-pass filter [93] in order to prevent excessive amplification of frequencies with low SNR that could result from inverse filtering. Low-pass regularization is a common component of inverse filtering. Regularization may induce systematic errors that can be addressed by uncertainty contributions using methods described in [94]. Pressure signals were deconvolved for hydrophone sensitivity. Noise in the rarefactional component of sensitivity-deconvolved signals was suppressed with a rarefactional filter [57].

III. RESULTS

A. Spectra

Fig. 1 shows spectra of HFO and HNA hydrophon measurements from the three transducers. Spectra were deconvolved for hydrophone frequency-dependent sensitivities and normalized to their values at their fundamental frequencies. The nonlinear nature of the signals results in spectral peaks at integer multiples of the fundamental frequency. HNA data decrease with frequency more rapidly than HFO data due to greater spatial averaging effects resulting from the larger geometrical sensitive element diameter (400 μm vs. 100 μm).

B. Nonlinearity Indexes

Table II shows measurements of σ_m , σ_q , and SI for the axial signals produced by the three transducers. The approximate factor of 6 between σ_m and SI is similar to that found by 1) Duck for a pulsed single-element 3.38 MHz transducer with a focal depth of 95 mm (see Fig. 7 in [72]), 2) Duncan *et al.* for many transducers when energy transferred from the fundamental frequency to higher harmonics was less than 20 percent (see Fig. 5 in [71]), and 3) Wear for 6 transducers for $SI < 0.4$, $\sigma_m < 2.4$ and $\sigma_q < 3$ [50]. Values for σ_q are well in excess of the IEC 62127-1 threshold for “considerable nonlinear distortion” of $\sigma_q > 1.5$ [95].

Table II indicates that the average value for σ_m for the pressure fields produced by the three transducers was approximately 2.4. The exponent q was approximately 0.5 - 0.6 (power law fits from 0 MHz to 40 MHz) or 0.6 - 0.7 (power law fits over the first 5 harmonics). The latter range is very consistent with previously-reported simulations based on 6 transducer geometries for $\sigma_m \approx 2.4$ (See Fig. 9 in [50] which shows least-squares linear fit of $q = 0.79 - 0.042\sigma_m$ implying that $q = 0.69$ when $\sigma_m = 2.4$).

C. Beam Properties

Figs 2–4 show harmonic beam profile plots at three different zoom levels for nonlinear pressure waves produced by the three transducers. The harmonic number is denoted by n . Gaussian fits are shown in dotted lines. Error bars denote plus and minus one standard deviation, obtained from transverse scans obtained horizontally and vertically. The black vertical lines show the spatial extent of the HNA-0400 geometrical sensitive element. The beam plots support the Gaussian model (6) for radial profiles throughout the spatial extent of the HNA-0400 sensitive element.

Fig. 5 shows RMS differences (RMSD) between experimental beam radial profiles and Gaussian fits over the HNA-0400 geometrical sensitive element ($\pm 200 \mu\text{m}$) as functions of frequency. RMSD remained below 9% for all three transducers over the range of frequencies shown. Error bars are not shown (to reduce clutter), but the average standard deviations of RMSD for the three transducers over the ranges of frequency shown were 6% (1.45 MHz), 3% (1.53 MHz), and 1% (3.91 MHz). These relatively low values for RMSD support the Gaussian model for radial profiles across the HNA-0400 sensitive element.

Fig. 6 shows full width half maxima (FWHM) of harmonic radial profiles vs. harmonic number for the three transducers. Least-squares power law fits are shown in the continuous curves. The RMSDs between experimental and power-law-fit FWHM for data shown in Fig. 5 were 11% (1.45 MHz), 10% (1.53 MHz), and 7% (3.91 MHz). It is conceivable that the measured FWHM values are larger than the true FWHM values for higher harmonic numbers due to convolution with the HFO transverse spatial response. However, it can be seen that the power law fits are quite good for those harmonics for which $\text{FWHM} > 0.4 \text{ mm}$ (four times the HFO sensitive element diameter) and therefore relatively unaffected by the transverse convolution. Therefore, the power law fits appear to be reasonable approximations. If q is estimated based on just the first 5 harmonics rather than all the harmonics shown in Fig. 6, estimates of q increase by approximately 0.1 (see Table II).

D. Spatial Averaging Filters

Fig. 7 shows spatial averaging filters computed for the HNA hydrophone using 1) the substitution formula (9), 2) σ_1 estimated from classic diffraction theory and the effective transducer radius (see Section II.E), 3) values of exponent q shown in Fig. 6 and Table II, and 4) the frequency-dependent effective hydrophone sensitive element radius (7). The spatial averaging filters for these signals are monotonically decreasing functions of harmonic frequency. The RMSDs between experimental and theoretical spatial averaging filters for data shown in Fig. 7 are $11\% \pm 1\%$ (1.45 MHz), $8\% \pm 1\%$ (1.53 MHz), and $4\% \pm 1\%$ (3.91 MHz).

Fig. 8 shows averaged hydrophone pressure tone burst measurements from the 1.45 MHz transducer (windowed steady-state signals excluding ring-up and ring-down portions) before (top) and after (bottom) correction for spatial averaging effects. Spatial averaging affects compressional segments more than rarefactional segments because spatial averaging is a low-pass filter and compressional segments have far more high-frequency content than rarefactional segments (see Fig. 3 in [57]). After spatial averaging correction, the waveforms

acquired with the two hydrophones were much more consistent with each other. After spatial averaging correction, the HNA signal is somewhat noisier than before, which is a common result of inverse filtering.

E. Effect of Spatial Averaging on Pressure Measurements

The effects of spatial averaging were greater for the two F/1 (nominally) transducers than for the F/1.5 transducer because of their tighter focusing. For the two F/1 transducers, the effect of spatial averaging was to underestimate peak compressional pressure by $4.9\% \pm 0.5\%$ (HFO) and $28.3\% \pm 9.6\%$ (HNA) (mean $\pm$ standard deviation; results from the two transducers are averaged). The first value is similar to that reported by Canney *et al.* [28] (2%) obtained by simulation for a 2 MHz, F/1 (nominally) transducer measured using a reflectance-based fiber-optic hydrophone with a similar sensitive element diameter (100 μm). The present investigation supports Canney *et al.*'s conclusion that the difference that they observed between measured and modeled values for peak compressional pressure at high drive levels was not primarily attributable to spatial averaging effects. Canney *et al.* also reported "significant distortion" when the simulated hydrophone diameter was changed from 100 μm to 500 μm . Similarly, in the present investigation, distortion significantly increased when the 100 μm diameter hydrophone was replaced by the 400 μm diameter hydrophone.

For the two F/1 transducers, the effect of spatial averaging was to underestimate peak rarefactional pressure by $0.4\% \pm 0.2\%$ (HFO) and $6.0\% \pm 2.4\%$ (HNA) (results from the two transducers are averaged). These effects are much smaller than those measured for peak compressional pressure because (again) spatial averaging is a low-pass filter and compressional segments have far more high-frequency content than rarefactional segments (see Fig. 3 in [57]).

For the two F/1 transducers, the effect of spatial averaging was to underestimate pulse intensity integral by $2.9\% \pm 1.0\%$ (HFO) and $24.3\% \pm 6.7\%$ (HNA) (results from the two transducers are averaged).

IV. DISCUSSION

Many investigations have considered corrections for spatial averaging across a hydrophone sensitive element [50, 62–66, 96–101], but only one, to our knowledge, derives an analytic formula for spatial averaging of a nonlinear field [50]. The formula expresses the spatial averaging filter as a function of frequency-dependent hydrophone sensitive element size and frequency-dependent beam width [50]. Spatial averaging is especially important for nonlinear fields with multiple harmonics, which are characterized by harmonic beam widths decreasing as harmonic number increases [40, 44–49]. The spatial averaging filter formula was previously validated for nonlinear focused pressure waves with maximum pressures of a few MPa generated using source transducers with center frequencies in the range from 1 MHz to 5 MHz and f-numbers in the range from 1.4 to 2 [51]. This previous validation supported a graphical guide to aid investigators in choosing an appropriate hydrophone sensitive element size for their measurements [50]. In the present paper, the validation was extended to HITU pressure beams with maximum pressures up to 48 MPa generated using

source transducers with center frequencies in the range of 1.5 MHz – 4 MHz and f-numbers in the range of 1 – 1.5.

The exponent q determines how rapidly harmonic beam width decreases with harmonic number n and therefore can play an influential role in determining the extent of spatial averaging across the hydrophone sensitive element. For the pressure waves investigated here, q fell approximately in the range from 0.6 to 0.7 if based on the first five harmonics and from 0.5 to 0.6 if based on all harmonics up to about 43-55 MHz (see Table II). The values of q (based on the first five harmonics) found in the present investigation are consistent with previous simulation analysis that suggested that q (based on the first five harmonics) would be expected to be approximately 0.69 when $\sigma_m \approx 2.4$ (see Fig. 9 in [50]). While a power law representation simplifies computation of the spatial averaging filter (4), it is not required. The spatial averaging filter formula (4) can accommodate any functional form for the dependence of the beam width parameter σ_n on harmonic number n .

The spatial averaging correction method used in this paper has at least two important advantages over the method found in IEC 62127-1 Annex E [95]. First, it accommodates nonlinear signals. Second, it provides an analytic expression for the spatial averaging filter in terms of beam and hydrophone dimensions.

The concordance between theory and experiment in Fig. 7 supports some assumptions underlying the spatial averaging filter formula [50] for the HITU conditions considered here. First, hydrophone spatiotemporal response is separable into the product of frequency-dependent sensitivity and a spatial averaging filter. Second, spatial averaging effects can be accurately modeled by integrating the magnitude of the acoustic pressure over a frequency-dependent effective sensitive element area.

The sensitivity deconvolutions performed here required sensitivity calibration for frequencies up to at least 40 MHz, which can be achieved using some reported methods [54, 56, 85, 102–106]. While the experiments were performed with rigid piston (RP) hydrophones (*i.e.*, needle and fiber-optic hydrophones), the spatial averaging filter formula (4) can be applied to non-RP hydrophones provided spectra that are accurately deconvolved for frequency-dependent sensitivity and the appropriate frequency-dependent hydrophone sensitive element size is used. The theory assumes uniform response across the active area of the hydrophone. The theory may be less accurate at frequencies where uniformity is compromised (for example, if a hydrophone has a strong higher order radial resonance).

The distinction between effective and geometrical source transducer diameter can be important [28]. As shown in Table II, effective source diameter was essentially equal to geometrical source diameter for the 1.45 MHz transducer but considerably less than the geometrical source diameter for the 1.53 MHz and 3.91 MHz transducers. The mean reductions in spatial averaging filter (over the ranges of frequencies in Fig. 7) produced by using geometrical instead of effective source transducer diameter in (4) were 1% (1.45 MHz), 5% (1.53 MHz), and 18% (3.91 MHz). In the first two cases, the difference is not very consequential. In the third case, the difference is greater but still provides a reasonable approximation to the spatial averaging filter. In cases in which the effective source

transducer diameter is not known, the geometrical source diameter can be used to provide a useful lower bound for the spatial averaging filter (and therefore an upper bound for spatial averaging reduction).

V. CONCLUSION

This paper provides experimental validation for a theoretical model for spatial averaging effects for nonlinear HITU beams with focal pressures up to 48 MPa measured with hydrophones. Spatial averaging effects are characterized by a spatial averaging filter, which is a low-pass filter. Spatial averaging artifacts may be suppressed by applying the inverse of the spatial averaging filter to measurements.

The spatial averaging filter requires knowledge of the frequency-dependent hydrophone effective sensitive element radius, which can be obtained from a rigid piston model for needle and fiber optic hydrophones [50] or from empirical data for membrane hydrophones [107]. The spatial averaging filter also requires knowledge of frequency-dependent beam width. For the transducers and nonlinearity indexes considered here (center frequency: 1.5 MHz – 4 MHz; f-number: 1 – 1.5; $\sigma_m < 2.4$; $\sigma_q < 3.8$; $SI < 0.4$), the focal plane harmonic beams were accurately approximated by Gaussian radial functions. The width of the fundamental component, σ_f , was approximately equal to the width of the classic linear diffraction pattern based on the effective transducer diameter. Beam width varied with harmonic number approximately as a power law, $\sigma_n = \sigma_f / n^q$ where $q = 0.5 - 0.6$ (see Table II). For conditions outside the range of frequencies, f-numbers, and pressure levels considered here and previously [50, 51], nonlinear simulation tools [20, 28, 39, 41] may offer a useful alternative to estimating harmonic beam properties to be used as inputs to the spatial averaging filter formula (4). If upper and lower bounds for frequency-dependent effective hydrophone sensitive element size and harmonic beam width can be estimated (from theory, simulation, or experiment) then upper and lower bounds for the spatial averaging filter can be determined.

The spatial averaging filter is useful for 1) correction of hydrophone-based measurements for spatial averaging artifacts, 2) retrospective analysis of HITU acoustic output measurements, 3) informing choice of an appropriate hydrophone for measuring HITU system acoustic output, and 4) informing design of HITU systems in conjunction with hydrophone test procedures. In some cases, this approach may allow relatively expensive fiber-optic hydrophones to be replaced by relatively economical needle hydrophones (provided they are sufficiently robust to withstand HITU pressures) for characterization of HITU beams.

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Biographies

Keith A. Wear received his B.A. in Applied Physics from the University of California at San Diego. He received his M.S. and Ph.D. in Applied Physics with a Ph.D. minor in Electrical Engineering from Stanford University. He was a post-doctoral research fellow with the Physics department at Washington University, St. Louis. He is the FDA Acoustics Laboratory Leader. He is an Associate Editor-in-Chief for *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. He is an Associate Editor of 3 journals: *J. Acoust. Soc. Am.*; *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*; and *Ultrasonic Imaging*. He was the Technical Program Chair of the 2008 IEEE International Ultrasonics Symposium in Beijing, China. He was the General Program Chair of the 2017 IEEE International Ultrasonics Symposium in Washington, DC. He was elected to serve as vice chair (2012-2014) and chair (2014-2016) of the American Institute of Ultrasound in Medicine (AIUM) Technical Standards Committee. He was elected to serve as vice-chair of the AIUM Bioeffects Committee (2019-2021). He received the 2019 AIUM Joseph H. Holmes Basic Science Pioneer Award. He is a Fellow of the Acoustical Society of America, the American Institute for Medical and Biological Engineering, and the AIUM. He is a senior member of IEEE.

Samuel M. Howard received his A.B. in Engineering Sciences from Harvard University. He received his M.S. and Ph.D in Theoretical and Applied Mechanics from Cornell University with minors in Applied Mathematics and Physics. From 1989 to 2001 he worked for Acuson (later Siemens) in transducer R&D. From 2001 to the present he has been at Onda Corporation, where he is the CTO and directs the Acoustics Laboratory. His current interests focus on ultrasound metrology for medical and industrial applications.

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Fig. 1.

Spectra of HFO and HNA hydrophone measurements from three transducers. Transducer center frequencies are given in the upper right corner of each plot. Spectra are deconvolved for hydrophone frequency-dependent sensitivities and normalized to their values at their fundamental frequencies. HNA data decrease with frequency more rapidly than HFO data due to greater spatial averaging effects resulting from the larger nominal geometrical sensitive element diameter (400 μm vs. 100 μm).

Fig. 2.

Harmonic beam profile plots at three different zoom levels for nonlinear pressure waves produced by the 1.45 MHz transducer. The harmonic number is denoted by n . Gaussian fits are shown in dotted lines. Error bars denote plus and minus one standard deviation, obtained from transverse scans obtained horizontally and vertically. The black vertical lines show the spatial extent of the HNA-0400 sensitive element, within which Gaussian shape is assumed by (4). The beam plots support the Gaussian model for radial profiles across the HNA-0400 sensitive element.

Fig. 3.

Harmonic beam profile plots at three different zoom levels for nonlinear pressure waves produced by the 1.53 MHz transducer. The harmonic number is denoted by n . Gaussian fits are shown in dotted lines. Error bars denote plus and minus one standard deviation, obtained from transverse scans obtained horizontally and vertically. The black vertical lines show the spatial extent of the HNA-0400 sensitive element, within which Gaussian shape is assumed by (4). The beam plots support the Gaussian model for radial profiles across the HNA-0400 sensitive element.

Fig. 4.

Harmonic beam profile plots at three different zoom levels for nonlinear pressure waves produced by the 3.91 MHz transducer. The harmonic number is denoted by n . Gaussian fits are shown in dotted lines. Error bars denote plus and minus one standard deviation, obtained from transverse scans obtained horizontally and vertically. The black vertical lines show the spatial extent of the HNA-0400 sensitive element, within which Gaussian shape is assumed by (4). The beam plots support the Gaussian model for radial profiles across the HNA-0400 sensitive element.

Fig. 5. RMS differences (RMSD) between experimental beam radial profiles and Gaussian fits as functions of frequency. Error bars are not shown (to reduce clutter), but the average standard deviations of RMSD values for the three transducers over the ranges of frequency shown were 6% (1.45 MHz), 3% (1.53 MHz), and 1% (3.91 MHz).

Fig. 6. Full width half maxima (FWHM) of harmonic radial profiles vs. harmonic number for the three transducers. Least-squares power law fits are shown in the continuous curves.

Fig. 7.

Spatial averaging filters for the three transducers: 1.45 MHz (top), 1.53 MHz (middle), and 3.91 MHz (bottom). Error bars denote plus and minus one standard deviation, obtained from transverse scans obtained horizontally and vertically.

Fig. 8. Hydrophone pressure measurements from the 1.45 MHz transducer before (a) and after (b) correction for spatial averaging. All waveforms in (a) and (b) were deconvolved for hydrophone sensitivities.

TABLE I**HYDROPHONES**

Hydrophone	Type	Nominal Geometrical Sensitive Element Diameter d_g (μm)
Onda HFO	Fiber optic	100
Onda HNA-0400	Ceramic	400

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TABLE II.

TRANSDUCER AND WAVE PROPERTIES

Frequency (MHz)		1.45	1.53	3.91
Diameter (mm)	Geometrical	100	100	25
	Effective	100 ± 3	83 ± 1	17 ± 1
Focal Length (mm)		100	150	25
Spectral Index SI		0.42 ± 0.01	0.34 ± 0.01	0.41 ± 0.01
Nonlinear propagation parameter σ_n		2.45 ± 0.06	2.30 ± 0.03	2.44 ± 0.07
Local distortion parameter σ_q		3.79 ± 0.06	2.97 ± 0.01	2.89 ± 0.05
Exponent q ($\sigma_n = \sigma_q / n^q$)	$n=1-5$	0.72 ± 0.01	0.64 ± 0.03	0.59 ± 0.01
	0-40 MHz	0.60 ± 0.01	0.50 ± 0.03	0.53 ± 0.01
Focal pressure (MPa)		48.7 ± 0.3	16.2 ± 0.4	29.4 ± 0.4