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Directivity and Frequency-Dependent Effective Sensitive Element Size of a Reflectance-Based Fiber Optic Hydrophone: Predictions from Theoretical Models Compared with Measurements

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Abstract

The goal of this work was to measure directivity of a reflectance-based fiber-optic hydrophone at multiple frequencies and to compare it to four theoretical models: Rigid Baffle (RB), Rigid Piston (RP), Unbaffled (UB), and Soft Baffle (SB). The fiber had a nominal 105 μm diameter core and a 125 μm overall diameter (core + cladding). Directivity measurements were performed at 2.25, 3.5, 5, 7.5, 10, and 15 MHz from $\pm 90^\circ$ in two orthogonal planes. Effective hydrophone sensitive element radius was estimated by least-squares fitting the four models to directivity measurements using the sensitive element radius as an adjustable parameter. Over the range from 2.25 to 15 MHz, the average magnitudes of differences between the effective and nominal sensitive element radii were $59 \pm 49\%$ (RB), $10 \pm 5\%$ (RP), $46 \pm 38\%$ (UB), and $71 \pm 19\%$ (SB). Therefore, directivity of a reflectance-based fiber-optic hydrophone may be best estimated by the RP model.

Keywords

fiber optic hydrophone; directivity

I. INTRODUCTION

Quantitative measurement of acoustic pressure waveforms is essential to ensure safety and effectiveness for medical ultrasound devices. Pressure waveforms are usually measured using hydrophones. For diagnostic medical ultrasound applications, there is a variety of choices of hydrophones, including membrane, needle, capsule, and fiber-optic designs. However, for therapeutic applications, including high intensity therapeutic ultrasound (HITU), the choices are much more limited because the output pressure from HITU devices is often too great to measure with most common hydrophones without causing damage or cavitation-induced measurement unreliability.

Reflectance-based fiber optic hydrophones can withstand very high pressures (*e.g.*, up to 70 MPa and beyond [1–4]) and have been used for HITU [1–8] and lithotripsy [9] applications. The most common design of a reflectance-based fiber optic hydrophone propagates laser light along a fiber and measures the signal reflected from the tip immersed in a fluid. Changes in pressure due to an acoustic wave incident on the tip cause changes in index of refraction in the fluid, which result in changes in the reflection coefficient at the fiber tip [1, 10–13].

Fiber optic hydrophones have exceptional spatial resolution, often approximately 100 μm or less, making them appropriate to capture frequencies up to 100 MHz [1, 10–13]. The use of fiber tips tapered out to diameters down to 7 μm has been proposed to enhance spatial resolution [12, 13]. A membrane hydrophone with a steel foil front protection layer has been demonstrated to withstand peak compressional pressures up to 75 MPa and has a nominal geometrical sensitive element diameter of approximately 200 microns [14, 15]. A robust needle hydrophone has been developed for HITU applications and has a nominal geometrical sensitive element diameter of approximately 400 microns [16]. Fiber optic and needle hydrophones have smaller cross sections than membrane hydrophones, which reduces the magnitude of undesired reflections in a water tank due to planar interfaces. Fiber optic hydrophones that operate on the basis of Fabry-Perot interferometry [17, 18] have exceptional spatial resolution (10 μm) but have much lower maximum pressure tolerances than reflectance-based fiber-optic hydrophones [19].

Reflectance-based fiber optic hydrophones have drawbacks. First, they have relatively high minimum detectable (*e.g.* noise equivalent) pressure amplitudes, on the order of 0.5 MPa, making them unsuitable for low pressure measurements. While this is not a severe limitation for measuring maximum pressures on the order of tens of MPa from HITU systems, it can be a limitation for mapping the entire HITU field, including side lobes. Second, flexing of fiber optic probes due to radiation forces at clinical HITU levels can cause signal and positioning distortions.

Complete hydrophone characterization involves specification of complex sensitivity, directivity, and frequency-dependent effective sensitive element size. Sensitivity corresponds to voltage output for normally-incident, quasi-planar pressure waves as a function of frequency. Frequency-dependent sensitivity functions are useful for deconvolving the hydrophone impulse response from the hydrophone voltage output, resulting in improved accuracy in pressure measurements [18, 20–27]. For example, in one study of eight hydrophones (4 membrane, 2 needle, 1 capsule, and one fiber optic) measuring the same reference pressure signal, deconvolution reduced the coefficient of variation (ratio of standard deviation to mean across all 8 hydrophones) from 29% to 8% (peak compressional pressure), 39% to 13% (peak rarefactional pressure), and 58% to 10% (pulse intensity integral) [23].

While sensitivity of reflectance-based fiber-optic hydrophones has been considered in previous publications [1, 11, 28, 29], directivity has received less attention. Directivity corresponds to voltage output for quasi-planar pressure waves as a function of angle of incidence. Directivity is important because 1) its measurement can be used to determine the

effective size of the sensitive element, 2) it describes how critical the angular orientation of the hydrophone must be to faithfully measure an incoming pressure wave, 3) it describes the potential for distortion of highly-focused beams with wide angular spectra, and 4) it describes how well the hydrophone can reject undesired off-axis waves (*e.g.*, reflections in a water tank).

Hydrophone directivity is often modeled by integrating the complex free-field pressure incident on a surface corresponding to the hydrophone sensitive element. This leads to the rigid baffle (RB) model for hydrophone directivity [30] (p. 381),

$$D_{RB}(k, \theta) = \frac{2J_1(ka \sin \theta)}{ka \sin \theta}$$

where θ = angle of incidence, $k = 2\pi / \lambda$, λ = wavelength, and a = the radius of the hydrophone sensitive element [31]. This model is commonly used to infer a value for “effective” sensitive element radius, a_{eff} from measurements of directivity (IEC). Effective radius a_{eff} may be distinguished from nominal or geometrical radius a_g . One limitation of the RB model is that it does not necessarily fully account for the effect that the presence of the hydrophone can have on the field that it is used to measure. Other models for hydrophone directivity have been proposed, including the unbaffled (UB) model [32]

$$D_{UB}(k, \theta) = D_{RB}(k, \theta) \left(\frac{1 + \cos \theta}{2} \right),$$

and the soft baffle (SB) model [33],

$$D_{SB}(k, \theta) = D_{RB}(k, \theta) \cos \theta.$$

The RB, UB, and SB approaches have previously been used to model membrane and needle hydrophones [31].

Krucker *et al.* modeled a reflectance-based fiber optic hydrophone as a rigid piston (RP) [34]. The RP model imposes a boundary condition that the component of acoustic velocity perpendicular to the sensitive element must be zero [34]. Although the RP model was primarily motivated by reflectance-based fiber optic hydrophones, Krucker *et al.* suggested that the RP model could also be appropriate for needle hydrophones. Their theoretical directivity (Eq. 19) is in the form of an integral that must be evaluated numerically. For the sake of brevity, the reader is referred to their paper [34]. Krucker *et al.* did not provide experimental validation for the RP model for sensitivity or directivity of fiber-optic or needle hydrophones. However, Wear *et al.* subsequently demonstrated good agreement between the RP model and experimental measurements of sensitivity of needle and reflectance-based fiber optic hydrophones ($12\% \pm 3\%$ root-mean-square difference in normalized sensitivity [29]) and directivity of needle hydrophones ($7\% \pm 5\%$ accuracy in measurement of geometrical sensitive element radius [35]).

The goal of the present paper is to report measurements of directivity and frequency-dependent effective sensitive element size of a reflectance-based fiber optic hydrophone at multiple frequencies and compare them to predictions based on RB, RP, UB, and SB models.

II. METHODS

An Onda (Sunnyvale, CA) HFO-690 fiber optic hydrophone was used for directivity measurements. The multi-mode fiber, operated at a wavelength of 690 nm, has a nominal 105 μm diameter core and a 125 μm overall diameter (core + cladding). The fiber-tip was cleaved prior to the measurements according to the manufacturer's instructions, in order to present a flat tip to an incoming pressure wave.

The hydrophone was inserted into a tank custom-designed for directivity measurements. The water temperature was $23.5 \pm 0.5^\circ$, as measured with a calibrated mercury-in-glass thermometer (VWR Scientific Products Corporation, East Hills, NY, USA).

Directivity measurements were performed at 2.25, 3.5, 5 MHz, 7.5, 10 MHz, and 15 MHz, which meant that the wavelength ranged from approximately 1 to 6.5 times the nominal fiber core diameter. The acquisition method followed IEC 62127-2, Section 12 (IEC). The hydrophone was aligned to the axis of rotation by comparing the time of flight of the ultrasound signal at three or more angles of incidence and adjusting the hydrophone position to minimize any differences.

Source transducers were driven with tone-bursts from a Hewlett-Packard (Santa Clara, CA) 3314A function generator through an ENI (Rochester, NY) 3100LA power amplifier (nominal 55 dB gain). The function generator voltage of 600 mV was chosen to be comfortably within the power amplifiers input limit of 1 V input. Table 1 lists transducer properties and experimental parameters. For measurements at 2.25 and 3.5 MHz, the sources were Olympus (Waltham, MA) nondestructive evaluation transducers. For measurements at 5 MHz and above, the source was an Onda BBS, which is a broadband, mildly-focused (F/10) transducer made with PVDF film [36]. When paired with the amplifier, the BBS has a center frequency of about 10 MHz and a -6 dB bandwidth of approximately 16 MHz. Waveforms were acquired through a Tektronix (Beaverton, OR) TDS 540 oscilloscope. Waveform acquisition was delayed to acquire five (Olympus) or ten (BBS) microseconds of signal, which had pulse duration of ten (Olympus) or fifteen (BBS) microseconds. To minimize noise and harmonic distortion, the oscilloscope's 20 MHz bandwidth filter was used. Below 10 MHz, an additional Mini-Circuits (Brooklyn, NY) 10 MHz filter was used. 64 waveforms were averaged for data collected with the BBS (*i.e.*, at 5 MHz and above). 256 waveforms were averaged for data collected with the Olympus transducers (*i.e.* at 2.25 and 3.5 MHz).

Directivity measurements were performed in two orthogonal planes by rotating a fiber holder (which gripped the fiber) around its axis of symmetry. Two hundred measurements were performed in each plane for angles ranging from -90° to 90° with angular interval between measurements of 0.9° . Approximately 2 cm of bare fiber stuck out of the fiber

holder. This distance provided sufficient fiber rigidity, while delaying the potential arrival of spurious reflections until after the signal was acquired. In all cases a duty factor of less than 1% was utilized in the measurements, as a precaution to avoid flexing of the fiber tip due to acoustic radiation pressure. Temporal average intensities were less than 10 mW/cm², which corresponds to a radiation pressure of 0.06 Pa (based on the standard plane wave approximation of calculating radiation pressure by dividing intensity by speed of sound).

Alternative methods for directivity measurement include a pulsed near-field method [37], a harmonic-based approach [35, 38] a time-delay-spectrometry (TDS) based method [39], and a method based on using a photoacoustic source consisting of a blackened planar surface illuminated by a laser [40, 41].

In order to estimate uncertainty of measurements, the standard deviations of paired directivity measurements taken at the same angle from both orthogonal planes were computed for each frequency. These standard deviations were then averaged over all angles for each frequency. These uncertainty estimates included random uncertainties, temperature variations ($\pm 0.5^\circ\text{C}$), source stability ($\pm 2\%$), digitizer error ($\pm 2\%$), positional repeatability (this effect varies with frequency from $\pm 2.5\%$ at 1 MHz to 5% at 20 MHz), and potential imperfect symmetry of the fiber optic hydrophone.

“Effective” sensitive element radii, a_{eff} , were estimated for all four models at each of the six frequencies. The hydrophone sensitive element radius a was used as a free parameter in functional fits of theoretical directivity models to experimental data. For each model and frequency, the value of a that minimized the mean square difference between the theoretical form and experimental data was designated as a_{eff} . Effective radius a_{eff} may be distinguished from nominal or geometrical radius a_g . Note that while IEC 62127-3 defines effective radius by comparing measured directivity data to the RB model (IEC 62127-3), the present paper defines multiple effective radii obtained by fitting measured directivity data to multiple models. IEC 62127-3 recommends computation of a_{eff} from directivity values at -3 dB and -6 dB. However, because of the small sensitive element size of the fiber-optic hydrophone, and the corresponding wide directivity patterns, directivity measurements did not always fall to -3 dB or -6 dB over the range of angles investigated (-90° to 90°), especially at low frequencies. Therefore, the fitting method was used instead. A similar method was described by Wilkens and Molkenstruck for estimating a_{eff} from directivity measurements for a membrane hydrophone [42].

III. RESULTS

Figure 1 shows directivity measurements for six frequencies as functions of angle of incidence θ . As frequency increases, the directivity functions get narrower. This is expected because wavelength is inversely related to frequency, and at a given angle of incidence, decreasing wavelength is associated with increasing phase cancellation across the hydrophone sensitive element. Figure 1 shows that the lower frequency measurements (2.25 and 3.5 MHz) appear to be noisier than the higher frequency measurements. This is likely due to lower acoustic pressures produced by the lower frequency transducers, which were unfocussed, and also the -6 dB loss in hydrophone response at lower frequencies [11, 29].

(RP hydrophone sensitivity roughly doubles between zero frequency and $f_{max} = 1.2c/(\pi a_g)$ where c = speed of sound [29]. For the present reflectance-based fiber optic hydrophone, $f_{max} = 11$ MHz. See Fig. 2 in [11]. Similar behavior has been observed for needle hydrophone sensitivity [29, 43, 44].)

The standard deviations of directivity measurements, averaged over all angles were 0.03 (2.25 MHz), 0.03 (3.5 MHz), 0.02 (5 MHz), 0.01 (7.5 MHz), 0.01 (10 MHz), and 0.02 (15 MHz). These were small ($\sim 3\%$) compared with the maximum value of directivity, which is 1 by definition.

Figure 2 shows theoretical and experimental directivity plots at all six frequencies. The theoretical models were computed based on the nominal (geometrical) sensitive element radius a_g (52.5 μm). The RP model appears to conform to the data more consistently across all six frequencies than the other three models. For frequencies 5 MHz and above ($ka_g > 1.1$ where $k = 2\pi/\lambda$ and λ is the wavelength), the RP and UB models are very close to each other and appear to model the experimental directivity better than the common RB model until ka_g exceeds 3 and the three models become comparable.

At 15 MHz ($ka_g = 3.3$), all four models approach each other but noticeably underestimate the experimental directivity at $|\theta| > 45^\circ$. This discrepancy is likely due to acoustic pressure from the 15 MHz transducer falling to low values at the hydrophone sensitive element for $|\theta| > 45^\circ$ and becoming comparable to the noise, thus making the directivity measurements less reliable. The fiber-optic hydrophone has a noise equivalent pressure ranging from 0.25 MPa at 2 MHz bandwidth to 0.5 MPa at 100 MHz bandwidth, defined by the manufacturer as the rms signal measured in the absence of sonication. The averaging described in Section II further improved the SNR, which nevertheless varied with frequency because of variations in the source and hydrophone responses. At normal incidences, it is estimated that SNR varied from 11 at 10 MHz to 4 at 2.25 MHz, 3.5 MHz and 15 MHz.

Root-mean-square differences (RMSDs) between models (based on a_g) and measurements (averaged over frequencies from 2.25 to 10 MHz over the range from -90° to 90°) were 17% (RB), 6% (RP), 8% (UB), and 31% (SB). (The 15 MHz data were excluded because of the unreliable measurements for $|\theta| > 45^\circ$).

Figure 3 shows effective radius, a_{eff} , plotted vs. ka_g for all 6 frequencies and all 4 models. The RP model conforms most consistently to the nominal (geometrical) effective radius, a_g . The discrepancies between effective and nominal radii decrease with ka_g for all four models. Over the range from 2.25 to 15 MHz, the average magnitudes of differences between the effective and nominal sensitive element radii were $59 \pm 49\%$ (RB), $10 \pm 5\%$ (RP), $46 \pm 38\%$ (UB), and $71 \pm 19\%$ (SB). The decline of a_{eff} with frequency is consistent with reported measurements for needle [35, 39, 45], fiber optic [45], and membrane [42] hydrophones. (Recall that k is directly proportional to frequency.)

Figure 4 shows the relative differences between effective and geometrical sensitive element radii for the four models. A fit to the RB model of the form C/ka_g is also shown. The value of C that yielded the minimum squared difference between model and data was 0.67 with a 95% confidence interval of (0.56, 0.79).

IV. CONCLUSION

The commonly-used rigid baffle (RB) model for characterizing hydrophone directivity was compared to three alternative models—soft baffle (SB), unbaffled (UB), and rigid piston (RP)—for a reflectance-based fiber-optic hydrophone over the range from 2.25 to 15 MHz ($0.5 < ka_g < 3.3$). The discrepancies among the four models are considerable for low ka_g (e.g., $0 < ka_g < 1$) and decrease as ka_g increases. The RP model proved superior to the other three models in terms of similarity of nominal or geometric sensitive element radius, a_g , and effective sensitive element radius, a_{eff} , derived by fitting model directivity functions to measured directivity data. The UB model is much easier to compute than the RP model (because it does not require numerical analysis of an integral) and is nearly identical to the RP model for $ka > 1.3$. The superior performance of the RP model, which is similar to previous findings with needle hydrophones, may be attributable to its more realistic representation of the boundary condition on the surface of the needle hydrophone sensitive element.

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Biography

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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.
Directivity measurements at 6 frequencies.

Fig. 2.

Directivity measurements at 6 frequencies compared with 4 theoretical models: Rigid Baffle (RB), Rigid Piston (RP), Unbaffled (UB), and Soft Baffle (SB). Model functions are based on nominal or geometrical sensitive element size, a_g , for the fiber optic hydrophone.

Fig. 3.

Effective sensitive element radii based on best fit model functions with sensitive element size as an adjustable parameter. The nominal or geometric sensitive element radius, a_g , is shown in the horizontal black dotted line. The average standard deviation, obtained by comparing estimates of a_{eff} derived from directivity measurements in two orthogonal planes, is 2 μm .

Fig. 4.

Relative difference between effective and geometrical sensitive element sizes as a function of ka_g . A fit to the RB model is also shown. The average standard deviation, obtained by comparing estimates of $(a_{eff} - a_g) / a_g$ derived from directivity measurements in two orthogonal planes, is 4%.

TABLE I

SOURCE TRANSDUCERS

Model	Frequency (MHz)		Diameter (cm)	Focal Properties	Distance between source and hydrophone (cm)
	Center	Drive			
Olympus A304-SU	2.25	2.25	2.54	Planar	12.7
Olympus V381	3.5	3.5	1.91	Planar	12.7
Onda BBS	10	5	2.54	F/10	25.4
Onda BBS	10	7.5	2.54	F/10	25.4
Onda BBS	10	10	2.54	F/10	25.4
Onda BBS	10	15	2.54	F/10	25.4