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Directivity and Frequency-Dependent Effective Sensitive Element Size of Needle Hydrophones: Predictions from Four Theoretical Forms Compared with Measurements

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Abstract

Directivity is a hydrophone specification that describes response as a function of angle of incidence. The goal of this study was to compare, in the context of needle hydrophones, the commonly-used rigid baffle (RB) model for hydrophone directivity to three alternative models: soft baffle (SB), unbaffled (UB), and rigid piston (RP). Directivity measurements were performed at 1, 2, 3, 4, 6, 8, and 10 MHz from $\pm 70^\circ$ in two orthogonal planes for two ceramic and two polymer needle hydrophones with nominal geometrical sensitive element diameters of 200, 400, 600, and 1000 μm . Effective hydrophone sensitive element radius was estimated by least-squares fitting the four models to directivity measurement data using the sensitive element radius (a) as an adjustable parameter. For $ka < 4$ (where $k = 2\pi/\lambda$ and λ = wavelength), the RP model outperformed the other three models. For $ka = 1$, the average error in estimated sensitive element radius was 7% (95% Confidence Interval: 3% - 12%) for the RP model while the lowest average error by the other three models was 46% (95% CI: 38% - 54%) for the UB model.

Keywords

hydrophone; directivity; needle; acoustic output measurement

I. Introduction

NEEDLE hydrophones are commonly used to measure acoustic pressure. They are often more economical and more compact than the most common alternative, membrane hydrophones. Their small sizes and narrow shapes enable them to be placed in small spaces inaccessible to membrane hydrophones. Unlike membrane hydrophones, they do not present big planar interfaces that can produce reflections that possibly could interfere with measurements, especially for long-pulse or continuous-wave operation. Needle hydrophones are often used for cavitation detection [1], transcranial ultrasound system characterization [2–9], high-intensity therapeutic ultrasound system characterization [10–12], gene-delivery

system characterization [13], high-frequency transducer characterization [14], and other medical applications [15, 16].

Complete hydrophone characterization includes specification of sensitivity and directivity. Sensitivity corresponds to voltage output for normally-incident, quasi-planar pressure waves as a function of frequency. Sensitivity is important because it contains information required to convert measured voltages into acoustic pressures. If the sensitivity is approximately uniform over the band of frequencies in the pressure spectrum, then this simply entails multiplication by a scale factor. For very broadband signals (*e.g.*, nonlinear signals containing multiple harmonics), however, the sensitivity may vary considerably over the band of frequencies in the pressure spectrum, and a deconvolution can provide substantial improvement in accuracy compared with scaling [12, 17–24].

Directivity corresponds to voltage output for quasi-planar pressure waves as a function of angle of incidence [25]. Directivity depends on frequency and sensitive element size. Directivity is important because 1) its measurement can be used to determine the effective size of the sensitive element, 2) it describes how precise the angular alignment of the hydrophone must be in order 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).

Directivity is often taken to be equal to the predicted transmitted diffraction pattern of an equivalent source corresponding to the sensitive element of the hydrophone. The principle of reciprocity is used to equate transmit and receive patterns. Three functional forms have been applied previously to model needle hydrophone directivity [25]. The first form for directivity assumes a circular piston in a rigid planar baffle (RB) [26] (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 [25]. An International Electrotechnical Commission standard invokes this formula for estimating hydrophone effective sensitive element size from directivity measurements [27]. The second form for directivity uses the assumption of a circular piston in a soft (pressure-release) baffle (SB), which involves multiplication of the RB form by $\cos \theta$ [28].

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

The third form uses the assumption of an un baffled (UB) circular piston, which involves multiplication of the RB form by $(1 + \cos \theta)/2$ [29].

$$D_{UB}(k, \theta) = \frac{2J_1(ka \sin \theta)}{ka \sin \theta} \left(\frac{1 + \cos \theta}{2} \right)$$

As an alternative to these approaches, Krucker *et al.* developed a rigid-piston (RP) hydrophone model in which the presence of the hydrophone imposes a boundary condition that the component of acoustic velocity perpendicular to the sensitive element must be zero [30]. Although Krucker *et al.*'s main application was fiber-optic hydrophones, they speculated that the theory could also apply to needle hydrophones. Their theoretical directivity is in the form of an integral that must be evaluated numerically. For the sake of brevity, the reader is referred to their paper [30]. Although Krucker *et al.* did not provide experimental validation for their model, Wear *et al.* recently provided experimental validation that the RP model can accurately predict sensitivity for some needle and fiber-optic hydrophones [31].

Another model for needle hydrophone sensitivity accounts not only for diffraction but also for multiple reflections within the layered structure and includes properties of polyvinylidene fluoride (PVDF) such as attenuation [32]. This model, however, requires detailed knowledge of the hydrophone structural characteristics, which is not always available.

The goal of the present paper is to compare theoretical predictions from four models (RB, SB, UB, and RP) to experimental measurements of needle hydrophone directivity and to identify conditions (*i.e.*, combinations of sensitive element size, frequency, and angle) for which substantial disparities among the models exist.

Although directivity of needle hydrophones has been investigated previously [25, 33–39], it makes sense to revisit this issue because 1) the RP model has not been tested experimentally for needle hydrophone directivity (to the authors' knowledge) but is a promising approach given its recent success in modeling needle hydrophone sensitivity[31], 2) some previous investigations were conducted decades ago[25, 33–35], raising concerns about their relevance to modern hydrophone technology, 3) all the investigations cited above except one [25] considered only the common RB model [33, 34, 36–38] or no theoretical model[35, 39], 4) one investigation considered only a single frequency [39], 5) some investigations considered only a single sensitive element diameter [34, 36, 38, 39] or a limited range of 300 – 600 μm [35], and 6) some investigations involved a limited range of angles up to a maximum of 40 degrees or less [33, 38].

II. Methods

A. Experimental Methods

The hydrophones investigated are listed in Table I. They included two ceramic hydrophones and two polymer (PVDF) hydrophones. The Onda HNA-0400 hydrophone is designed to accommodate therapeutic levels of acoustic output [10]. The hydrophones span a wide range of sensitive element diameters, from 200 to 1000 μm .

Directivity measurements were performed using the National Physical Laboratory (NPL) Scanning Tank with the hydrophone immersed in deionized water. The method employed nonlinear sawtooth waveforms generated by nonlinear sawtooth waveforms generated by

non-linear propagation so that measurements could be performed at multiple harmonics of the source transducer fundamental frequency [35].

The mean water temperature, measured with a calibrated mercury-in-glass thermometer (GH Zeal Ltd, London UK), was $19.0 \pm 0.5^\circ\text{C}$. The three Onda hydrophones were connected to an Onda AG-2020 signal preamplifier and an Onda AH-2020-DCBSW DC block with an amplification of 10 dB. The combination was matched through a calibrated $50\ \Omega$ shunt to a bespoke broadband amplifier (Kenelec Scientific, London, UK). The Force Technology hydrophone was connected directly to the Kenelec amplifier. The signal was acquired with a calibrated Tektronics (Beaverton, OR) DPO-7254 digital phosphor oscilloscope. The active element of the hydrophone under test was aligned to the beam alignment axis of each of three plane-piston Olympus (Tokyo, Japan) source transducers with nominal center frequencies of 1, 2 and 3 MHz, in turn. The nominal diameters of the transducers were 25.4 mm, 12.7 mm and 9.5 mm. The source transducers were operated at their nominal frequency in a short burst mode (< 10 cycles) via a Keysight (Santa Rosa, CA) 33250 A arbitrary waveform generator. The signal was amplified using an Amplifier Research (Chippenham, UK) 150A100B RF amplifier. The hydrophone was positioned in the transducer far-field where -6 dB beam widths at all frequencies of interest were larger than 20 times the largest hydrophone diameter (approximately 400 mm transducer – hydrophone separation), minimizing the likelihood of misalignment affecting the result. The hydrophone element was aligned to the axis of rotation by comparing the time-of-flight of the ultrasound pulse at two angles of incidence, and adjusting the hydrophone position to minimize the difference between them. The drive voltage was set high enough to generate nonlinear fields containing multiple harmonics. Directivity data were acquired with the three source transducers at 1, 2, 3, 4, 6, 8 and 10 MHz.

The hydrophone was first rotated through its horizontal plane about its reference center in steps of 10° to generate angles of incidence ranging from -70° to 70° , with 0° indicating the angle of maximum signal. At each position, 32 waveforms were acquired from the hydrophone and averaged. The mean waveforms were then windowed using a short (3 to 6 μs) Blackman-Harris window function to remove reflections from the hydrophone mounting, which were particularly noticeable at large angles of incidence. The windowed waveforms were processed with a Fast Fourier Transform, and the magnitudes of the relevant harmonics were extracted and normalized relative to 0° . This process was then repeated with the hydrophone rotated 90° around its axis of symmetry. The average value of the horizontal and vertical measurements of directivity was taken.

Alternative methods for directivity measurement include a pulsed near-field method [33], a time-delay-spectrometry (TDS) based method [38], and a method based on using a photoacoustic source consisting of a blackened planar surface illuminated by a laser[40, 41]. The nonlinear approach used for the present study was chosen because of its established consistency with multiple other methods for hydrophone calibration[35].

Measurement repeatability was characterized by standard deviations of paired directivity measurements taken at the same angle from two orthogonal planes, computed for each

frequency for each hydrophone. These standard deviations were averaged over all angles (-70° to 70°) for each frequency.

B. Estimation of Effective Sensitive Element Radii

The four models were used to estimate effective sensitive element radii for each of the four hydrophones from directivity measurements. The value for effective sensitive element radius chosen for each model and each hydrophone was the value that minimized the root mean square difference between the experimental directivity and the model directivity over angles from -70° to 70° . The difference between the estimated sensitive element size and the nominal geometrical sensitive element size a_g was designated as the error in the estimate. The relative error in the estimate of sensitive element radius,

$$\frac{\Delta a}{a_g} = \frac{a_{estimated} - a_g}{a_g}$$

was fit to a function inversely proportional to ka_g ,

$$\frac{\Delta a}{a_g} = \frac{C_i}{ka_g}$$

where i is an index for the four models: RB, RP, UB, and SB. The 95% confidence intervals (CIs) for estimates of C_i were compared for the four models. Values of C_i and 95% CI's were computed using the Matlab (Natick, MA) regress function.

Note that while IEC 62127-3 defines effective radius by fitting measured directivity data to the RB model [27], the present paper defines multiple effective radii obtained by fitting measured directivity data to multiple models.

III. Results

Figures 1, 2, 3 and 4 show directivity patterns for the four hydrophones. All models yielded similar directivity patterns for $ka_g > 4$. However, the four models showed greater differences for $ka_g < 4$, with the RB model yielding the broadest directivity patterns followed by the RP, UB, and SB models. The RP model predictions appeared to most closely match the experimental measurements.

Figure 1 shows that at 10 MHz, for $\theta = 60^\circ$, directivity measurements were higher than predictions of all four models. A similar discrepancy is seen in Figure 2 at 10 MHz for $\theta = 40^\circ$. These discrepancies are likely due to diminished signal-to-noise ratio at wide angles. Alternatively, the HNC-0200 and HNA-0400 could have been exhibiting some complex behavior for high angles at 10 MHz. Apart from these disparities, the data in Figures 1 – 4 seem quite consistent with the RP model.

Figure 5 shows standard deviations of paired directivity measurements (horizontal and vertical planes) averaged over angles (-70° to 70°) plotted versus frequency. The average value of standard deviation was 0.014 or less than 2% of the maximum directivity value

(1.0). The least-squares linear regression suggests a trend of standard deviation increasing with frequency.

Figure 6 shows estimated hydrophone sensitive element radii (a_{eff}) as functions of frequency for the four hydrophones and four models. The estimates based on the RP model are the most consistent with the nominal geometrical radius, especially at low frequencies. At low frequencies, the RB model overestimates sensitive element radii because it predicts directivity patterns that are too broad while the UB and SB models underestimate sensitive element radii because they predict directivity patterns that are too narrow.

Figure 7 shows the dependence of the relative error in the estimate of sensitive element radius (a/a_g) for the four models. Data from all four hydrophones are plotted collectively. The RP model exhibited the smallest errors.

Table II shows values of C_i for the four models along with 95% CIs. The 95% CI for C_{RP} is well separated from the 95% CIs for the other models, indicating that the RP model resulted in significantly lower errors in estimates of effective sensitive element radii (a_{eff}) than the other models. The values for C_i suggest that when $ka_g = 1$, the RP model can be expected to produce errors on the order of 7% while the other models can be expected to produce errors on the order of 46% or greater.

IV. Discussion

Four theoretical models were compared to experimental measurements of directivities of ceramic and polymer needle hydrophones over a broad range of values for ka_g ($0.4 < ka_g < 21.2$). For $ka_g > 4$, all four models provided comparable directivity patterns and agreed well with the measurements. Of the four models, the RP model exhibited the best consistency with experimental directivity for $ka_g < 4$. The commonly-used RB model predicted directivity patterns that were broader than measurements for $ka_g < 2.5$. This discrepancy is most noticeable for $0.8 < ka_g < 2.5$. For $ka_g < 0.4$, the experimental directivity, the RB model and the RP model approach a constant value of one between -70° and 70° . The UB model and the RB model can serve as lower and upper bounds to the RP model and are much easier to compute (see Figs 1 – 4). For $ka_g > 1.3$, the UB model and the RP model are nearly identical.

Table III summarizes experimental parameters used in this study and previous investigations of needle hydrophone directivity. The present study investigated relatively broad spans of sensitive element size and ka_g . The investigation of low ka values down to 0.4 was particularly important because the disparity between the RP and the UB models do not become apparent until $ka_g < 1.3$. There may be some conceivable value in investigating values of $ka_g < 0.4$. However, at such low values for ka_g , the RP and RB models begin to converge toward uniform (*i.e.*, angle-independent) directivity of one.

Shombert *et al.* compared the RB, UB, and SB models with hydrophone directivity measurements for four PVDF and four ceramic needle hydrophones [25]. They found good agreement between measurements and all three theoretical models for two PVDF hydrophones for $ka_g > 6$. However, the agreement was not good for the other two PVDF

hydrophones or the ceramic hydrophones. They suggested that discrepancies in the case of ceramic hydrophones might have been due to the ceramic element operating in modes other than the thickness mode and possibly due to vibrational modes of the hydrophone supporting structure.

Shombert *et al.* suggested that, based on physical considerations, the UB model might be more reasonable for hydrophones than the RB model because a hydrophone more closely resembles a piston in free space than a piston in a rigid baffle [25]. The data in the present paper did not reveal a statistically significant difference in performances of these two models with regard to magnitudes of errors in estimates of effective sensitive element. However, as indicated in Figs. 1 – 4, the UB model is closer to the RB model for $ka_g > 0.8$, in support of Shombert *et al.*'s suggestion.

Figure 6 shows that effective radii a_{eff} obtained by fitting to the RB model (red circles joined by red dashed lines) decline with frequency. Similar behavior has also been reported for membrane hydrophones [38, 42]. Frequency-dependent effective sensitive element size for membrane hydrophones has been attributed to Lamb waves induced in the obliquely insonated membrane at low source frequencies [42].

V. Conclusion

The commonly-used rigid baffle (RB) model for hydrophone directivity was compared to three alternative models: soft baffle (SB), unbaffled (UB), and rigid piston (RP) in four needle hydrophones with nominal geometrical sensitive element diameters ranging from 200 – 1000 μm . For $ka_g < 4$, the RP model outperformed the other three models, exhibiting average errors in estimated effective sensitive element size of 7% at $ka_g = 1$ while the other models exhibited average errors of 46% or greater. The UB model is much easier to compute than the RP model and is nearly identical to the RP model for $ka_g > 1.3$. The superior performance of the RP model 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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REFERENCES

- [1]. Holt RG and Roy RA, "Measurements of bubble-enhanced heating from focused, MHz-frequency ultrasound in a tissue-mimicking material," *Ultrasound Med Biol*, vol. 27, no. 10, pp. 1399–412, 10 2001. [PubMed: 11731053]
- [2]. 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]
- [3]. Clement GT, "Spectral image reconstruction for transcranial ultrasound measurement," *Phys Med Biol*, vol. 50, no. 23, pp. 5557–72, 12 07 2005. [PubMed: 16306652]
- [4]. White J, Clement GT, and Hynynen K, "Transcranial ultrasound focus reconstruction with phase and amplitude correction," *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 52, no. 9, pp. 1518–22, 9 2005. [PubMed: 16285450]
- [5]. Choi JJ, Pernot M, Small SA, and Konofagou EE, "Noninvasive, transcranial and localized opening of the blood-brain barrier using focused ultrasound in mice," *Ultrasound Med Biol*, vol. 33, no. 1, pp. 95–104, 1 2007. [PubMed: 17189051]
- [6]. Konofagou EE, "Optimization of the ultrasound-induced blood-brain barrier opening," *Theranostics*, vol. 2, no. 12, pp. 1223–37, 2012. [PubMed: 23382778]
- [7]. Konofagou EE, Tung YS, Choi J, Deffieux T, Baseri B, and Vlachos F, "Ultrasound-induced blood-brain barrier opening," *Curr Pharm Biotechnol*, vol. 13, no. 7, pp. 1332–45, 6 2012. [PubMed: 22201586]
- [8]. Robertson J, Martin E, Cox B, and Treeby BE, "Sensitivity of simulated transcranial ultrasound fields to acoustic medium property maps," *Phys Med Biol*, vol. 62, no. 7, pp. 2559–2580, 4 07 2017. [PubMed: 28165334]
- [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]. Zanelli CI and Howard SM, "A robust hydrophone for HIFU metrology," (in English), *Therapeutic Ultrasound*, vol. 829, pp. 618–+, 2006.
- [11]. Haller J, Jenderka KV, Durando G, and Shaw A, "A comparative evaluation of three hydrophones and a numerical model in high intensity focused ultrasound fields," (in English), *Journal of the Acoustical Society of America*, vol. 131, no. 2, pp. 1121–1130, 2 2012. [PubMed: 22352487]
- [12]. Liu Y, Wear KA, and Harris GR, "Variation of High-Intensity Therapeutic Ultrasound (HITU) Pressure Field Characterization: Effects of Hydrophone Choice, Nonlinearity, Spatial Averaging

and Complex Deconvolution,” *Ultrasound Med Biol*, vol. 43, no. 10, pp. 2329–2342, 10 2017. [PubMed: 28735734]

- [13]. Rahim A, Taylor SL, Bush NL, ter Haar GR, Bamber JC, and Porter CD, “Physical parameters affecting ultrasound/microbubble-mediated gene delivery efficiency in vitro,” *Ultrasound Med Biol*, vol. 32, no. 8, pp. 1269–79, 8 2006. [PubMed: 16875960]
- [14]. Brown JA, Foster FS, Needles A, Cherin E, and Lockwood GR, “Fabrication and performance of a 40-MHz linear array based on a 1–3 composite with geometric elevation focusing,” *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 54, no. 9, pp. 1888–94, 9 2007. [PubMed: 17941395]
- [15]. Giesecke T and Hynynen K, “Ultrasound-mediated cavitation thresholds of liquid perfluorocarbon droplets in vitro,” *Ultrasound Med Biol*, vol. 29, no. 9, pp. 1359–65, 9 2003. [PubMed: 14553814]
- [16]. 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]
- [17]. 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.
- [18]. 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.
- [19]. 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]
- [20]. 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]
- [21]. 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.
- [22]. 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.
- [23]. 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]
- [24]. 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]
- [25]. Shombert DG, Smith SW, and Harris GR, “Angular Response of Miniature Ultrasonic Hydrophones,” (in English), *Medical Physics*, vol. 9, no. 4, pp. 484–492, 1982. [PubMed: 7110078]
- [26]. Morse PM and Ingard KU, *Theoretical Acoustics*. Princeton, NJ: Princeton University Press, 1968.
- [27]. IEC 62127–3 Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz, 2013.
- [28]. Selfridge AR, Kino GS, and Khuriyakub BT, “A Theory for the Radiation-Pattern of a Narrow-Strip Acoustic Transducer,” (in English), *Appl. Phys. Lett*, vol. 37, no. 1, pp. 35–36, 1980.
- [29]. Delannoy B, Lasota H, Bruneel C, Torguet R, and Bridoux E, “Infinite Planar Baffles Problem in Acoustic Radiation and Its Experimental-Verification,” (in English), *J. Appl. Phys*, vol. 50, no. 8, pp. 5189–5195, 1979.
- [30]. 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]
- [31]. 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]
- [32]. Fay B, Ludwig G, Lankjaer C, and Lewin PA, “Frequency-Response of PvdF Needle-Type Hydrophones,” (in English), *Ultrasound in Med. & Biol.*, vol. 20, no. 4, pp. 361–366, 1994. [PubMed: 8085292]
- [33]. Harris GR and Shombert DG, “A Pulsed near-Field Technique for Measuring the Directional Characteristics of Acoustic Receivers,” (in English), *IEEE Trans Son. Ultrason*, vol. 32, no. 6, pp. 802–808, 1985.
- [34]. Platte M, “A Polyvinylidene Fluoride Needle Hydrophone for Ultrasonic Applications,” (in English), *Ultrasonics*, vol. 23, no. 3, pp. 113–118, 1985.
- [35]. Smith RA and Bacon DR, “A Multiple-Frequency Hydrophone Calibration Technique,” (in English), *J. Acoust. Soc. Am.*, vol. 87, no. 5, pp. 2231–2243, 5 1990. [PubMed: 2189922]
- [36]. Beard PC, Hurrell AM, and Mills TN, “Characterization of a polymer film optical fiber hydrophone for use in the range 1 to 20 MHz: A comparison with PVDF needle and membrane hydrophones,” (in English), *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 47, no. 1, pp. 256–264, 1 2000. [PubMed: 18238538]
- [37]. Hurrell A and Duck F, “A two-dimensional hydrophone array using piezo-electric PVDF,” (in English), *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 47, no. 6, pp. 1345–1353, 11 2000. [PubMed: 18238680]
- [38]. 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]
- [39]. Kitsunai H, Kawashima N, Takeuchi S, Ishikawa M, Kurosawa M, and Odaira E, “Development of miniature needle-type hydrophone with lead zirconate titanate polycrystalline film deposited by hydrothermal method,” (in English), *Jap. J. Appl. Phys. Pt 1-Regular Papers Brief Communications & Review Papers*, vol. 45, no. 5b, pp. 4688–4692, 5 2006.
- [40]. Conjusteau A, Ermilov SA, Su R, Brecht HP, Fronheiser MP, and Oraevsky AA, “Measurement of the spectral directivity of optoacoustic and ultrasonic transducers with a laser ultrasonic source,” *Rev Sci Instrum*, vol. 80, no. 9, p. 093708, 9 2009. [PubMed: 19791945]
- [41]. Guggenheim JA, Zhang EZ, and Beard PC, “A Method for Measuring the Directional Response of Ultrasound Receivers in the Range 0.3–80 MHz Using a Laser-Generated Ultrasound Source,” (in English), *IEEE Trans. Ultrason. Ferroelectr., Freq. Control*, vol. 64, no. 12, pp. 1857–1863, 12 2017. [PubMed: 28976314]
- [42]. Bessonova O and Wilkens V, “Investigation of Spatial Averaging Effect of Membrane Hydrophones for Working Frequencies in the Low MHz Range,” *DAGA 2012 - Darmstadt*, pp. 937–938, 2012.

Figure 1.

Directivity of the Onda HNC-0200 hydrophone at 1, 2, 3, 4, 6, 8, and 10 MHz. The RP and UB models exhibit substantial overlap for $ka_g = 1.3$ and may appear as one curve.

Figure 2.

Directivity of the Onda HNA-0400 hydrophone at 1, 2, 3, 4, 6, 8, and 10 MHz. The RP and UB models exhibit substantial overlap for $ka_g > 1.3$ and may appear as one curve.

Figure 3.

Directivity of the DIBE-0600 hydrophone at 1, 2, 3, 4, 6, 8, and 10 MHz. The RP and UB models exhibit substantial overlap for $ka_g \leq 1.3$ and may appear as one curve.

Figure 4.

Directivity of the HNP-1000 hydrophone at 1, 2, 3, 4, 6, 8, and 10 MHz. The RP and UB models exhibit substantial overlap for $ka_g \geq 1.3$ and may appear as one curve.

Figure 5. Standard deviations of paired directivity measurements (horizontal and vertical planes) averaged over angles plotted versus frequency. A least-squares linear fit is shown.

Figure 6.

Estimated effective hydrophone sensitive element radii as functions of frequency for all four hydrophones and all four models.

Figure 7. Differences between estimated and nominal geometric sensitive element radii (expressed as percentages) as functions of ka_g for all four hydrophones and all four models.

TABLE I

Hydrophones Used for Experimental Measurements

Manufacturer	Model	Type	Nominal Geometrical Sensitive Element Diameter $d(\mu\text{m})$
Onda (Sunnyvale, CA)	HNC-200	Ceramic	200
Onda	HNA-400	Ceramic	400
Force Technology Inst. (Brøndby, DK).	Custom	PVDF	600
Onda	HNP-1000	PVDF	1000

TABLE II

Functional fits for percent error between estimated sensitive element radius and nominal geometrical radius

Model	$a(ka_g) = C/(ka_g)$
	C (%) (95% CI)
Rigid Baffle (RB)	52 (45, 59)
Rigid Piston (RP)	-7 (-12, -3)
Unbaffled (UB)	-46 (-54, -38)
Soft Baffle (SB)	-69 (-84, -53)

TABLE III

Experimental Parameters for Hydrophone Directivity Studies

Reference	Frequency (MHz)	Sensitive Element Diameter (μm)	ka_g	Angle ($^\circ$)
[25]	2.5 – 8	250–1020	1.3 – 16.7	0 – 90
[33]	1 – 10	600–1000	1.2 – 20.4	0 – 30
[34]	1 – 10	300	0.6 – 6.1	0 – 90
[35]	1 – 5	300–600	0.6 – 6.1	0 – 60
[36]	1 – 10	75 – 200	0.2 – 4.1	0 – 80
[37]	5 – 20	200	2.0 – 8.2	0 – 60
[38]	1 – 40	150	0.3 – 12.2	0 – 40
[39]	5	300	3.1 – 3.1	0 – 90
present	1 – 10	200–1000	0.4 – 21.2	0 – 70