# A Robust Hydrophone for HIFU Metrology

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**Abstract.** The high acoustic intensities generated by HIFU systems cause conventional hydrophones to fail before measurements can be reliably made. To address this challenge, we present a new piezoelectric needle hydrophone, which is resistant to cavitation while possessing a flat frequency response (+/- 3 dB from 1 to 10 MHz) and a small effective aperture (400 micron effective diameter). This hydrophone has been used in a high intensity field (1.5 MHz tone burst of 30 microseconds and 3% duty cycle, with rarefactional pressures exceeding 4 MPa and positive pressures exceeding 15 MPa) without degradation in the hydrophone's performance, as indicated in before-and after calibration checks of the device.

**Keywords**: Hydrophone, HIFU, cavitation

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## INTRODUCTION

Acoustic fields generated by HIFU (High Intensity Focused Ultrasound) pose two dangers to hydrophones: excessive heating and cavitation. Excessive heating may be avoided by making measurements at a low duty cycle, and then scaling results for higher duty cycles, if necessary. However, transient cavitation may still be nucleated at the tips of currently available hydrophones and destroy them, even at low duty cycles.

We have recently developed a new hydrophone with the intention of significantly reducing the risk of cavitation damage. The design consists of a miniature piezoceramic sensing element encased in a metallic coating twenty to seventy microns thick. The proprietary coating process provides a smooth outer surface to minimize nucleation sites for cavitation, and the coating thickness is chosen to preserve the hydrophone's acoustic response while providing a level of "blast protection".

## DESIGN

Figure 1 provides a picture of the device. Fig. 2 shows a schematic cross section of a finite element model of the tip, constructed in the PZFLEX software code (Weidlinger Associates, Los Altos, CA). The FEA model was used to facilitate a critical design choice: the thickness of the coating. While a thicker coating may be desirable to protect the hydrophone, it also degrades its frequency response, as shown by the FEA results in Fig 3. The worsening frequency response results in poor response to field harmonics (which are prominent in the nonlinear fields generated by

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HIFU) and correlates with poor directivity.  We therefore believe that a coating of no more than 90 microns is desirable.  The current coating process we employ applies the coating in a thickness ranging from 30 to 70 microns.

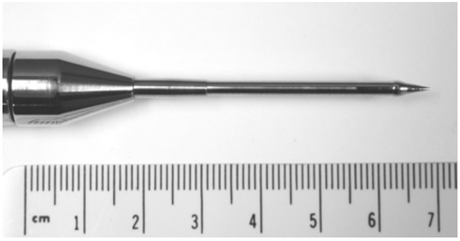


**Figure 1.** Device as built

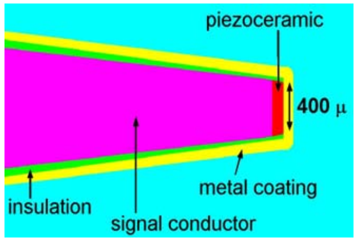


**Figure 2.** FEA model

## MEASUREMENTS OF FREQUENCY RESPONSE AND EFFECTIVE APERTURE

Fig. 4 shows the calibration obtained for the hydrophone by comparison with a membrane hydrophone calibrated by NPL (the comparison was done at pressure levels well below cavitation).  The general features are reproduced by the FEA model in Fig. 3.  The drop-off in sensitivity below 3 MHz is a generic property of all needle hydrophones in this size range; it is a result of the frequency dependence of acoustic scattering off of the hydrophone tip [1].  The hydrophone response is then fairly flat between 3 and 10 MHz, and then it drops at higher frequencies due to the internal structure of the device.

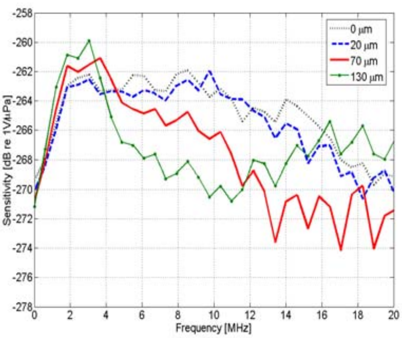


**Figure 3.** FEA study on coating thickness

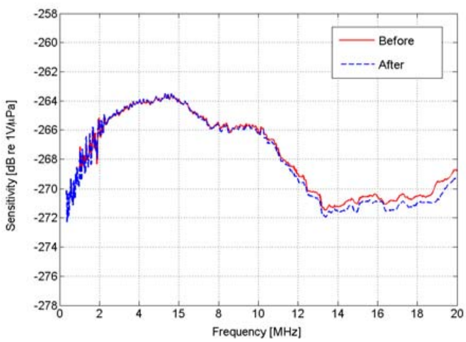


**Figure 4.** Sensitivity before and after exposure (see description of tests below).

Fig. 5 shows a plot of the hydrophone's angular response at 5 MHz.  The directivity function expected for a circular geometric aperture is given by [2,3]:

$$D(\theta) = \frac{2J_1[(2\pi a_e/\lambda)\sin(\theta)}{(2\pi a_e/\lambda)\sin(\theta)}] \qquad (1)$$

where $J_1$ is the first order Bessel function of the first kind. $a_e$ is the effective radius and λ is the acoustic wavelength. Metrology standards[2,3] provide a means of estimating $a_e$ by determining the –3 and –6 dB points from the directivity plot, and using Eq. (1) to determine an effective radius corresponding to these points, i.e.:

$$a_{e3} = \frac{1.62\lambda}{2\pi \sin(\theta)} \qquad a_{e6} = \frac{2.22\lambda}{2\pi \sin(\theta)} \tag{2}$$

Applying Eq. (2) to the data, and taking the average, we obtain $a_e$ = 0.44mm, which is within our expected manufacturing tolerances for this design.

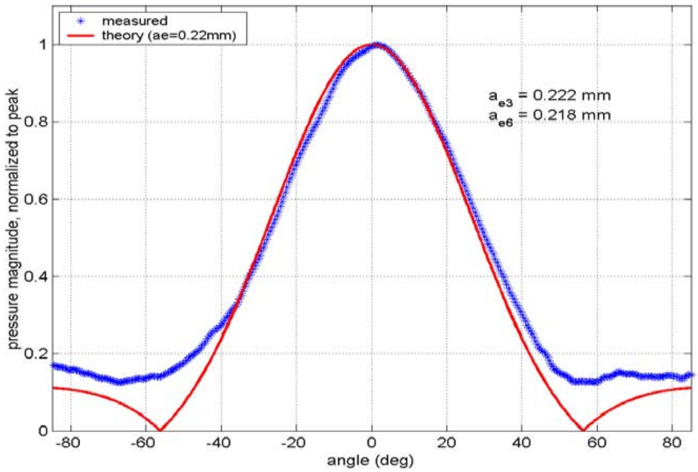


**Figure 5.** Hydrophone directivity at 5 MHz

## PRELIMINARY TESTS IN HIGH INTENSITY FIELDS

The hydrophone has been tested by placing it at the focus of a HIFU source manufactured by the authors (1.50 MHz, 100 mm diameter, 150 mm focus) in a tank of degassed, deionized water. The source, which has a measured electrical impedance of 50 ohms (real) was driven by an HP 8165A function generator through an ENI 240L amplifier. The hydrophone was connected to a pre-amplifier (AH2020-025, manufactured by Onda corporation) set to 0-dB gain, and the signal was recorded using a Tektronics 724A oscilloscope. It was found that the pressure signal achieved a steady-state response within 12 microseconds of the pulse arrival; consequently, the function generator was adjusted to provide a 30 microsecond burst, and the hydrophone signal was captured over a 10 microsecond time window starting at 15 microseconds from the pulse arrival. To obtain pressure readings, this data was then scaled by the sensitivity of 39.8 mV per MPa, obtained from the calibration curve of Fig. 4, at 1.5 MHz. The voltage waveforms supplied to the source transducer were also captured via a high-impedance probe, allowing the pulse-average power input to be calculated.

Fig. 6 shows four of the eighteen pressure waveforms, which were recorded as input power to the transducer was varied from 1 Watts to 120 Watts. The pattern typical of distortion due to nonlinear propagation in water is observed; the positive peaks become spiked, and the rarefactional troughs become broadened. As the rarefactional pressure exceeded 3.5 MPa, the trough of the waveform becomes increasingly irregular and noisy, with slight variations from cycle to cycle. We also observed occasional jumps of the signal on the oscilloscope. We believe these to be signs of cavitation. In fact, another hydrophone (HNR-0400, manufactured by Onda Corporation) was observed to fail in the same field at approximately 40W input power (corresponding to 2.5 MPa rarefactional pressure).

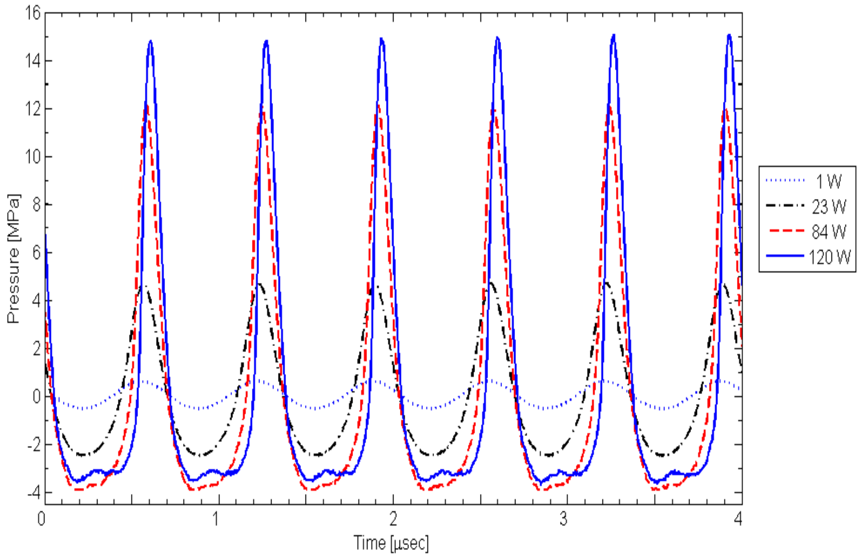


**Figure 6.** Measured waveforms

Figure 7 shows the full dataset as a function of input power, after the waveforms are reduced to the metrics of rarefactional pressure (Pr) and peak pressure (Pmax). Although Pmax monotonically increased as the input power was increased, Pr levels off and even slightly decreases. At this time, we cannot tell whether the phenomenon is due to the finite bandwidth of the hydrophone (i.e., some energy may lie outside of it's pass band) or whether it is a property of the field measured (e.g., cavitational screening).

Although we believe the hydrophone was exposed to cavitation for approximately 30 minutes, we observed no sign of degraded performance when we repeated the calibration after exposure (see Fig. 4).

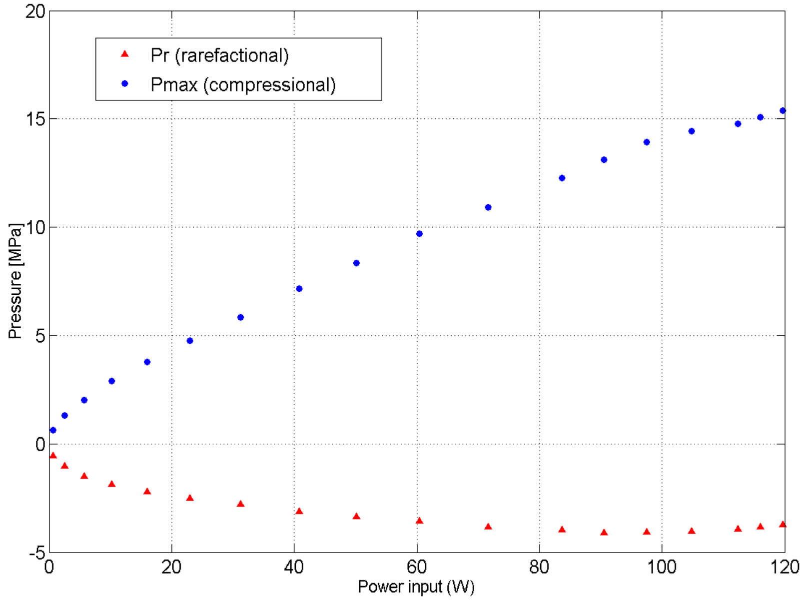


**Figure 7.** Measured pressures vs. power input

## CONCLUSIONS AND FUTURE WORK

These results are preliminary, and performed on the first completed device of this design. The probabilistic nature of cavitation calls for a more exhaustive set of tests involving more devices. This study should include increasing the exposure levels until the point of failure is reached for each hydrophone in the study. This would establish statistically valid criteria for failure. It would also be valuable to make a measurement by deconvolving the hydrophone response, using a calibration for the hydrophone that includes phase.

## REFERENCES


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