Characterization of a HIFU Field at High Intensity

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***Abstract*—Accurate quantification of HIFU fields has been hampered by the inability of traditional hydrophones to survive the high pressures encountered. We present a set of data at high intensities taken with a hydrophone capable of surviving this environment, which included 5 MPa maximum rarefactional pressure, pulse-average-spatial-peak intensity of 3760 W/cm^2, and a total power of 101 Watts. Comparisons are made to predictions of a KZK model and an independent measurement of total power via radiation force balance, and are found to be favorable. Beamplots show more than 50% reduction in the –3 dB beam area measured at low power, in agreement with KZK predictions.**

Keywords: HIFU; metrology; beamplotting

I. Motivation and Background

Accurate quantification of HIFU (High Intensity Focused Ultrasound) fields has been hampered by the inability of traditional hydrophones to survive the high pressures encountered. The most trusted method has been to measure the beams at low power and to assume the beam pattern to scale at high powers. Yet it is known that this is incorrect because of the non-linearity of the medium, and because in some cases the transducer itself changes at high power, resulting in altered acoustic field patterns. In this paper, we present a set of data at high intensities using a hydrophone capable of surviving this environment and compare it with data taken at low power as well as the KZK model.

II. Materials and Methods

All measurements were made on a HIFU transducer manufactured by the authors, which has a 100 mm diameter, and 150 mm geometric focus (F-number 1.5). The nominal frequency of this device is 1.5 MHz, and measurements (as described below) determined an optimal driving frequency of 1.505 MHz. The transducer impedance was tuned to provide a 50 ohms (real) impedance at this frequency. This transducer was inserted in a tank (filled with water degassed to < 3 ppm oxygen content, and deionized to < 1 µS conductivity) as shown in Fig. 1, and mounted on a fixture, which allowed its angular orientation to be adjusted. The transducer was driven by a Hewlett-Packard 3314A function generator, through an AP400B RF amplifier, manufactured by ENI Corporation of Rochester, NY.

To measure the field, a needle hydrophone designed for HIFU fields (Model HNA, manufactured by the authors'

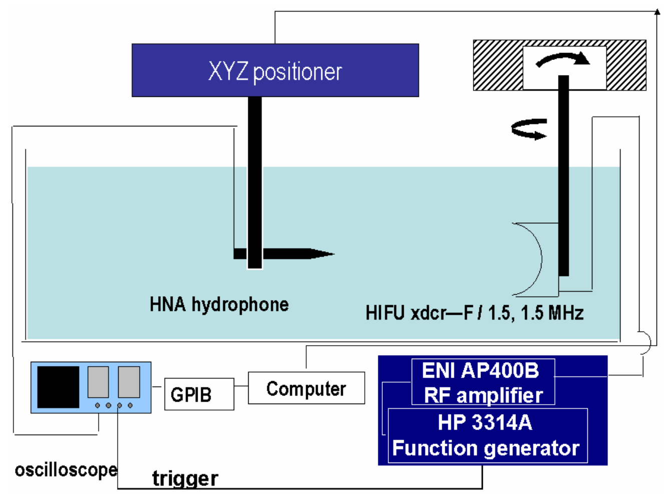

Figure 1. Measurement Set-up

company) was used. As described previously [1] the HNA is a piezoceramic needle hydrophone encased in a smooth metallic coating. The smoothness of the coating reduces the likelihood of nucleation of cavitation, while the metallic layer provides added protection from cavitation if it should occur. The coating thickness is chosen to preserve the frequency response and 400-micron effective diameter of the hydrophone [1]. The hydrophone was connected to a short (20 cm) coaxial cable, which in turn was connected to a high impedance oscilloscope probe which was detected at an input channel on a Tektronix 724A scope set to 1 Mohm input impedance. The hydrophone was calibrated as discussed in Section V

The hydrophone was mounted in a stepper-motor-driven XYZ stage constructed by the authors, which was under the control of a desktop computer, which allowed automated raster scanning of the hydrophone with acquisition and storage of waveforms from the hydrophone at each point of the scan.

The voltage and power supplied to the transducer was monitored via a high impedance scope probe attached to the output of the ENI AP 400B amplifier. While amplifier nonlinearities were observed, resulting in harmonic distortion of the driving voltage, the driving voltage waveforms could be FFT'ed to determine the component at 1.505 MHz. Hence the input power could be calculated by considering only the fundamental of the driving signal, because the transducer impedance is extremely mismatched to the amplifier at the harmonics.

The transducer was pulsed at a low duty cycle in order to avoid the formation of large bubble clouds, water heating, and temporal overlap between the main signal and acoustic reverberations. The driving voltage was increased until the fundamental component appeared to reach its maximum value of 90 volts rms—beyond this point only the voltage harmonics increased significantly. A pulse burst of 350 cycles was selected, and sampled between the 295th and 310th cycle, which allowed avoidance of both turn-on and turn-off transients and was judged representative of steady-state operation. A pulse repetition rate of 100 Hz was used, and it was verified by varying this setting that no echoes from earlier pulses overlapped with the main signal.

The total power output from the transducer was measured via a radiation force balance (RFB), using a nylon brush target constructed by the authors to match a design previously used successfully by other researchers [2,3]. The power was measured in continuous wave mode, and found to be 101 Watts.

III. DETERMINATION OF PEAK SPATIAL VALUES

After the transducer was aligned, the hydrophone was scanned down the beam axis while adjusting the driving frequency and it was found that a driving frequency of 1.505 MHz provided the optimal I_{PA} (pulse-average intensity), at a focal distance of 152 mm. All subsequent measurements were made at this depth. Fig. 2 shows the waveforms measured at this position (solid line).

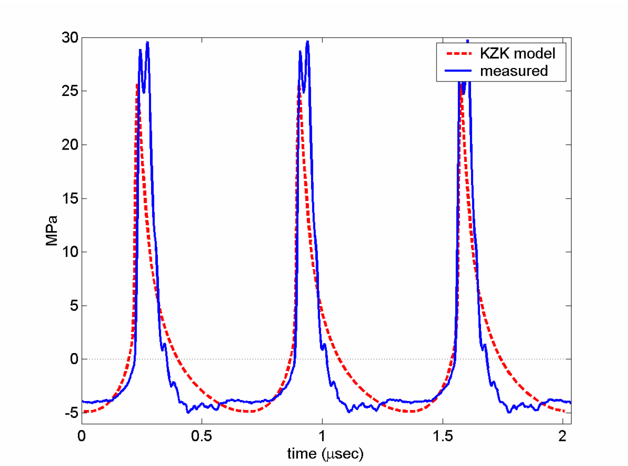

Figure 2. Waveforms at 151 mm

IV. COMPARISON WITH A MODEL

As a check on the results, we employed a numerical solution of the time domain version of the KZK equation [4] which describes the propagation of the nonlinear wave from the source, assuming axial symmetry. For the source distribution, a uniform spherical shell with diameter 98 mm and radius of 154 mm, was used because it fit the results obtained when driving this transducer in the linear regime, as described previously [5]. Source pressure was calculated by assuming that the 101 Watts of output power (as measured by RFB) was distributed uniformly across the surface of the transducer—i.e., a source pressure amplitude of 196 kPa.

The model's results are shown in Fig. 2, as a dashed line. The model demonstrates the sawtooth wave behavior expected of a HIFU source, but the experimental data shows a double peak, and additional ripples in the waveform. These artifacts are due to the non-uniform frequency response of the hydrophone, which is discussed in the next section.

V. COMPENSATING FOR THE HYDROPHONE'S FREQUENCY RESPONSE

Fig. 3 shows the frequency response of the hydrophone, as measured by the authors using broadband comparison to a membrane hydrophone calibrated by NPL in the UK, and employing a low-power source [6]. The uncertainty (95% confidence level) of this calibration from 1 to 10 MHz has been assessed to be +/- 10%.

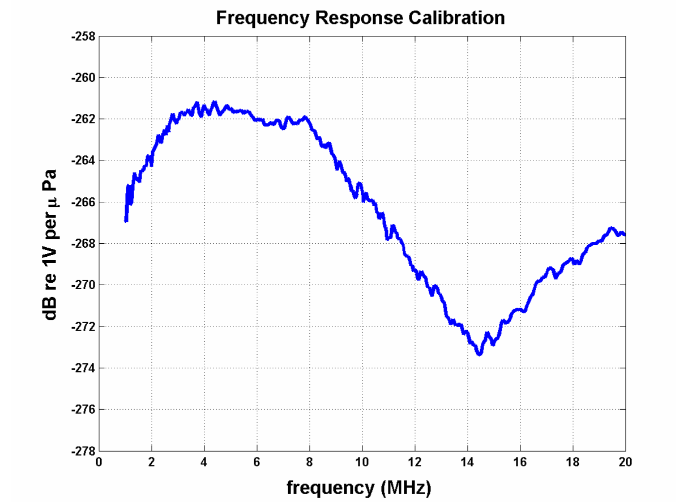

Figure 3. Frequency Response for the HNA hydrophone

Considerations arising from the hydrophone's non-uniform frequency response were discussed in detail previously in [5], where comparisons were made to a membrane hydrophone (exposure time was carefully limited to protect the fragile membrane), at pressure excursions of roughly half that measured here. Comparisons were made to both the scaled HNA waveforms (i.e., where the waveform was scaled according to the hydrophone's sensitivity at 1.505 MHz) and to HNA data, which was deconvolved with the amplitude response of Fig. 3. Under those conditions, it was shown that: (a) the non-uniform frequency response caused less than 10% error in rarefactional pressure, even without deconvolution, and (b) with amplitude deconvolution of the frequency response, the pulse-average intensity measured by the HNA was within 3% of that of the membrane hydrophone. The double peak and ripples in the HNA waveform were also observed previously, and it is believed that they are due to a 27 MHz resonance in the hydrophone. Unfortunately, because phase calibration is not readily available for hydrophones, temporal deconvolution of the waveform is not possible, and it is therefore difficult to remove the time-domain waveform artifacts.

Therefore, in the measurements reported here, the scaled waveforms were used for any evaluation of temporally recorded pressure, but in order to calculate intensity or power, the spectra of the waveforms were calculated by deconvolving the hydrophone's amplitude response and summing the spectral components between 1 and 20 MHz.

VI. BEAMPLOTS

Beamplots were performed at the focal depth of 152 mm with a spatial resolution of 102 µm in both transverse directions, across a range of. 7.72 mm centered on the beam axis. At each point in the raster scan, an entire waveform of 2500 points was acquired at a sampling rate of 250 MHz, and stored. Each stored waveform was later FFT'ed and deconvolved with the hydrophone's amplitude response, in order to calculate I_{PA}.

A 2-dimensional beamplot is shown in Fig. 4, in which the I_{SPPA} (i.e., spatial peak, pulse-average intensity) is 3760 Watts / cm^2. Spatial integration yielded a total power of 91 Watts, which is within 10% of the RFB measurement of 101 Watts discussed in Section IV—the difference is within the calibration uncertainty for the hydrophone (+/- 10% for amplitude, or +/- 20% for intensity).

Fig. 5 shows the RMS pressure (after amplitude deconvolution) averaged over the x and y axes of the scan, and compares these to predictions of the KZK model, as well as measurements made at low power, where no significant propagational nonlinearities were observed. The data shows excellent agreement with the theory, with a 31% reduction in -3dB diameter for the measurement and 29% reduction for the theory. Such reductions correspond to a 50% reduction in beam area due to the nonlinear propagation.

Fig. 6 shows the corresponding beamplots for the fundamental and its first five harmonics. These first six spectral components account for over 98% of the total power in the first 13 spectral components (i.e., to 19.5 MHz) which supports: the notion that only the first few harmonics are important, and that deconvolving over a 20 MHz bandwidth should be adequate for intensity measurement.

VII. DISCUSSION

We have demonstrated the use of a cavitation-resistant hydrophone in the characterization of a HIFU field which had: (a) pulse-averaged intensity Isppa = 3760 W/cm^2 (b) peak rarefactional pressure of 5 MPa (c) peak pressures of approximately 30 MPa. A summary of key metrics is given in Table I.

The hydrophone's non-uniform frequency response poses unresolved challenges for measuring the peak pressure, but the agreement with the KZK model and earlier results [5] indicate that the maximum rarefactional pressure measurement is far less affected by the hydrophone's frequency response. Intensity and power measurements can be reasonably corrected by deconvolving the hydrophone's amplitude response, and the agreement with radiation force measurements for total power support this conclusion. An additional potential value is the ability to measure beamwidths which have been significantly reduced due to non-linear propagation effects which occur at high intensity (in this example there was over 50% reduction in beam area compared with low power measurements)

Perhaps most significantly, the hydrophone survived this exposure for over four hours while the raster scan was completed, and no significant difference was found when the calibration of Fig. 3 was repeated after the measurement.

TABLE I. SUMMARY COMPARISON OF MEASUREMENTS AND MODEL

Acoustic Metric	*KZK Model*	*HNA measurement*
P_r (max. rarefactional pressure, in MPa)	4.87	5.04
I_{SPPA} (Watts / cm^2)	3012	3700
P_+ (peak pressure)	25.7	29.9
Power (Watts)	101 (RFB measurement)	91
- 3 dB beam diameter (mm)	1.20	1.14

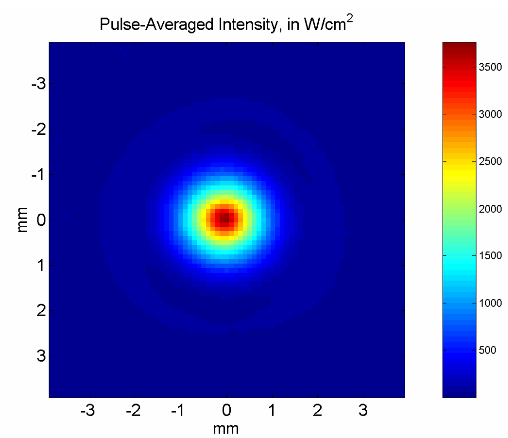

Figure 4. 2D beamplot

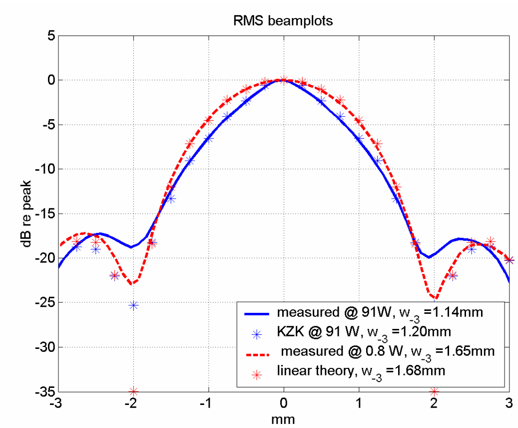

Figure 5. 1D beamplot of RMS pressure, normalized to peak

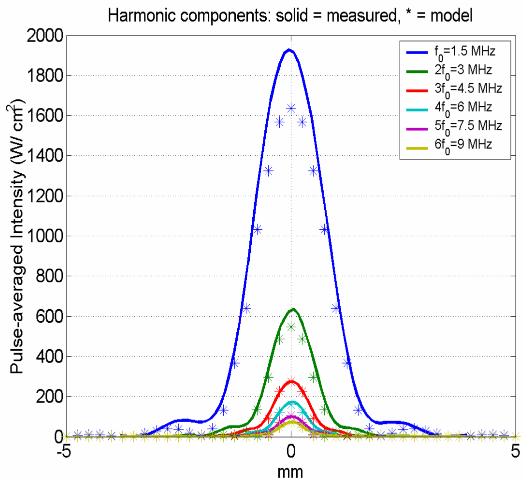

Figure 6. 1D beamplot of spectral components

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