Proceedings of the ASME 2007 Summer Bioengineering Conference (SBC2007)
June 20-24, Keystone Resort & Conference Center, Keystone, Colorado, USA

SBC2007-176653

HIGH INTENSITY FOCUSED ULTRASOUND (HIFU) TRANSDUCER CHARACTERIZATION USING ACOUSTIC STREAMING

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ABSTRACT

A new, non-perturbing optical measurement technique was developed to characterize medical ultrasound fields generated by High Intensity Focused Ultrasound (HIFU) transducers using a phenomenon called 'acoustic streaming'. The acoustic streaming velocity generated by HIFU transducers was measured experimentally using Digital Particle Image Velocimetry (DPIV). The streaming velocity was then calculated numerically using the finite-element method. An optimization algorithm was developed to back-calculate acoustic power and intensity field by minimizing the difference between experimental and numerical streaming velocities. The intensity field and acoustic power calculated using this approach was validated with standard measurement techniques. Results showed that the inverse method was able to predict acoustic power and intensity fields within 10% of the actual value measured using standard techniques, at the low powers where standard methods can be safely applied. This technique is also potentially useful for evaluating medical ultrasound transducers at the higher power levels used in clinical practice.

INTRODUCTION

Medical ultrasound fields generated by focused transducers during HIFU ablation procedures are usually characterized in water using i) hydrophones and ii) radiation force balances. Though these two techniques are well established and widely used, there are known limitations in both this methods such as i) sensor damage due to heating and cavitation, ii) effect of focusing, and iii) effect of non-linearity. For clinically relevant high powers, there is a need for sensor-less alternate measurement methods for characterizing medical ultrasound fields.

In this study, a new non-perturbing method is developed to estimate acoustic power and intensity using an acoustical phenomenon called ***'acoustic streaming'***. Acoustic streaming is the fluid motion setup due to the momentum flux created by the viscous dissipation of acoustic energy. Several studies have observed a direct correlation between the acoustic intensity field and the acoustic streaming field [1-3]. In this study, the correlation between acoustic and streaming fields is used to characterize the HIFU transducers.

METHODOLOGY

The transducer-characterization method, employed in this study, utilizes an *optimization algorithm* to minimize the difference between the experimental streaming velocity and the computed velocity, as a parameter (or parameter set) characterizing the acoustic field is varied (Fig. 1). The parameters of interest are often the total power and intensity field, though quantities such as acoustic absorption or viscosity of fluid medium may also be determined.

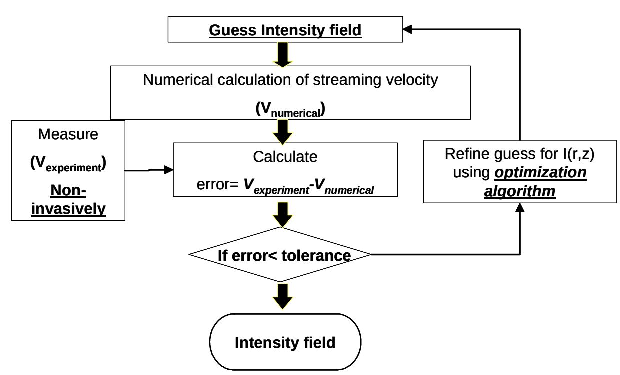

Figure 1: *Flow Chart for inverse method*

The first stage in the algorithm is experimentally measuring the streaming velocity field (Fig.1). In this study, streaming velocity was measured experimentally using Digital Particle Image Velocimetry (DPIV) technique. In the next step, acoustic pressure and intensity are predicted by solving the KZK non-linear sound propagation equation in a fluid medium:

$$\frac{\partial}{\partial t'}\left[\frac{\partial p}{\partial z}+\frac{D}{2c^3}\frac{\partial^2 p}{\partial t'^2}+\frac{\beta}{2\rho_0 c^3}\frac{\partial p^2}{\partial t'}\right]=\frac{c}{2}\left(\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}\right) \qquad (1)$$

where p - acoustic pressure, t′- retarded time, c - speed of sound D- sound diffusivity of fluid medium, and β - coefficient of non-linearity. Once the acoustic intensity is calculated, streaming velocity is computed numerically by solving the time-averaged conservation equations of fluid flow.

$$\rho\frac{\partial \overline{u_i}}{\partial x_i}=0 \ ; \qquad \rho_0\left(\overline{u_i}\frac{\partial \overline{u_j}}{\partial x_j}\right)=-\frac{\partial \overline{p}}{\partial x_j}+\mu\nabla^2\overline{u_j}+F_j \qquad (2)$$

where $\overline{u_i}$ is the steaming velocity and F_j is the Reynolds stress term calculated from the acoustic intensity field.

An optimization routine (Nelder Mead method) is employed to refine the guesses for the transducer characterization parameters, and the computation procedure is repeated. Once the difference between the computed and measured velocity fields falls below the threshold value, the final estimate for the ultrasound intensity field is obtained.

RESULTS

Figure 2 compares the radial streaming velocity profiles obtained experimentally and computationally, for the back- calculated power of 5.2 W. Figure 2 shows that the computational velocity profile matches closely with the experimental data. The peak streaming velocity estimated numerically is about 6% more than the peak velocity measured from the DPIV system.

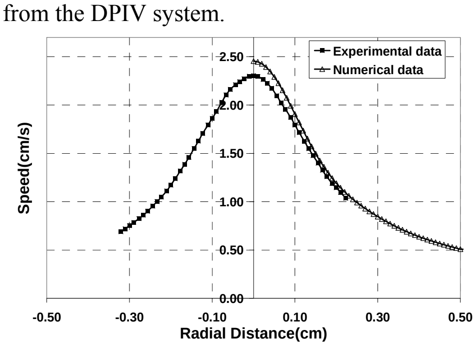

Figure 2 : *Radial plot of streaming velocity for power: 5.2W*

Comparison with Radiation Force Balance (RFB): In Fig.3 total acoustic power estimated using our inverse method (Fig. 1) is validated with the standard measurement technique (RFB). RFB measured the acoustic power emitted by the HIFU transducer to be 3.6 and 5.2 W for driving voltages of 15 and 18 V_{rms}, respectively. Our inverse method predicted the power to be 3.2 and 4.8 W. The inverse method was able to measure the acoustic power within ~11% of the existing standard.

Comparison with hydrophone scan: In Fig. 4, the acoustic intensity field estimated using our inverse method is validated with the hydrophone scanned data. Peak intensity at the focus measured by the inverse method is 65 W/cm^2, which is very close to the intensity measured by hydrophone (67.8 W/cm^2). In addition, axial and radial intensities obtained from both the techniques are very similar (Fig. 4). The 6 dB length and width (length and width at which the acoustic intensity becomes 25% of the peak intensity) back calculated from the streaming velocities are 2.7 cm × 2.7 mm; these values match well with those obtained from hydrophone scanning (2.8 cm × 2.8 mm).

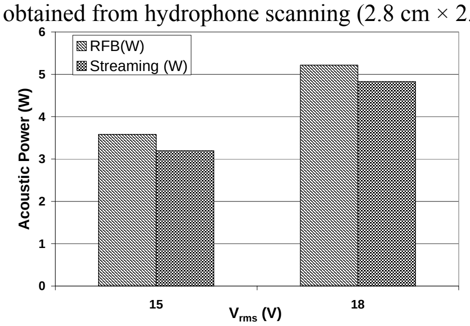

Figure 3: *Comparison of acoustic power obtained from inverse method and radiation force balance (RFB)*

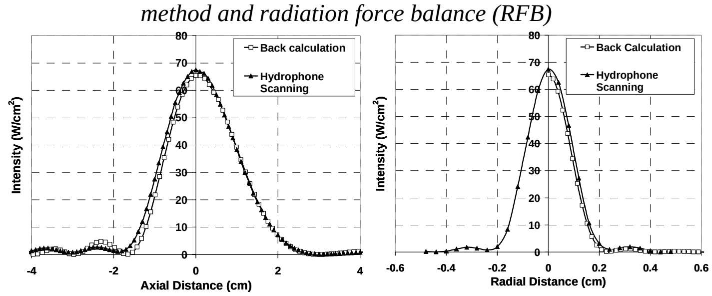

Figure 4: *Comparison of intensities along a) axial and b) radial distances, obtained from back calculation and hydrophone scanning*

DISCUSSIONS

A close match (~6%) is obtained between the experimental and numerical velocity fields (Fig. 2), suggesting that the acoustic power field back-calculated from the velocity fields can be accurate. Fig. 3 and 4 showed that at low power levels, the acoustic power and intensity field estimated using our technique matched well with the standard techniques. Results also showed that our optimization is able to consistently estimate the actual intensity field in 30-40 iterations, indicating the robustness of this method. Moreover, being non-intrusive this method eliminates all the sensor-damage related inaccuracies from the measurement.

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CONCLUSION

This new, non-perturbing technique in a promising tool for accurately evaluating the performance of HIFU transducers. In future investigations, this method will be extended to evaluate acoustic streaming and intensity field at clinically relevant higher powers (~80-150 W).

ACKNOWLEDGEMENT

Financial support from FDA Center for Device and Radiological Health and NSF (Grant No. 0552036) is gratefully acknowledged,

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