Echo-PIV Imaging of HIFU-Induced Acoustic Streaming

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Abstract

Particle image velocimetry (PIV) allows the motion of a fluid to be determined nonintrusively by recording the position of tracer particles in the fluid at different time intervals and measuring the particle displacement over the time interval. Cellulose microparticles were added to a fluid and were passed at various speeds through a channel within an acrylamide-based tissue-mimicking phantom. The flow channel was sonicated with a 1.0-MHz HIFU transducer (diameter = 7.0 cm) at intensities in the range 10 – 120 W/cm^2 (below the threshold for significant cavitation) for about 5 seconds, a duration which is long enough to produce a steady flow field inside the tissue phantom. The flow in the phantom was imaged before and during sonication with a BK Medical imaging transducer type 8811 operating at 10 MHz and connected to an Analogic AN2300 imaging engine. Sequential digitally acquired image frames were analyzed with PIV algorithms to determine the velocity fields before and during sonication, and the results were compared to finite difference time domain (FDTD) simulations of the HIFU-induced streaming field.

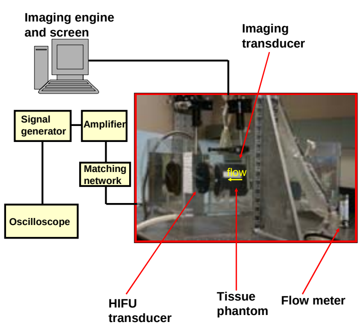
Introduction

Optical particle image velocimetry (PIV) has been widely used to measure flow fields. Microparticles are added to a transparent fluid, and the motions of these particles are illuminated by a laser source and tracked with a high speed camera. PIV algorithms are used to process the images to obtain velocity field data. The analogous acoustic PIV method (echo-PIV) utilizes the same PIV algorithms to process acoustic images. The technique uses a high frame rate ultrasound array transducer instead of a high speed camera and strong acoustic scatters in the flow instead of fluorescent particles. With echo-PIV, opaque fluids, such as blood, can be imaged and unlike Doppler techniques, the measured velocity is independent of the angle at which the imaging transducer is oriented. However, echo-PIV is limited by the image resolution and the frame rate of the imaging hardware.

In the experiment described here, the streaming field induced by high intensity focused ultrasound (HIFU) in a fluid flowing opposite in direction to the acoustic beam is imaged.

Materials and Methods: Experiment

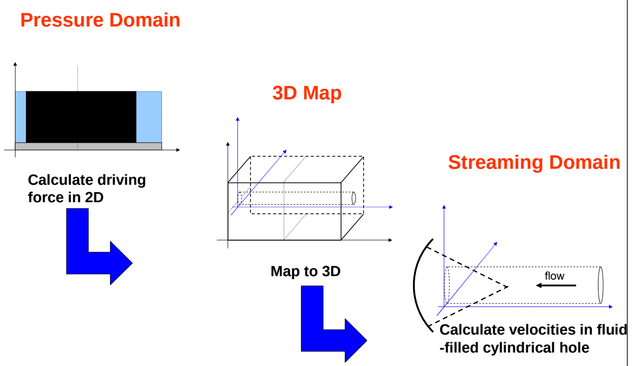
- Closed continuous flow system; 6.4mm Tygon tubing, Cole-Parmer 75211-22 pump.
- Cylindrical tissue phantom, diameter 10cm, length 10.5cm with cylindrical hole through it, diameter 6.4mm.
- Tubing connected to entrance and exit of cylindrical hole.
- 1.1MHz Sonic Concepts H102 HIFU transducer to provide driving force.
- BK Medical type 8811 imaging transducer.
- Analogic AN2300 Imaging engine.



Experimental Procedure

- Imaging technique: Echo particle image velocimetry with microparticles as tracers
  - Fluid was seeded with 2-20μm cellulose particles.
  - HIFU transducer switched on for about 5 seconds to provides acoustic driving force.
  - Sequential images of particles in the flow taken with imaging transducer (frame rate 152 frames per second) for offline processing.
- Processing: Single exposed image pair
  - Process image pair with EDPIV software; 10 pixel horizontal window shift, 64x32 pixel window size, 10x6 pixel grid size, 12 pixel search radius.
  - Use frame rate parameters and particle displacement in pixels to determine true velocity.

Materials and Methods: Numerical Simulation



Numerical Procedure

- Finite difference time domain numerical computation.
  - Compute acoustic pressure in 2D using nonlinear wave equation.

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)p - \frac{1}{\rho}\nabla p \bullet \nabla\rho + \frac{\delta}{c^4}\frac{\partial^3 p}{\partial t^3} + \frac{\beta}{\rho c^4}\frac{\partial^2 p^2}{\partial t^2} = 0$$

  - Compute driving force in 2D from pressure.

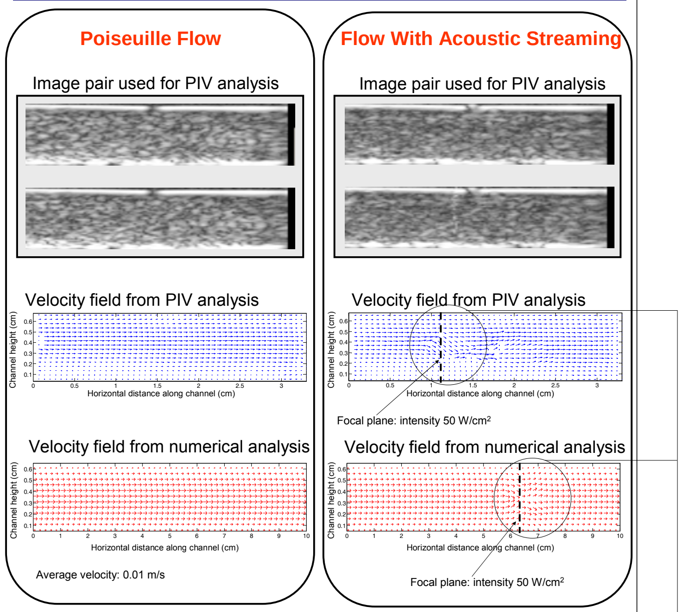
$$\vec{F}_z = -\frac{1}{\rho_0 c_0^2}\frac{\partial}{\partial z}\left\langle p_1^2\right\rangle = -\frac{1}{c_0}\frac{\partial I}{\partial z} = \frac{2\alpha_{ABS}}{c_0} I$$

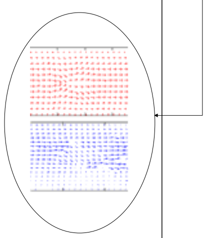
  - Map 2D driving force into 3D assuming axial symmetry.
  - Use 3D driving force to calculate streaming velocities from Navier-Stokes and continuity equations.

$$\nabla \bullet \vec{U} = 0 \qquad \frac{\partial \vec{U}}{\partial t} + \left(U \bullet \nabla\right)\vec{U} - \frac{\mu}{\rho_0}\nabla^2\vec{U} = -\frac{1}{\rho_0}\nabla P + \frac{1}{\rho_0}\vec{F}$$

- Plot velocity vectors in streaming velocity domain.

Results





- Parabolic flow profiles were obtained from the numerical simulations and using the echo-PIV technique (no HIFU).
- With HIFU on, acoustic streaming profiles were obtained from numerical simulation and echo-PIV techniques. In both PIV and numerically obtained profiles, the flow velocity is reduced at the focal point and increased below the focal point. However, the numerically obtained flow profile is symmetric around the focus. There is increased flow upward above the focal point and downward below the focal point. No upward flow above the focus is observed with PIV.

Conclusions and Future Work

- Parabolic flow profiles obtained numerically and with PIV are in good agreement.
- The cellulose microparticles are denser than water and tend to sink to the bottom of the channel. This may explain why no upward flow is observed above the focus using the echo-PIV technique.
- Microparticles with density close to the density of the fluid to be imaged are necessary for good particle distribution and flow tracking. Work with lighter microparticles is currently in progress.
- These preliminary results show the feasibility of using echo-PIV technique in studies of HIFU-induced streaming in flows inside opaque phantoms.

Acknowledgments

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