Background and Motivation: Importance of Pressure Measurements

- **Importance of Pressure Measurements:**
  - Pressure is a primary concern for many engineering applications, e.g. lift and form drag.
  - **Cavitation**: Pressure is of fundamental importance in understanding and modeling cavitation.
  - **Turbulence**: Velocity-Pressure-Gradient tensor, which can be decomposed into the *pressure diffusion* and *pressure-strain* tensors, is critical for modeling turbulence, especially near boundaries. However, due to the lack of the experimental capability, this tensor has never been measured directly*.

\[
- \frac{1}{\rho} \left( u'_i \frac{\partial p'}{\partial x_j} + u'_j \frac{\partial p'}{\partial x_i} \right) = - \left( \frac{\partial}{\partial x_i} \frac{u'_j p'}{\rho} + \frac{\partial}{\partial x_j} \frac{u'_i p'}{\rho} \right) + \frac{p'}{\rho} \left( \frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right)
\]

*Has been determined based on balance of all other terms in turbulence kinetic energy transport equation, e.g., Liu and Thomas (2004), Gutmark and Wygnanski (1976) and Wygnanski and Fiedler (1969).
Background and Motivation: Toolbox Available for Pressure Measurement

• **Available Techniques for Pressure Measurement Are Quite Limited:**

  – **Surface Pressure Measurement:**
    – Pressure taps leading to transducers;
    – Surface flush-mounted pressure transducers
    – Pressure sensitive paint.

  – **Pressure Measurement away from Boundaries:**
    – Pitot Tube; Five Hole Probe and Seven Hole Probes.
    – Drawbacks:
      ➢ Intrusive;
      ➢ Frequency response is limited;
      ➢ Point measurement, no simultaneous global data.
Background and Motivation: Objectives

• Objectives and Unique Features of the Present Method:

– To develop a system that can measure the instantaneous global pressure distribution in a non-intrusive manner based on PIV technology.

– The system utilizes four-exposure PIV to measure the distribution of material acceleration and then integrating it to obtain the pressure field.

– The system can measure the instantaneous velocity, material acceleration and pressure field simultaneously.
Principles of the Technique

- Navier-Stokes Equation:

\[ \nabla p = -\rho \left( \frac{D\vec{U}}{Dt} - \nu \nabla^2 \vec{U} \right) \]

- Obtain the **material acceleration** \( \frac{D\vec{U}}{Dt} \) based on PIV technology.

- With a measured reference pressure at one point, one can integrate the pressure gradient field to obtain the instantaneous pressure distribution.
Obtaining the Material Acceleration from Four-Exposure PIV Images

Lagrangian Velocity: \[ \vec{U}_a \bigg|_{\left(x_a + U_a \delta t/2, \ t+\delta t/2\right)} = \frac{\vec{U}_{13}(x_a, t) + \vec{U}_{24}(x_a + \vec{U}_a \delta t, t + \delta t)}{2} \]

Material Acceleration: \[ \frac{D\vec{U}}{Dt} \bigg|_{\left(x_a + U_a \delta t/2, \ t+\delta t/2\right)} \approx \frac{\vec{U}_{24}(\vec{x}_a + \vec{U}_a \delta t, t + \delta t) - \vec{U}_{13}(\vec{x}_a, t)}{\delta t} \]
Virtual Boundary Omni-Directional Integration

- Integrate the measured vector map of material acceleration, starting from a reference point.
- To reduce uncertainty, use Virtual Boundary Omni-Directional Integration over the entire flow field to obtain the instantaneous spatial pressure distribution:
Feasibility Study with Synthetic Images: Pure Rotational Flow

• Image size: 2048×2048 pixels
• Interrogation window : 32×32 pixel.
• Particle density: 25 particles per interrogation window.
• Particle size: Gaussian distributed with mean diameter of 2.4 pixel, standard deviation of 0.8 pixel.
• Particles rotated between images.
• Rotation Rate: $\omega=0.0625$/sec.
• Time interval between consecutive images: $dt=0.5$ sec.
• Theoretical flow field: $u=-\omega y$; $v=\omega x$. 
Demonstration Using a Synthetic Vortex Flow

Radial Pressure Distribution

\[ p = \frac{1}{2} \rho \omega^2 r^2 + C \]

Measured from the synthetic vortex flow data.

Spatial Pressure Distribution

Magntitude of Material Acceleration

Averaged, shortest path, omni-directional integration is utilized for pressure calculation in order to minimize the error.

PDF of the Relative Error of Pressure

Standard Deviation of the Relative Error
\[ \sigma = 1.2\% \]
Synthetic Image: Constant Strain Rate Flow (Stagnation Point Flow)

- Image size: 2048x2048 pixel
- Particle Intensity: 25 per interrogation window of 32x32 pixel
- Interrogation window size: 32x32 pixel
- Strain Rate: $S=0.025$ (1/sec.)
- Time Interval between images: 0.5sec.
- Particle size: Gaussian distributed with mean diameter of 2.4 pixel, standard deviation of 0.8 pixel.
Results of the Constant Strain Rate Flow (Stagnation Point Flow)

Velocity Vector Map

\[ u = ax \]
\[ v = -ay \]

Material Acceleration Magnitude Contour

\[ p = \frac{1}{2} \rho S^2 r^2 + C \]

Radial Pressure Distribution

PDF of the Relative Error of Pressure

Standard Deviation \( \sigma = 1.9\% \)