CFD Validation vs. PIV Data Using Explicit PIV Filtering of CFD Results

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Motivation

- Comparisons between PIV data & CFD results are often necessary for code validation
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• PIV experiments and CFD simulations are subject to different bias/uncertainty sources, so how do we know if the agreement is good enough?
Motivation

• **Challenge:**
  – De-convolving & quantifying biases in experimental data is hard
  – Often these biases strongly depend on local flow features
  – PIV experiments usually report a single uncertainty value

• **New approach:** simulate PIV biases onto CFD results
  – What flow field would you get if you used PIV to measure the flow field predicted by CFD?
  – Compare the modified CFD result to experimental data
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![Graphs showing comparison of simulated and experimental data](image)
PIV Data Acquisition

- **PIV Overview**
  - Laser
  - Camera & optics
  - Mirror & optics

- **Modeling PIV Biases**
- **Results/Conclusions**

**PIV Data Acquisition Process**

- Seeded flow

**Diagram**

- Timing box
- Computer
- Image at $t$
- Image at $t + \Delta t$
PIV Data Acquisition

PIV Overview

Modeling PIV Biases

Results/Conclusions
PIV Data Acquisition

- **Motivation**
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- **Modeling PIV Biases**
- **Results/Conclusions**
Main Sources of PIV Bias

• Spatial averaging: high speed flows
Main Sources of PIV Bias

- **Spatial averaging**: high speed flows
  - Finite size of interrogation regions
  - Particle travel between image frames

![Interrogation Region A](image1)

![Interrogation Region B](image2)
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- **Particle inertia**: large $\mathbf{U} \cdot \text{grad}(\mathbf{U})$
Finite Size of Interrogation Regions

- Chop up CFD domain into areas corresponding to the size of the PIV interrogation regions (IRs)
- **Spatially average** all CFD “samples” within each IR (downsampling to a coarser grid)
• Determine average velocity \((U_A, V_A)\) in Frame A
• Sweep out approximate trajectory \((U_A dt, V_A dt)\)
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• Sweep out approximate trajectory \((U_A dt, V_A dt)\)
• Spatially average all CFD “samples” within the region & assign velocity vector to center of Frame A
• Sample CFD dataset at N locations within IR
- Sample CFD dataset at $N$ locations within IR
- Integrate streamlines originating at sample points over $\Delta t$
  - Each path leads to one velocity sample for that IR
  - For higher fidelity, integrate inertial particle paths
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Particle Travel & Sampling

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- Integrate streamlines originating at sample points over $\Delta t$
  - Each path leads to one velocity sample for that IR
  - For higher fidelity, integrate inertial particle paths

$$U = \frac{1}{N\Delta t} \sum_{i=1}^{N} (X_{i,final} - X_{i,initial})$$
Test Case

- Shock boundary layer interaction
  - $U_\infty = 525$ m/s
  - Large gradients
  - Boundary layers
  - High resolution PIV
  - LES of same case

![Diagram showing velocity profile with color gradient indicating flow characteristics.](image)
Test Case

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- Assume particles track flow exactly at domain inlet
  - Good assumption since inlet flow has $v \approx 0, \nabla u \approx 0$

- Expect particle paths to deviate from streamlines in regions where $U \cdot \nabla U$ is large
Implementation – Step 1

• Solve for particle paths throughout domain
  – Use a very fine rake of points at inlet
  – Implemented using RK4 solver with time step such that max particle travel per step is $|\Delta \mathbf{X}| \approx 10 \mu m$
  – Interpolate onto CFD grid to find particle velocity field

Displaying 5% of total paths computed
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$$|U_{\text{particle}} - U_{\text{fluid}}| \text{ [m/s]}$$
Implementation – Step 2

• Apply filtering scheme for each PIV interrogation region
  – Sample & integrate trajectories over PIV inter-frame time, for our case $\Delta t = 800\,ns$
    • Integrate particle velocity field $\rightarrow$ particle paths
    • Integrate fluid velocity field $\rightarrow$ streamlines (particles w/ no inertia)
  – Can easily apply multiple filters to determine effects of varying PIV resolution
Incident Shock PIV/LES comparison

**LES**

**PIV**

**LES + PIV bias (inertia)**

**LES + PIV bias (no inertia)**

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**LES + PIV bias (inertia)**

**LES + PIV bias (no inertia)**

**PIV**
Profile Comparisons

x = 25mm

Streamwise Velocity

Wall-Normal Velocity

Lesion

LES + PIV bias (no inertia)

LES + PIV bias (inertia)
Profile Comparisons

$x = 25\text{mm}$

Streamwise Velocity

Wall-Normal Velocity

- LES
- LES + PIV bias (no inertia)
- LES + PIV bias (inertia)
- PIV data
Profile Comparisons

$x = 30\text{mm}$

Streamwise Velocity

Wall-Normal Velocity

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- LES + PIV bias (no inertia)
- LES + PIV bias (inertia)
Profile Comparisons

x = 30mm

Streamwise Velocity

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Conclusions

• Technique gives estimate of PIV bias errors that are dependent on local flow features
  – PIV bias can be significant in high speed flows with shock waves
  – Useful for both experimental and numerical studies
  – Allows for better comparisons between PIV experiment and CFD

• Procedure is general -- can be applied to any CFD simulation result that is to be validated using PIV data
Questions?

$$|U_{\text{particle}} - U_{\text{fluid}}| \; [\text{m/s}]$$

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