High-magnification, high-speed PIV for near-wall boundary layer studies

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Outline

- “Profile PIV” Measurement principle
- Some highlights of recent applications
  - EuHIT Project “Large Scale Structures”, LML, May 2015
  - EuHIT Project “HoloPipe”, CICLoPE, Forli, May 2016
Basic measurement setup

Highspeed camera with lens
  • Photron SA5, 1024x1024 @ 7kHz
  • Zeiss Makro Planar, 100mm/f#2

CW Laser
  • Coherent Verdi, $P_{\text{max}} = 5\text{W}$

Light sheet optics + mirror
  • 1 cylinder lens (-25mm)
  • 1 spherical lens (200mm)

Seeding
  • 1µm paraffin oil droplets from Laskin seeder with impactor
Sample image data

- Laser power: $P \approx 3$ W
- Frame rate: 20 kHz
- Shutter: 25 $\mu$s
- Resolution: 256 × 1024 pixel
- Depth: 8 bit/pixel (TIFF)
- Signal: ~50 counts
- $m = 25.27$ px/mm (39.6 $\mu$m/px)

Wall

Single image

Mean

4 m/s

10mm
Time resolved PIV of boundary layer* at 20 kHz

*) square channel of 76 x 76 mm²
Multi-PIV Measurements of an Adverse Pressure Gradient Turbulent Boundary Layer

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Large Scale Structure under Adverse Pressure Gradient

Facility: LML Boundary Layer Wind Tunnel (LML), France

Partners
- LML-Lille
- UniBW-München
- DLR (Gö/KP)
- Monash University
PIV Measurement methods utilized

- **2C 2D PIV** to capture entire APG region (3.5m) using 16 cameras
- 3C 2D PIV (Stereo) of selected spanwise positions in APG (and upstream)
- **High-speed 2C 2D PIV** to measure near wall characteristics (wall shear stress) at selected positions
- 2D wall shear measurements based on shear film
- Long-range microscopy to measure wall shear stress
High-speed 2C-2D PIV

→ wall-shear stress and near wall statistics

~ 1m working distance
  (Zeiss ApoTessar 300mm/2.8 lens)
  → m = 0.44 (~25 µm/Pixel) → (> 1y+ / Pixel)

Camera: PCO Dimax-S4, 36GB
  → up 503,000 images per run (178x288 pixels)
Position A – Upstream of model, $U_\infty = 5 \text{ m/s}$

6.7 kHz acquisition rate ($\Delta t = 150\mu s$) 125,000 images (~19 s)
Mean velocity profiles upstream of model

for $U_\infty = 5$ m/s
$y^+ = 76.9$ µm
$u_\tau = 0.198$ m/s
Reynolds Stresses upstream of model

- DNS Retheta=2540
- DNS Retheta=4060
- $U=5 \text{ m/s}$
- $U=5 \text{ m/s}$
- $U=9 \text{ m/s}$
- $U=9 \text{ m/s}$
Profile of mean and variances at Pos. 4

Part of material just published
J. Turbulence, Feb. 2017
PDF of Wall-Shear Stress

τ_w = 0

Re_T = 1590

Hu, Morfey & Sandham, AIAA J 44(7) 2006

σP(τ'_w)

P (τ'_w / σ_T)

σP(τ'_w / σ_T)

Re_T = 1440
Re_T = 720
Re_T = 360
Re_T = 180
Re_T = 90
Gaussian
Exp. Colella & Keith
Exp. Wietrzak & Lueptow
Exp. Sreenivasan & Antonia
Evidence of rare back-flow events (ZPG Turb-BL)

Time-trace of wall-normal profile of streamwise velocity $U$

(5000 samples of 126,000 samples @ 6.7kHz)
Evidence of rare back-flow events

Probability density functions of streamwise velocity $u^+$ at wall distances of 0.5$y^+$ and 5$y^+$ ($Re_τ = 1070$, $U_∞ = 5m/s$)

Good agreement with DNS reported in:

Events ~5-10x more frequent in APG region (detailed investigation pending)
Time resolved, near wall PIV measurements in a high Reynolds number turbulent pipe flow

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Motivation

- near wall flow structure of pipe flow so far has not been characterized well quantitatively through measurements, mainly due to finite size of probes
- for high-Re hotwire data is only available for wall distances $y > 20^+$ (e.g. SuperPipe Princeton)
- DNS only available at low Reynolds numbers for pipe flows $Re_{\tau,\text{max}} \leq 1050$ (Satake et al, HPC, 2000), for channel flow $Re_{\tau,\text{max}} = 5200$ (Lee & Moser, JFM, 2015)
- DNS difficult to perform using spectral methods due to singularity at center of pipe.
- CICLoPE pipe facility offers combination of high Reynolds number and viscous scales that can be experimentally captured → application of PIV becomes possible using standard imaging

CICLoPE = Center for International Cooperation in Long Pipe Experiments
www.ciclope.unibo.it
Reynolds number range for various pipe facilities

Talamelli et al. “CICLoPE—a response to the need for high Reynolds number experiments”, Fluid Dyn. Res. 41 (2009) 021407

**CICLoPE**
- Working: fluid air
- Pressure: ambient
- Diameter: 900 mm
- Length: 110m (122D)

**Princeton Super-Pipe**
- Working: fluid air
- Pressure: up to 200 bar
- Diameter: 129 mm
- Length: 26m (202D)
CICLoPE Facility

Center for International Cooperation in Long Pipe Experiments

- length: 115 m
- diameter: 0.9 m ±0.5 mm
- surface roughness: < 10 µm
- $Re_T$: 3000 – 40000 (60000)
- Viscous scales: 100 … 10 µm
- $U_{\text{mean}} = \sim 5 … 40$ m/s (55 m/s)
Measurement insert

- Concave window (laser)
- 45° mirror
- Plane window (camera)
Setup for near-wall PIV measurements

Light source:
- Darwin Duo (2x40W)
- Pulse width ~300ns
- max freq. 10 kHz
Facility vibrations

- present at $U \geq 30$ m/s
- structural vibration (carbon/aluminum tube)
- tracked using correlation approach
- image shifting prior to PIV analysis
Time-record of stream-wise velocity profile

\[ \text{Re}_t = 20,000 \]

\[ U_o = 22 \text{ m/s} \quad 1000 \text{ of 70000 samples} \quad 10 \text{ kHz sample rate} \]

also have wall-normal velocity component (and vorticity \( \omega_z \))
Mean velocity profiles

DNS data:

\[ \kappa = 0.38 \quad B = 4.3 \]
\[ \kappa = 0.42 \quad B = 5.45 \]
Mean velocity profiles – incl. hotwire data

\[ U^+ \]

- \( \kappa = 0.38 \), \( B = 4.3 \)
- \( \kappa = 0.42 \), \( B = 5.45 \)

Hotwire data by:
Fiorini T, Bellani G, Talamelli A,

Legend:
- DNS, Pipe \( \text{Re}_\tau = 3008 \)
- DNS, Chan. \( \text{Re}_\tau = 5200 \)
- Hotwire, \( \text{Re}_\tau = 15000 \)
- Hotwire, \( \text{Re}_\tau = 25000 \)
- Hotwire, \( \text{Re}_\tau = 40000 \)
Reynolds stress profiles

\(\langle u'_i u'_j \rangle^+\)

- DNS, Pipe \(Re = 3008\)
- DNS, Chan. \(Re = 5200\)
- \(Re = 5383\)
- \(Re = 11708\)
- \(Re = 19918\)
- \(Re = 27983\)
- \(Re = 39944\)
Reynolds stress profiles, incl. SuperPipe data

SuperPipe data from Hultmark et al. PRL (2012)
Hultmark et al. JFM (2013)
Dependence of maximum of variance $u$ on Reynolds number and wall-normal location of maximum

\[ 3.66 + 0.642 \log(Re_\tau) \]
Joint-PDFs: Pipe vs. Flat Plate Turbulent BL

\( \text{Re}_f = 20,000 \ (U_\infty = 22 \text{ m/s}) \)

\( \text{Re}_f = 830 \ (U_\infty = 5 \text{ m/s}) \)
Summary – High-Re turbulent pipe flow measurements

- first application of PIV in new pipe flow facility CICLoPE (in operation since 2015)
- PIV measurements at Reynolds number range $Re_T = 5,000 \ldots 40,000$
- imaging with spatial resolution of $O(10\mu m) \rightarrow$ resolves viscous sublayer
- statistical convergence through multiple time-records of up to 70,000 samples each
- inner peak grows with $Re_T$ (behaviour very similar to ZPG-Turb. BL)

- work in progress:
  - extract unsteady wall-shear stress from images (comparison with dP-based estimates)
  - reprocess using PTV methods (STB) to get max. spatial resolution,…
  - …