Development of PIV in Korea

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25 Years of Particle Image Velocimetry in Aerodynamics

Second Stage (1995-2001): Expanding Period, PIV community comes up, Japan-Korea Joint Seminar, KSV Launched

Third Stage (2002-Present): Matured Period, PIV Standardization, Original PIV Techniques, Micro/Nano/Bio-Applications
Major Events in PIV History of Korea

**Korea-Japan Joint Seminar on PIV**
1\(^{\text{st}}\) : Korea Maritime Univ. & Busan National Univ., Korea, 1999, Dec. 7~9  
2\(^{\text{nd}}\) : Seoul National Univ., Korea, 2001, Dec. 3~4  
(coordinated by Prof. J.Y. Yoo and Prof. Kobayashi), KSV foundation has been done
3\(^{\text{rd}}\) : Fukuoka, Japan, 2003, Dec. 2~4. (coordinated by Prof. J.Y. Yoo and Prof. Kobayashi)
4\(^{\text{th}}\) : POSTECH, Korea, 2004, Dec. 9-11. (coordinated by Prof. S.J. Lee and Prof. Kawahashi)
5\(^{\text{th}}\) : Awaji, Japan, 2006, Sept. 29~Oct. 1 (coordinated by Prof. S.J. Lee and Prof. Kawahashi)
6\(^{\text{th}}\) : KonKuk Univ., 2008, Dec. 5~6. (coordinated by Prof. K.C. Kim and Prof. Okamoto)
7\(^{\text{th}}\) : Okinawa, Japan, 2010, Feb. 26~28. (coordinated by Prof. S.J. Lee and Prof. Okamoto)

**International Congresses related to PIV**
Foundation of Korean Society of Visualization, Seoul, 2001 Dec. 3.
5\(^{\text{th}}\) International Symp. on PIV, Busan, 2003, Sept. 22~24, 03
PIV Short Courses held in Korea (Prof. SJ Lee, Postech)

- PIV - Velocity Field Measurement (1999.9.30-10.2)
- PIV Velocimetry – Measurement and application (2002.3.29-30)
- PIV Velocimetry – Theory and Practice (2005.4.1-2)
- PIV Velocimetry – Measurement and application (2007.2.12)
- PIV Velocimetry – Measurement and application (2008.9.27)
Detection of FID of hydrogen protons with phase encoding technique

Phase of MRI signal

\[
\Phi = \Phi_r^0 + \Phi_V = \gamma r_0 \cdot \int G(t)dt + \gamma V \cdot \int G(t)dt
\]

\[
V = V_x i + V_y j + V_z k, \quad r = r_0 + Vt
\]

*S.J. Lee et. al, J. Applied Physics, Vol.60 (1986)*

Velocity field meas. of the unsteady flow of surface discharge of heated water

Comparison between NMR-CT & LDV

*S.J. Lee et. al, Exp. in Fluids (1987)*
The First PIV paper in Korea (Prof. YH Lee, Korea Maritime U, 1991)

Analysis on the Uncertainty Accompanied by PIV velocity Measurements (1991)

Schematic Experimental Apparatus

A : SCR DC Motor & Reduction Gear
B: Roller & Stainless Belt
C: Encoder & Digital Tachometer
D: Cavity (100mm L, B, H)
E: Cylindrical Lens & Fiber Line
F: TV Camera or CCD Camera
G: Monitor TV
H: Color Image Printer
I: Argon Laser
J: Video Tape Recorder
K: Time Base Corrector
L: X-Y Plotter
M: Digitizer
N: Image Processor & Monitor
O: External Memory
P: Laser Printer
Q: Host Computer

Distribution of Velocity Vectors (Re=1000, SAR=1:1, z=0.5)

Re=1000, SAR=1:1, Nylon12, V.C.: x=0.532, y=0.522
Prof. YH Lee founded a University Venture Company for PIV commercial system (CACTUS) in 1997.
1) Development of 2-Frame PTV Technique: Prof. SJ Lee (Postech)

- Based on the iterative estimation of **match probability** for each particle between two consecutive image frames.
- Probability of the object point is updated by match probabilities of neighboring points satisfying the **quasi-rigidity condition**.
- The 2-frame PTV method shows good performance: **high** recovery rate and **low** error with **less** computation time.

![Diagram](a) Max. movement threshold $T_m$ and Neighborhood threshold $T_n$

![Diagram](c) Common motion

**Three thresholds for calculating match probability**

*SJ Baek and SJ Lee, Exp. in Fluids, Vol.22, pp.23-32, 1996*
2) Development of Hybrid 2-frame PTV: Prof. SJ Lee

- Combine the merits of FFT-based PIV and 2-frame PTV methods

1. PIV gives the matching parameters $T_m$, $T_n$, and $T_q$ to 2-frame PTV method
2. PIV results are used to validate the PTV results

![Diagram of Hybrid 2-frame PTV method]
3) Development of Single-frame PIV Technique: Prof. SJ Lee

- Resolution: 2K×2K pixels
- Fill factor: 100%
- Dynamic range: 12 bit
- Frame rate: 4 fps
- Image shifting with translation of pixel lines

4) Development of Recursive PIV Algorithm with CBC (Correlation Based Correction)

Principle of Recursive Local-Correlation

Using estimated displacement data, offset the half sized interrogation window in the next step according to one quarter rule.

(a) Schematics of recursive PIV method

(b) Principle of window offset

5) Development of Stereoscopic PIV/PTV: Prof. SJ Lee

- Two 1Kx1K CCD cameras
- Tilt/shift lenses
- Rotating stages
- Calibration plate
- Laser & camera synchronization

- SJ Lee et al. Exp. in Fluids, Vol.36, pp.575-585, 2004
6) Development of Digital Holographic PIV: Prof. SJ Lee
 DHPTV measurement of a turbulent jet flow

Jet direction

Jet dia \( d = 1.9 \text{mm}, \) \( Re = 1,500 \)
\( \phi = 10 \mu m \) hollow glass particle

\( \Delta t = 75 \mu s \)

3813 particles in total volume

6.5 x 6 x 7.5 mm

1st exposure

2nd exposure

Instantaneous jet flow


Vector number: 2523 vectors

6.5 x 6 x 7.5 mm³
Digital HPTV Measurement of Flow in a Micro-tube

[Experimental Setup of Micro DHPTV]

- High speed camera (1K x 1K)
  - 4000 fps
  - Shutter speed = 1/15000s
- He-Ne laser
- Objective lens
  - Water emersion, 60x, NA= 1.1
- Particles: Nylon (d=2μm, SG=1.05)
- Particle concentration
  - 0.25 %, 0.5 %, 1% for volume ratio
- FEP Tube (n = 1.338, same as water)

7) Development of Dynamic PIV: Prof. SJ Lee

[Dynamic PIV measurement of a turbulent jet]

1. High-speed CMOS camera: Fastcam-ultra APX
   - resolution: \(1024 \times 1024\) pixel, 8bit @ 2000fps
   - maximum frame rate: 20kHz
   - storage memory: 4000 images (2GB)

2. High-repetition rate Nd:YAG laser: Pegasus
   - firing rate: 2~20 KHz
   - maximum pulse energy: 10mJ @ 2,000 Hz
   - pulse width: < 180ns

- Jet diameter: 9.6mm
- Experimental condition
  - \(U_0 = 0.32\) m/s
  - \(Re_D = 3000\)

- 4000fps at \(1024\times512\) pixels

\(\tau_{\text{char}} = 8\) msec:

8) Development of Micro-PIV: Prof. SJ Lee

Flow Characteristics

- Reynolds number: \( \text{Re} = 9(10^{-2}) - 9(10^1) \)
- Surface tension, deviation from no-slip condition
- Length scale: Taylor microscale, \( \lambda \)
- Sensitive to vibration, difficult to align

- Micro-channel with stenosis
- Blood flow of chicken embryo
- Hybrid with dynamic PIV system and holographic PTV system

Micro-PIV system can measure \( \mu \)-scale flow with several \( \mu \)m focal depth resolution in \( \mu \)-channels

9) Development of X-ray PIV: Prof. SJ Lee

PIV with laser: transparent flows inside a clear window → Impossible to measure organic flow of living creatures
Transmittance imaging: X-ray, Ultrasonic

- In-vitro blood flow measurements
- In-vivo blood flow measurements
- Sap flow in Xylem vessels
- Blood-sucking of a female mosquito
- High spatial and temporal resolution

Patent 2003-0003039

**X-ray PIV meas. of whole blood flow in an opaque channel**

Enhancement of fringe patterns of blood samples without any additive on x-rays

<table>
<thead>
<tr>
<th>A</th>
<th>Sample-scintillator distance ( (d) ) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>0.3</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>0.6</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>1.0</td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>5.0</td>
<td><img src="image13.png" alt="Image" /></td>
</tr>
<tr>
<td>10.0</td>
<td><img src="image17.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- The sample-detector distance: 40 cm
- Sample thickness of RBC flow: 1390 μm
- Opaque microchannel
- No seeding particle
- Cooled CCD camera of 1280 x 1024 pixels

**Lee SJ; Kim GB; Synchrotron micro-imaging technique for measuring the velocity field of real blood flows. J. Appl. Phys. 97, 064701, 2005**

**Movie of speckle pattern**
X-ray PIV meas. of blood flow in an opaque μ-channel

Displacement of intensity profile

About 3.5 μm shifting

Second image

First image

• The sample-detector distance: 40 cm
• Sample thickness of RBC flow: 1390 μm
• Opaque flow microchannel
• No seeding particle
• Cooled CCD: 1280 x 1024 pixels

GB Kim & SJ Lee, Exp. in Fluids. Vol. 41(2), 2006
Flow Visualization

Neutral
\( \left( \frac{dT}{dz} = 0^\circ C/m \right) \)

Unstable
\( \left( \frac{dT}{dz} = -53.5^\circ C/m \right) \)
Prof. KC Kim (PNU): Turbulent Flow Measurements using 2-D PIV

2D PIV Measurement

1998-99

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PIV 기법을 이용한 횡단류 제트유동의 와류구조 해석
A Study on the Vortical Structure of Jet in a Cross Flow
Using Particle Image Velocimetry

Kyung Chun Kim (Pusan National Univ.), Dae Sig Shin (RIMT)
Kee Young Park (Graduate school, Pusan National Univ.)

Instantaneous velocity field
Instantaneous vorticity field
Prof. KC Kim: Development of Miniature-PIV (MPIV) 1999-2000

Principle of a MPIV system

The schematic diagram of a MPIV (Side-scatter illumination)

1. Camera mode setup
2. flash pattern to RAM transmission
3. flash generation (logic)
4. Camera to RAM image transmission
5. RAM to PC image transmission

MPIV system prototype

- CPLD board, CMOS camera, RAM (128k), pulsed laser (or pulsed LED)
- View size: 6.4mm x 4.8mm (Image size 288 x 216)
- Light source: laser or LED
Miniature Stereo PIV

- 2 camera boards, 1 main board
- 1 pulsed laser driver board
- Dual CMOS camera
- RAM : 512K SRAM
- 3 CPLD chip
- Angular method

Schematic Diagram of Stereoscopic MPIV
Experimental setup for MSPIV system

Combined stereoscopic velocity field

The manufactured MSPIV system
3D Stereoscopic PIV Measurement

Turbulent Kinetic Energy

Prof. KC Kim: Phase Averaged 3D3C Velocity Measurements Using Multiplane Stereo-PIV Method, 2000
PIV/LIF simultaneous measurement

- Prof. KC Kim: Velocity/Concentration Simultaneous Measurements using PIV/LIF (2001)

- PUSAN NATIONAL UNIVERSITY
Dual-plane PIV Measurement

Prof. KC Kim: Orthogonal Dual Planes Velocity Field Measurements using Polarization Technique (EiF, 2003)
Prof. KC Kim: Development of Micro-PIV, Oil-Water Droplet Flow in Microchannel

Micro - PIV Measurement 2003 - 2004

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3D Defocusing Micro Particle Tracking

Highlights of 2006

I am delighted to present the journal highlights from *Measurement Science and Technology* in 2006. I hope you enjoy reading this collection of articles, all of which are free to read until 31 December 2007. You can also view the *Highlights of 2005*.

To find out more about *Measurement Science and Technology*, please visit the journal homepage or you can e-mail the journal publishing team at mst@iop.org.

Sharon D'Souza, Publisher

Design and characterization of a passive wireless strain sensor
Yi Jia, Ke Sun, Fredrick Just Agosto and Manuel Toledo Quiñones

3D particle position and 3D velocity field measurement in a microvolume via the defocusing concept
Sang Youl Yoon and Kyung Chun Kim

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• Mixing Blade Speed is 200 rpm.
• Wall pressure distribution was predicted by using the 3D-Vector obtained by 3D-PTV.
• Two CCD Cameras (640 x 480 pixel, 30Hz) were used.
• A seagull is moving freely.
• Wing’s motion and its flow fields were measured simultaneously.
• Two CMOS Cameras (1024 x 1024 pixel, 200Hz) were used.
• A cylindrical structure is floating in a flow field.
• Wavy flow is generated by the wave generator at upstream.
• Cylinder’s motion is measured by the camera 3, 4,
   the fluid flow field is measured by camera 1, 2 simultaneously.
• Four CMOS Cameras(1024 x 1024 pixel, 60Hz) were used.

<table>
<thead>
<tr>
<th>Wave Frequency [Hz]</th>
<th>1, 1.33, 1.67</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder Diameter</td>
<td>25 mm</td>
</tr>
<tr>
<td>Reynolds No.</td>
<td>3,500</td>
</tr>
<tr>
<td>Draft</td>
<td>5 cm</td>
</tr>
<tr>
<td>Center of Gravity</td>
<td>3.5 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>0.03 kgf</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.114 kgf</td>
</tr>
</tbody>
</table>
Prof. DH Doh: Raw Image of Each Camera

Image of Camera 1

Image of Camera 2

Image of Camera 3

Image of Camera 4
Prof. DH Doh: Measured Motion Field and Flow Fields [1Hz]

Image of Camera 1

Image of Camera 2

Motion Fields
A elastic plate is attached to the rear of a cylinder body.
The elastic plate is moved freely by the cylinder wake.
The flows over the elastic plate are measured by 4 cameras.
Four CMOS Cameras (1024 x 1024 pixel, 120Hz) were used.

Cylinder Dia. : 5 cm
Flag size : 50mm x 140mm x 0.3mm
Flow Velocity : 0.16 m/s
• Elastic plate stabilizes the vortices: Spreads over the spanwise directions
The Results from Prof. JY Yoo (SNU), Meas. Sci. Tech.

Three-dimensional phase averaging of time-resolved PIV measurement data (2001)

Schematic diagram of time-resolved PIV system

(a) An instantaneous flow field on the z-x plane
(b) Phase-averaged velocity and vorticity field on the x-y plane
(c) Phase-averaged velocity and vorticity field on the z-x plane

Iso-vorticity surfaces of the secondary vortex ($\omega_y$). The origin of the z-axis is arbitrary. The left and right surfaces of the vortex pair correspond to $\omega_y = 9$ and $-9 \text{ s}^{-1}$, respectively: (a) phase = 0°, (b) phase = 45°, (c) phase = 90°, (d) phase = 135°.

Schematic of objective-based TIRFM

Particle images of different illumination methods
(a) Widefield (direct, flood) illumination
(b) Near-wall TIRFM image
Quantification of the Cell-Substratum Contact and Cell Lift-off Under Different Intra/Extracellular Conditions (2009)

Schematic of the experimental setup and the chip

Time-series of TIRF images during the adhesion process: (a) normal cell, (b) virus-infected cell.
The combination of echo imaging (B-mode scanning) and PIV velocity measurement technique

- The echo imaging technique enables to visualize the opaque flow condition such as blood flow.
- The PIV technique gives the instantaneous two-dimensional velocity field which can be used for the diagnose information.

Utilizes gas-filled microbubbles (ultrasound contrast agent) as markers of flow for PIV analysis.
Prof. HB Kim: Echo PIV results (In vitro and In vivo), 2005

(a) *In vitro* application: vortex flow measurement

(b) *In vivo* application: Left ventricular filling flow
Ultrasonic forcing is newly employed to control a turbulent boundary layer.

Strong wall normal velocity is generated by ultrasonic forcing.

Streamwise velocity is decreased by ultrasonic forcing.

Skin friction is reduced up to 60%.
- Moving interface tracking by generating textons.
- Textons are employed at the interface tracking procedure.
- Interface images are transformed to those in a rectangular coordinate.

\[ \text{Probability}(\theta) = I(x+i, y+j) \cdot T(i, j, \theta) \]

\[ U_{\text{free stream}} = 0.25 \text{ m/s} \]
14th International Symposium on Flow Visualization
June 21~24, 2010
Daegu, Republic of Korea