Recounting 20 Years of Digital Particle Image Velocimetry

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Recounting 20 Years of DPIV

- Particle Tracing Velocimetry (1987-1988)
- Early DPIV efforts at UC San Diego (1988-1990)
- Evolution of hardware through the mid 1990’s
- First applications of DPIV in Aerodynamics at DLR
- Current developments & trends
Alternative Techniques: Particle Tracing Velocimetry

- (complete) flow field recorded in single image
- intensity coding to determine flow direction

Photograph of flow around flap by Rignot & Spedding (USC), 1988
Imaging Processing of the late 1980’s (PC’s)

- Computing hardware: IBM AT or clone
  - 6-10 MHz Intel 80286 microprocessor
  - 80287 coprocessor for computation
  - 16 bit DOS
  - 640 kB RAM (max 4-16MB $$$
  - 20-40MB hard drives
  - Graphics: EGA mode:
    - 640 x 350 resolution!

- Imaging hardware:
  - analog (RS-170, CCIR) cameras, 30 Hz
  - frame grabbers on ISA-bus
    (challenging to get working)
  - external (TV) video monitor

- 16-bit programming environment:
  (BASIC, FORTRAN , PASCAL, Assembler)
  - 64kB max. array size: 128 x 128 floats or 128 lines x 512 pixels of 8 bit image
  - image processing quite challenging on PC
Imaging Processing of the late 1980’s (Workstations)

- dedicated workstations using RISC processors (e.g. MC680xx-Series)
- 32-bit environment (UNIX, VMS,…)
  - simple memory management
  - multitasking
  - graphical user interface
    (X11, SunView,…)
- large file systems (SCSI drives, >100 MB)
- 20-50 MHz CPU clock
- 4 – 64 MB RAM
- special systems catered to image or signal processing:
  i.e. VICOM, Kontron IBAS, MASSCOMP

VICOM Image Processing System, 1990
VICOM Image Processor - 1988

(practically no archival information available today !!)

- designed by William K. Pratt (President, VICOM)
- based on SUN 3/160
  with Motorola RISC Processors 68020 / 68881
  (16 MHz, 4 MB RAM)
- support for digital VIDEK Megaplus camera (1 Hz frame rate)
- real time RS-170 video acquisition via VME-bus
- dedicated VME cards for real-time 3x3 convolution, LUT, morphology, and other (simple) image processing
- macro language for image processing
- real-time image disk for video acquisition (30 fps, 512x512)
  - 1988: 750 frames 200 MB dedicated 18in hard disk
  - 1990: 12500 frames 3GB SCSI-RAID system

back in 1988: excellent system for trying out various ideas in image-based flow diagnostics
1987 Videk Magaplus (Kodak) CCD Camera

- Full frame CCD: 1320 H x 1024 V
- mechanical shutter, ~1Hz frame rate
- not suited for multiple frame, single exposure PIV
- useful for double exposure PIV (i.e. replacement of photographic camera)

© Jim Reda, Videk VP.
Particle Tracing using Digital Imaging

Flow downstream of cylinder

Drawbacks:
- very low seeding density
- velocity dynamic range ~ 5-10
- not really suited to study vortex dynamics
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How DPIV got started...

Step 1: stop work on tracing velocimetry
Step 2: use VICOM real-time disc to acquire continuous image sequences of single exposed images
Step 3: try to extract frame-to-frame displacement (not really knowing how)

DECONVOLVER
Sequence of Images

\[ a + ib \cdot \frac{c-\text{id}}{c+\text{id}} = \frac{c\cdot c + b\cdot d + i(b\cdot c - a\cdot d)}{c^2 + d^2} \]

Notebook sketch (Nov./Dec. 88)
Initial Idea behind DPIV
Idea: Extract Transfer Function between Input and Output Image

Input $f$

“Output” $g$

Transfer function $h$
Strategy for Recovering Transfer Function

- Piecewise analysis using small samples of images (windows)
- Apply **de-convolution** by making use of Fourier transform property.
  
  Given Fourier transforms of functions
  
  \[ F = \text{FT}(f), \quad G = \text{FT}(g), \quad H = \text{FT}(h) \]

  then convolution

  \[ f * h = g \quad \Rightarrow \quad F \cdot H = G \]

- implementation using FFTs
  
  $\rightarrow$ division of complex spectra by each other

- sub-pixel peak fits (from PTV exercise):
  
  - 3 point parabola
  - 3 point Gauss fit (after ~May 1989)

- de-convolution *seemed* to work on translated dot patterns
Some things turn out not always as expected

- complex division of Fourier spectra

\[ H = \frac{G}{F} = \frac{G_{re} + iG_{im}}{F_{re} + iF_{im}} \]

\[ = \frac{G_{re}F_{re} + G_{im}F_{im} + i(G_{re}F_{im} - G_{im}F_{re})}{F_{re}^2 + F_{im}^2} \]

- coding error caused denominator to evaluate to unity

- numerator = cross-power spectrum

- inverse Fourier transform actually yielded the **cross-correlation** function(!)
Time to try it on a real flow…
First DPIV on Thermal Plume – Feb. 1989

30 Hz frame rate
~4ms exposure
DPIV of Thermal Plume – Feb. 1989

Camera: CIDTEC 512x512 (progressive scan, but interline readout)
Sampling window: 32 x 32 pixel with Cosine-taper window
Grid: 16 x 16 pixels
Processing time: 35 min (SUN 3/160)
DPIV of Thermal Plume, No. 2 – March 1989
DPIV Thermal Plume – March 1989

Camera: CIDTEC 512x512
Sampling window: 20 x 24 pixel
Grid: 6 x 6 pixels
Processing time: ~1h (SUN 3/160)
DPIV on Vortex Ring – April 1989
Challenges for DPIV in 1989/1990

mainly technological hurdles limit application to low speed flows (<10 cm/s)

- strongly limited frame rate (30 Hz)
- low spatial resolution (512x512)
- frame-straddling not possible with commonly available interline imaging

further technical problems

- synchronization of camera and shutter
- RS170 video (field only exposure)
- extracting synchronization signal from camera
- impedance mismatch of video signal
- non-square pixels

Interline artifacts
Why didn’t we patent DPIV?

Feedback from UCSD patent office:
None of the questioned companies was interested in the technique!

→ submission to Experiments in Fluids (July 1989)
Momentanes Geschwindigkeitsfeld (PIV)

maximale Vektorlänge: 0.59 m/s

\( (u + u_{\text{shift}} - U), U = 5.18 \text{ m/s} \)

Laminarkanal

Grid 3

\( u_{\infty} = 10.00 \text{ m/s} \)
\( u_{\text{shift}} = -5.84 \text{ m/s} \)
\( \tau = 225.00 \mu \text{sec} \)
Photographic PIV in use at DLR in 1993 – Young’s Fringe Evaluation Method

Laser  Spatial filter  Fourier lens  Object  Fourier plane (Ground glass)  Camera

Image pairs  Young’s fringes
1995 – The End of Analog PIV Processing at DLR

- Film scanners have come of age up to 4000 dpi.
- No need for contact copy prior to analysis.
- Cross-correlation processing (adaptive window offset).
- 35 mm negatives scanned at >3600 x 2400 pixels.
- ~2 x 5 mm².
Photographic PIV on 35 mm Film

Cylinder vortex shedding (A. Schröder, 1995)
Photographic PIV Recording + Digital Analysis

- 230 x 157 nodes at 50% overlap (36110 nodes)
- interrogation spot ~0.3mm diameter (32x32 px)
DLR Double CCD Camera – 1995

Willert, Raffel, Kompenhans, Stasicki, San Diego, SPIE 1995

- interframing time 1µs
- asynchronous trigger
Various Frame Straddling Cameras

1990 Texas Instruments Multicam
   Frame Transfer CCD, ~1 ms inter-framing time,
   30 fps @ 1180 x 484 lines
   (T.Rösgen, D.Dabiri)

1994 DLR Dual-CCD PIV-Camera

1994 Pulnix TM9700
   30 fps @ 768 x 484 px
   (D.Dabiri, M.Gharib, A.Vogt, P.Baumann)

1995 Pulnix TM1001
   15 fps @ 1008 x 1018 px
   (C.Willert, J.Kompenhans)

1995 Kodak Megaplus ES1.0
   ~10 fps @ 1008 x 1018 px
   first true double-shutter camera for PIV (L.Lourenco)

1997 PCO Sensicam DoubleShutter
   ~7 fps @ 1280 x 1024 px
   first cooled, double-shutter camera, fiber optic link
1995: Interline Transfer CCD Camera

**PULNIX TM-1001**
- 1008 (H) x 1018 (V) pixels
- 15 Hz frame rate
- 1 µs inter-framing time
- PCI Acquisition board on PC, (running DOS with 32-bit extender),
- 15 Hz into RAM (16 MB = 8 image pairs !)

drawbacks
- no suitable asynchronous reset
  → camera was system master driving laser
- <10 m cable length
  → operator sitting inside, below or on-top of wind tunnel
Jan./Feb. 1996: First use of DPIV for Aerodynamics Research at DLR
1996 – DPIV in Large Industrial Windtunnel

![Flow field diagram and DPIV equipment image]
Development of PIV from 1996 onward...

- at DLR: numerous applications in aerodynamics, turbo-machinery and combustion
- numerous EU-projects that fostered further development through cooperation between groups from universities, research agencies and industry (EUROPIV, PIVNET, APIAN, C-WAKE, EWA, …)
- 3 “PIV-Challenge” rounds
- rapid spread of PIV into many fields beyond engineering itself
- considerable improvement in software and hardware
- extending the technique, pushing the limits (stereo PIV, µPIV, long-range µPIV, multi-plane PIV, tomographic PIV, high frame rate PIV, defocusing DPIV, …)
PIV for Real-Time Flow Monitoring and Control

M. Munson, C. Willert & M. Gharib (Caltech & DLR)

- use PIV to actively control an experiment
- make use of data not available with conventional instrumentation
  - vorticity field $\omega$
  - circulation $\Gamma$
  - local averages: $|u|$, $|v|$, $|\omega|$
  - velocity gradients
  - time- & space-integrated quantities …
Oil Tunnel Experiments - Real-Time PIV

Re = 1050 - No Blowing

Re = 1050 - Blowing at $C_\mu = 0.24\%$

- NACA 0012 profile wing
- 10 cm chord, AR 2
- Mid-chord actuator slots, directed down stream
Oil Tunnel Experiments - Real-Time PIV
Status of Digital Particle Imaging Methods of Today

- 2-C planar PIV
  - now the de-facto standard flow field measurement technique
  - consensus on algorithms (see PIV-Challenges 1-3)
- stereo PIV (3-C planar) wide-spread
  - considerable improvement in calibration methods in recent years
- time-resolved PIV (TR-PIV)
  - steadily increasing frame rates
  - bottle-neck due to rather weak light sources, expensive lasers
- 3-D imaging methods
  - still under considerable development
  - 3D-PTV (e.g. Virant & Dracos, 1996)
  - defocussing-DPIV (since ~2000)
  - tomographic reconstruction methods (since 2005)
Current Trends

- tomographic/volume PIV techniques
  - algorithms
  - applications
  - microscopy
- applications pushing the limits of 2-C and 3-C planar PIV
  - turbulence research
  - transonic & supersonic flows
- increased availability of low-cost systems for
  - flow monitoring / embedded systems
  - educational purposes / student labs
- cheaper light sources and cameras
Low-cost PIV based on pulsed LED

- Online PIV processing
- Pulsed LED + optics
- USB CCD-camera
- High-current LED pulser
LED-based PIV using Light-sheet Illumination
Photron APX-RS
1500 fps
$\Delta t = 667\mu s$
$t_{\text{LED}} = 10\mu s$
$I_{f,\text{LED}} = 30A$
$f_l = 55\text{mm} / f_\# 2.8
Photron APX-RS
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+ a large number of people in the world-wide PIV community
Some special PIV-Moments at DLR...