PIV Cameras and time resolved PIV measurement

B. Lecordier et M. Trinite

CORIA
UMR CNRS 6614
Université & INSA de Rouen (France)
Mail : Bertrand.Lecordier@coria.fr
Web: http://www.coria.fr
Outlines

Introduction

Interline transfer CCD in the 1990’s for PIV
- Frame straddling technique
- Transition toward cross-correlation approach
- Actual CCD cameras

Time Resolved PIV measurement for high speed flows (> 1000 Hz)
- High speed photographic camera for PIV in 90’s
- First high speed CMOS video camera for PIV
- Actual high speed CMOS cameras

Conclusions et perspectives
Introduction 1/3 - End of the 80’s: Video Camera for PIV measurement

- At the end of 80’s more or less all the PIV systems were based double exposed images

- Recording support
  - Photographic film
  - High resolution full frame CCD

- Use of video for
  - Digitized the film or one step of the treatment
  - Direct recording of double exposed image

Support: photographic film

Support: Full frame CCD camera

From: http://25-years-piv.dlr.de/
Introduction 2/3 - End of the 80's: Video Camera for PIV measurement

Auto-correlation
- Directional ambiguity (Image shift)
- Lower seeding density than CC
- Small dynamic range than CC
- The recording media permitted to investigate high speed flow

Cross-correlation
- The mains advantages of CC technique were well established, but the flow velocity range was limited by the video frame rate: (water flow...)

Support: Full frame CCD camera

Frame
n-2 n-1 n n+1

Laser

\( \Delta t = \frac{1}{F} > 10 \text{ ms to } 1 \text{ s} \)
Common pixel storage for odd and even fields

Rapid transfer of odd or even fields into the pixel storage

Frame rate

Field rate

Elec. Shutter

**Positioning of the two laser pulses on the transition between odd and even field**

| Frame rate |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|------------|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Even       |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Odd        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Even       |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

<table>
<thead>
<tr>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Odd field**

**Even field**

---

Wenert *et al.* (1991)
Lecordier *et al.* (1994) EiF
Huang, H.T. & Fieldler H.E. (1994) EiF
Interline transfer CCD: frame Straddling synchronisation 2/2

<table>
<thead>
<tr>
<th>Frame rate</th>
<th>Field rate</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Even</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Even</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Even</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Even</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Even</td>
<td></td>
</tr>
</tbody>
</table>

Format : 2 * 768.256 pixel image size

Odd field (t)

Even field (t+Δt)

Complete the two fields to avoid one pixel shift between images

Minimum Δt fixed by the transfer of field into the storage area (< 10 μs)
First acquisition with frame-straddling at CORIA laboratory: Pulsed jet

- **Camera**: XC 77CE-SONY (similar: Pulnix, JAI...)
  - Square pixels, 11×11 µm
  - Resolution: 756×581 (CCIR)
  - Minimum inter-frame delay 10 µs
  - Restart Reset function
- **Frame gabber connected to a PC**
- **Copper vapour laser (only two pulses)**

Unsteady injection

- **Combustion chamber**
- **Solenoid valves**
- **Pressurized tank**
First acquisition with frame-straddling at CORIA laboratory: Pulsed jet

- Camera: XC77CE-SONY (similar: Pulnix, JAI...)
  - Square pixels, 11×11 µm
  - Resolution: 756×581 (CCIR)
  - Minimum inter-frame delay 10 µs
  - Restart Reset function
- Frame grabber connected to a PC
- Copper vapour laser (only two pulses)

Synchronisation on the injection
First acquisition with frame-straddling at CORIA laboratory: Pulsed jet

- Camera: XC77CE-SONY (similar: Pulnix, JAI,...)
- Frame grabber connected to a PC
- Copper vapour laser (only two pulses)

Odd field: 768x256 pixels (t)

Even field: 768x256 pixels (t+\Delta t)

Original images: Lecordier, 1994 - CORIA
First acquisition with frame-straddling at CORIA laboratory: Pulsed jet

- Camera: XC77CE-SONY (similar: Pulnix, JAI...)
- Frame grabber connected to a PC
- Copper vapour laser (only two pulses)

Velocity field
EUROPIV 1: Comparison of stereoscopic PIV (translation conf.) to holography

Collaboration: CORIA and ISL (H. Royer) in a swirling flow (EUROPIV 1 Project)
Growing popularity of CC PIV method in the 90’s with low resolution interline CCD

- Simplest way to resolve the directional ambiguity
- Range of particle density larger than auto-correlation
- Large range of velocity, including zero displacement
- Easier to develop advanced PIV algorithms

Other aspects which contributed to the transition towards CC method

- Sub-pixel accuracy to compensate low resolution of images (768x256 pixels)

- Increasing of computer power for image processing
- Development of full digital PIV system for recording and processing
And Today ? CCD Camera for PIV : Full-Frame Interline Transfer CCD

- **Introduce in the first half of the 1990's**
- **Derivate of the interline transfer CCD**
- **Each pixel has its own storage site**
  - Fast transfer of the entire exposed images (< 1 μs)

CCD structure of Full frame interline transfer

---

And Today ? CCD Camera for PIV : Full-Frame Interline Transfer CCD

- Introduced in the first half of the 1990’s
- Derivative of the interline transfer CCD
- Each pixel has its own storage site
  - Fast transfer of the entire exposed images
- Inter-frame delay < 1 μs
- Reset/restart capability
- Resolution 1k.1k up to 4k.4k
- Pixel size 5~10 μm
- Microlenses to improve fill factor

- Time resolved measurement confined only for slow flow due to low frame rate (1 à 100 Hz).
- Integration of the signal in the second image
Time Resolved PIV in the 1990’s for high speed flow

- High speed photographic camera for PIV in 90’s
- First high speed CMOS video camera for PIV
- Actual high speed CMOS cameras
High speed photographic PIV: Principle HS photographic camera

- Maximum linear speed of the film: 0.135 mm/ms, namely 135 m/s (~10 000 rpm)
- Drum size: 80 cm to 100 cm
- Minimal recording duration: 6 ms
- Image size on film: 20x25 mm² - 40 to 150 images at each run
High speed photographic PIV: Acquisition cycle with a drum camera

- Load the film on the drum (1 min)
- Start the rotation and wait stabilization of drum speed (≈ 30 s)
- Acquisition (1 drum rotation) (6 to 100 ms)
- Chemical process of the film (1/2 h)
- Film digitalization for treatment (1/2 h to 1 h)
High speed photographic PIV: Film digitalization with high resolution scanner

**Film digitalization:**
- 8 bits in 2000 dpi
- 2000x1500 pixels²/image

2000x3000 pixels in 24x36 mm film format
High speed photographic PIV: Unsteady laminar and turbulent combustion

- Pressure: 1 à 5 bars
- Seeding: olive oil
- Duration of recording: ≈ 6 ms
- Variable turbulence level
- Central mixture ignition

Acquisition devices
- Cording camera (80 cm)
  - Photographic film: Kodak N&B - TMAX 400
- Copper vapor laser (Oxford)
  - Power: 45 W, soit: 5 to 10 mJ/pulse
  - Repetitive rate: 2 à 20 kH
High speed photographic PIV: Unsteady laminar and turbulent combustion

CORIA, 1993
High speed photographic PIV: Example of flame propagation

5000 fr/s - Laminar case

6800 images/s: turbulent case

Ignition

5.8 ms
High speed photographic PIV: Time evolution of the flame contour

Exemple de flamme sphérique: propane-air, $\Delta t = 0,2 \, ms$, $T_0 = 298 \, K$ et $P = 1 \, bar$
High speed photographic PIV: Computation of PIV velocity field

- **Laminar flame (5000 images/s)**
  - Use two successive images for PIV measurement using cross-correlation

- **Turbulent flame**
High speed photographic PIV: Film positioning difficulties for CC (1/2)
**High speed photographic PIV: Film positioning difficulties for CC (1/2)**

1. **Fixed pattern of particle in the corner of each image for positioning**

2. **Avoid film deformation during digitalization step**

---

*Figure 1: Diagram showing the positioning of the film and the avoidance of deformation during digitalization.*

*Figure 2: Graphs showing RMS and Mean flow with and without glass plates.*
High speed photographic PIV: Error introduced by film positioning

Measurement in a flow at rest (compared to the acquisition rate: 5000 Hz)

Error: 0.05 to 0.1 pixel

RMS

Mean Flow

Pixel

Moyenne et fluctuation (pixel)

Time (ms)
High speed photographic PIV: Laminar flame - 5000 fr/s - 2000x1500 pixels

propane/air : $\phi = 1.0$
High speed photographic PIV: Laminar flame - 5000 fr/s - 2000x1500 pixels
High speed photographic PIV: Turbulent flame - 6800 fr/s - 2000x1500 pixels

(propane/air : $\phi=1.0$, $u'/S_l=1.5$)
High speed photographic PIV: Turbulent flame - 6800 fr/s - 2000x1500 pixels

(propane/air : $\phi=1.0$, $u'/Sl=1.5$)
High speed photographic PIV: Turbulent flame - 6800 fr/s - 2000x1500 pixels

(propane/air : $\phi=1.0$, $u'/Sl=1.5$)
High speed photographic PIV: Turbulent flame - 6800 fr/s - 2000x1500 pixels

(propane/air : $\phi=1.0$, $u'/S_l=1.5$)
High speed photographic PIV: Time evolution of flame contour

![Flame contour diagrams with velocity and temperature fields]
High speed photographic PIV: Avantages et drawbacks

- High repetitive rate
- High resolution of image (> 2000x1500 pixels at 6000 fr/s)
- No statistic
- Fixed film length → limited duration of recording
**High speed photographic PIV: Increasing of recording duration**

Camera opening → N drum rotations → 1 or more drum rotation

Laser

Drum Rotation

1 or more drum rotation

**Recording duration ≈ 100 ms**

First time resolved PIV with high speed CMOS video camera

KODAK EKTAPRO HS Motion Analyzer, Model 4540
High speed CMOS camera: KODAK EKTAPRO HS - Model 4540

- Resolution: 256x256 at 4500 fr/s
- Frame rate: Records up to 4,500 full frames per second or up to 40,500 partial frames per second
- Pixel size: 22 μm
- No frame straddling synchronisation

<table>
<thead>
<tr>
<th>Recording rate [s⁻¹]</th>
<th>Number of frames in memory</th>
<th>Recording time [s]</th>
<th>Time between subsequent images [ms]</th>
<th>Image size in pixels (X × Y)</th>
<th>File size [bytes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 - 4500</td>
<td>3072</td>
<td>0.6824</td>
<td>0.222</td>
<td>256 × 256</td>
<td>65696</td>
</tr>
<tr>
<td>9000</td>
<td>6144</td>
<td>0.6826</td>
<td>0.111</td>
<td>256 × 128</td>
<td>32928</td>
</tr>
<tr>
<td>13500</td>
<td>12288</td>
<td>0.9101</td>
<td>0.074</td>
<td>128 × 128</td>
<td>16544</td>
</tr>
<tr>
<td>18000</td>
<td>12288</td>
<td>0.6826</td>
<td>0.056</td>
<td>256 × 64</td>
<td>16544</td>
</tr>
<tr>
<td>27000</td>
<td>24576</td>
<td>0.9102</td>
<td>0.037</td>
<td>128 × 64</td>
<td>8352</td>
</tr>
<tr>
<td>40500</td>
<td>49152</td>
<td>1.2136</td>
<td>0.025</td>
<td>64 × 64</td>
<td>4256</td>
</tr>
</tbody>
</table>

Table 1. Properties of images and tiff-files as a function of recording rate.

Image size in pixels as a function of recording rate.
High speed CMOS camera: KODAK EKTAPRO HS - Model 4540

≈ ms

Video

Exposure

Laser

No frame straddling synchronisation

$$\Delta t = \frac{1}{f_{\text{laser}}}$$
High speed CMOS camera: KODAK EKTAPRO HS - Model 4540

Lifted turbulent flame

- Camera: KODAK EKTAPRO HS - Model 4540
- Laser: Copper vapour Laser at 9kHz
- Seeding particle: Olive oil

Demarre (93) CORIA
High speed CMOS camera: KODAK EKTAPRO HS - Model 4540

9000 fr/s resolution: 256x128 pixel

Demarre (93) CORIA
High speed CMOS camera: KODAK EKTAPRO HS - Model 4540

9000 fr/s
256x128 pixels

Demarre (93) CORIA
High speed CMOS camera: “New” generation

- Resolution: larger than 2k.2k
- Acquisition rate: 1 to 6kHz at full size
- Depth: 8 to 12 bits
- Pixel size 10 to 20 μm
- Frame straddling feature (Δt < 5 μs)
High speed CMOS camera: New generation - frame straddling

Frame rate

Exposure

< 5 µs

Laser

≈ ms
**Conclusions**

- **Low repetitive rate camera**
  - High resolution (up to 4k.4k)
  - \( \Delta t < 300 \text{ ns} \)
  - High sensitivity
  - 8 to 12 bits images
  - Frame rate 1 to 100 Hz
  - Integration of the signal in the second image
  - Reduction of pixel size to reduce peak locking

- **High speed CMOS video camera**
  - Resolution up to 2k.2k at more than 4kHz
  - 8 to 12 bits images
  - Pixels size (10 to 22 \( \mu \text{m} \)) - To be decreased
  - Sensitivity has to be improved
  - Straddling synchronization

- **Increasing of the laser power**
  - 50 to 100 mJ/pulse @5kHz with 10 ns pulse duration would be perfect

- **Unfortunately, PIV is a “marginal” market for camera manufacturers**
  - In the early stage of development, custom cameras were possible
  - Now, we have to wait new models on the market