ME-301 MEASUREMENT TECHNIQUES

Fluid velocity measurements

K. Mulleners

Overview

Rotating mechanical flow meters

Pressure-based velocity measurements

Thermal anemometry

Particle-based velocimetry

anemometer *noun* • instrument for measuring the speed and direction of a flow (from Greek *anemos*=wind, *metron*=measure)

anemometry *noun* • the technique of measuring wind speed and direction

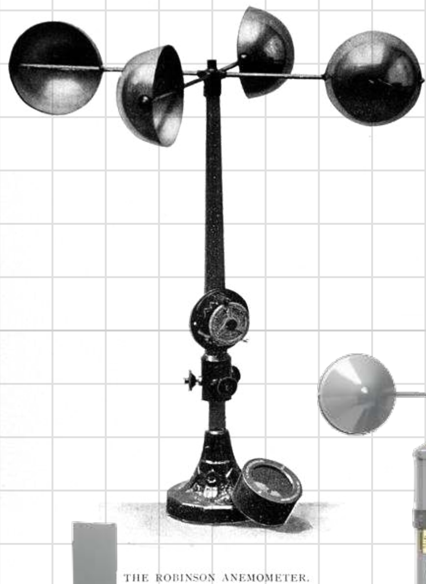
velocimetery *noun* • the technique of measuring the velocity of fluids

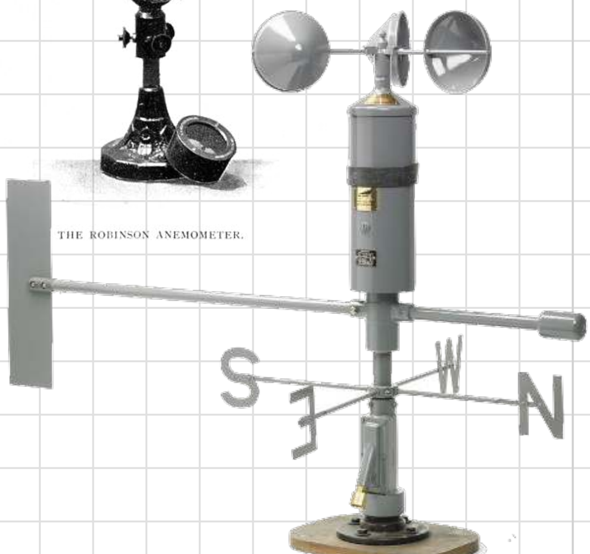
Main reference

Chapter 5 in

Rotating mechanical flow meters

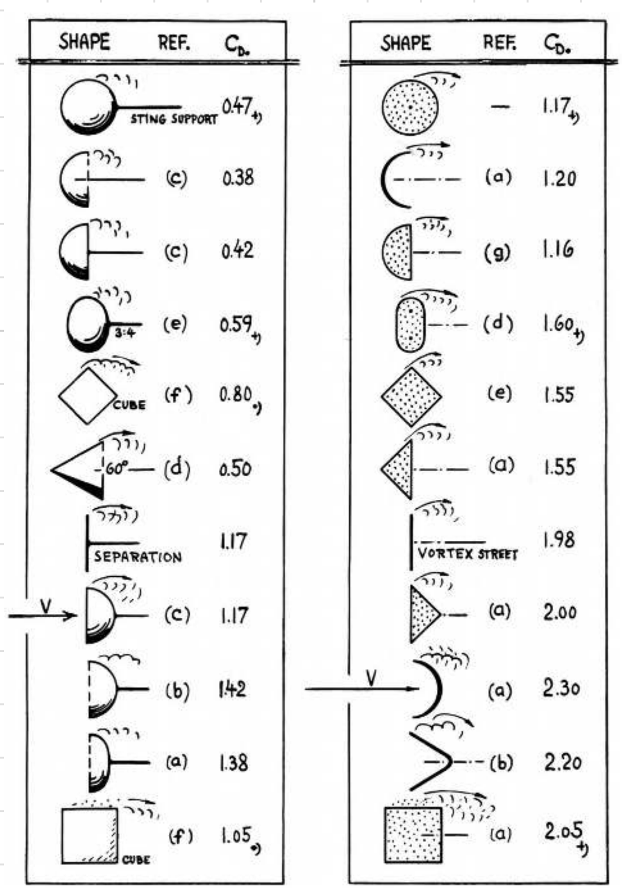
Cup and vane anemometers





Rotating mechanical flow meters

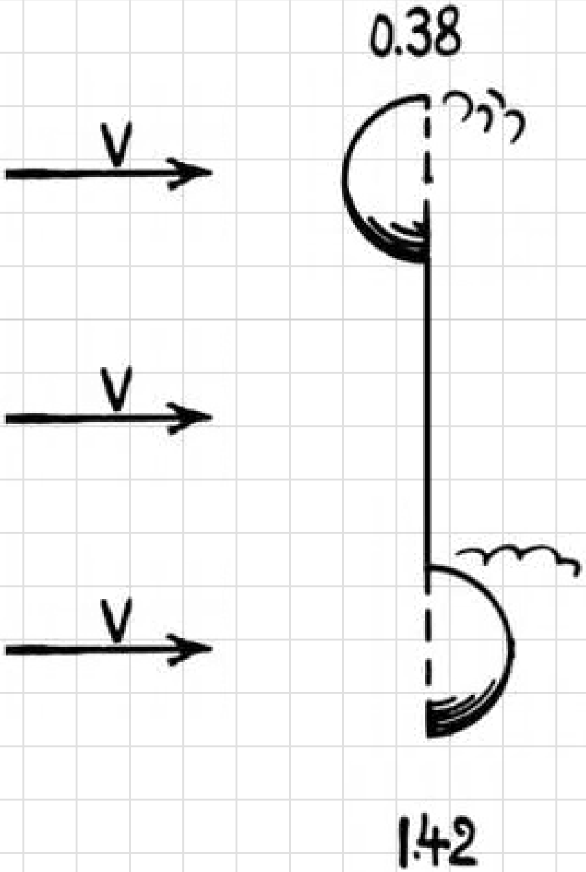
Cup anemometer working principle



from *Fluid-dynamic drag* by Hoerner (1965)

Rotating mechanical flow meters

Cup anemometer working principle



$$F_{\text{top}} = F_{\text{bottom}}$$

$$C_{\text{D,top}} \frac{1}{2} \rho A (\mathrm{U}_{\text{wind}} + \omega R)^2 = C_{\text{D,bottom}} \frac{1}{2} \rho A (\mathrm{U}_{\text{wind}} + \omega R)^2$$

...

$$\mathrm{U}_{\text{wind}} = \omega R \frac{\sqrt{C_{\text{D,bottom}}} + \sqrt{C_{\text{D,top}}}}{\sqrt{C_{\text{D,bottom}}} - \sqrt{C_{\text{D,top}}}}$$

$$\mathrm{U}_{\text{wind}} \approx 3.14\, \omega R$$

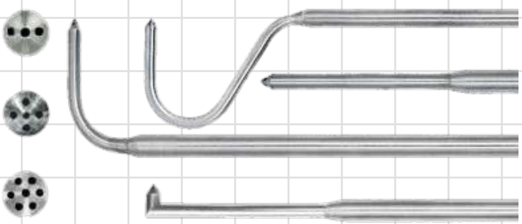
Pressure-based velocity measurements

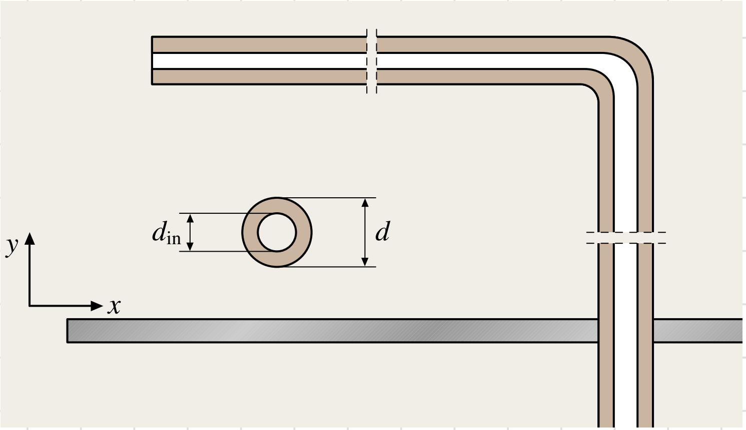
Governing equation:

Bernoulli equation: $\frac{\mathrm{d}p}{p} + U\,\mathrm{d}U = 0$
along a streamline in a steady, inviscid flow.

- Pitot tubes

- Multihole probes



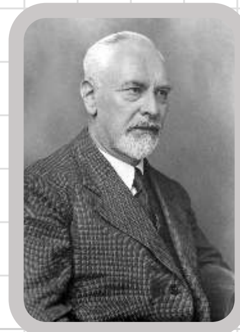


Pressure-based velocity measurements

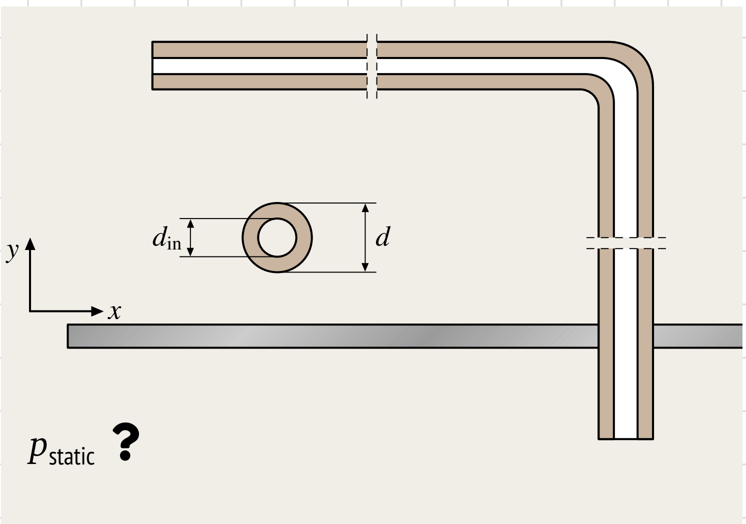
$$U_\infty = \sqrt{\frac{2(p_0 - p_{static})}{\rho}}$$

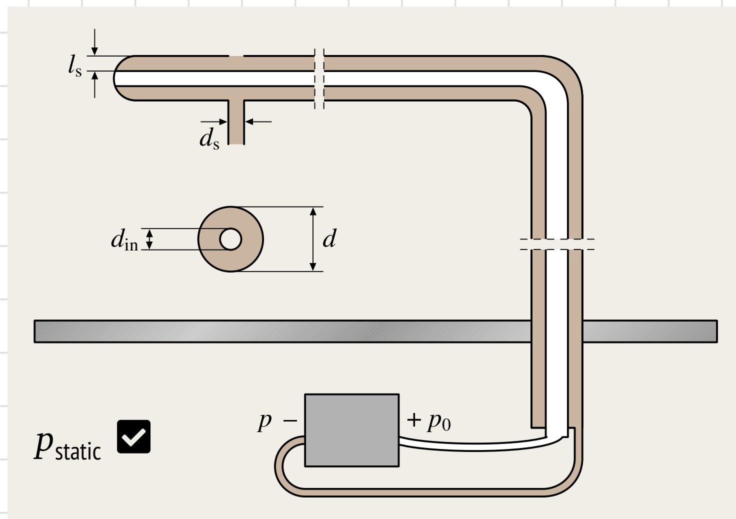
Pitot & Prandtl tube

Henri Pitot (1695 – 1771) was a French hydraulic engineer and the inventor of the pitot tube.



Ludwig Prandtl (1875 – 1953) was a German fluid dynamicist, physicist and aerospace scientist.

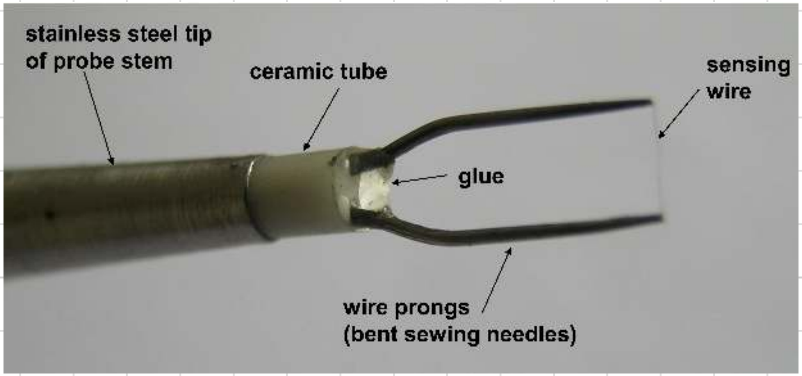


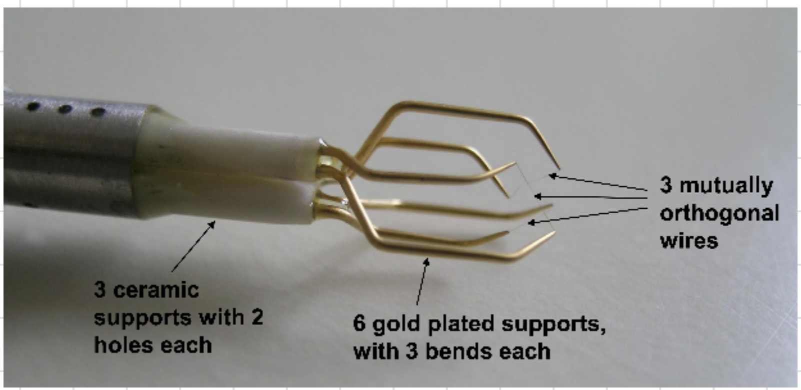


Thermal anemometry

relies on the relationship between the heat transfer from a small heated sensor (=hot-wire) and the velocity of the surrounding fluid in motion

Hot-wire probes





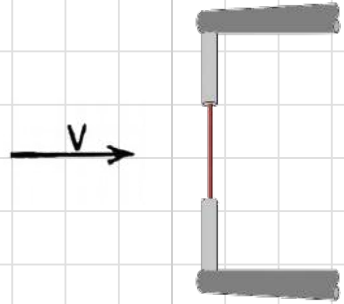
$\varnothing \approx 5\,\mu\mathrm{m}$, $L \approx 1\,\mathrm{mm}$

- intrusive
- fragile

- high spatial resolution
- high temporal resolution

Thermal anemometry

Hot-wire probes



R_w	sensor resistance when heated
I_w	current intensity in the sensor
T_w	temperature of the wire when heated
T_a	temperature of the surrounding fluid
$\phi_{conv}(V)$	forced convection effect
m_w	mass of the sensor
c_w	specific heat of the sensor material

Heat is introduced in the sensor by Joule heating, and is primarily lost by forced convection.
In steady flows:

$$R_w I_w^2 = (T_w - T_f)\phi_{conv}(V)$$

In unsteady flows:

$$m_w c_w \frac{dT_w}{dt} = R_w I_w^2 - (T_w - T_f)\phi_{conv}(V)$$

Hot-wires can be operated in three modes:

- constant current → change in V creates a change in R_w
- constant temperature → change in V creates a change in I_w to be fed to keep the temperature constant
- constant voltage → change in V creates a change in I_w to be fed to keep the V_w=$R_w I_w$ constant

Particle-based velocimetry

- laser Doppler anemometry (LDA or LDV)
- particle image velocimetry (PIV)

Particle-based velocimetry

Tracer particles

Particle-based techniques are indirect, they determine the particle velocity instead of the fluid velocity
⇒ need suitable seeding particles to avoid discrepancies between fluid and particle motion

A primary source of error = mismatch between the densities of the fluid ρ and the tracer particles ρ_p

Gravitationally induced velocity of spherical particles acceleration (assuming Stokes' flow)

$$\vec{U}_g = d_p^2 \frac{(\rho_p - \rho)}{18\mu} \vec{g}$$

⇒ velocity lag of a particle in a continuously accelerating fluid:

$$\vec{U}_s = \vec{U}_p - \vec{U} = d_p^2 \frac{(\rho_p - \rho)}{18\mu} \vec{a}$$

$\vec{g}$	the acceleration due to gravity
μ	dynamic fluid viscosity
d_p	particle diameter
$\vec{U}_p$	particle velocity

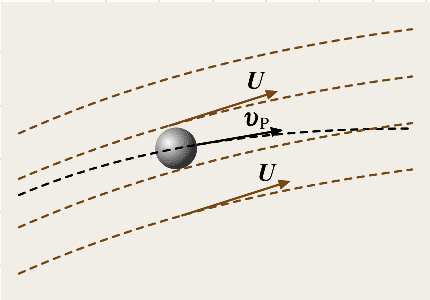


Fig. 5.58 Velocity discrepancy between the particle and the surrounding fluid velocity

Particle-based velocimetry

Laser Doppler anemometry (LDA or LDV)

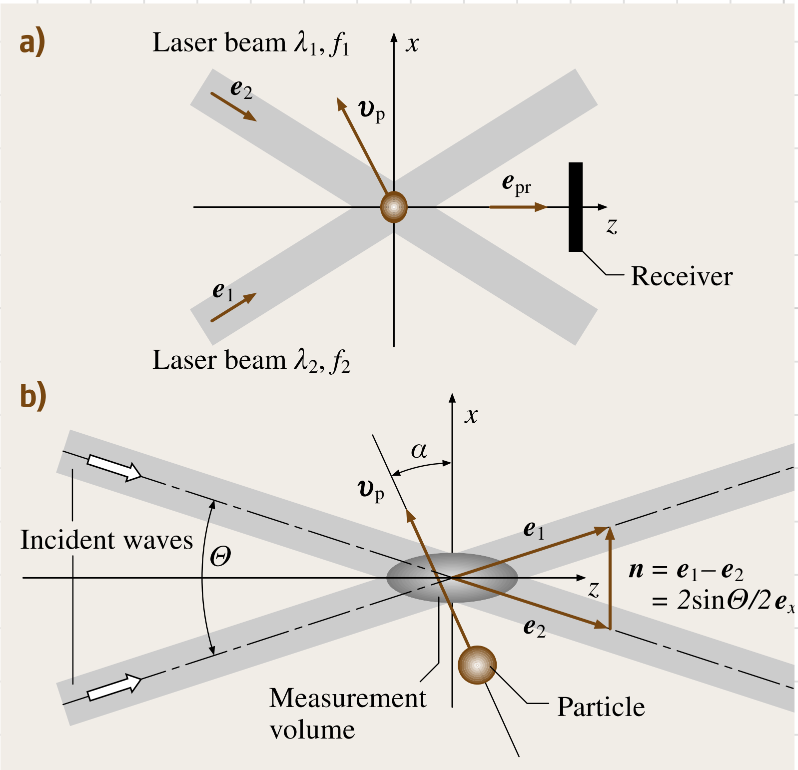


Fig. 5.70 **(a)** Dual-beam configuration. **(b)** Vector relations rel to determining the Doppler frequency

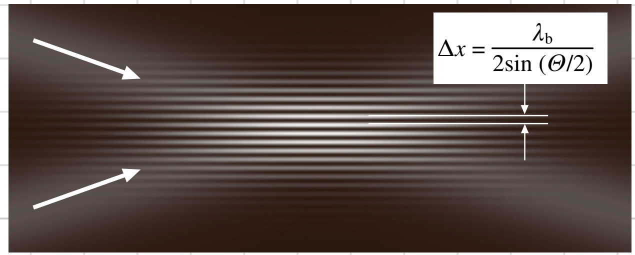
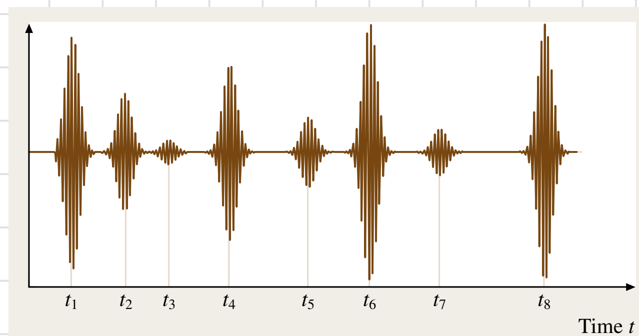
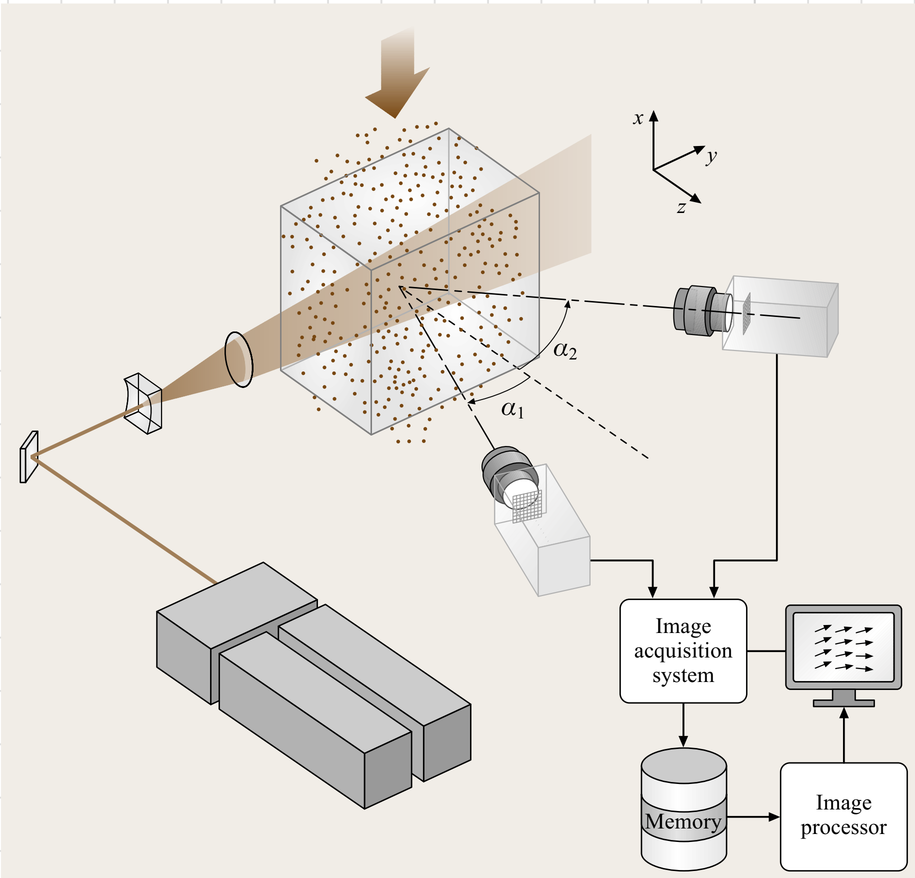


Fig. 5.71 Interference pattern in the measurement volume – fringe model



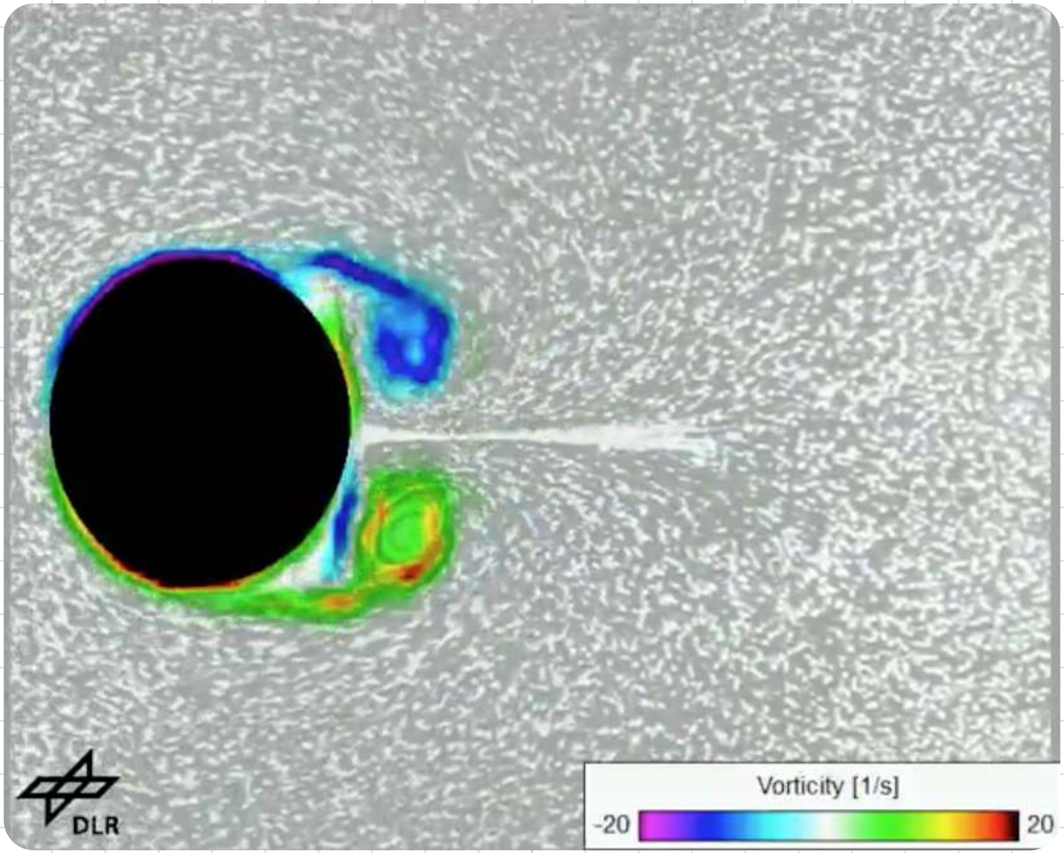
Particle-based velocimetry

Particle image velocimetry (PIV)



Particle image velocimetry (PIV)

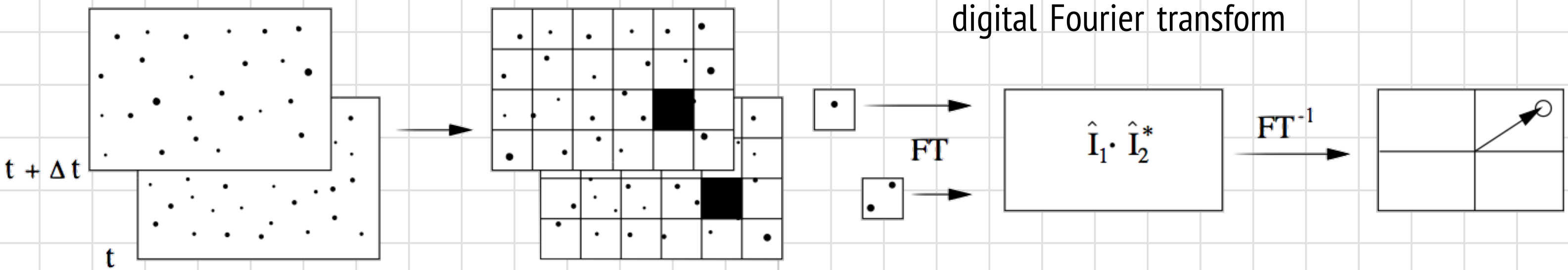
Example



Particle image velocimetry (PIV)

Cross-correlation

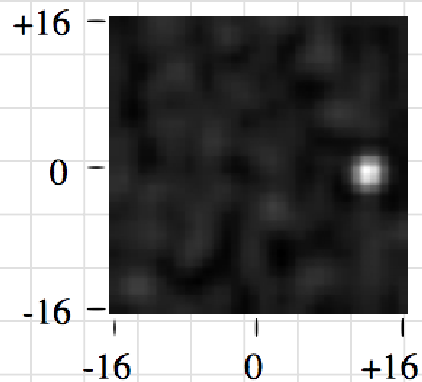
cross-correlation via
digital Fourier transform



divide in interrogation windows

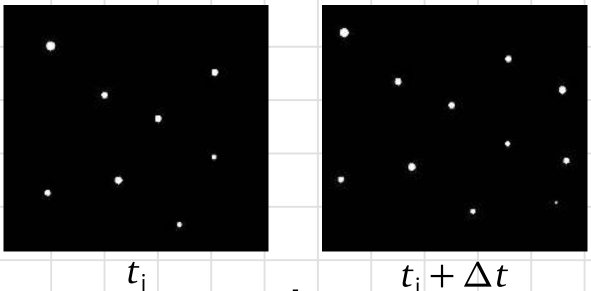
peak fit the correlation peak
to obtain displacement in px

cross-correlation plane $C(\Delta x, \Delta y)$

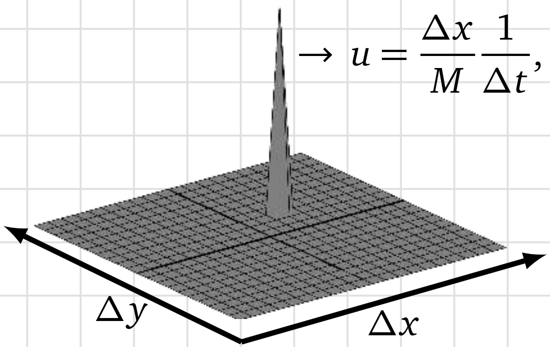


Particle image velocimetry (PIV)

Cross-correlation



$$C(\Delta x, \Delta y) = \iint I_1(x, y)\, I_2(x + \Delta x, y + \Delta y)\, \mathrm{d}x\, \mathrm{d}y$$

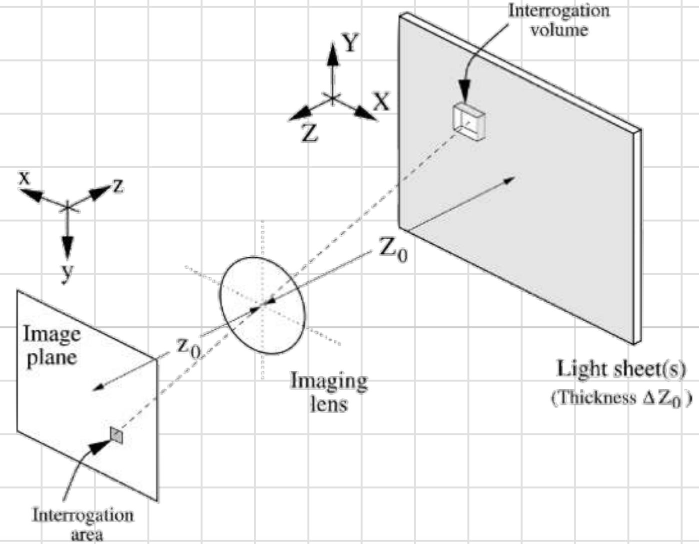


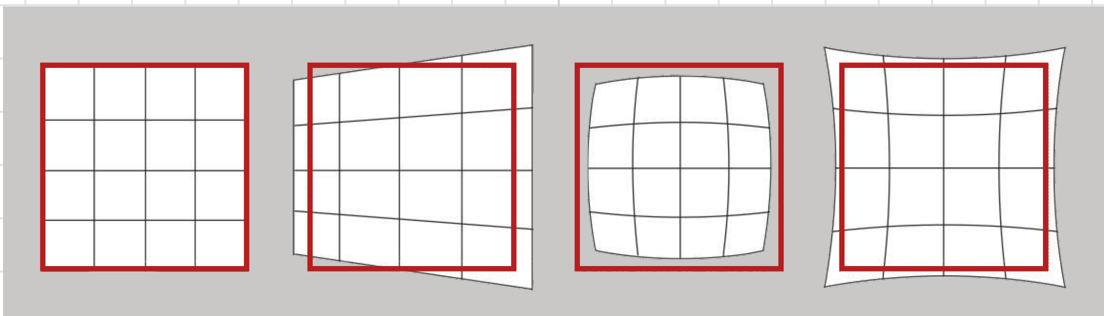
$$\rightarrow u = \frac{\Delta x}{M}\frac{1}{\Delta t},\; v = \frac{\Delta y}{M}\frac{1}{\Delta t}$$

Calibration

Why?

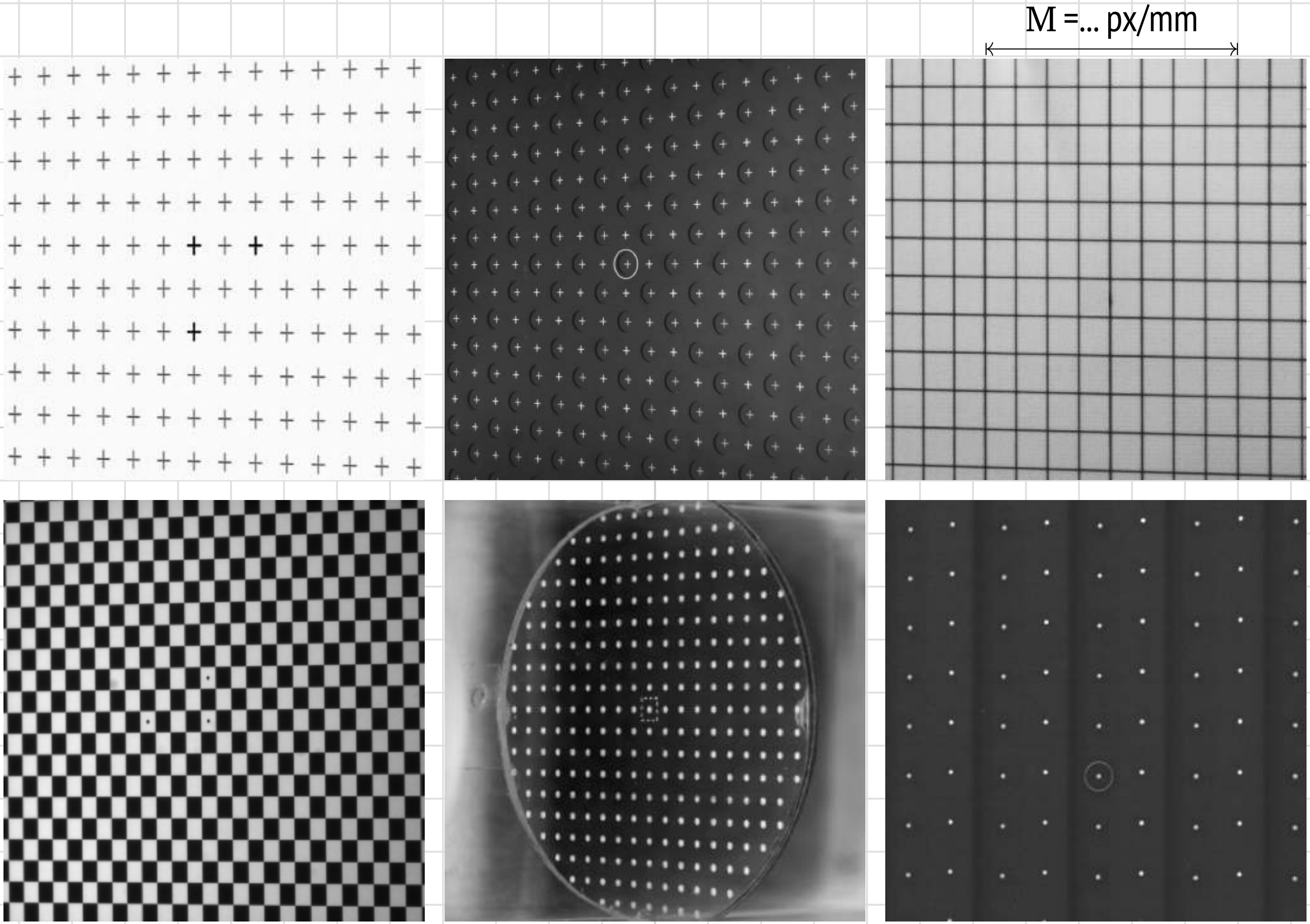
- determine the imaging magnification factor M
- correct for lens distortions
- stereo mapping





Calibration

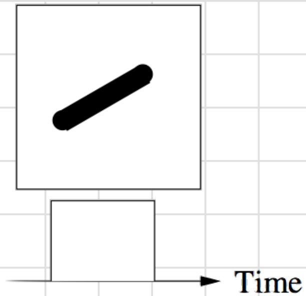
$$u = \frac{\Delta x}{\mathrm{M}} \frac{1}{\Delta t}, \quad [\Delta x] = \mathrm{px}, \quad [\Delta t] = \mathrm{s}$$



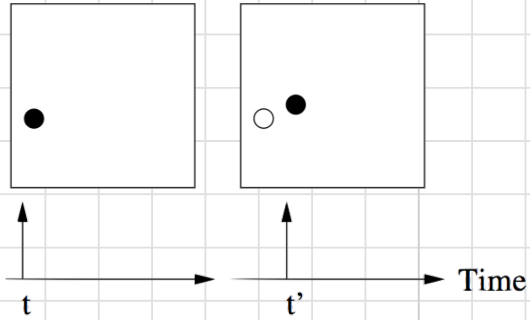
Particle image velocimetry (PIV)

Timescales

camera exposure time

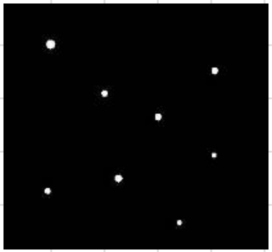


time delay between snapshots

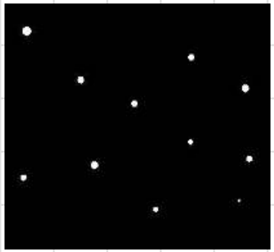


Particle image velocimetry (PIV)

Cross-correlation

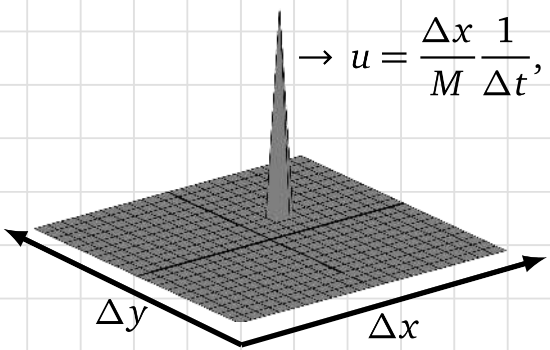


t_i



$t_i + \Delta t$

$$C(\Delta x, \Delta y) = \iint I_1(x, y)\, I_2(x + \Delta x, y + \Delta y)\, \mathrm{d}x\, \mathrm{d}y$$



$$\rightarrow u = \frac{\Delta x}{M}\frac{1}{\Delta t},\; v = \frac{\Delta y}{M}\frac{1}{\Delta t}$$

Particle image velocimetry (PIV)

Interrogation window size

How to choose the right interrogation window?

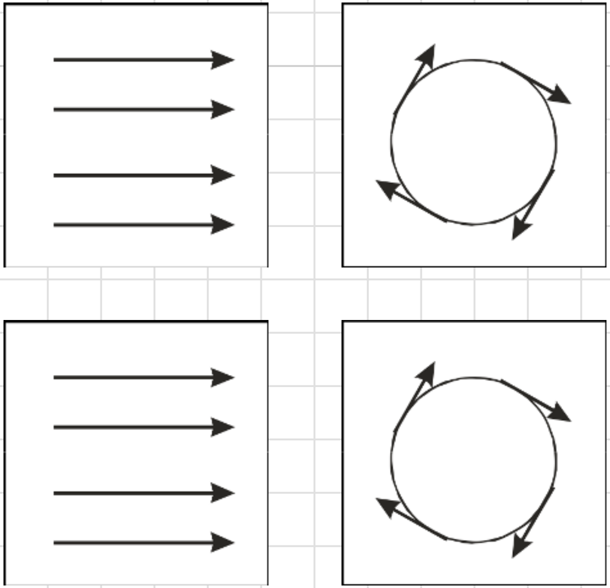
The choice depends on:

- flow
- seeding
- imaging
- timing

too small interrogation window size
→ not enough particles in interrogation window
→ particles 'leave' interrogation window

too large interrogation window size
→ decreased spatial resolution
→ multiple correlation peaks

⇒ **one choice does not fit all**



Particle image velocimetry (PIV)

Advanced correlation techniques

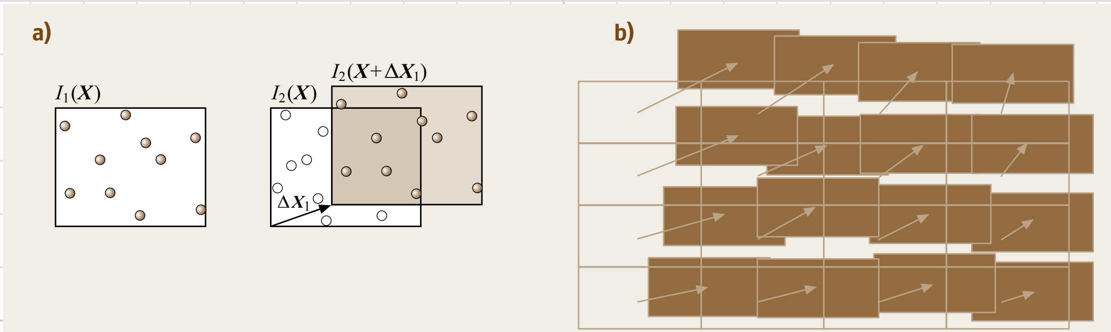


Fig. 5.115a,b Window shift technique. **(a)** The correlation is evaluated between two particles patterns shifted, accounting for the translation due to the flow motion. Shaded shifted window with the estimated displacement. **(b)** Window shift for a group of windows.

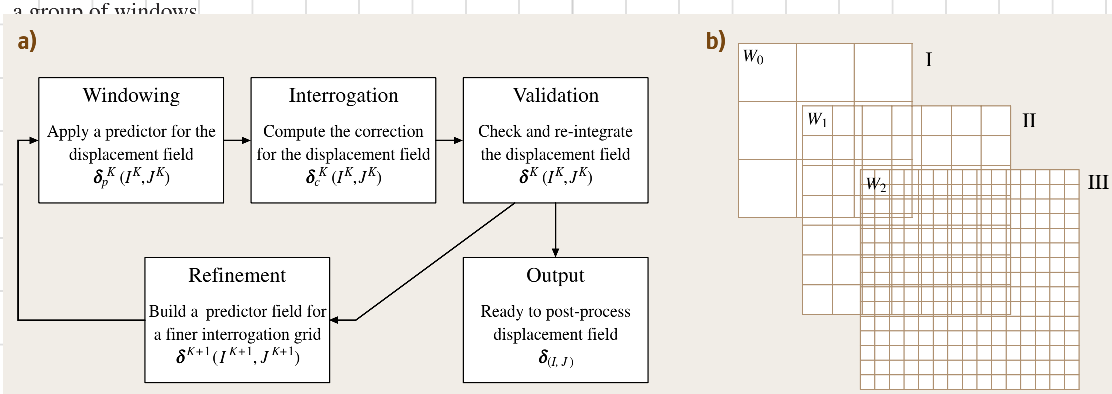


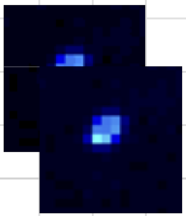
Fig. 5.116a,b Block diagram of multigrid interrogation **(a)** and graphical description of the interrogation grids **(b)**

Particle image velocimetry (PIV)

Peak fitting and peak locking

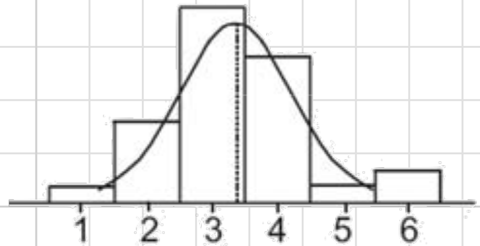
Particle image

Correlation Map (in x-direction)

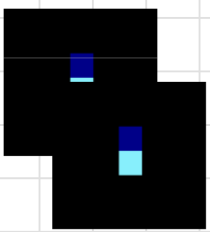


Partial overlap :

Broad peak →
gaussian bell fit →
Subpixel accuracy

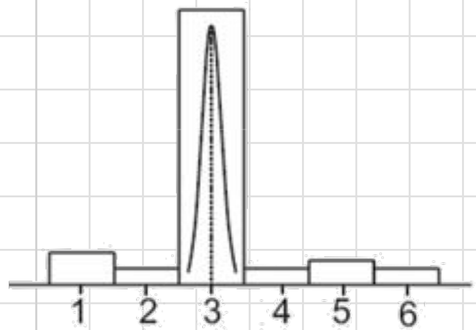


particle image size of 2-3 pixel



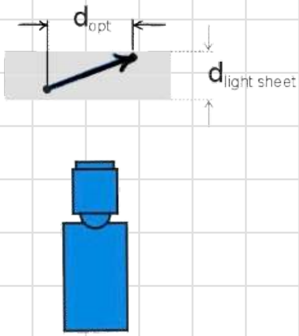
Overlap or not :

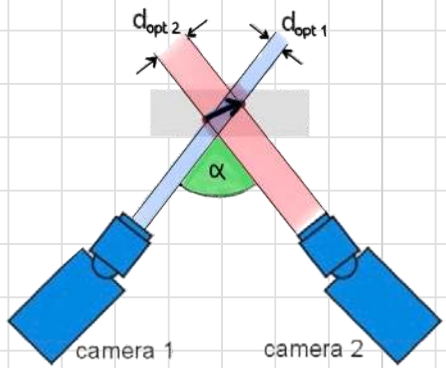
Single peak →
gaussian bell fit →
Pixel accuracy

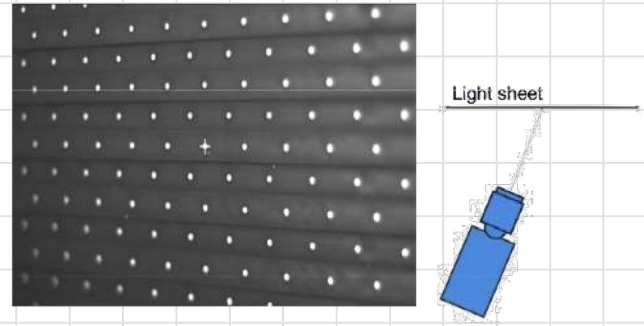


particle image size smaller than 1 pixel

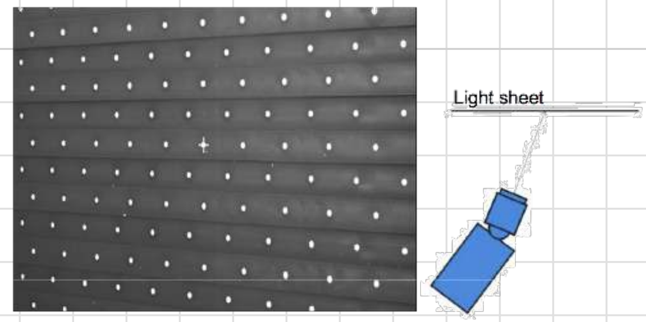
Stereo particle image velocimetry (PIV)



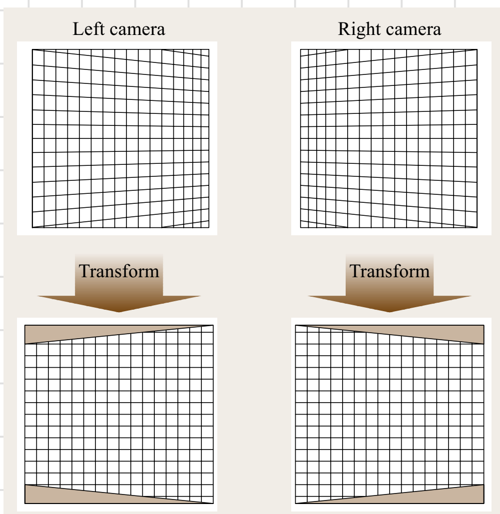


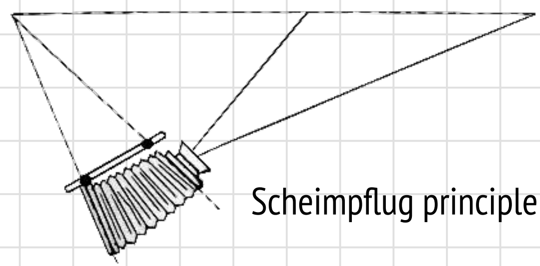


Only vertical line in the center is focussed.



Complete FOV is focussed.





Scheimpflug principle

Using PIV for your project?

What do you need?

- particles
- camera
- fluid motion
- illumination
- processing software: e.g. PIVlab