Particle Image Velocimetry

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INTRODUCTION

- Basic Idea: Add tracer particles to the flow; image the position of particles; find displacement of particles between two time instants; obtain velocity
- Allows wholefield measurement of velocity in a flow
- Optical based technique
- PIV has become a standard tool in Fluids labs across the world
- PIV can be used in a wide range of flow conditions (laminar/ transition/ turbulent; compressible/ incompressible; Newtonian/ non-Newtonian; steady/ unsteady; etc)

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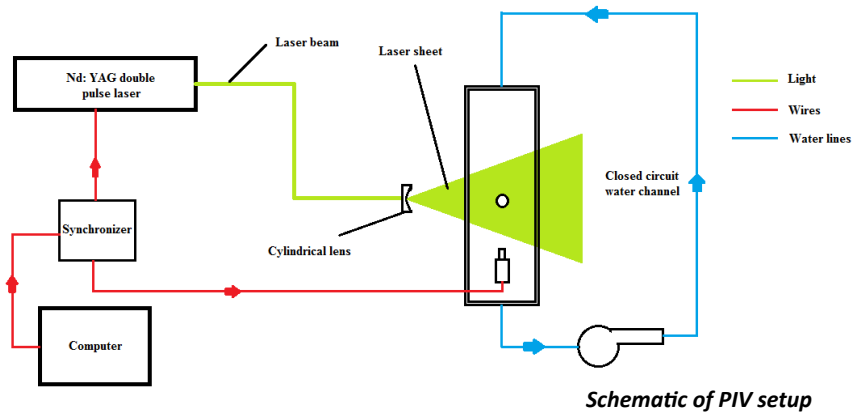
PARTICLE IMAGE VELOCIMETRY



Schematic of PIV setup

PIV gives two-dimensional velocity in a plane: (u, v) = f(x, y)

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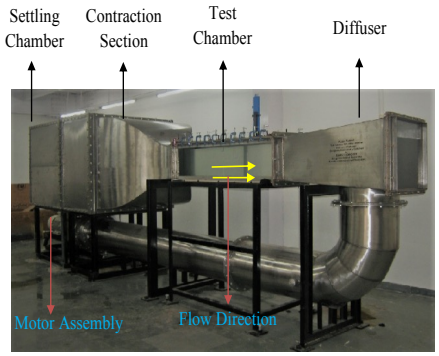
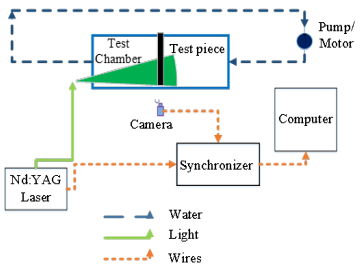
Plane of Measurement



Water Tunnel facility @ IIT Bombay



Schematic of PIV setup

PARTICLE IMAGE VELOCIMETRY :*SAMPLE IMAGE 1*

Image A

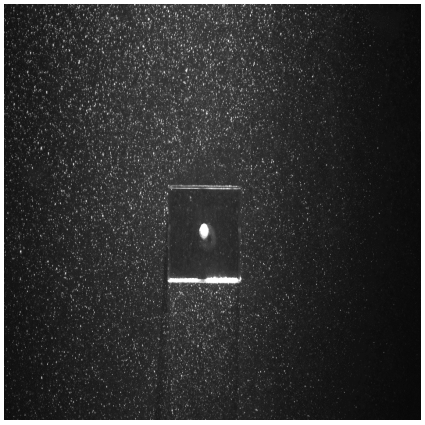
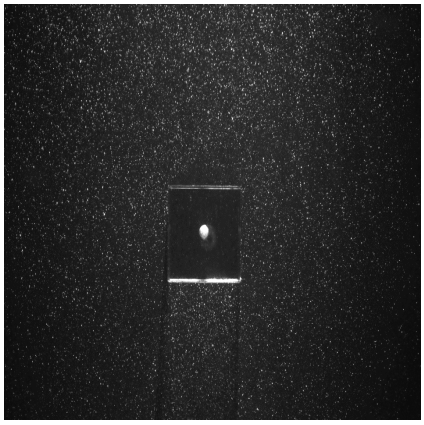


Image B



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This section explains the position of PIV on a timeline of evolution of flow visualization technique and mentions different components of PIV.

EVOLUTION AND COMPONENTS OF PIV

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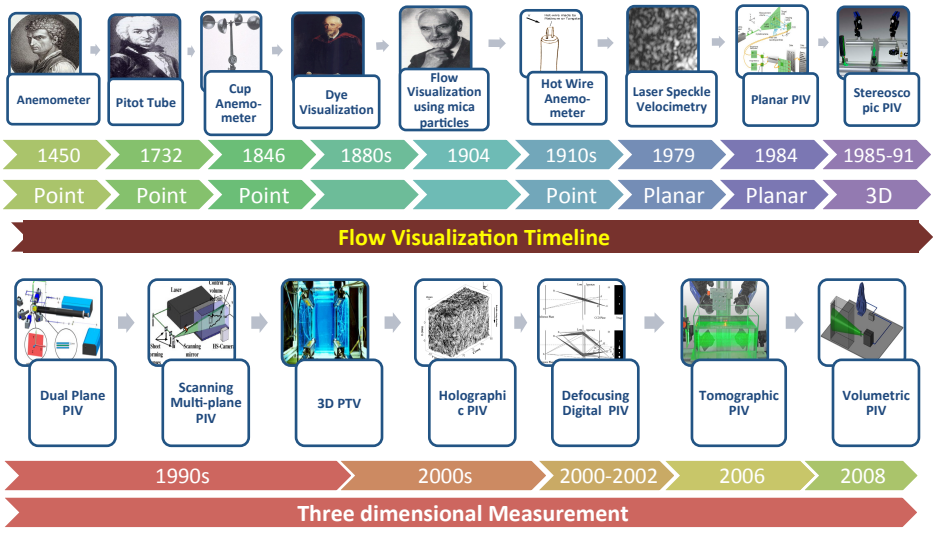
TIME LINE FOR FLOW VISUALIZATION



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Conventional Techniques versus PIV

Pitot tube

- Intrusive
- Point-wise
- One velocity component
- Steady flow

- Easy to use
- Cheap
- Optical access not required
- No special requirement

PIV

- Non-intrusive
- Wholefield (5000+ points)
- Two-velocity components
- Time-varying velocity can be measured

- Not so easy to use
- Expensive
- Requires optical access
- Requires clean, controlled environment

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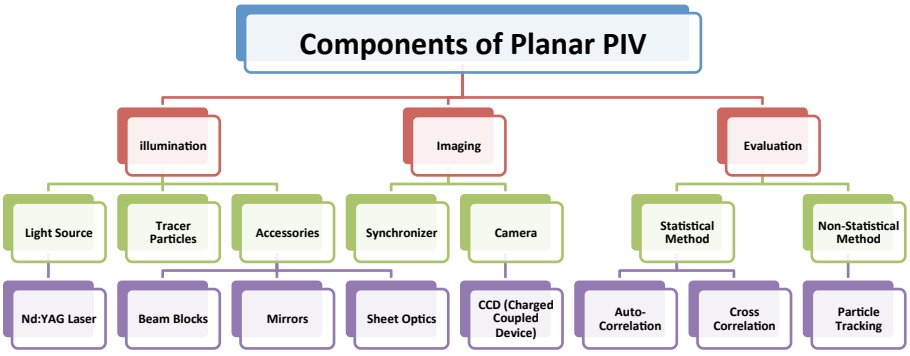
PIV COMPONENTS



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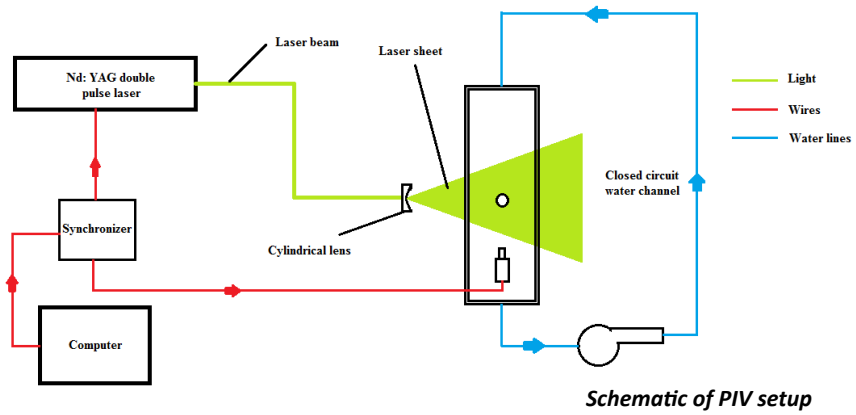
PARTICLE IMAGE VELOCIMETRY



Schematic of PIV setup

PIV gives two-dimensional velocity in a plane: (u, v) = f(x, y)

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ILLUMINATION

Laser	Sheet Optics	Particles
• Nd:YAG pulsed laser, 25-200 mJ/ pulse with a pulse width of 4-9 ns	• Spherical lens followed by a cylindrical lens	• Mean particle size of 8-11 μm, density around 1.1 g/ cm^3, made of fused borosilicate glass

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COMMON LASERS FOR PIV

- Helium-neon lasers
- Copper-vapor lasers
- Argon-ion
- Semiconductor lasers
- Ruby lasers
- Neodym-YAG lasers
  - Most Commonly used
- Neodym-YLF lasers

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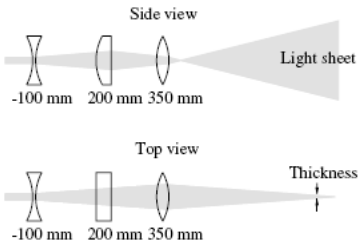
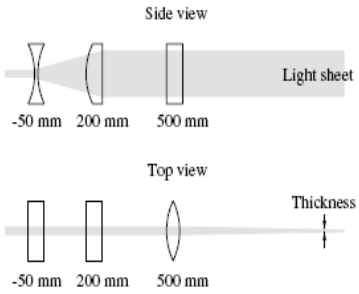
LIGHT SHEET OPTICS …

The essential element for the generation of light sheet element is cylindrical lens.
Diverging lens is used to avoid focal lines.
The combination of cylindrical lens together with two telescope lenses make the system more versatile.



Light sheet optics using two spherical lenses (one of them with negative focal length) **and one cylindrical Lens**.



Light sheet optics using three cylindrical lenses (one of them with negative focal length**).**

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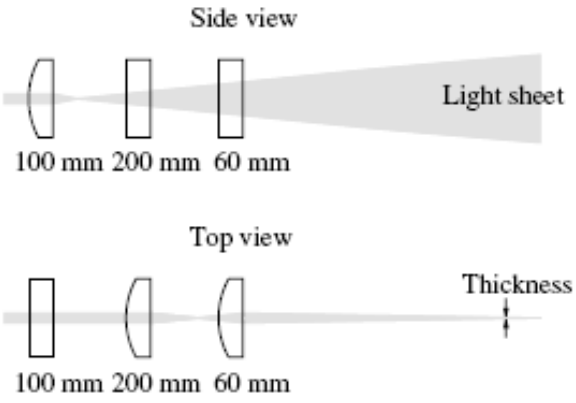
LIGHT SHEET OPTICS … CONT



Light sheet optics using three cylindrical lenses.

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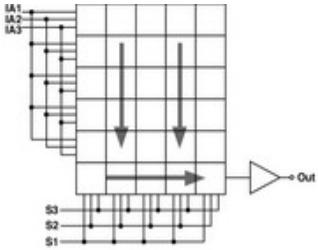
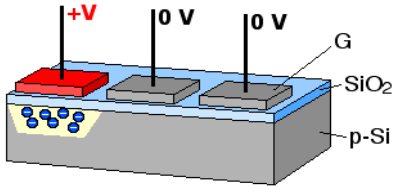
IMAGING DEVICE

- CCD – Charge coupled device.
  - 1.4 Megapixels
  - Normal Used Range:
    - 1-4Megapixels for Planar PIV
    - 3-12 Megapixels for 3D PIV



a. Full-frame imager



Working of CCD

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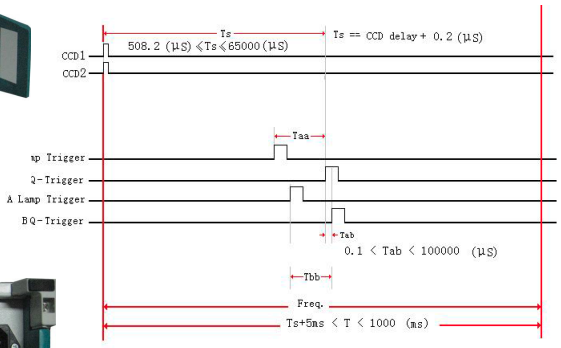
SYNCHRONIZATION AND TIMING DIAGRAM



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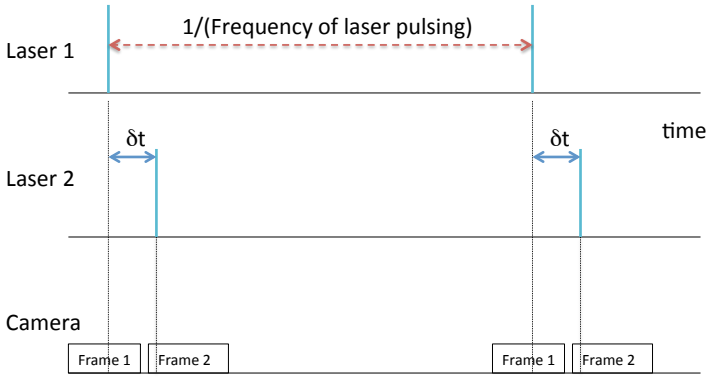
Timing Diagram



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SEEDING

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TRACER PARTICLES & PROPERTIES

Mechanical

Fluid mechanical Properties
Should faithfully follow the flow i.e sp gravity near to that of water

Stokes number (St) << 1

$St = \frac{\tau_P}{\tau_F}$ where $\tau_P = \frac{\rho_P d_p^2}{18\mu}$

and τ_F is the flow response time = Length scale/ Characteristic velocity

Optical

Light scattering properties
Should religiously scatter light

Rayleigh scattering regime ($\frac{d_P}{\lambda} < 1$)

Mie-scattering regime ($\frac{d_P}{\lambda} > 1$)

Where:

d_P = particle diameter

λ = wavelength.

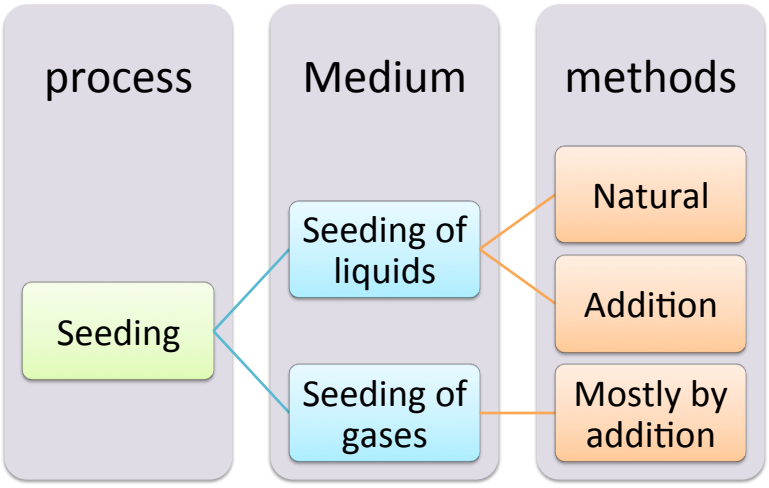
More laser energy is required in Rayleigh regime.

Chemical

Should not React with Fluid

Seeding/ Tracer Particles are added to scatter the light and track flow pattern 19

SEEDING CLASSIFICATION …



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SEEDING MATERIALS FOR LIQUIDS

Type	Material	Mean Diameter in microns
Solid	Polystyrene	10-100
	Aluminum flakes	2-7
	Hollow glass spheres	10-100
	Granules for synthetic coatings	10-500
Liquid	Different oils	50-500
Gases	Oxygen bubbles	50-1000

The general trend is hollow coated glass spheres of 10 microns

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TECHNIQUES FOR GASES FLOWS

To generate and supply particles

Disperse dry powders

- In fluidized bed
- By air jets

Evaporate liquid followed by condensation in generators

Atomization

Use atomizers to disperse solid particles suspended in evaporating liquids

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SEEDING MATERIALS FOR GASES

Type	Materials	Mean diameter in microns
Solid	Polystyrene	0.5-10
	Alumina	0.2-5
	Titania	0.1-5
	Glass microspheres	0.2-3
	Glass micro balloons	30-100
	Granules for synthetic coatings	10-50
	Dioctylphathalae	1-10
	Smoke	< 1
Liquid	Different oils	0.5-10
	Di-ethyl-hexyl-sebacate(DEHS)	0.5-1.5
	Helium filled soap bubbles	1000-3000

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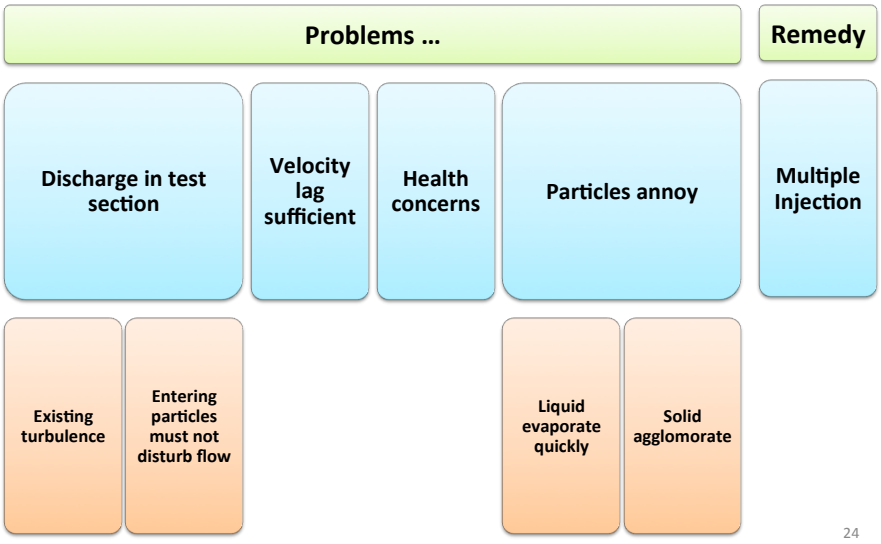
SEEDING OF GASES ...



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This section Explains the how an image is formed and in PIV how image is recorded after certain displacement of δx. Principle behind PIV as a velocity measurement technique is explained.

IMAGE FORMATION AND NATURE OF PARTICLE IMAGE

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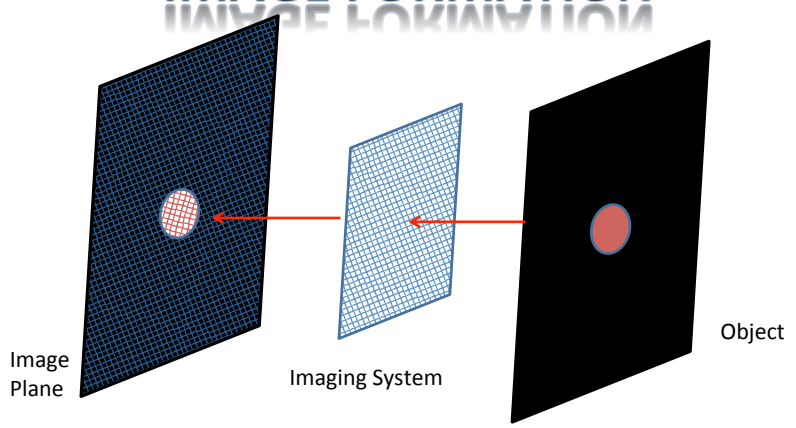
IMAGE FORMATION



Input Distribution (object) → Imaging System PSF(o)+noise → Output Distribution (s)

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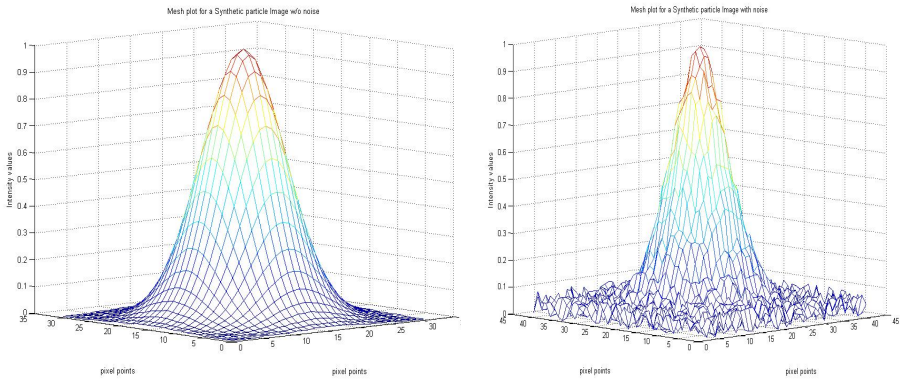
SYNTHETIC PARTICLE

Particle Profile Without Noise **Particle Profile With Noise**



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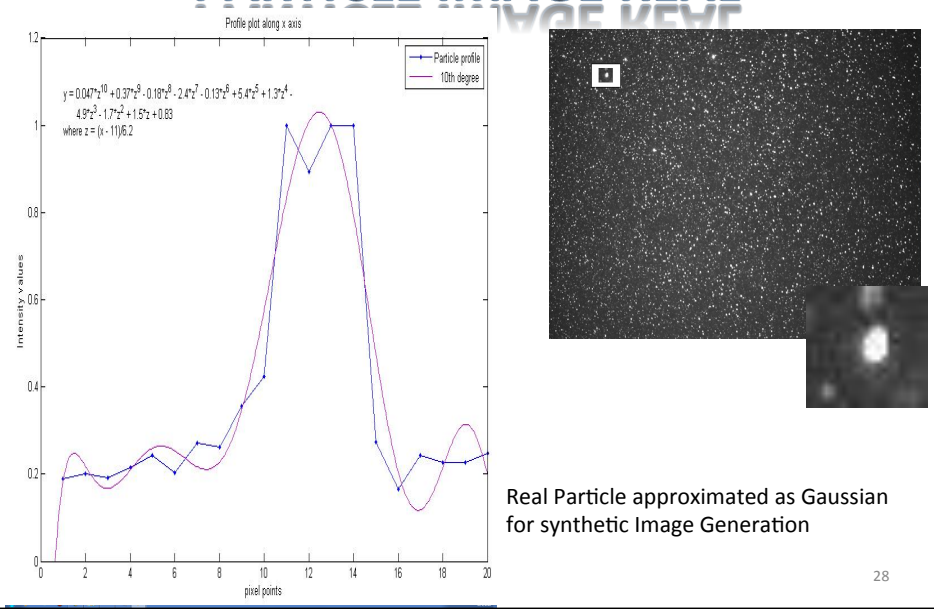
PARTICLE IMAGE REAL



Real Particle approximated as Gaussian for synthetic Image Generation

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This section mentions the evaluation method used in PIV. Detailed discussion about FFT-based cross-correlation is mentioned.

EVALUATION OF IMAGES

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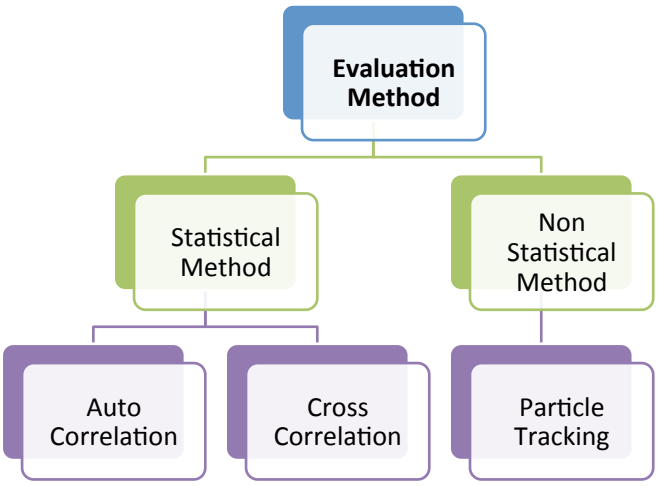
EVALUATION



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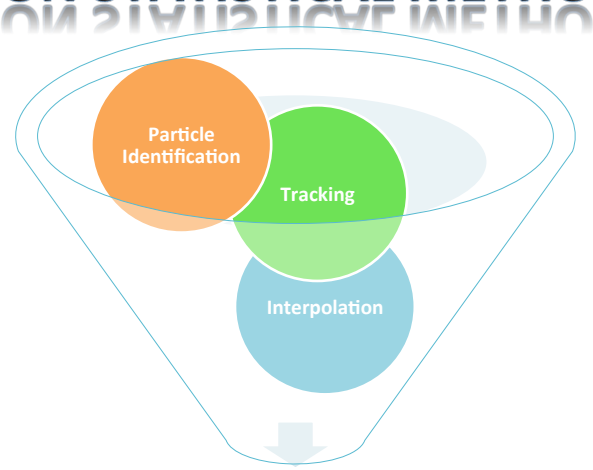
NON STATISTICAL METHOD



Particle Tracking method

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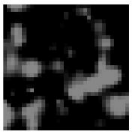
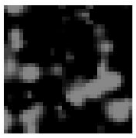
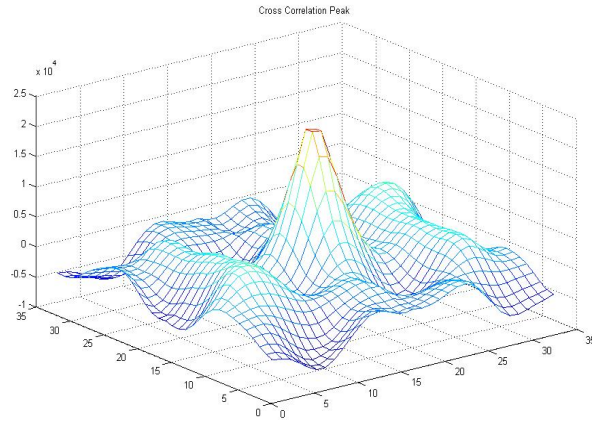
CROSS CORRELATION FOR AN INTERROGATION WINDOW



Window A



Window B



Using real data!

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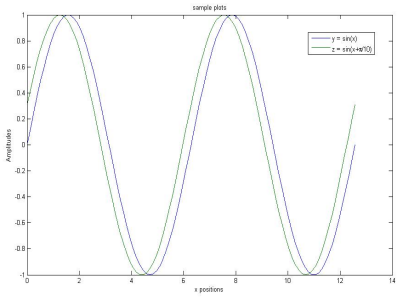
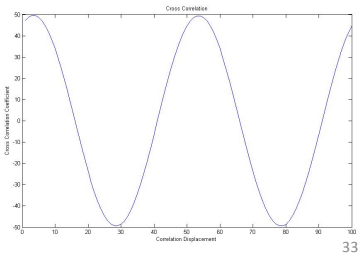
CROSS CORRELATION

$$(f \star g)(t) = \int_{-\infty}^{\infty} f^*(\tau) g(t + \tau) d\tau$$

$$(f \star g)(t) = f^*(t - \tau) * g(t)$$
$$= F^{-1}\{F(f^*(t - \tau)).F(g(t))\}$$

Where $\star$ *is for correlation*
$*$ *is for convolution*
f^* *is complex conjugate*





Cross Correlation for a shifted sine

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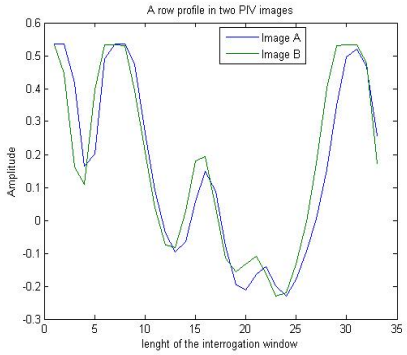
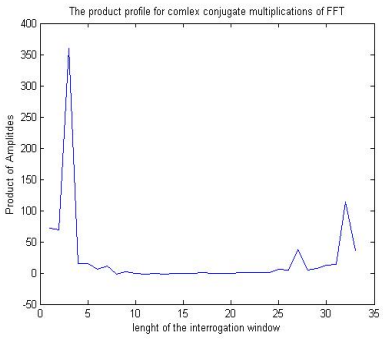
CROSS CORRELATION FOR A REAL PIV IMAGE (SINGLE ROW ONLY)





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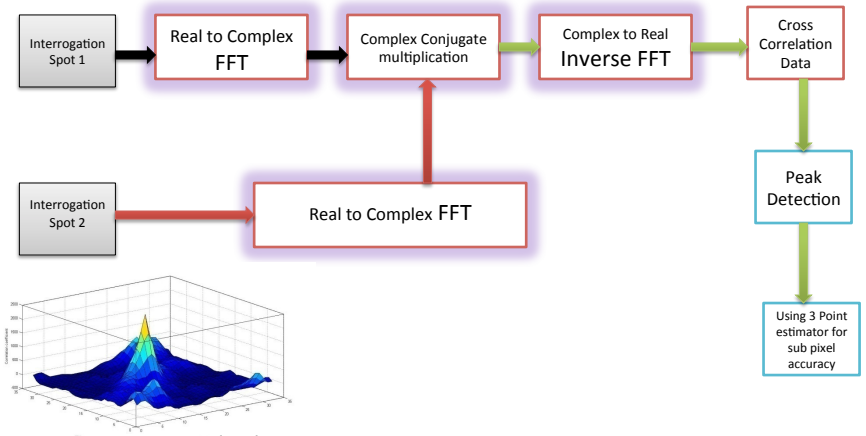
2 DIMENSIONAL FFT BASED CROSS CORRELATION



Raffel M, Willert C, Kompenhans J (1998) Particle Image Velocimetry. A practical guide. Springer, Berlin Heidelberg New York.

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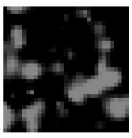
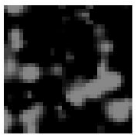
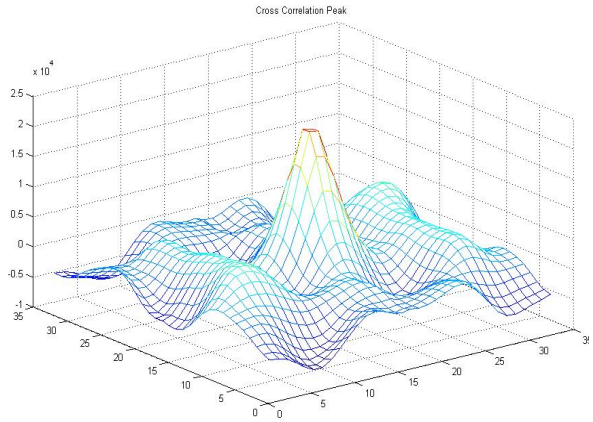
CROSS CORRELATION FOR AN INTERROGATION WINDOW



Window A



Window B



Using real data!

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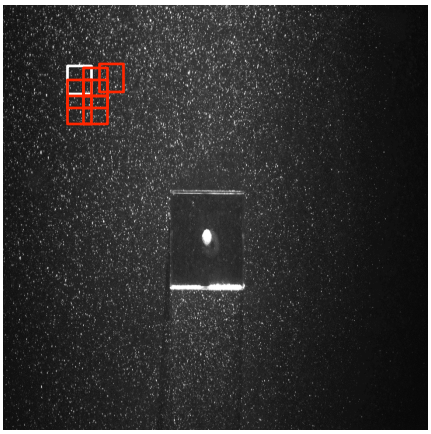
INTERROGATION SPOT

- Interrogation spot is the smallest region taken from the bigger image to detect the particle movements pattern.
- Size of Interrogation spot should be 3 times the particle displacement to avoid aliasing.
- Total Number of particles is determined by the % overlap between two interrogation spots.
- For Image of 1024x1392 px. An interrogation spot of 32x32 pixels with 50%(16x16px) overlap has 63x86 vectors



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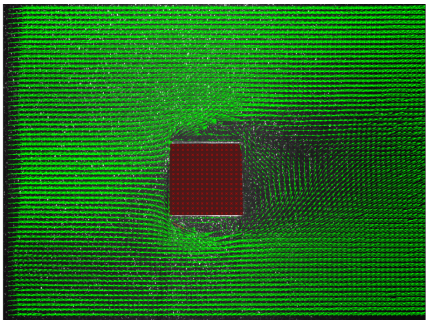
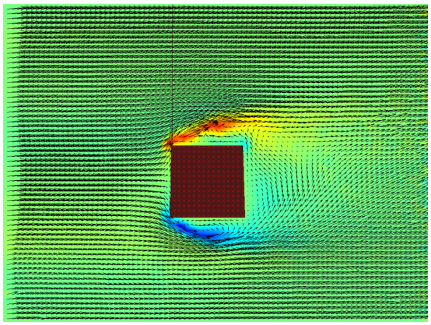
AFTER EVALUATION

Mean Velocity Field



Vectors and Vorticity contours



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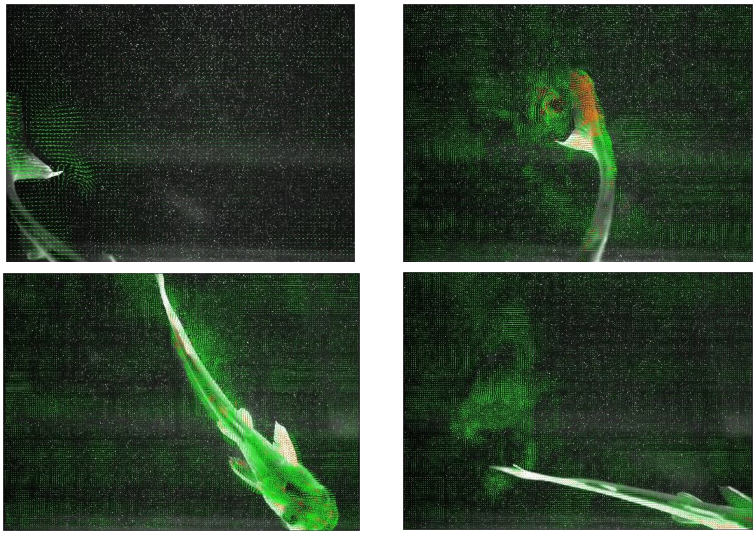
Flow around a fish



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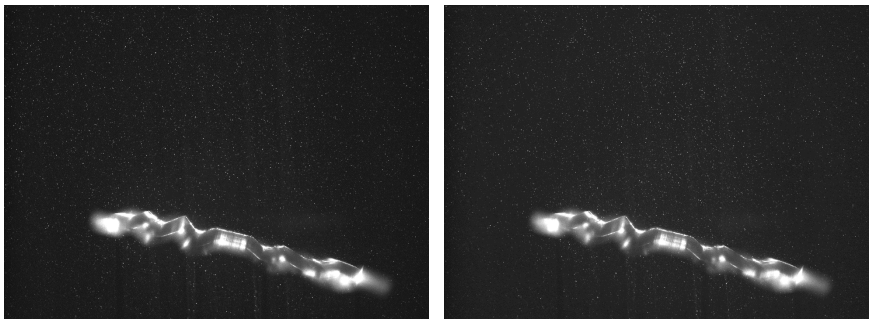
Sample Image

Image A **Image B**



Corrugated airfoil angle of attack 12°

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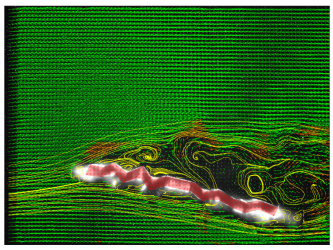
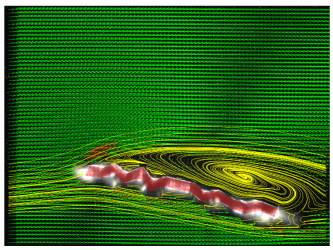
Evaluation of Sample Image

Instantaneous Velocity field **Mean Velocity field**





Corrugated airfoil angle of attack 12°

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Volume flow rate and shear stress

- Flow in pipe

$$V = \int 2\pi r \, dr v$$

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POST PROCESSING

- Displacement of particles (in pixels/frame) after calibration give velocity u, v in xy plane.
- Since only planar information is available. Differential Quantities which can be calculated are
  - Vorticitynormal to the light sheet $\omega_z = \frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y}$
  - In-plane shearing $\epsilon_{XY} = \frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X}$
  - In-plane extensional strains $\eta = \epsilon_{XX} + \epsilon_{YY} = \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y}$

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POST PROCESSING

Vortices in turbulent jet

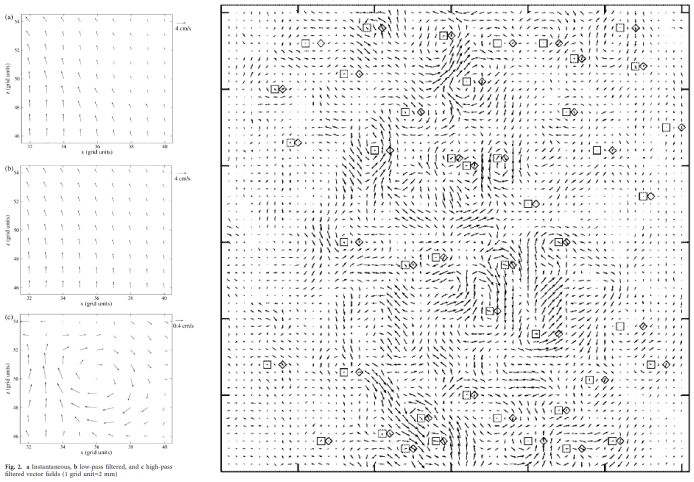

Fig. 2. a Instantaneous, b low-pass filtered, and c high-pass filtered vector fields (1 grid unit=2 mm)

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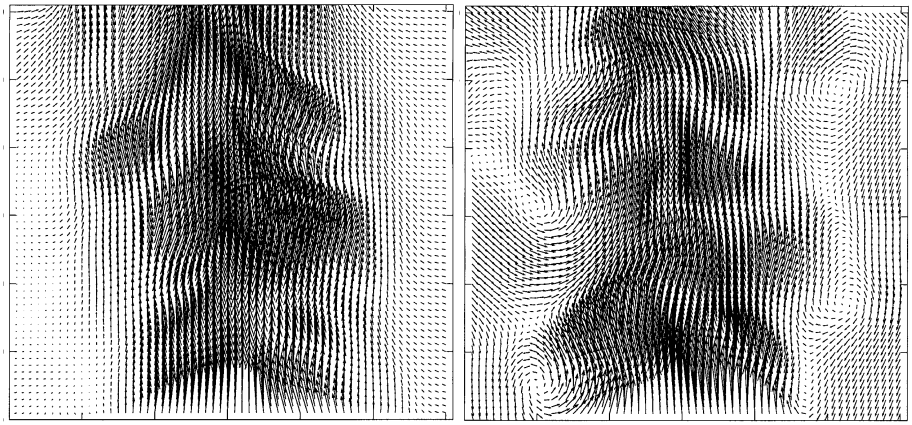
POST PROCESSING (IN CONJUNCTION WITH LINEAR STOCHASTIC ESTIMATE)

Coherent structures in turbulent jet



Arrow-head structures

Helical mode

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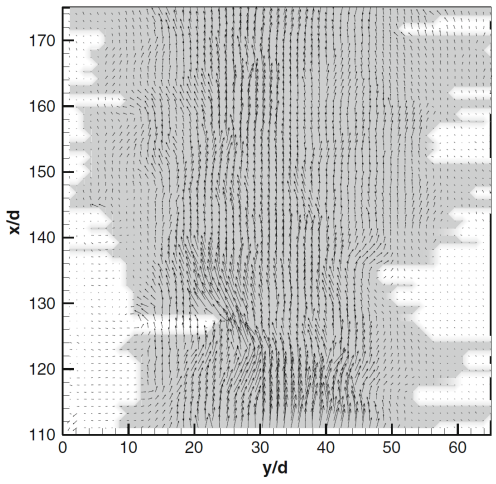
POST PROCESSING

Detection of turbulent / non-turbulent interface in turbulent jet



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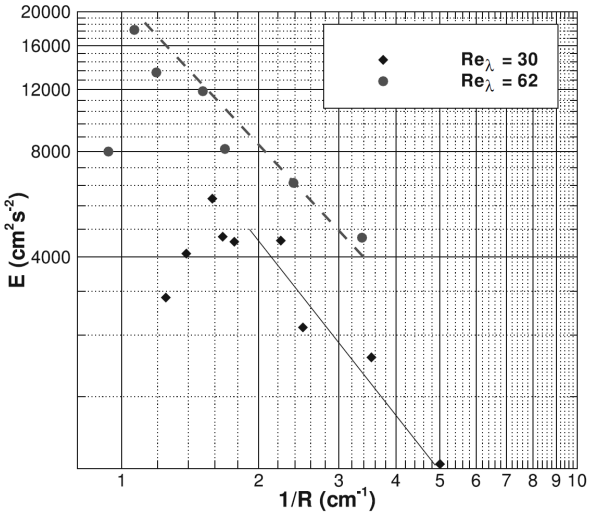
POST PROCESSING

Measurement of turbulence spectrum



Average energy (unnormalized) associated with a given vortex size. Note that the plot is on a log-log scale and the inverse of vortex size is plotted on the abscissa. The line-of-best-fit (solid and dashed lines for Rek = 30 and 62, respectively) has also been shown

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ACCURACY OF PIV/ ERROR ESTIMATION

- $\epsilon_{total} = \epsilon_{bias} + \epsilon_{rms}$
  - Bias error due to inaccuracies in correlating image pairs to get vectors.
- Random errors:
  - particle to pixel size, peak locking, interrogation area size, frequency distribution of light intensity
- Typically, the velocity accuracy of PIV measurements is of order one per cent, and the spatial resolution is of order one millimeter. (Adrian 1997)

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