B-TECH PROJECT REPORT

<u>PARTICLE IMAGE VELOCIMETRY</u>

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CERTIFICATE

It is certified that the work contained in the thesis entitled "**PARTICLE IMAGE VELOCIMETRY**", by "Mr. Ramavath Jagadeesh and Mr. Naveen Pareek", has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

Dr. Atul Kumar Soti

November 2022

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Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Abstract

This report is the record of our learning about PIV (Particle Image Velocimetry). In this report we recoded how do PIV works, what is the basic principle of PIV, apparatus of PIV, and some applications.

In this project, we first generated code for analyzing velocity field then tried to implement it on pendulum and a moving fan. And as a result, it shows velocity distribution of fan along its radius.

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LIST OF FIGURES

Nomenclature

a	aperture radius
a_{I}	interrogation area
$\mathbf{a}$	local acceleration vector
A	area
A_{crit}	critical area
C_{I}	spatial auto-covariance
C_{II}	spatial cross-covariance
C_{R}	constant factor of the correlation function
C_{S}	scattering cross section
c_{I}	spatial correlation coefficient
c_{II}	spatial cross-correlation coefficient
c_1, c_2	constant factors for outlier detection
D	diffusion coefficient
$\boldsymbol{D}$	particle displacement between the two light pulses
D_{I}	interrogation area
D_{a}	aperture diameter
D_{max}	maximum particle displacement
D_{Photo}	photographic emulsion density
$\mathbf{d}$	particle image displacement
$\overline{d}$	mean value of measured image displacement
d'	approximation of the image diameter
d_{diff}	diffraction limited imaging diameter
d_{max}	maximum particle image displacement
d_{min}	minimum particle image displacement
d_{opt}	optimum particle image displacement
d_{p}	particle diameter
d_{r}	difference between real and ideal particle image diameter
d_{s}	diameter of the Airy pattern
d_{shift}	particle image displacement due to the rotating mirror system
d_B	blur circle diameter
d_τ	particle image diameter

$d_{\tau x}, d_{\tau y}$	correlation peak widths along x and y respectively
d_τ^*	normalized particle image diameter
E	exposure during recording
$E\{\}$	expected value
E_1, E_2	energy states of an atom
e	resolution limit of a microscope
F_I	in-plane loss of correlation
F_O	out-of-plane loss of correlation
f	lens focal length
$f_\#$	lens f-number
$f(x)$	function
$\boldsymbol{F}$	body forces
$\mathbf{g}$	acceleration due to gravity
$g(x, y)$	gray value distribution
h	Planck's constant
$\boldsymbol{H}$	system transfer function
I	image intensity field of the first exposure
I_median	grayscale median image intensity
I'	image intensity field of the second exposure
I_0	laser intensity, incident on a particle
$I_0(Z)$	light sheet intensity profile in the Z direction
I_p	peak particle image intensity
I_z	maximum intensity of the light sheet
I^+	correlation of the intensity field with itself
$\hat{I}, \hat{I}'$	Fourier transforms of I and I'
J_B	light flux
J_n	Bessel function of first kind
k_smooth	filter kernel width
K	Boltzmann's constant
$\mathrm{Kn_p}$	particle Knudsen number
l_w	imaging depth
lps	line pairs
M^2	spatial mode
M	magnification factor
M_0	magnification along the principal optical axis
Ma	Mach number
$\tilde{M}_\mathrm{TF}(r')$	modulation transfer at a certain spatial frequency (r')
N	total number
m_p	particle mass
N	total number
N_P	number of individual particle images
N_I	length of tracks
N_0	number of overlapping particle images
NA	numerical aperture
$\mathcal{N}$	particle image density (per unit area)

$\mathcal{N}_{\mathrm{I}}$	number of particle images per interrogation window
n_{exp}	number of exposures per recording
NS	source density (for volume PIV)
n	refractive index
n_0	refractive index of glass
n_w	refractive index of water
Pr	Prandtl number
P_{S}	total scattered power
q	normalized diameter
q_1	particle size distribution of length
q_2	particle size distribution of area
q_3	particle size distribution of volume
QE	quantum efficiency
QL	number of quantization levels
r	spatial frequency, radius
r'	characteristic value of the spatial frequency
r_x, r_y	spatial frequencies in orthogonal directions
R_{12}	probability of correct particle pairing
Ra	Rayleigh number
Re	Reynolds number
R_{C}	mean background correlation
R_{D}	displacement correlation peak
$R_{\mathrm{D^+}}$	positive displacement correlation peak
$R_{\mathrm{D^-}}$	negative displacement correlation peak
R_{F}	noise term due to random particle correlations
R_{I}	spatial auto-correlation
R_{II}	spatial cross-correlation
R_{P}	particle image self-correlation peak
R_{τ}	correlation of a particle image
$\mathbf{s}$	separation vector in the correlation plane
$\mathbf{s}_{\mathrm{D}}$	displacement vector in the correlation plane
Stk	Stokes number
T_{a}	absolute temperature
$T(x, y)$	local varying intensity transmittance of photographic emulsion
t	time of the first exposure
t'	time of the second exposure
t''	time of the third exposure
t_{exp}	exposure time
t_{e}	frame transfer time
t_{f}	pulse length
Δt	exposure time delay
Δt_{min}	minimum time delay
$\Delta t_{\mathrm{row\text{-}shift}}$	charge transfer time of a single row in a CCD sensor
$\Delta t_{\mathrm{transfer}}$	charge transfer time in a CCD sensor
U, V	in-plane components of the velocity $\mathbf{U}$

$\overline{U}$	mean flow velocity in streamwise direction
$\mathbf{U}$	flow velocity vector
$\mathbf{U}_g$	gravitationally induced velocity
U_{max}	maximum flow velocity in streamwise direction
U_{mean}	mean flow velocity in streamwise direction
U_{min}	minimum flow velocity in streamwise direction
$U_n(u, v)$	Lommel function
$\mathbf{U}_p$	velocity of the particle
$\mathbf{U}_s$	velocity lag
U_{shift}	shift velocity
U_τ	friction velocity, $\sqrt{\tau_w/\rho}$
U_∞	free stream velocity
u, v	dimensionless diffraction variables
$V_0(\mathbf{x}_i)$	intensity transfer function for individual particle images
V_F	fluid volume that has been seeded with particles
V_I	interrogation volume in the flow
V_{fr}	volume fraction of particles
$V_n(u, v)$	Lommel function
v_I	interrogation area (image plane)
W	out-of-plane component of the velocity $\mathbf{U}$
$W_0(X, Y)$	interrogation window function back projected into the light sheet
X, Y, Z	flow field coordinate system
X_m	distance between rotating mirror and optical axis
$\mathbf{X}_p$	particle position within flow field
$\mathbf{X}_v, \mathbf{X}'_v$	point in the virtual light sheet plane
x, y, z	image plane coordinate system
$x^\star, y^\star, z^\star$	mirror coordinate system
$\mathbf{x}$	point in the image plane, $\mathbf{x} = \mathbf{x}(x, y)$
$\boldsymbol{x_0}, \boldsymbol{y_0}, \boldsymbol{z_0}$	position of the center of the interrogation window
$\Delta x_0, \Delta y_0$	interrogation area dimensions
$\Delta X_0, \Delta Y_0$	horizontal, vertical interrogation area dimensions within light sheet
$\Delta x_{step}, \Delta y_{step}$	distance between two interrogation areas
ΔZ	depth of (illumination) volume
$\Delta X, \Delta Y$	grid spacing in object plane
Z_0	distance between object plane and lens plane
Z_m	distance between object plane and mirror axis
z_0	distance between image plane and lens plane
Z_{corr}	depth of correlation
ΔZ_0	light sheet thickness

Greek Symbols

$\delta(\mathbf{x})$	Dirac delta function at position **x**
δ_X	measurement error
δ_Z	depth of focus
$\delta_{Z_{\text{corr}}}$	depth of correlation
$\delta_{Z_{\text{diff}}}$	depth of correlation due to geometrical optics
$\delta_{Z_{\text{geo}}}$	depth of correlation due to diffraction
$\varDelta_{\text{pix}}$	sensor pixel size
ε	cutoff of image intensity
ε_{tot}	total displacement error
$\varepsilon_{\text{bias}}$	displacement bias error
ε_{sys}	systematic error
$\varepsilon_{\text{resid}}$	residual (nonsystematic) error
$\varepsilon_{\text{resid}}$	residuals from stereo PIV vector reconstruction
ϵ_{thresh}	threshold for outlier detection
ϵ_U	velocity measurement uncertainty
γ	photographic gamma
$\mathbf{\Gamma}$	state of the ensemble
λ	wavelength of light
λ_0	vacuum wavelength of light
λ_{unst}	spatial wavelength
μ	dynamic viscosity
μ_{I}	spatial average of I
ν	kinematic viscosity, μ/ρ
ω_{m}	angular velocity of the rotating mirror
ρ	fluid density
ρ_{m}	spatial resolution limit during recording
ρ_{p}	particle density
σ	width parameter of Gaussian bell curve
σ	standard deviation
σ_I	spatial variance of I
θ	half angle subtended by the aperture
$\tau(\mathbf{x})$	point spread function of imaging lens
τ_{f}	characteristic time scale in the flow
τ_{P}	response time
τ_{s}	relaxation time
ω	vorticity vector
$\omega_x, \omega_y, \omega_z$	vorticity components
$\varOmega$	solid angle

Abbreviations and Acronyms

Mod	image modulation
pixel	picture element
ppp	particles per pixel
CCD	charge coupled device
PIV	particle image velocimetry
μPIV	micro particle image velocimetry

Chapter 1

Introduction

1.1 WHAT IS PARTICLE IMAGE VELOCIMETRY?

Particle Image Velocimetry (PIV) is an experimental technique for measuring the velocity of fluid particles. In this method, we measure the displacement of fluid particles over a short period of time and divide it by the time to get the velocity of fluid particles.

For measurement of displacement, neutrally buoyant particles, such as 20 micro size hollow glass spheres for water, are used. Now, we use a planer light sheet to illuminate these particles and their images are recorded by a high-speed camera. Now we calculate the displacement of particles by using these photos captured by the camera by using a technical approach. Velocity can be derived by dividing displacement by time.

1.2 THE PROBLEM: -

Usually, in PIV, high-power continuous or pulsed lasers are used for creating light sheets. These lasers are very costly as well as dangerous to work with. So, our main objective is to work on the possibility of using multiple low-power lasers to reduce the cost as well as make it more suitable to work.

Also, to make the process of image processing faster and to make it suitable for real-time image processing applications, we need to develop a code that reduces the time for processing images and which directly gives us displacement as well as velocity field in real-time.

1.3 SCOPE OF THE WORK: -

Through this project, we learned about Particle Image Velocimetry. In this report, we are trying to record the learning and understanding which we got from this project. We generated a code in Matlab through which we can calculate the displacement field of particles. Later, which is further used to calculate the velocity of the particle

Chapter 2

Literature Review

Due to lack of time, we were not able to go over many research papers for the present work. Although a lot of work have done in this field and now 3D PIV is in development Stage. Some of these works were done to analyze aerodynamics like in helicopter and others, other in analyzing of boundary layers and turbulent flows. In this phase we mainly focus on the book titled "**Particle Image Velocimetry a Practical Guide, Markus Raffel • Christian E. Willert Fulvio Scarano • Christian J. Kähler Steven T. Wereley • Jürgen Kompenhans".**

We will try to go through as much as works in this field in our next phase of this project.

Chapter 3

Theory of Particle Image Velocimetry

3.1 HISTORICAL BACKGROUND-

Humans are always keen to know about nature and its phenomenon as it is important to their survival and the development of humanity.

Similarly, when we see a moving water flow, let us say a river, we always want to know the flow speed of the river to know whether it is suitable for swimming or riding a road. We can often see children throwing leaves or wood stems to estimate the flow of the river. Which makes them realize the qualitative flow speed, but not the quantitative.

To know the active flow speed quantitatively, many methods have been generated by scientists. In the late 15th century, Leonardo Da Vinci, an Italian polymath of the High Renaissance who was active as a painter, draughtsman, engineer, scientist, theorist, sculptor, and architect, drew many drawings of structures of water flows for a variety of flows by mere observations.

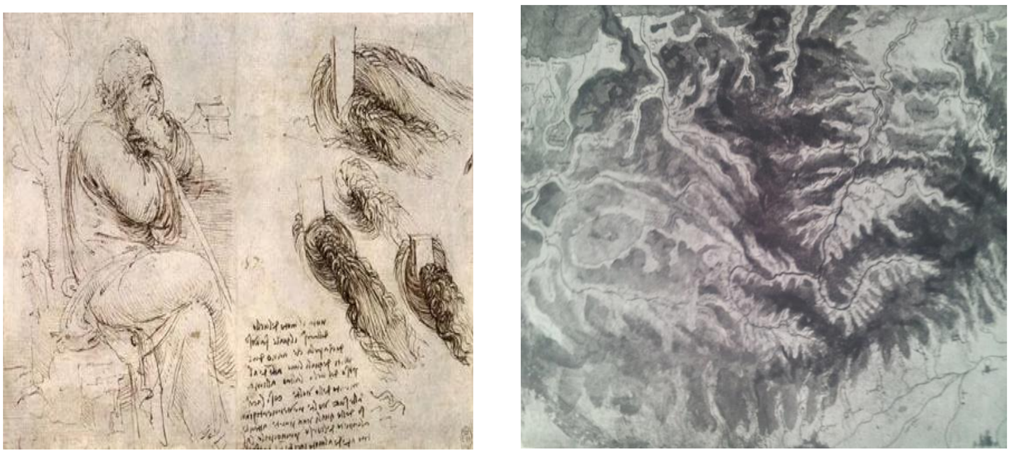

Fig. 3.1: - Leonardo's drawing of the Arno drainage basin, northern Italy

Source: - https://paulhumphriesriverecology.wordpress.com/2013/02/05/leonardo-da-vinci-water-rivers-science-and-art-part-1

Later, Ludwig Prandtl, was a German fluid dynamicist, physicist, and aerospace scientist. designed flow visualization techniques in a water tunnel to study flow fields of the different situations of water flow.

He introduced small aluminum particles to make the flow of water clearly visible. His experiment is the base of modern Particle Image Velocimetry (PIV).

In fig. 3.2 we can see Prandtl, rotating the shaft or water turbine to generate water flow.

Fig 3.2: - Ludwig Prandtl in front of his water channel for flow visualization in 1904

Source: - Particle Image Velocimetry a Practical Guide, Markus Raffel • Christian E. Willert Fulvio Scarano • Christian J. Kähler Steven T. Wereley • Jürgen Kompenhans

In his experiment, Prandtl used a tunnel separated by a horizontal wall, which divides this chamber into two floors. Prandtl manually rotates the shaft to flow the water, which after flowing deposited below the floor and then recirculated with help of a manual shaft that acts a water turbine. He fixed several types of obstacles in the path and analyze the flow field. But he was also able to do qualitative analysis but not quantitatively.

Further, many scientists give their contributed throughout the decade, which generate a method for quantitative analysis of fluid flow. Among these many methods, one of the most preferred is Particle Image Velocimetry (PIV).

3.2 WHAT IS PIV?

PIV stands for Particle Image Velocimetry. As the name suggests, it is a method to calculate the velocity of particles with the help of images. It is one most preferred method to calculate the velocity of particles of fluid or fluid flow.

3.3 EXPERIMENTAL SETUP FOR PIV: -

In this method, small tracing particles are added to the fluid which is later illuminated in the plane of flow with the help of a laser. Images are captured in a very small-time interval, which is later used to determine the flow velocity with the help of technical methods. The below figure (fig. 3.3) shows the setup of PIV.

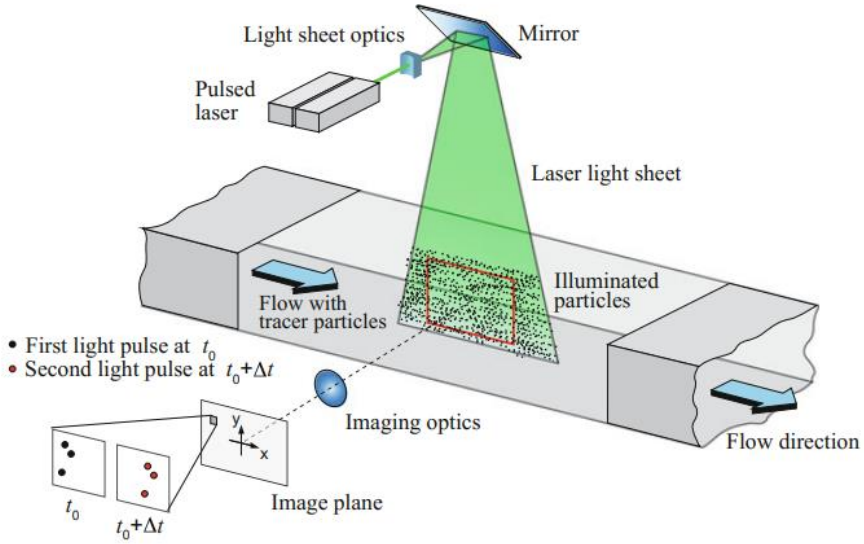

Fig 3.3: - Experimental arrangement for planar 2C-2D PIV in a wind tunnel

Source: - Particle Image Velocimetry a Practical Guide, Markus Raffel • Christian E. Willert Fulvio Scarano • Christian J. Kähler Steven T. Wereley • Jürgen Kompenhans

3.4 APPARATUS OF PIV SETUP: -

The basic apparatus of PIV contains elements as follows: -

- Tracing Particles: - to track fluid movement.
- Illumination System: - to illuminate the tracing particles.
- Synchronizer: - to synchronize the camera and laser.
- Host Computer: - to store the particle image and conduct image processing.

3.4.1 TRACING PARTICLES: -

As we know, in PIV we need to click the images of fluid flow, but as we know we cannot click the pictures of fluid particles. That is why we add some particles which behave as fluid particles and emit light on illumination, by which we analyze the fluid flow. These particles are known as Tracer Particles.

Properties of tracing particles: -

- If tracing particle density does not match fluid density, it will generate an error due to gravitational force difference.
- Trancing particles should be sufficiently small not to interfere with fluid flow and flow at the same speed as of fluid.
- Particles should also be sufficiently large to scatter light, which we are providing by laser.
- Density of particles should be equal to or close to the density of the fluid, so that the gravitational effect act equally on both.

3.4.2 ILLUMINATION SYSTEM: -

This the part of the apparatus which is responsible to illuminate the tracing particles. Illumination system mainly consists of light sources and optics of light.

Light sources are used to illuminate the tracer particles.

Types of light sources used in PIV: -

- Lasers
  - Helium-neon Lasers
  - Argon-ion Lasers
  - Nd: YAG Laser
- White Light Sources

Optics contain arrangement of mirrors, lens and light source, so that light beam from light source get converts into plane sheet of light.

Fig 3.4 Apparatus showing conversion of linear light into planer light.

3.4.3 SYNCHRONIZER

synchronizer is an important part of PIV setup, which used to synchronize the camera and laser. As we know, high exposure of high-power lasers is harmful for us, also it needs high electricity. So, reducing these losses and to make PIV setup more friendly with humans we need an instrument which synchronize our light sources with the camera. Similar type of synchronizer can be seen in camera having flashes.

3.4.4 CAMERA: -

Camera is the one of the most essential parts of the PIV setup we need a high-speed camera which can click pictures with high frequency. For serving this objective we use cameras with CCD sensors.

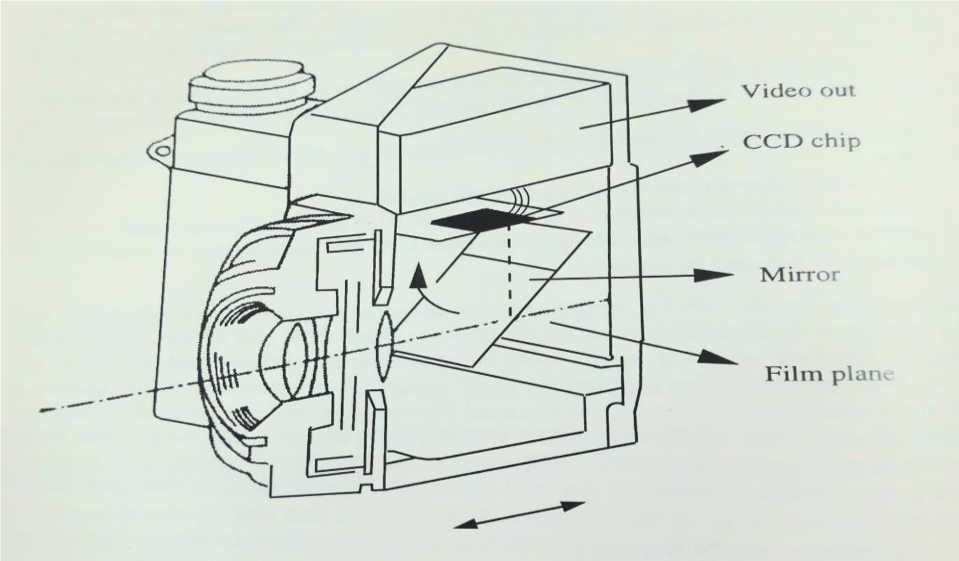

Fig.3.5: - Photo camera with CCD

Source: - Particle Image Velocimetry a Practical Guide, Markus Raffel • Christian E. Willert Fulvio Scarano • Christian J. Kähler Steven T. Wereley • Jürgen Kompenhans

3.4.5 HOST COMPUTER: -

We also need a host computer setup for storing our images, running our code and analyzing results.

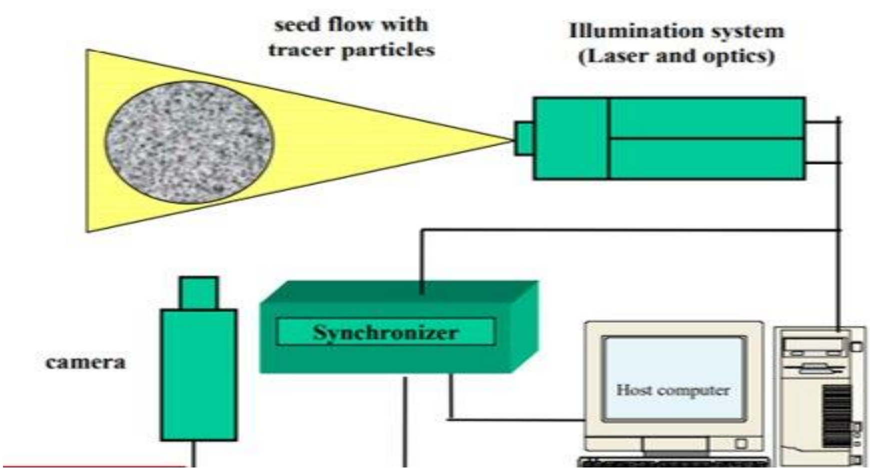

Fig.3.6: - Experimental setup for PIV

Source: - Particle Image Velocimetry a Practical Guide, Markus Raffel • Christian E. Willert Fulvio Scarano • Christian J. Kähler Steven T. Wereley • Jürgen Kompenhans

Chapter 4

Image Evaluation method

After getting images of fluid flow, our main objective is to determine the displacement vector. To fulfill this requirement, we are generating a Matlab code which after Taking the input of our images will show us displacement vector as output. From this, we can get velocity by dividing it by time (multiplying it with the frequency of the camera).

4.1 Algorithm of the code

The code works on an in-built function called **normaxcorr2** which searches a template in the main image on the principle of cross-correlation and gives you the peak value of the difference in the template and the main image

- It reads the input and stores the images in the matrix form
- Then divides into smaller windows of image one
- Creating the search area in image two of [width/2, height/2]
- Then takes the first window as a template and starts searching in the image two
- Then using normaxcorr2 correlating the image and the template and storing their peaks values
- Similarly repeating for other windows and finally displaying the vectors of displacement

4.2 what is cross-correlation?

Cross-correlation is **a measurement that tracks the movements of two or more sets of time series data relative to one another**. It is used to compare multiple time series and objectively determine how well they match up with each other and, in particular, at what point the best match occurs.

The cross correlation function is defined:

$$R_{xy}(\tau) = \frac{1}{T}\int_{0}^{T} x(t-\tau)y(t)dt$$

where *x(t)* and *y(t)* are signals from the sensing transducers.

Correlation is **a mathematical technique to see how close two things are related**. In image processing terms, it is used to compute the response of a mask on an image. A mask is applied on a matrix from left to right. Mask slides over the matrix from left to right by one unit every time

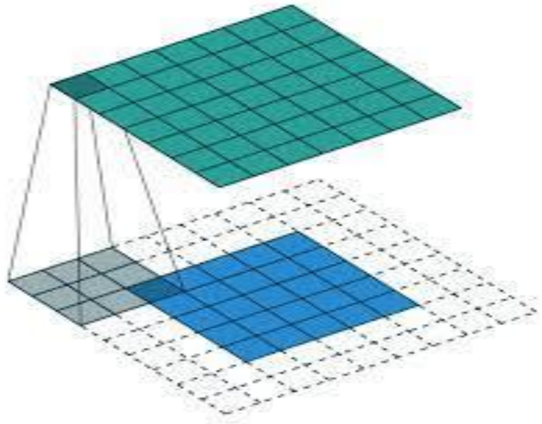

Figure 4.1 moving a filter mask often referred to as kernel

Correlation is the process of moving a filter mask often referred to as kernel over the image and computing the sum of products at each location. Correlation is the function of displacement of the filter.

4.3 what is normaxxcorr2?

It is an in-built function in Matlab where you can correlate images and find the displacement or take part of the image search it in the main image it returns 0 if it’s not present else return 1 and position coordinates of the template in the main image

syntax :

```
{
        C = normxcorr2(template,A) ;
}
```

C = normxcorr2(template, A) computes the normalized cross-correlation of the matrices template and A. The resulting matrix C contains the correlation coefficients.

A small example for a better understanding

```
onion = im2gray(imread('onion.png'));
peppers = im2gray(imread('peppers.png'));
montage({peppers,onion})
```

Figure 4.2 'onion.png’

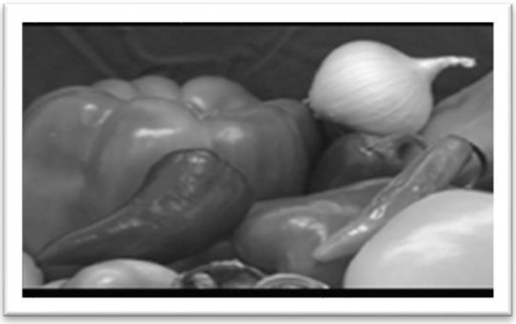

Figure 4.3 ‘'peppers.png’

4.4 Matlab code for image Evaluation follows

```
imagea = imread('exp1_001_b.bmp');
imageb= imread('exp1_001_c.bmp');

[xmax, ymax] = size (imagea);

%Windowa sizes
wsize = [64, 64];
w_width = wsize(1);
w_height = wsize(2);


xmin = w_width/2;
ymin = w_height/2;
xgrid = 50:w_width/2:512;
```

```
ygrid = 50:w_height/2:512;


w_xcount = length(xgrid);
w_ycount = length(ygrid);


x_disp_max = w_width/2;
y_disp_max = w_height/2;


test_ima(w_width, w_height) = 0;
test_imb(w_width+2*x_disp_max, w_height+2*y_disp_max) = 0;
 dpx(w_xcount, w_ycount) = 0;
 dpy(w_xcount, w_ycount) = 0;
 xpeak1= 0;
 ypeak1= 0;

 for i=1: (w_xcount)
    for j=1: (w_ycount)
        max_correlation = 0;
        test_xmin = xgrid(i)-w_width/2;
        test_xmax = xgrid(i)+w_width/2;
        test_ymin = ygrid(j)-w_height/2;
        test_ymax = ygrid(j)+w_height/2;
        x_disp = 0;
        y_disp = 0;
        test_ima = imagea(test_xmin:test_xmax, test_ymin:test_ymax);
        a =  test_xmin-x_disp_max;
        b = test_xmax+x_disp_max;
        c = test_ymin-y_disp_max;
        d = test_ymax+y_disp_max;
        if (a<0)
            a = -a;
        end
        if (b<0)
            b = -b;
        end
        if (c<0)
            c = -c;
        end
        if (d<0)
            d = -d;
        end
        test_imb = imageb((a):(b),...
                            (c):(d));
        c = normxcorr2(test_ima, test_imb);
        [xpeak, ypeak] = find (c==max(c(:)));

        xpeak1 = test_xmin + xpeak - wsize(1)/2 - x_disp_max;
        ypeak1 = test_ymin+ypeak - wsize(2)/2 - y_disp_max;
        dpx(i,j)=xpeak1 - xgrid(i);
        dpy(i,j)=ypeak1 - ygrid (j);

    end
 end
 quiver(dpy,-dpx)
```

Chapter 5 Implementation and Result

After generating the code, it is very necessary to verify it by using some basic practical examples. Here, we first implemented this code on pre- defined data sets from google. And tried to implemented on various apparatus like simple pendulum and a moving fan. Although due to time constraint, we cannot quantitate analysis of result. But we have tried to do qualitative analysis of code.

5.1 Simple Pendulum: -

We implemented this code on images taken from simple pendulum, and got following result:

Fig 5.1:- Images of simple pendulum

5.2 A Moving Fan: -

After simple pendulum, to see the radial distribution of velocity, we implemented this code on a moving fan image. We got following distribution: -

Fig 5.2:- Images of moving fan

We got following results: -

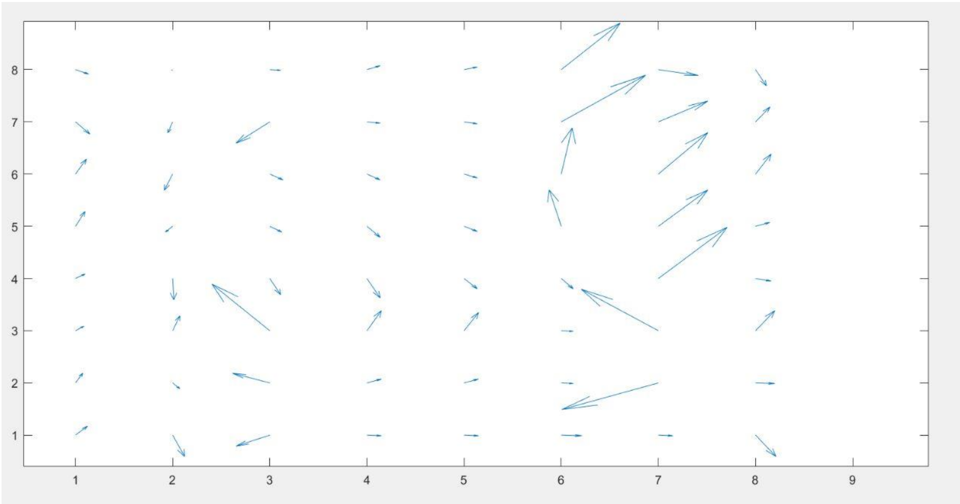

Fig. 5.3 velocity distribution of simple pendulum

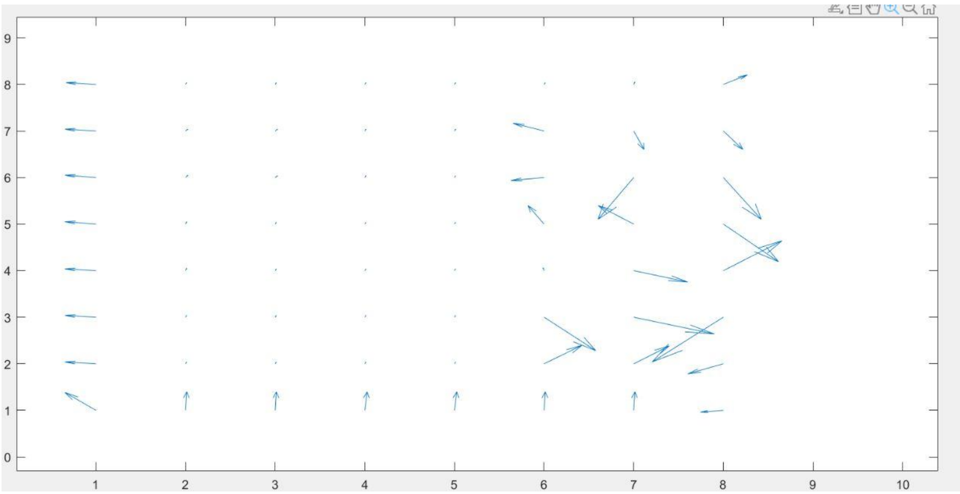

Fig. 5.4 velocity distribution of fan

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

As, due to lack of time, we were not able to go through many literatures. But we have tried to gain as much knowledge as possible.

6.1 CONCLUSION: -

We make following conclusions after going through resources: -

- PIV is a method for calculation of velocity of fluid particles and have variety of applications. In this method we mix tracing particles in fluid and click the images of flow by illuminating these tracing particles with the help of lasers, and then we pass these images from our generated code and get the displacement and velocity flow field.
- Here, in our project we generated code on Matlab, later to increase speed and decreasing run time to make PIV more suitable for real time operations we can convert this code to C or C++ code.
- After writing code, we verified our code with pre-defined data and two small experiments. further we can do more such experiments to verify our code. Firstly, we tried our experiment with Simple Pendulum, to see its displacement Vector Field, and later we analyze the fan rotation.

6.2 FUTURE SCOPE: -

- In the first phase of our BTP i.e., this project, as PIV is a completely new topic for us, we focus on getting knowledge about PIV, how it works, and what are the basic apparatus, principles, and applications of PIV.
- In the next phase we are looking forward to developing our code in C++ language to reduce the runtime and make our code more suitable for real-time applications. Also, we will try to do as many as practical to get deep knowledge about the working of PIV.

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