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Particle Image Velocimetry

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PIV is a non-intrusive method of flow visualisation, it works via the illumination of particles suspended in the fluid, these particles follow the fluid flow and as such can be used to study the properties of the flow such as its structure.

PIV does not track each particle individually, that is a similar but separate technique known as Particle Tracking Velocimetry (PTV), rather the bulk movement of particles within an interrogation area is tracked.

The main components of a PIV system are the illumination system, and the camera and imaging system. A schematic of a typical PIV set up can be seen in *Figure 1*.

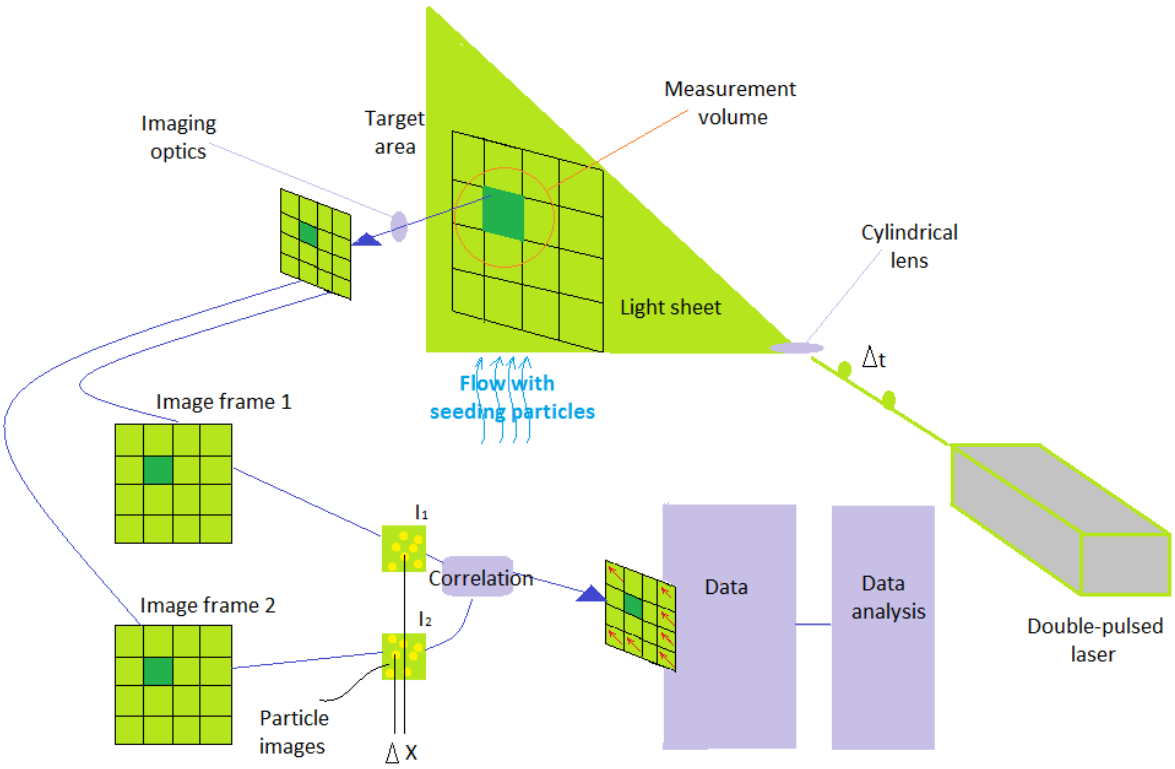

Figure 1 – Schematic depicting a typical PIV system

Evaluation of image acquisition is based on the elemental equation where the distance expresses shift trace particles entrained in the fluid stream at a time.

Therefore, the desired position of particles to record as accurately as possible. It is important that the position of the particles did not change during the illumination. That is, the light has to be short, therefore, the laser light is continuous, but the laser. He sends pulses. It is necessary to record two records the position of the particle. First record captures the initial position of the particle and the second recording captures its end position. There are two methods and to record the individual exposure method and doubled exposure method.

Exposures method - each entry location of the particle in the image plane is exposed in one frame. The first image is therefore the initial position of the particle. In the second pictured is the end position. Currently, this method outweighs the method of twofold exposures.

Doubled exposure method - the first and the second recording position of the particle is exposed to single shot, and so it is impossible to determine which is the initial position of the particle and whose position is end. Record the image used in the past, the photographic film, is presently used CCD camera because it allows a digital image post-processing data using a computer.

2 Analysis of PIV image

The recorded images are divided into smaller areas evaluation which are square shape. The analysis deals with the investigation of the average displacement of particles in each of the evaluation area.

The relationship between the dimensions of the investigated area in object and image plane magnification M.

$$M = \frac{object}{image}$$

$$\Delta x = \frac{\Delta X}{M}, \Delta \mathrm{y} = \frac{\Delta Y}{M}$$

Where Δx and Δy are the displacements in object plane.

Ax, ΔY are the displacements in the image plane.

Each particle has an associated velocity vector w_x, w_y.

$$w_x = \frac{\Delta x}{\Delta t}, w_y = \frac{\Delta y}{\Delta t}$$

To evaluate the average displacement of the particles has an effect saturation flow.

<u>Types of the flow saturation:</u>

- Poor saturation

- Medium saturation

- Strong saturation

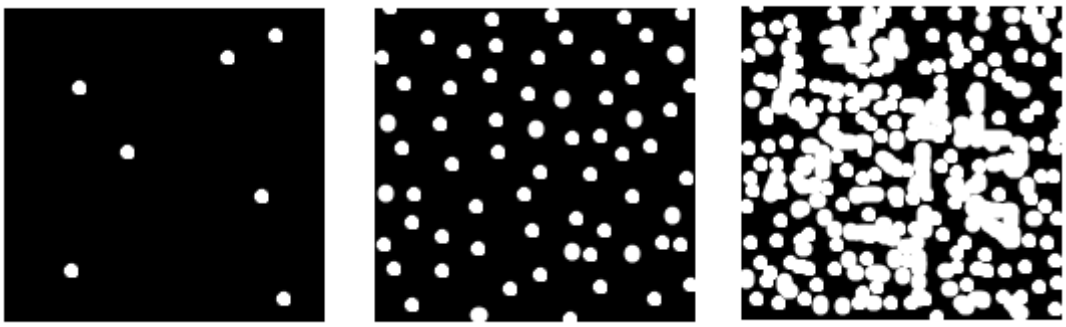

Figure 2 – Types of the flow saturation

Poor saturation - can be expected with high probability that the evaluation range is not more than 1 part. When using double exposure will be in two images - start and end position of the particle. The determination of the average displacement in this case is simple, but in practice, this saturation unsuitable because of the fact that in certain areas, evaluation may occur more particles and some particles may be completely missing. And then the information about the speed field is incomplete.

Medium saturation - sufficient concentration of the reference particles, and it is foreseeable occurrence of more particles in each field of the evaluation. In this case, we get a complete information about the speed field. However, it is not easy to assign the initial position the particles end position. To assign a start and end location is used by the algorithm to determine the average displacement of all the particles in each evaluation range. This method is mostly used saturation.

The strong saturation - concentration of reference particles is so high that it is not possible to distinguish individual particles. The image in this case, but not particles of spots that represent a cluster of particles. The average displacement in the area is designated an average displacing spots. Again, the algorithm is used. With strong carbonation may experience problems with insufficient lighting through the evaluation area.

2.1. Particles

PIV as the measuring method does not measure the rate of flow, respectively medium, but the rate of particles entrained in the fluid flow. Seeding particles have a major impact on the accuracy of the measurement results - are captured during measurement with the mention further work.

The particles must be of sufficient size must be small to detect them scanning techniques, have to follow the same fluid flow - turbulent flow structure. The size of all the particles should be the same because of the unequal area can cause the entrained particles to have different speeds.

The main requirements:

• Reliably monitor the flow,

• Good light scattering,

• Price,

• A non-interacting with the use of copper,

• Non-abrasive.

Use of seedings particles depends on the substance to be observed by us - the flow. For most liquid flows, seeding can easily be done by suspending solid particles into the fluid and mixing them in order to ensure a homogeneous distribution. A number of different particles which can be used for flow visualization, LDV and PIV are listed in table 1 for liquid and in table 2 for gas flows.

Table 1 – Seeding materials for liquid flows

Type	Material	Mean diameter in μm
Solid	Polystyrene	10 – 100
	Aluminum flakes	2 – 7
	Hollow glass spheres	10 – 100
	Granules for synthetic coatings	10 – 500
Liquid	Different oils	50 – 500
Gaseous	Oxygen bubbles	50 – 1000

Table 2 – Seeding materials for gas flows

Type	Material	Mean diameter in μm
Solid	Polystyrene	0.5 – 10
	Alumina Al_2O_3	0.2 – 5
	Titania TiO_2	0.1 – 5
	Glass micro-spheres	0.2 – 3
	Glass micro-balloons	30 – 100
	Granules for synthetic coatings	10 – 50
	Dioctylphathalate	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

The choice of the right seeding material to scatter the light from laser beams or a light sheet can be crucial to the acquisition of successful experimental data.

	PSP Polyamide seeding particles	HGS Hollow glass spheres	S-HGS Silver-coated hollow glass spheres	FPP Fluorescent polymer particles
Mean particle size (µm)	5, 20, 50	10	10	10, 30
Size distribution	1 - 10 µm 5 - 35 µm 30 - 70 µm	2 - 20 µm	2 - 20 µm	1 - 20 µm 20 - 50 µm
Particle shape	non-spherical but round	spherical	spherical	spherical
Density (g/cm3)	1.03	1.1	1.4	1.19
Melting point (°C)	175	740	740	125
Refractive index	1.5	1.52	–	1.479
Material	Polyamide 12	Borosilicate glass	Borosilicate glass	Poly (Methyl methacrylate) (Labeled with Rhodium B)

Figure 3 – Offer particles on Dantenc Dynamics webside[3]

Example: The main intermediary equipment for laser anemometer in Europe - Dantec Dynamics on the website offers the purchase of such particles. [3]

2.2. Correlation

The algorithm that is used for the analysis of PIV images. It is a statistical analysis that determines the relationship between the two processes or values. The output correlation when evaluating PIV images is the average displacement of all the particles in each reference the evaluation area. We know the different types of correlations. For individual exposure method is used so-called cross-correlation method and the double exposure is a start and end position of particles exposed to the same image, so it is impossible to determine which is the initial position and that end.

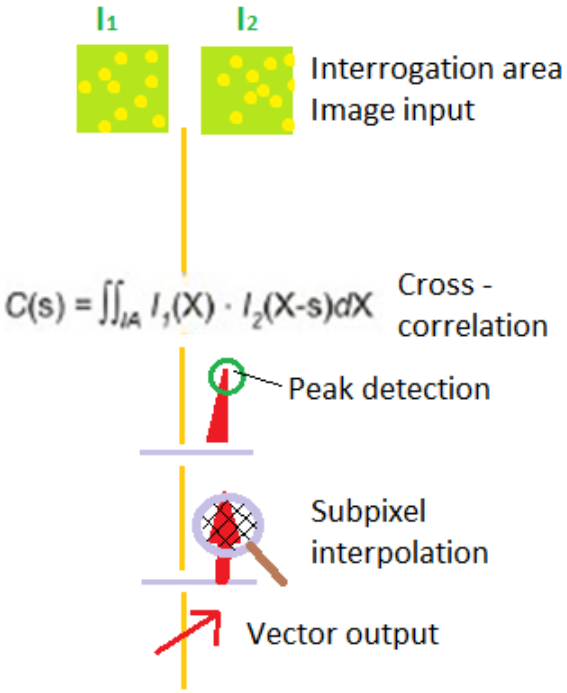

Figure 4 – Evaluation process

The autocorrelation is different from the cross-correlation does not provide information on the direction of displacement. For this reason, the method of double

exposure now often used. Clearly outweighs the individual exposure method as this method associated cross-correlation.

Fourier transformation

Fourier transformation can be generally carried out in one, two or more dimensions. The importance of 1D Fourier transformation is that the Use this function to be represented by each 1D periodic function as a sum of complex exponential of a number of means well the sum of the sine and cosine, see the Euler equations.

$$e^{i\varphi} = cos\varphi + i.sin\varphi$$

In practice, the Fourier transform is used to express the time-dependent signal using harmonic functions sine and cosine. It may also be interpreted as the transformation of the signal transfer time domain to the frequency. 2D Fourier transform provides distribution function of the sum of the sine and cosine as a 1D Fourier transform. In this case it is the function of two variables, and the (x, y). This function can not imagine a digital image that captures the camera with PIV.

1D Fourier transformation:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)e^{-i\omega t}dt$$

1D Inverse Fourier transformation:

$$f(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f(t)e^{-i\omega t}d\omega$$

2D Fourier transformation:

$$F(u,v) = \iint_{-\infty}^{+\infty} f(x,y)e^{-i(xu,yv)}dxdy$$

2D Inverse Fourier transformation:

$$F(x,y) = \frac{1}{4\pi^2}\iint_{-\infty}^{+\infty} F(u,v)e^{-i(xu,yv)}dudv$$

Discrete Fourier transformation

The definition equation Fourier require knowledge of the mathematical expression of the signal or the spectrum of a finite interval. The problem is how to determine the range of the signal samples or signal from the sample spectrum. For this purpose, a numerical method - Discrete Fourier transformation. The input signal is seen as a sequence f (n) with elements

n = 0, 1, ..., n = N - 1. Consequently, f (k) is the Fourier spectrum of the signal f (n).

Mathematical expressions of discrete Fourier transform and inverse discrete Fourier transformation:

$$F(k) = \sum_{n=0}^{N-1} f(n)e^{\frac{-2\pi ikn}{N}}$$

$$f(n) = \frac{1}{N}\sum_{n=0}^{N-1} F(k)e^{\frac{-2\pi ikn}{N}}$$

Method Wienerova - Khinchin theorem

Method Wienerova - Khinchin theorem is a second method of applying a Fourier transform. The method is used to calculate the auto-correlation and also the cross-correlation. To obtain a recording is used as the first Fourier transformation. Consequently, it is determined by the absolute root of the complex function of the power spectrum. Correlation function is then obtained by applying an inverse discrete Fourier transform.

Fast Fourier Transform

Fast Fourier Transform is an efficient algorithm for calculating the discrete Fourier transform and its inversion. While calculating the discrete Fourier transform of the formula needs to be N2 arithmetic to calculate the FFT is enough to N.logN arithmetic operations. Fast Fourier transform and provides a very significant speed up the calculation. For the current extensive numerical calculations of the fast Fourier transform indispensable. However, the principle of the FFT algorithm, an artificial increase in the apparent correlation of noise, particularly at the edges of the evaluation range. To eliminate the noise of the correlation window are used in a filter function in the frequency domain.

2.3. PIV data processing

PIV processing the record using optical methods as well as numerical methods.

Optical methods

Optical methods, which are based on an optical Fourier transformation. The main advantage of these methods is their speed of processing. On the other hand, the biggest drawback is the relative difficulty of execution. Optical processing methods were carried out in laboratories, but for commercial purposes are not used. With the rapid development of computer technology it is much easier to process PIV records numerically.

Numerical Methods

The recording image is divided into smaller square areas, called area evaluated. The distribution of the image is required for numerical processing. In the case of analog cameras, it is necessary to carry out video capture. If the PIV record of the used CCD

camera - digitization is directly represented by a single pixel camera. Based on the light intensity in the evaluation range at time t and time t + Dt, the calculated average shift function. The calculation should take into account the noise correlation, which complicates calculation. Calculate the correlation is quite time consuming and it is therefore accelerated by Fast Fourier Transform. This method assumes periodicity captured images. This may cause a systematic error called phantom steam. This error causes is correlated between real and phantom initial positions and end positions, especially at the edges of evaluation areas. This error increases correlation noise.

Window function

Window function - is used to suppress the effects of particulate matter at the edge of the area being evaluated, the result of the average displacement. This function multiplies the correlation values at the center of one value and gradually to the edges of the field values are multiplied by a smaller figure and eventually zero.

Overlapping areas evaluated

Using the window functions it is prevented by indirect effects of particulate matter from the edges of the area being evaluated, but on the other hand, these particles without overlapping the evaluation areas remain unused. Evaluation method of overlapping areas, ensure the use of uncultivated area in the adjacent areas covering it. This has the advantage that the area of overlap is more likely to find that the finding matching start and end location. As a disadvantage is taken into account that the amount of time required for calculation.

The filters in the frequency domain

Light entering to the camera lens causes noise themselves as a result of multiple reflections on the matter and for the optical component of the camera. In a reduction of the background noise on the various filters are used. The filters in the frequency domain correlation spike extending represent the size and direction of displacement. His position remains unchanged and is not affected by the displacement of particles measured.

Errors and limits of PIV method and treatment

Based on the characteristics of the PIV follows that in measurement and evaluation can cause various errors. It is therefore necessary to deal with them.

Lost pairs

This error occurs if the time span between the two exposures occur particles entering into the detection area which it has an initial position. Only afterwards it can not be properly assign the particle a starting and ending location. In the calculation it occurs so-called random correlations that brings to calculation errors in the increased correlation noise. This error is more likely for faster particles in a given time period rather fly out of the search area. It is, therefore, lost information on the speed, therefore, the measured average speed lower than the actual.

The maximum displacement of particles

From the computational point of view, the maximum possible displacement is equal to one half the length of side evaluation of areas. In practice, the recommended lower maximum displacement, and ¼ length party evaluation of areas, because with increasing sliding the increasing number of couples siding and thus the correlation noise.

Density of seeding particles

Error measured the average displacement of particles increases with decreasing density of the reference particles. The calculated offset is smaller than the real. Error grows with the size of the average displacement. Suggested minimum values for saturation currents are the cross-correlation 5 parts per evaluated field.

Dynamic range

The absolute dynamic range of R a is defined as the difference between the maximum and the minimum detectable rate in the evaluation region. The flow can generally take place in both directions, so the notion of minimum speed means the minimum speed in the opposite direction to the direction of maximum speed.

$$R_a = |w_{max}| - |w_{min}|$$

Picture geometric mean d_g calculated from the following equation, where d_p is particle diameter:

$$d_g = M.d_p$$

This equation determines the calculation of the effective diameter of particles d_e, where d_s is the actual diameter of the particles in the image plane, d_r is the minimum resolution recording media.

$$d_e = \sqrt[2]{d_g^2.d_s^2.d_r^2}$$

The minimum measurable displacement | Dmin | is equal to the effective diameter of the particle image. The minimum measurable speed is then equal to:

$$w_{min} = \frac{d_e}{M\Delta t}$$

Maximum measurable displacement D_{max} is equal to ¼ of party evaluation of areas. The maximum measurable speed is:

$$w_{max} = \frac{D_{max}}{M\Delta t}$$

The relative dynamic range R_r is the proportion of the absolute values of the maximum and minimum measurable speed.

$$R_r = \frac{|w_{max}|}{|W_{min}|}$$

From the above equations, with the rise in the time interval Δt is decreasing and also the maximum speed of the minimum detectable.

On the dynamic range of the method used has an effect of exposure as those related to type correlations. The autocorrelation is unknown by moving the particles, and therefore, the total dynamic range is less than the method of cross-correlation. In general, the dynamic range of speed measurement increases with increasing size of the evaluation area and decreases with increasing effective diameter Reference particles.

Displacement of the second image

If we want to enlarge the dynamic range of PIV method is used method of shifting the second image, which is also called offset. Would advance the evaluation of the second region relative to the first, depending on the size and direction of the average velocity. CCD cameras currently can ensure same-defined offset. As a result, particles that during the time intervals between the exposure received by the assessment of the area outside, will remain in the second image shift. So can reduce the number of lost couples. Another advantage is offset, that allows to shrink the dimensions of the individual evaluation areas, keeping the same dynamic range. The

greater number of evaluation areas is obtained by a larger number of velocity vectors and tada a description of the fluid jet in more detail.

Adaptive correlation

In classical offset in most cases the amount of displacement of the second image compared to the first facility-wide same plane. When the adaptive correlation vector for further defines each offset from the previous offset. This would result in a more accurate calculation of the average displacement. The consequence of this shift is highly significant restriction pairs lost and thus the greater the distance from the peak of the correlation noise. It is also possible to use a smaller evaluation range and thus get detailed map of vector flow to classic offset value. Even if it is not filled under the maximum displacement of particles of an adaptive correlation it can be obtained correct results.

Nevertheless, thanks to the adaptive offset is obtained more vectors in a vector map, there is not a higher resolution. Since the resolution in most cases related to the time interval Δt between exposures. If the time step is very small, then the vector map will actually describe the flow. This is because the actual trajectory of the reference particles during the time of a small well approximated by a line segment between the start and end location. If the interval between the two exposures may be relatively long, the actual trajectory significantly from the lines, therefore the length of the segment will grow. The results are not credible.

Velocity gradients in the evaluation range

Ideally, the flow rate should be within the evaluation range is constant throughout. But this is the real situation hampered rate gradient.

3. Measuring equipment

CCD camera

Recording PIV images can be recorded position of the reference particle CCD camera or camera. Is currently used to record the particular CCD camera used at intervals of less than one microsecond will record and store the two images together. These Dato provide important information on the evolution of current to be measured over time. The screen display can be animated to follow the temporal evolution of the vector field. Maximum image resolution is 2048x2048 pixels.

Figure 5 – CCD camera

Laser

The basis of the captured reference particles are those of the light intensity of the plane and thus the light energy in the measurement plane to be large enough for the light intensity distribution on the reference particles was sufficient for the camera preview camera optionally no optical noise. The length of the light pulse to be so short that illuminated tracer particles undergone the least possible distance. The time

interval of consecutive light pulses must be as short reference to the movement of particles in the flow field was very small. Thus, the maximum displacement of the reference particles in divided areas of evaluation, to be measured for the level distribution is less than a quarter of the area being evaluated.

The laser: 15 Hz with pulse energy 65-200mJ, compact, lightweight, stable. The cooling system allows long-term use of the laser.

Working with laser is dangerous because most frequently used YAG laser emits infrared light with a wavelength of 1064nm especially for vision, therefore it is necessary to wear protective clothing, namely: jacket, glasses.

Volume Illumination Optics with aspect (height to width) ratios from 1:1, 1:2, 1:5 to 1:10 are available, covering almost any flow illumination application. They can be directly mounted on a laser head without any additional benches. [5]

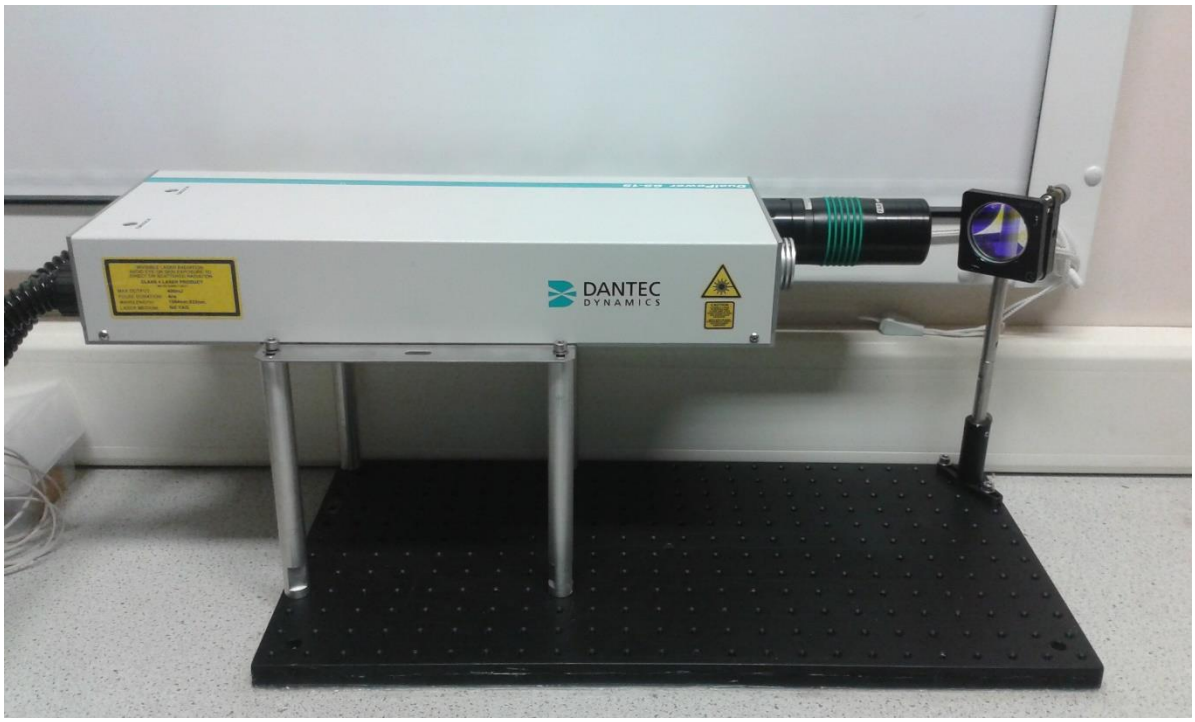

Figure 6 – Laser

Electro-valve

Electro-valve is a device that interrupts the continuous laser praprsek and thus produce light pulses, which are then shaped using a cylindrical lens to form a light plane.

Synchronizer

For the efficient measurement is necessary to synchronize pulsation laser and recording images Reference particles CCD camera and a system that naskôr particles will be illuminated by the first laser pulse, the reflected light is detected by the camera - ideally as white circular spots on a dark background. Captured by a CCD camera signal is stored as an initial reference position of the particle. The light beam of the laser is switched off, the reference particles carried by the - this were delayed. Starts the second light pulse laser and reference particle is detected by a CCD camera. Enters the second slide end position particles.

4. More complex PIV setups

In a number of cases, e.g. with animal induced flow phenomena that cannot be reproduced, or with a highly variable 3D flow component, other flow analysis techniques may be necessary. StereoPIV, Holographic PIV (H-PIV) or modern 3DPTV variants are potential candidates when it comes to mapping 3D flow phenomena. Plain PTV may be valuable when very low seeding densities are required, and Micro-PIV may assist in resolving flow phenomena at the very small scale.

4.1. Stereo PIV

Stereo PIV is a method for measuring three velocity components in a plane (2D3C) based on the principle of parallax.

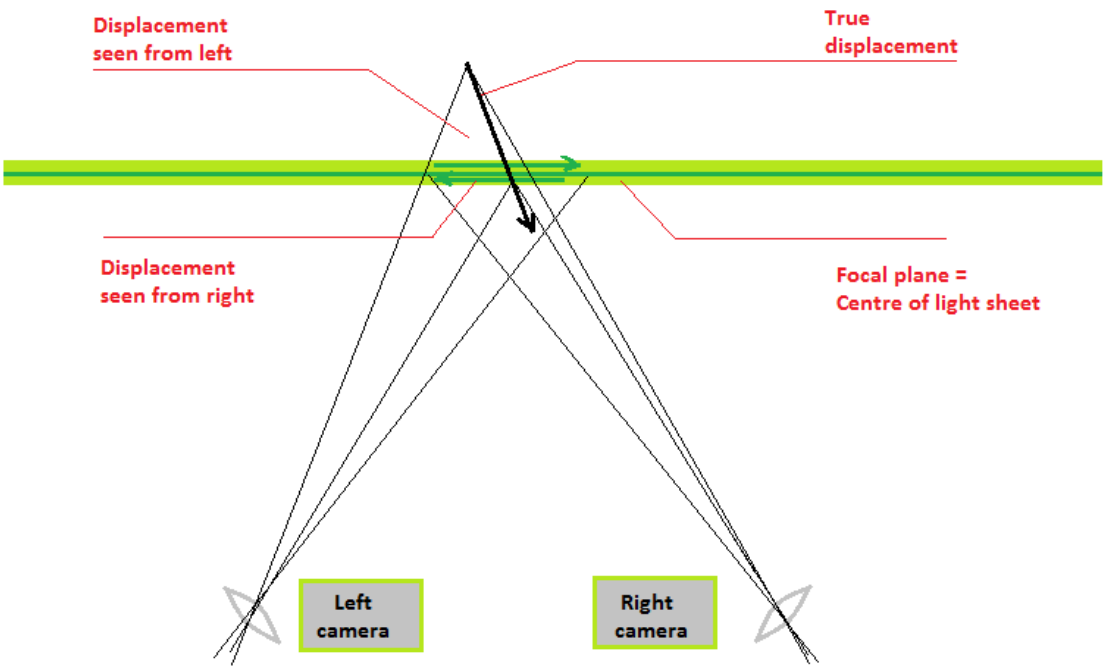

Figure 7– Stereo PIV

The two cameras are positioned that they observe the light-sheet plane from two different angles, you obtain slightly different two-component velocity vector maps from each camera due to the parallax effect.

The differences between them arise from the third, out-of-plane velocity component and the geometrical configuration of the two cameras.

Subsequently After image calibration, this third velocity component can be evaluated. In addition, the two in-plane velocity components can be recalculated, correcting for parallax errors.4.2.Volumetric Velocimetry (3D PIV). [8]

4.2.Time Resolved PIV

Dantec Dynamics was the first company to introduce Time Resolved PIV systems based on practical Nd:Yag lasers and a new high performance, high speed camera.

Time-Resolved PIV systems open up new possibilities for quantitative flow mapping at frequencies up to tens of kHz. Time-resolved PIV combines the instantaneous velocity mapping of conventional PIV with high frame rate CMOS cameras and high repetition rate pulsed and cw lasers. Velocity mapping at high frequencies allows characterization of flow features that are short lived and unrepeatable, allowing the measurement of flow features in time as well as space. Most flows of scientific and engineering interest are characterized as turbulent and unsteady. Investigators can make use of time-resolved PIV as a powerful tool with extended experimental measurement capabilities to allow for the investigation of the detailed interaction of flow structures in space and time. [10]

PIV has historically been a measurement technique that provided high spatial resolution data where individual vector maps are typically statistically independent

from the previous vector map (i.e. decorrelated in time). When time-correlated information was necessary, point measurement techniques (HWA, LDV) were utilized. In special cases these point measurement techniques can also be used to provide spatial information by virtue of Taylor's hypothesis. [10]

4.3. Micro PIV

Micron resolution particle image velocimetry is used for measuring the velocity profile across a plane in a microfluidic device. Because of the small dimensions of the flow field in micro channel flow, it is impossible to use conventional PIV systems to obtain two orthogonal planes for optical access to the flow field. Instead, micro PIV systems use a volume illumination technique where the light source and the view field are introduced through the same optics. With this approach the focal plane is moved down through the flow field to map the entire volume. [11]

Seeding is one of the most important elements for nobtaining successful MicroPIV results. First of all, the seeding particles provide a strong fluorescent signal. Second, the excitation and emission wavelengths of seeding particles, are compatible with the rest of the optical system, which is designed to maximise the signal to noise ratio. Finally, diameters down to 100nm are available in order to address the ever-increasing high spatial resolution requirements in microfluidics community. [12]

LITERATURE

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