Development of a PIV System using a Laser-Diode

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Abstract. *A low cost PIV (Particle Image Velocimetry) was developed for characterization, visualization and quantification of a flow test section. Optical devices are common nowadays in metrology, in fluid-flow measurement and studies of flow around structural models or industrial facilities in wind tunnels. The advantages of the optic devices are high resolution, precision, fast response time and, most important, it is not intrusive. The PIV system developed is composed by a quasi-continuous laser-diode with nominal power up to 100 W, monochromatic at 800 nm wave length. An orthogonal lens set defines the width and thickness of the light screen in the test section. Image acquisition is made by a CCD camera. Acquisition and processing image software was developed in C++ and Matlab. The flow field velocities are determined by processing successive images using cross correlation. Analysis of fluid flow around 1 and 2 cylinders, in parallel, were conducted. The tests were conducted in water seeded with micro-spheres with 30 μm mean diameter. The analysis were conducted with velocities of the order of 0.15 m/s, the optical window dimensions was about 100 mm x 150 mm. The results show that the PIV prototype is working even though further development is necessary.*

Keywords: *Particle image velocimetry, laser-diode, fluid-flow measurement, field flow velocities*

1. Introduction

To characterize flow fields is a problem that has no simple solution. Depending on the type of flow, it is very difficult to develop appropriate mathematical models and even if such models are available and used with powerful numerical methods (CFD) there still is need for a comparison of numerical and experimental results. In Brazil, laboratories interested in fluid flows use intrusive techniques that can measure the flow field in a single point. The most common instruments are Pitot tubes and thermo-anemometers. These instruments are introduced in the flow and several points in space are used to determine the flow field. This method is common and presents good results but has a few disadvantages, for instance: usually these instruments measure a single component of velocity. Thus it is necessary to measure each component (with multi-tube Pitot tubes or multi-wire anemometers). These instruments may also disturb the flow and there are cases where this disturbance is not tolerable. If the flow field is to be determined, several measurements are necessary. Even if enough probes are available, they can not be used simultaneously if too much interference is to be avoided. In the mean time the flow may change. Therefore mapping the flow may take a lot of time and flow changes may affect the experimental results.

To overcome these difficulties, sophisticated techniques are appearing. These techniques are a development of visualization methods very common in fluid dynamics research which allowed a qualitative analysis of the flow from, for example, the observation of streamlines in the flow. The development of computer vision allowed the automatic identification of these streamlines and a mathematical description of the flow field was possible and visualization methods developed into tools that can identify and map fluid flows. According to Merzkirch (1974), the visualization methods use images obtained from seeding the flow with particles or energy and variations in refraction index. This project proposes the implementation of a visualization and characterization technique based on the seeding of the flow with micro-particles, known in the literature by the initials PIV, *Particle Image Velocimetry*. This technology is used in universities and research centers usually related to automobilistic, chemical, mechanical, aeronautical, naval and civil industries.

The growing number of published papers in the last few years about implementations and practical results obtained with PIV characterizations of several types of flows is a strong indication of its potential (Merzkirch, 1974; Gonzalez and Wintz, 1977; Hesselink, 1988; Kirita and Pickering, 1988; Khalighi and Lee, 1989; Prenel et al., 1989; Gray et al., 1991). Most PIV systems where developed to attend specific needs of the laboratory and are not commercially available. There are now a few companies offering commercial PIV systems. These PIVs cost in the order of US$ 100,000.00 up to US$ 300,000.00 depending on the application, sample rate, laser intensity and other parameters.

This research developed a low cost PIV using a near infrared laser-diode with a rated maximum power of 100 W. The basic principle of the PIV, the instrumentation and software developed for this device are described in what follows.

2. Particle Image Velocimetry Technique

The PIV makes it possible to map a flow field as a result of visualization of micro-particles added to the fluid upstream of the measurement section. Using appropriate optical devices, a region of the flow field is illuminated with a laser beam. The particles in the flow field scatter the incoming light and a sequence of images may be obtained from one or more cameras that tracks the particles in the illuminated region. The flow is identified by image processing of the original sequence: the each particle or group of particles path is obtained from the correspondence of objects in the sequence of images, already preprocessed by a series of transformations that select only the objects of interest.

It is important to point out the difference of the PIV method and the more traditional laser anemometry (Whitelaw, 1989). The so called LDV (*Laser Doppler Velocimetry*) is used to measure the velocity in a single point. The PIV is a method the maps the flow from the particles path in successive instants of time and results in the determination of the *flow field* each instant of time. The high precision of the LDV makes it a reference for single point measurement. On the other hand, the PIV is essential to identify the flow field, including velocities, even though not as accurate as the LDV.

The necessary instrumentation and methodology to implement a PIV flow visualization and identification system depend mostly on the seeding density and flow type (two- or three-dimensional flow field). This research is concerned with two-dimensional flow only.

According to Hesselink (1988), the seeding density depends on a number of factors. When seeding density is low, the images have few objects located randomly and interpolation in post-processing is required. If the seeding density is high, speckle images may be obtained which, if pre-processed by appropriate optical instrumentation, produce information on a regular grid.

In this paper only two-dimensional flows are studied and every measurement results from the analysis of images of a section illuminated parallel to the flow direction taken with a camera located perpendicular to this plane of illumination.

When a steady flow is studied a single image acquisition computer board connected to one or more CCD cameras synchronized with a known delay is sufficient since in this situation, a single pair of images is necessary to characterize the flow and the fact that the sampling rate of the board is low (in the order of 30 Hz) would not hinder the sampling.

It is important to point out that the cameras used in the image acquisition system should be calibrated so that it is possible to relate the coordinates of the image to the coordinates of the object. The calibration uses images of objects with known dimensions. In general, a plate with equally spaced holes positioned in the plane of illumination is enough for the calibration. The images of the holes are used to determine the optical and geometrical characteristics of the camera and CCD sensor (intrinsic parameters) and its position and orientation (extrinsic parameters). The method normally used for the determination of these parameters is based on the work of Lenz and Tsai (1988).

2.1 The Developed PIV

The implementation of the PIV required the parallel development of several devices and softwares. In this section the optical setup used and the basic tools developed are described. A conceptual model of the PIV is illustrated in the block diagram present in Figure 1. The diagram is described in this section. The blocks in the diagram represent what was developed and will de described in detail in the following sections.

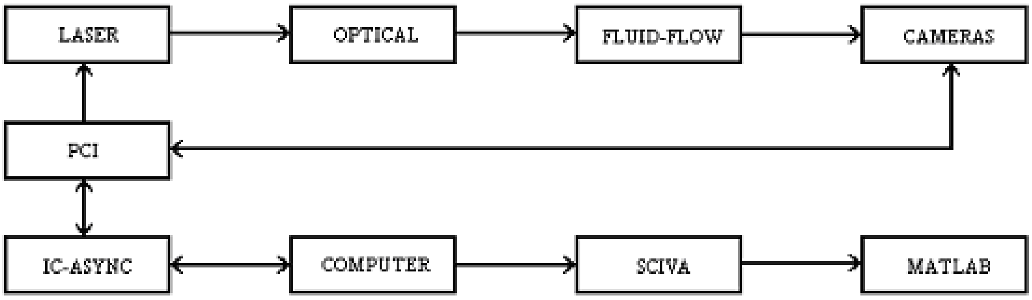

Figure 1. PIV block diagram.

In the diagram of Figure 1, LASER and OPTICAL represent the laser-diode, its power source and the optical components. FLUID-FLOW is the flow section which is to be measured and CAMERAS is the CCD which acquires the images, controlled by the IC-ASYNC board located on a PCI slot of a computer (COMPUTER) and is also the power source of the CCD camera. SCIVA is the software used to acquire the images and Matlab is used to process the data. Details on the optical instrumentation and acquisition and processing software are described in the following sections.

2.2 Optical Instrumentation

The PIV system is shown in Figure 2. PS is the power source of the laser-diode (LD), which is monochromatic with wave length of approximately 800 nm and rated output power of 100 W. The laser-diode can be operated in either continuous mode (CW) or pulsed mode depending on how the power source (PS) is programmed. The LD has a cylindrical lens connected to the diode array and is used to collimate the light beam. After the LD two cylindrical lenses in orthogonal positions are positioned. The first lens (L1) expands the laser beam, as illustrated in Figure 2 and controls the width of the beam in the test section. The lens L2 controls the thickness of the light plane. The acquisition board IC-ASYNC uses a PCI interface to communicate with the computer and is also used to power the camera. In this computer is located the software to acquire (SCIVA) and process the images (matlab scripts).

The CCD camera has highest sensitivity in wave lengths near 800 nm. The CCD uses a 16 mm objective lens with adjustable focus. The minimum distance between the lens and the object is 300 mm.

2.3 Image Acquisition and Processing

The acquisition software developed is called SCIVA (Sistema Computational de Inspecao Visual Automatica). This software was conceived to be easily extended from a basic nucleus with basic computational vision functionality including:

- File manipulation: it is capable to open and store monochromatic or color bitmap files;
- Image capture: it can handle general processes of synchronous or asynchronous image capture;
- Image management: it can store, select or visualize images captured or stored in a bitmap file;
- Algorithms: new algorithms may programmed in a simple way without altering the input / output interface.

In this software, the images generated by the camera are presented live on a visualization screen where they are available to storage or processing. A second window, an image gallery, has icons that refer to the original images and can be clicked to be viewed at any moment by the user.

The PIV software is a set of Matlab scripts that simplify the velocity calculation and flow field visualization of two images acquired in successive instants of time. This software is based on scripts MATPIV and URAPIV, available in the internet and developed in matlab. The basic principle of the image processing is as follows:

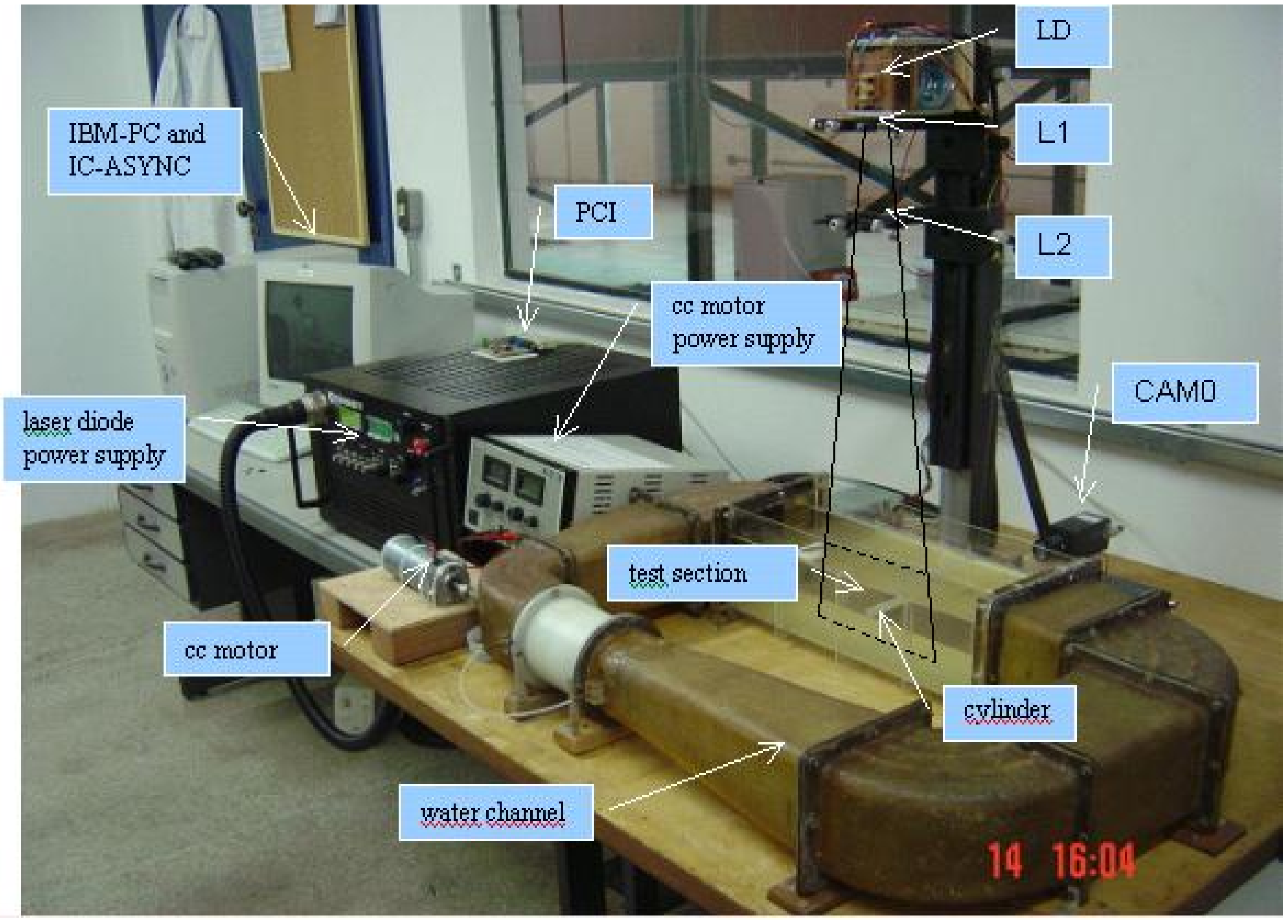

Figure 2. Experimental setup of the PIV by using a water channel. LD: laser-diode, L1 and L2: cylindrical lens, CAM0: CCD camera, cilindre: applied to introduce turbulence on flow, cc motor: rotor motor of the water channel, PCI: CAM0 control, IBM-PC and IC-ASYNC: acquisition card connected to a computer.

Two images of the flow in different time intervals should be acquired. Each image is a matrix with the intensities of each pixel that can vary from 0 (clear) to 255 (dark). The images are divided in small rectangles (interrogation cells) with sides that have powers of two pixels. The first interrogation cell is compared to the interrogation cell of the second image resulting in a cross-correlation of every pixel of the image. The interrogation cells are displaced, resulting in a new cross-correlation. This process is repeated until a maximum is achieved. Then a probable displacement was found. The velocity in this interrogation cell is simply the displacement divided by the time interval elapsed between between the two images. Noise in the data may result in wrong evaluation of the velocity. To avoid this problem, the data obtained by the cross-correlation is filtered. There are several possible filters but the ratio signal/noise filter should be pointed out. It eliminates data above a certain critical value defined by the operator; this value is the ratio of the cross-correlation in the observed position and the mean values near this point.

3. Results

Analysis were conducted to verify the PIV system. Initially a flow without any disturbance was analyzed, and then cylinders positioned across the flow were used to disturb the mean flow. All analysis were conducted in a test section of 150 mm x 100 mm, width and height, respectively, and the mean velocity was 0.2 m/s.

3.1 Flow without disturbances

In this test a plain flow was measured, as shown in Figure 3. However, it is possible to observe that this flow is turbulent, and some noise is introduced in the flow, as shown in Figure 3(b).

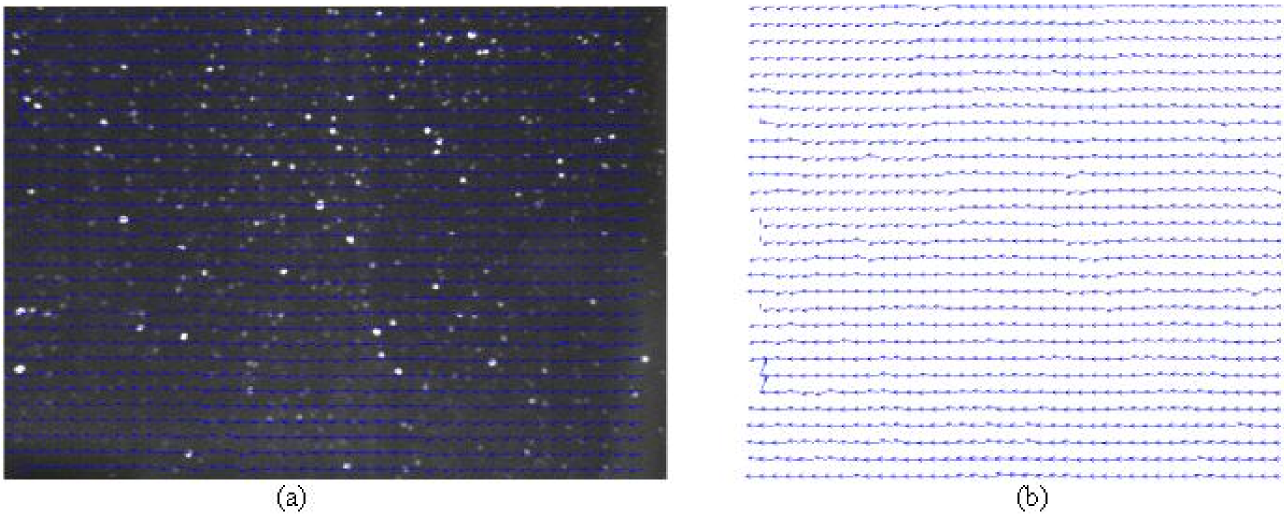

Figure 3. (a) Particle image without perturbation with velocity field and (b) velocity field only.

3.2 Single cylinder wake

In this analysis a cylinder was positioned before the test section, as illustrated in Figure 4. This cylinder has a 10 mm diameter and the test section has 150 mm x 100 mm, the cylinder was positioned upstream from the test section. Results are shown in Figure 5. In this figure, the velocity field subtracetd by the mean velocity is plotted (arrows) over the vorticity of the flow. Even though the results are noisy, it is clear on this figure a presence of vortices. On the upper side of the figure, the vortices turn anticlockwise and on the bottom of te figure the vortices turn clockwise, as is expected on the wake of a circular cylinder flowing from right to left (the von Karman vortex street).

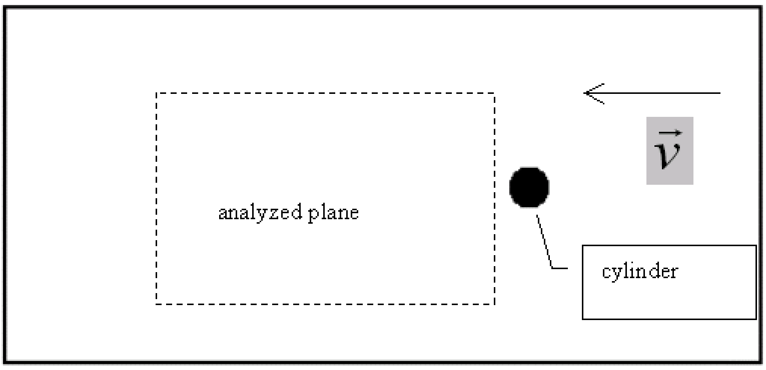

Figure 4. Test section used to measure the wake of a single cylinder.

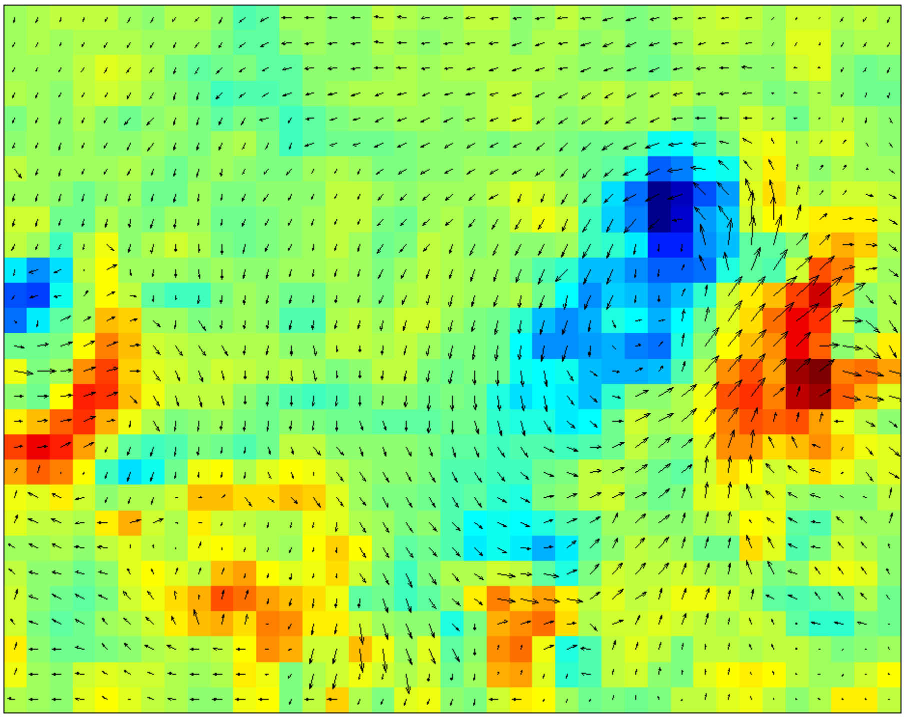

Figure 5. Velocity Field subtracted by the mean velocity plotted over the vorticity field for the flow on the wake of a single circular cylinder

3.3 Wake of two cylinders placed side-by-side

This analysis was conducted with two cylinders side-by-side. The cylinders had a gap of 2 diameters. The gap is defined as the center to center distance as shown in Figure 6, where s is the gap.

The results obtained with a gap of two diameter are shown in Figure 7. These results are, again, very noisy, and the mean velocity was subtracted from the velocity field so that vortices could be more easily distinguished. A few vortices apparently randomly located are seen in this figure but four rows of vortices can be seen (three of them very clearly) with opposite vorticities as is expected on the flow behind two circular cylinders side-by-side.

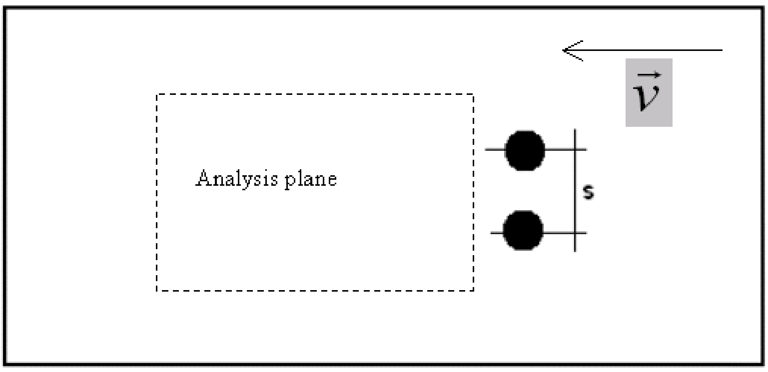

Figure 6. Test section used to measure the wake behind two cylinders.

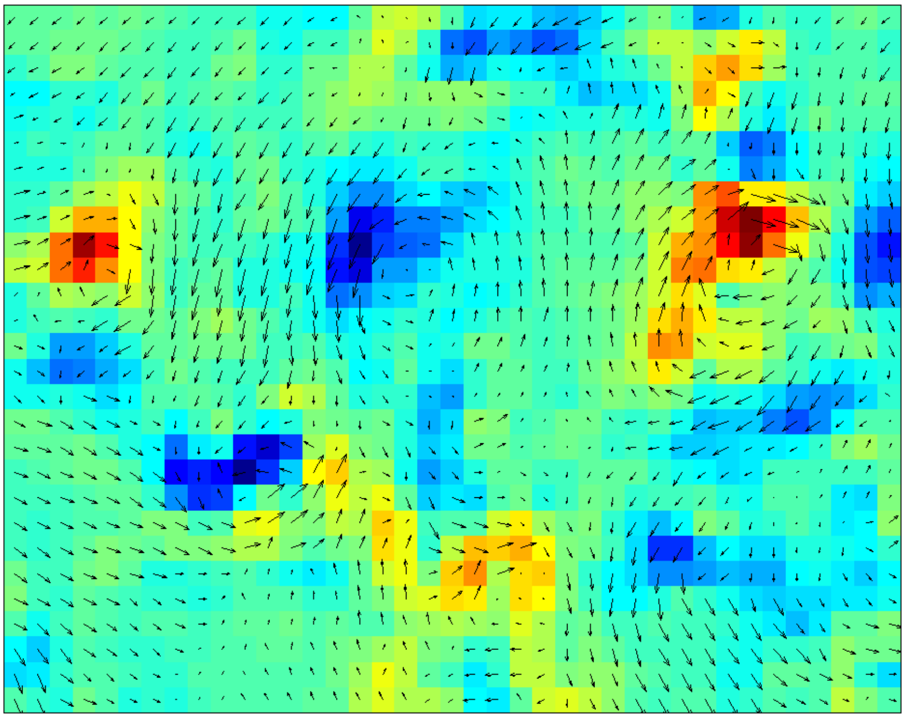

Figure 7. The velocity field subtracted by the mean velocity plotted over the vorticity field for the flow behind two circular cylinders positioned side-by-side.

4. Conclusions

This paper showed the possibility of a low cost PIV using a laser-diode with 800 nm wave length and 100 W rated power as a light source. The results obtained with this PIV shows the advantages of the use this optical technique to measure fluid flow. The direct measurement of a velocity field is very important in problems involving complex flows as, for example, flow around cylinders or buildings. This is an ongoing research and a hardware system is under development that can manage 2 CCD cameras with user variable delays in image acquisition that will allow much higher velocities to be measured. New image processing routines will be developed which includes sub-pixel processing. This will allow easier measurements in air where seeding particle size is much smaller than in water. This system will be used to measure flows in models of buildings and city blocks in the atmospheric boundary layer wind tunnel located at IPT.

5. Acknowledgements

The authors thanks to CNPq who sponsors this work by process number 62.0266/97-0. Thanks to Pedrão and Carlinhos for support in the manufacture of optical supports, and thanks to Josemir Coelho and Luiz Pinheiro for help and support in laser-diode mounting and operation.

6. References

Gonzalez, R. and Wintz, P. (1977). *Digital image processing*. Addison-Wesley, London.

Gray, C., Greated, C., Mc Cluskey, D., and Easson, W. (1991). An analysis of the scanning beam piv illumination system. *Measurements Science Technology*, 2:717–724.

Hesselink, L. (1988). Digital image processing in flow visualization. *Annual Review of Fluids Mechanics*, 20:421–485.

Khalighi, B. and Lee, Y. (1989). Particle tracking velocimetry: an automatic image processing algorithm. *Applied Optics*, 28(20):4328–4332.

Kirita, K. and Pickering, C. (1988). Particle image velocimetry: automatic fringe analysis by cross-correlation. *Optical Engineering*, 27(3).

Lenz, R. K. and Tsai, R. Y. (1988). Techniques for calibration of the scale factor and image center for high-accuracy 3-d machine vision metrology. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 10(5).

Merzkirch, W. (1974). *Flow Visualization*. Academic Press - New York.

Prenel, J., Porcar, R., and El-Rhassouli, A. (1989). Three-dimensional flow analysis by means of sequential and volumic laser sheet illumination. *Experiments in Fluids*, 7:133–137.

Whitelaw, J. A. (1989). *Principles and Practice of Laser-Doppler Anemometry*. Academic Press.

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