PARTICLE IMAGE VELOCIMETRY BY STEREOSCOPIC COMPUTATIONAL VISION - S-PIV-3D SYSTEM

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Abstract

The PIV system developed, by computational vision techniques, entitled S-PIV-3D, includes features as the optical method of image acquisition and the calibration process. The measurement system, resulted from these characteristics, uses a single conventional digital video camera to obtain three-dimensional data in low turbulence flow, a fact that provided significant economy in the system implantation. The acquisition of images is accomplished through an optical device built on a stereoscope that promotes the acquisition from two different viewpoints. The calibration process, that uses a calibration target and a transformation function, allows the calculation of the real coordinates and the free positioning of images production and acquisition devices. Results present fields of three-dimensional velocities obtained through specific software. The software, besides calibration functions, image processing and results, contains parts developed for specific applications as, for instance, the obtaining of vertical velocities in the surface of free flows and others. To test the measurement system a water tunnel prototype was developed to measure and visualize several situations involving especially the didactic demonstration of cinematic behavior of the flow around solid models. The measurement system permits flow diagnosis and flow visualization through interactive graphics for the vectorial velocity fields and slow motion videos. An engineering application was developed at the oscillating grids thank. In this thank the obtained data are related to the reaeration coefficient K_2 for estimation of water body's natural depuration.

Keywords: PIV – Particle Image Velocimetry, Computational Vision, Flow Visualization, Turbulence measurement.

1. Introduction

Starting on the 1960's the flow measurements through non-intrusive methods gained a strong development with the introduction of the LDA – Laser Doppler Anemometry – technique which, along the last decades, presented significant progresses with the implantation of new technologies regarding optical devices and signal processing.

In the last years, with the crescent increment of the cameras and lasers technology, hardware, software and digital processing, the PIV – Particle Image Velocimetry – technique became one of the most popular instruments for flow measurements in a wide range of applications (Jansen, 2004).

This PIV system was developed in a research project entitled "Particle Image Velocimetry by Stereoscopic Computational Vision – S-PIV-3D System", that involved the study and the application of alternatives in the generation, capture and processing of images and it was based on 5 items:

a) Development of the images processing software using the Matlab language, taking advantage of its mathematical resources and visualization tools;

b) Development of an adjustable stereoscope to work with a single digital camera, to make possible the acquisition of images under two different viewpoints, necessary to generate appropriate data for the three-dimensional definition in certain applications;

c) Development of the algorithm, programming and physical calibration devices for the coordinates system, through which was possible to establish the conversion factor of measurements obtained from the images to the real ones, to correct the optical distortion and to give wide freedom on the acquisition of images;

d) Use of a set of up to six 3mW or 100mW laser industrial units, line projection, to illuminate the measurement area establishing conditions for images acquisition in low velocity flows, with reduced cost of equipments;

e) Use of a conventional high definition digital camera aiming the viability of its use in a measurement laboratory. In this sense it was verified that this kind of camera can assist a wide range of applications providing satisfactory answers in low turbulence flows.

The velocity measurement as a space-time ratio uses the time between frames acquisition interval, and for higher precision on higher velocities it is necessary to increase the number of acquisition frames per time unit. This precision can be obtained using conventional cameras since that the application be restricted to low velocity fields avoiding the corruption of the images by long exposure time – "blurring" effect.

The software developed for image processing and velocity field calculation was denominated S-PIV-3D. This program, in Matlab Language, was elaborated in several parts. The calibration part uses a defined calibration target to obtain the parameters for the transformation function. The images processing part uses images files in the AVI – Audio Video Interleave – format and by the Normalized Cross Correlations algorithm furnishes the displacement of the photographed particles.

The visualization and output part presents interactive graphs for vectorial velocity field visualization, three-dimensional graphs of results, videos that can be observed with controlled frame-rate – slow-motion effect – and numeric spreadsheets. One of the applications for the system is the didactic support for exhibition classes on flow around solid models studies. In this sense the water tunnel was developed. This equipment was designed to furnish ideal conditions for production and acquisition of images in controlled flow.

An application developed for the S-PIV-3D system was the measurement of vertical velocities in a surface flow for obtaining correlations with the natural capability of depuration of bodies of water. In this sense, measurement where made in a specific tank in which turbulence is produced by oscillating grids.

Thus, the development of accessible equipment can provide the spread of the technique for the learning aid in disciplines as Fluid Mechanics, Transport Phenomena, Hydraulic, Hydrodynamic and others, besides techniques applications.

2. Bibliographical Review

An experimental installation of a PIV system typically consists of several subsystems. According to Raffel et al (2007) in most of the applications tracer particles, which should be added to the flow, are illuminated and its positioning are registered between short intervals of time. Usually the illumination is through laser sheet emission on the measurement interest region. The registration of images, through conventional or digital cameras, can happen in a single frame or in frames sequence.

The exposure time in the acquisition of the image should be small enough to freeze the particles movement and to avoid the "blurring" effect. Elsinga et al (2005) studied the "blurring" effect in shock waves in supersonic wind tunnel flows verifying the errors introduced in the computational processing of the images. The displacement of the particles on the images is determined through PIV techniques for the evaluation of the velocity using post processing methodologies. For the evaluation of the velocity field, a pair of PIV images are divided in small sub areas called of "interrogation areas".

The local vector displacement for the images of the particles is determined for each interrogation area through the Auto-correlation or Cross-correlation statistical methods. It's assumed that all of the particles inside of one interrogation area of the first image move in relatively homogeneous way to the interrogation area of the second image (Raffel et al, 2007).

Other important consideration for the definition of the displacement vectors consists on the projective geometry involved in the images acquisition and especially in the case of vectors with components perpendicular to the illumination plane. This subject is solved through trigonometric relationships assuming ideal conditions of light propagation and applying a modeling in a homogeneous coordinates system (Raffel et al, 2007).

To identify spurious vectors obtained from inconsistencies on the image, one of the used techniques consists in the application of filters. According to Westerwell and Scarano apud Raffel et al (2007), the data filtering from the Normalized Average is one of the best alternatives for the necessary corrections. In this filter, the average of the values of the neighboring vectors, in its components x or y, is compared with the components of the inspected vector through the following relation:

$$\frac{| U_{mean} - U_{i,j}}{r_{mean} + \varepsilon_0} < \varepsilon_{thereshold} \qquad \text{(eq. 1)}$$

in which U_{mean} is the mean of the neighboring components vectors, $U_{i,j}$ is the component of the inspected vector, $r_{mean} = |U_i - U_{mean}|$, ε_0 are the medium value of the data noise: between 0,1 and 0,2 pixels and $\varepsilon_{threshold}$ is the maximum tolerable value for the relation so that the inspected vector is accepted. If the relation is not satisfied the vector will have its values substituted by U_{mean}.

PIV is a technique of indirect velocities measurement, i.e., the measured velocities are velocities of the particles in suspension and not of the fluid in movement.

For flows with a very low Reynolds number an estimate of the discrepancy of velocities between the fluid and the particles, in a uniformly accelerated field, can be obtained by an expression derived from the Stokes Law:

$$\Delta U = U_P - U = d_P^2 \frac{\rho_P - \rho}{18\mu} a \qquad \text{(eq. 2)}$$

In this equation U_P is the particle velocity, U is the fluid velocity, d_P is the particle diameter, d and ρ are the density of the particle and of the fluid respectively, μ is the dynamic viscosity of the fluid and a is the field acceleration (Raffel et al, 2007). It's noticed that the use of particles with density close to the fluid density and reduced diameter can minimize the discrepancy of velocities. In fields with uniform velocities, it is waited an ideal accompaniment of the particles with the fluid movement.

Regarding the system calibration which consists of the relationship between the measurements on the image and the values in real coordinates system, Petracci et al (2003) demonstrate the need of a careful alignment between the calibration target and the light-sheet plane.

With the intention of establishing the popularization of the PIV technique, Okamoto et al (2000) proposed the PIV-STD Project that disposes standardized images artificially produced for verification of the recognition capacity and accurateness of PIV systems.

The PIV technique already is developed substantially in the worldwide. In the base research countless researchers can be mentioned, and as example, follow some references:

Smith and Glazer (2002) investigated the flow of jets of air through holes using a PIV system with cameras of high resolution, illumination with a NdYAg lasers pair and production of a light sheet with regulated thickness and width.

Tao et al (2002) using a HPIV system – Holographic Particle Image Velocimetry – obtained the tri-dimensional distribution of velocities in the turbulent flow in a tube of square section with Reynolds number in order of 1.2 10^5.

Cicca et al (2002) investigated the turbulence in the flow layer close to the outline wall subjects to external disturbances. In the study they used the processing of images of the system PIV with interrogation areas of 64x64 pixels and the cross-correlation algorithm in the displacements definition.

Alkislar et al (2003) investigated experimentally no steady flows formed by jets. The measurements demonstrated the spatial and temporal evolution of the jet with high fidelity presenting the velocity and vorticity fields. The acquisition occurred with a 1008 x1018 pixels resolution camera at 30 fps. A laser was used with pulse exposure time between 1 and 1,5 μs.

Dong et al (2005) combined the PIV technique with numeric simulations for the study of the flow close to the wall of a cylinder showing the influence of the Reynolds number in the flow structure.

Pu & Meng (2005) introduced innovations in the HPIV technique with visualizations of structures of vortexes through vorticity isosurfaces. Sengupta et al (2007) studied the incompressible and accelerated flow around an aerofoil. They accomplished measurements with the PIV technique and using computational simulation with the Navier-Stokes equation established comparisons between results.

Using the S-PIV-3D system, an application to engineering aimed at the prediction of environmental impacts was performed. The experiments were conducted for generation of turbulence in water using an oscillating grid tank that aims to reproduce in laboratory levels of turbulence found in natural bodies of water.

The velocity of free surface flow leads to parameters that evaluate the intensity of turbulence. Among these parameters, the vertical component of flow velocity can translate the turbulent intensity in terms of their influence on mass transfer and lead to a correlation for determining the reaeration capacity of a body of water. (Szeliga & Roma, 2004).

3. Methodology

The S-PIV-3D system presents some alternatives for implantation, operation and obtaining of results that turns it accessible for flow characteristics demonstration laboratories. The process of images acquisition uses an optical device to allow the three-dimensional manipulation.

A group of plane mirrors and a mirrored faces prism fixed on an appropriate geometry facilitate the acquisition of simultaneous images according to different viewpoints. With this stereoscope model optical device, it was possible to use a single camera for images acquisition. The mirrors are fixed to supports with fine positioning adjustment, allowing the geometric adjustment of the installation to supply two images per frame from the acquisition field. The illumination of the acquisition field uses 3mW or 100mW industrial laser emitter modules. Each module produces a light sheet with 90°opening and adjustable thickness.

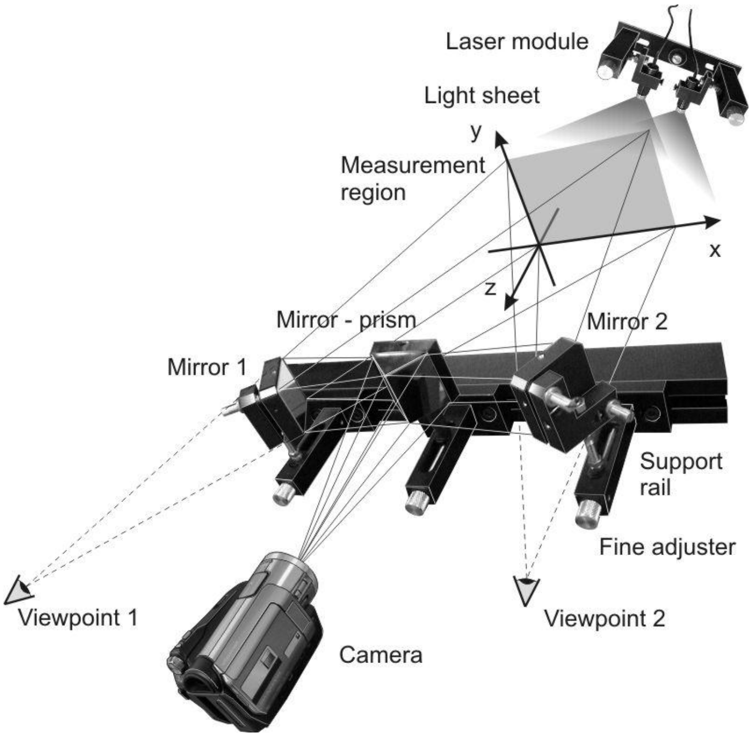

Figure 1 – Disposition of the image production and acquisition devices

Figure 1 represents the images production and acquisition devices. From the illustration it can be observed the positioning of the digital camera, the arrangement of the mirrors stereoscope and the scene spot. It can be noticed, in function of the established optical path, the consequent sharing of two images from de same picture in one frame, due to the stereoscopic arrangement. It is included, yet, the laser modules disposition and its respective adjustment supports.

The system calibration is obtained by calculating the coordinates transformation function that converts the measurements obtained from the images to the real world measurements. In this project it was used a calibration target with well determined dimensions to give the real world measurements. The calibration target has been performed by a grid made from a 50mm x 50mm square mesh of 11 by 11 points, 5mm spaced. The target is positioned on the measurement space and defines the xy coordinates plane of the real system of coordinates.

The calibration target is sustained by a support with appropriate mobility necessary to the establishment of the transformation parameters. The calibration procedure starts with the target positioning and the shot of a still picture, with the same definition and scene position as the measurement shot; and follow moving the target 20mm from the initial position on the z axis to shot the second calibration still picture. The image processing for these two pictures furnishes the calibration parameters that will remain valid as long as the acquisition devices remain unmoved. All necessary interference on the devices, as the target motion or the camera activation, must occurs by remote control.

The projective geometry, the space natural vision mathematical model, states a linear combination ratio function for the space graphic representation according to the natural vision deformation. This function – $f_{Tr}(X; Y)$ – applied on a Cartesian coordinates system has the aspect shown on eq. (3).

$$(x, y) = f_{Tr}(X, Y) = \left(\frac{aX + bY + c}{gX + hY + i}, \frac{dX + eY + f}{gX + hY + i}\right) \qquad \text{(eq. 3)}$$

Where: (x, y) are the coordinates in the real space and (X, Y) are the coordinates in the images system. The transformation parameters (a, b, c, d, e, f, g, h, i) are obtained by the balance between the values of X and Y on the images system and the respective real coordinates (x, y).

During the calibration process the real coordinates (x, y) are defined by the calibration target dimensions and the images coordinates (X,Y) are obtained on the calibration images processing.

The function relating images and real objects is optimized by numerical method applied to the calibration pictures, on the projective coordinates, and the calibration target, on real coordinates. The calibration configuration scheme is presented on Fig. 2, where it can be observed the real and calculation points of view in a system involving data acquisition through different physical mediums, for instance, water and air.

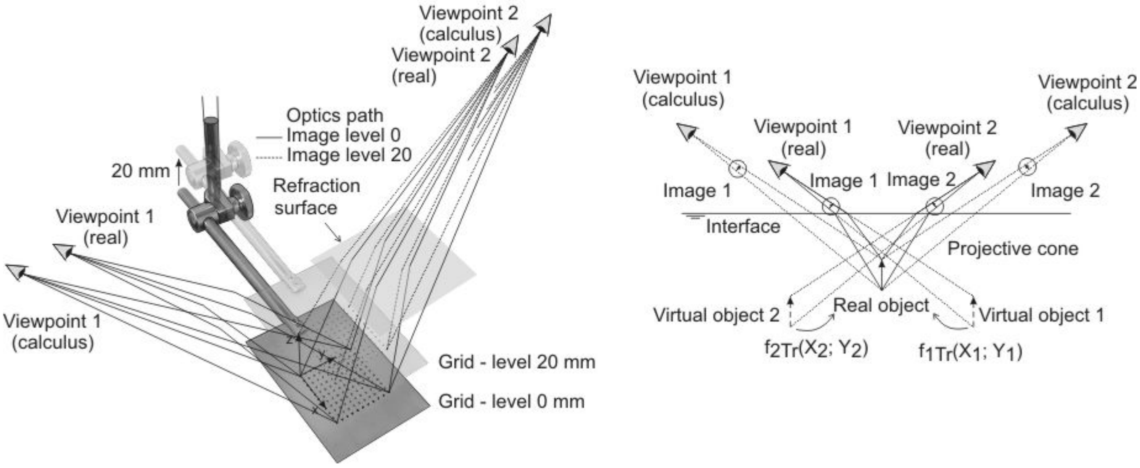

Figure 2 – Calibration configuration

In the acquisition of images was used a common Full HD camera operating at 30 fps (frames per second) for slow flow. For faster flow is necessary to increase the speed of acquisition and was used a camera operating at 60 fps, 300 fps or 600 fps. In the processing of images, the displacement of the particles is determinate through the normalized cross-correlation algorithm.

The algorithm is applied on the images of each viewpoint and values are obtained in the system of projective coordinates. Figure 3 contains a scheme that illustrates the application of the algorithm for images cut from a pair of PIV images.

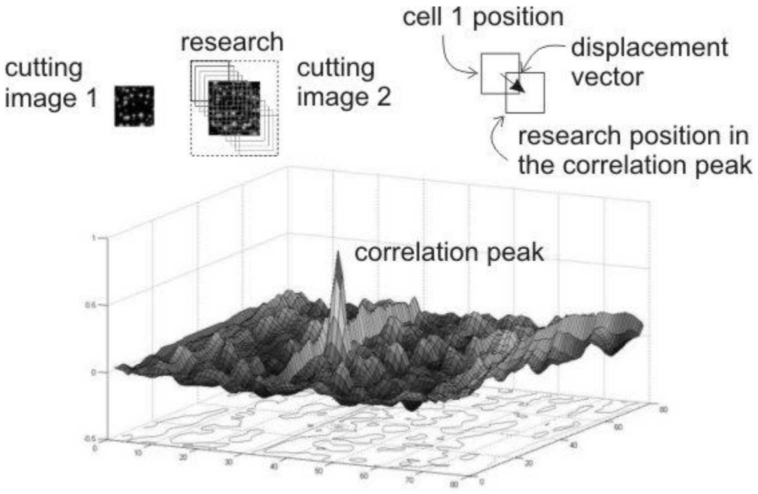

Figure 3 – Application of normalized cross-correlation in Particle Image Velocimetry

After the transformation of coordinates, the values of each viewpoint are related and hence are obtained three-dimensional displacements as it can be observed through the scheme shown in the Fig. 4.

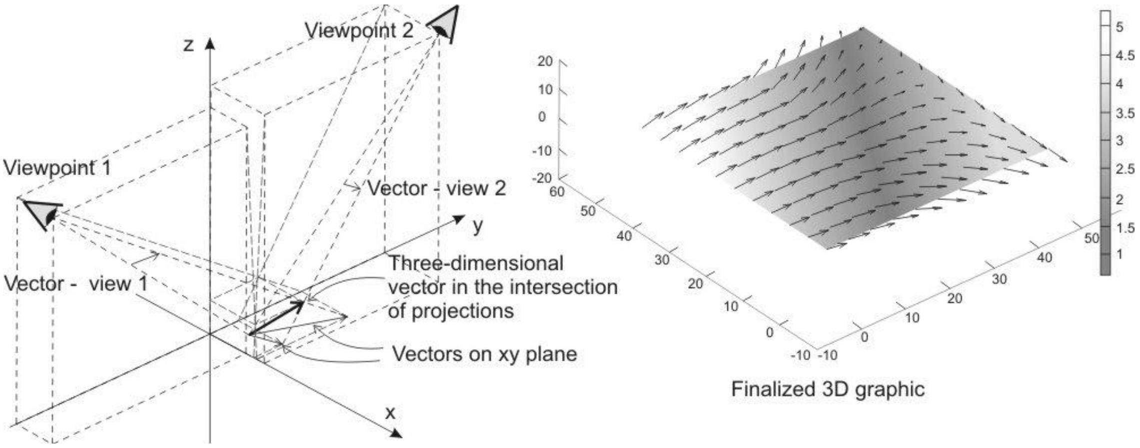

Figure 4 – 3D Vectors rebuilding from the images 1 and 2

The software S-PIV-3D elaborated for calibration, processing of images and obtaining of results purposes, also contemplates all of the requirements for the analysis and inferences on the results for the velocity fields. Figure 5 contains the reproduction of the main screen of the program S-PIV-3D.

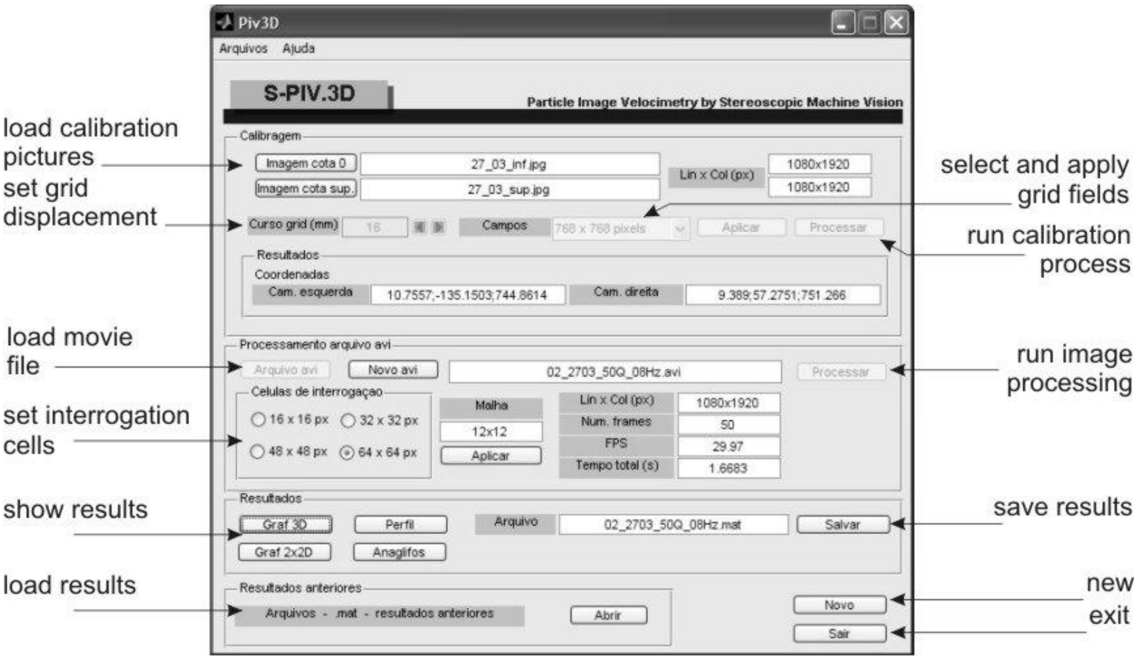
Imagem cota 0: 27_03_inf.jpg
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Lin x Col (px): 1080x1920
Lin x Col (px): 1080x1920
Curso grid (mm): 16
Campos: 768 x 768 pixels
Cam. esquerda: 10.7557;-135.1503;744.8614
Cam. direita: 9.389;57.2751;751.266
Novo avi: 02_2703_50Q_08Hz.avi
Celulas de interrogaçao: ○ 16 x 16 px ○ 32 x 32 px ○ 48 x 48 px ● 64 x 64 px
Malha: 12x12
Lin x Col (px): 1080x1920
Num. frames: 50
FPS: 29.97
Tempo total (s): 1.6683
Arquivo: 02_2703_50Q_08Hz.mat

Figure 5 – Main screen of S-PIV-3D program.

4. Results

Experiments at development phase were accomplished in the water tunnel. This equipment has been developed for application in didactic demonstration of controlled flow around solid models, allowing visualization and ideal conditions for production and acquisition of images. Figure 6 contains an outline of the water tunnel structure.

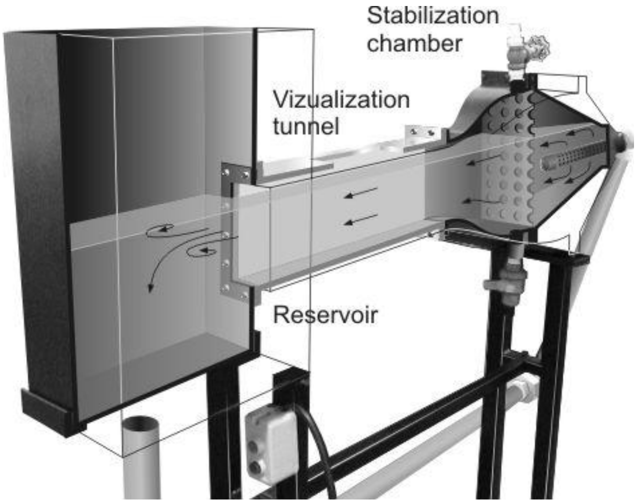


Figure 6 – Section – Water tunnel

Figure 7 illustrates a running for data acquisition from the flow around a cylinder. Figure 8 presents one of the results screens of the software S-PIV-3D showing one possible view of an interactive graph for the velocities field around a bottom floodgate. Figure 9 is the reproduction of the screen of results of the image processing for a flow through a square hole.

The graphic interactivity makes available several visualization resources and data access.

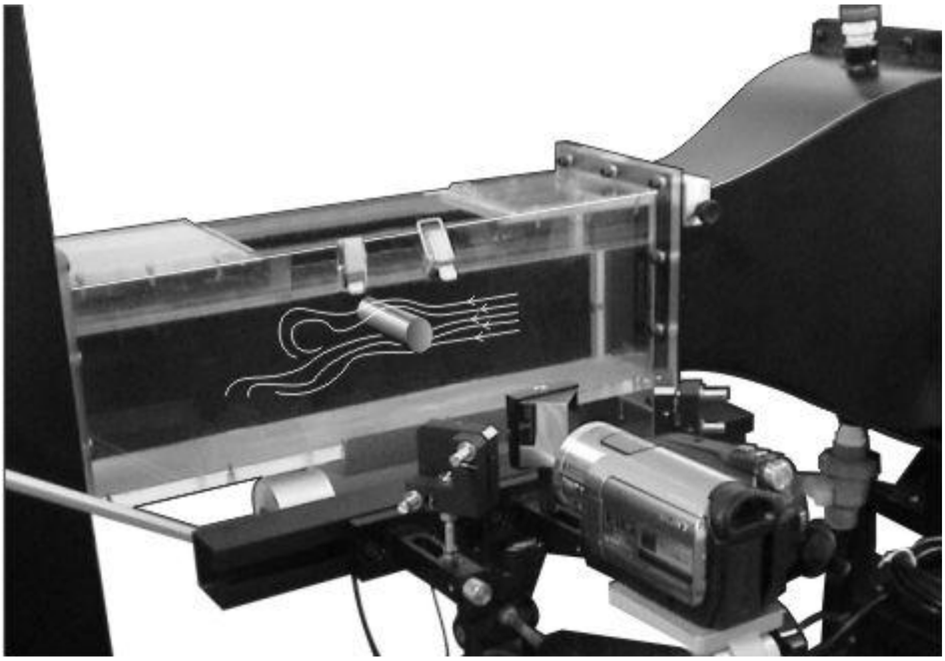
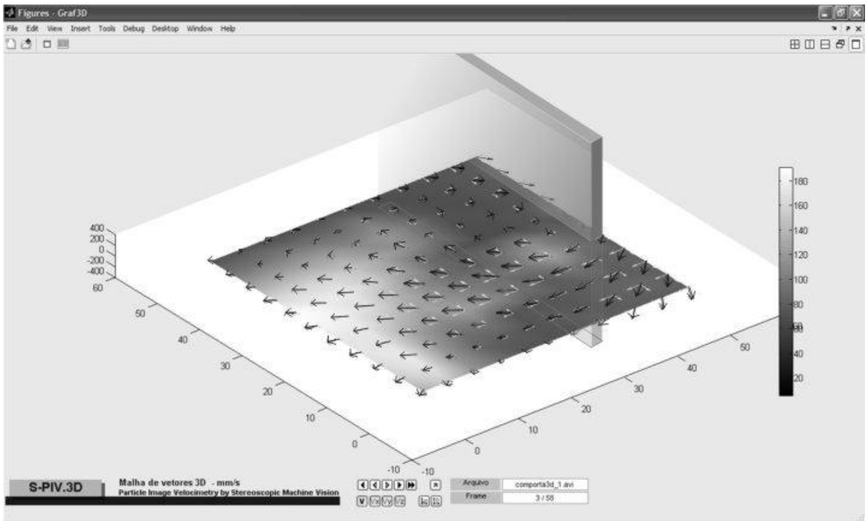


Figure 7 – Flow around a cylinder



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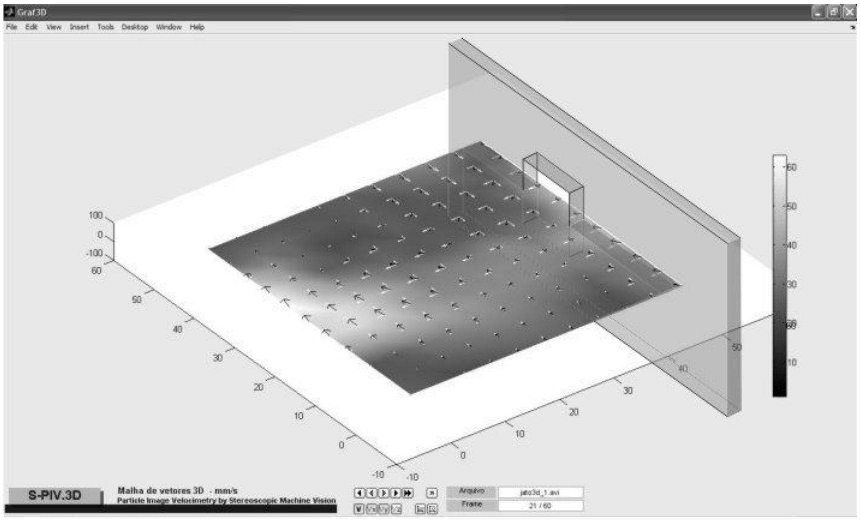
Frame: 3 / 58

Figure 8 – S-PIV-3D – Results screen – 3D velocities field around a bottom floodgate



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Frame: 21 / 60

Figure 9 – Screen of results of the image processing for a flow through a square hole

The environmental engineering application was developed at the oscillating grids tank. The apparatus is shown by the picture in the Figure 10. The experiments were run by different type of oscillating grids and rotation speeds. The data obtained by the S-PIV- 3D system is related to surface turbulence and together with experimental determination of the reaeration coefficient K_2, leads to a prevision environmental impact model. The velocities measurements are applied in a region of interest where the target of calibration is positioned.

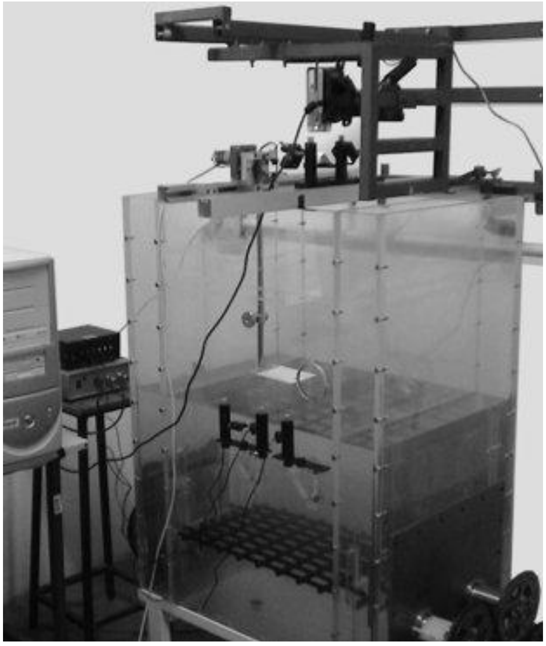

Figure 10 – Oscillating grids thank with S-PIV-3D apparatus

The results of this application consist on graphics of vertical velocities of the water surface oscillation with data obtained from the experiments. The expanded visualization of results is made by iso-surfaces of velocities calculated from each node (position 1 to 121) of the mesh of the calibration target and also graphics of average vertical velocities in the node. Some examples of these results are presented through the Figures 11 to 20. (Szeliga & Roma, 2009).

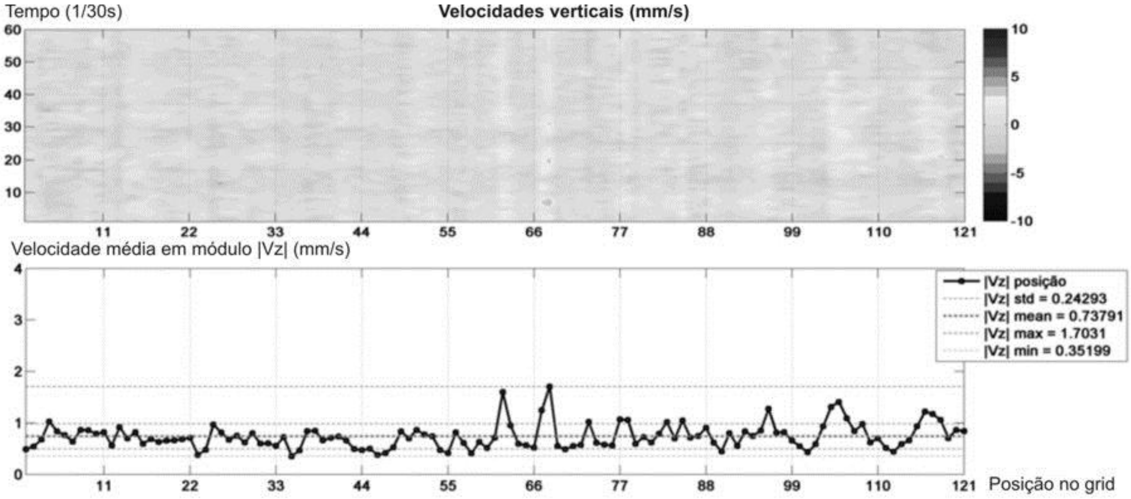

Figure 11 - Results for the grid oscillating at 1.33 Hz

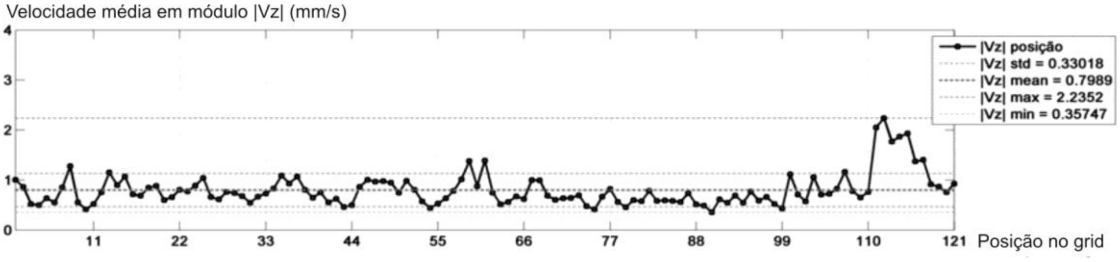

Figure 12 - Results for the grid oscillating at 1.5 Hz

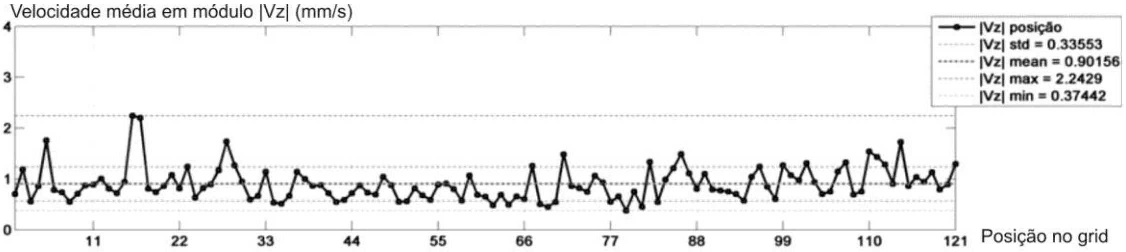

Figure 13 - Results for the grid oscillating at 1,67 Hz

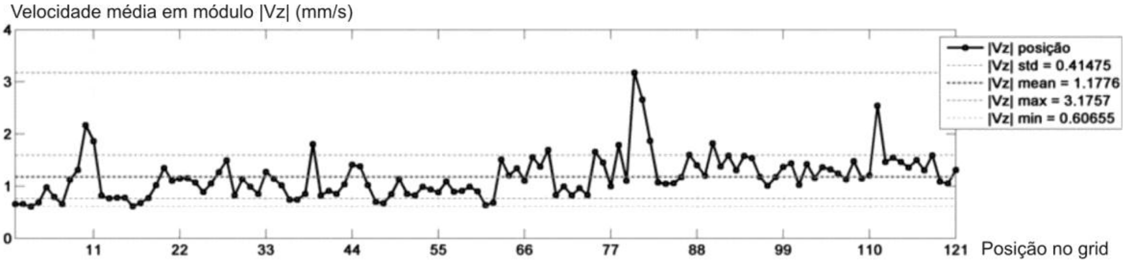

Figure 14 - Results for the grid oscillating at 2.0 Hz

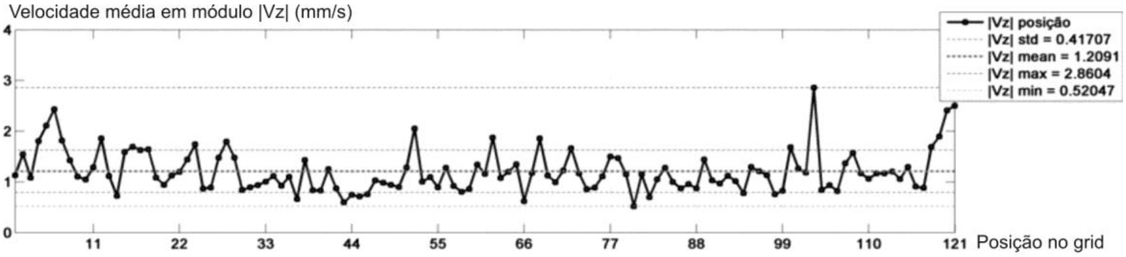

Figure 15 - Results for the grid oscillating at 2.17 Hz

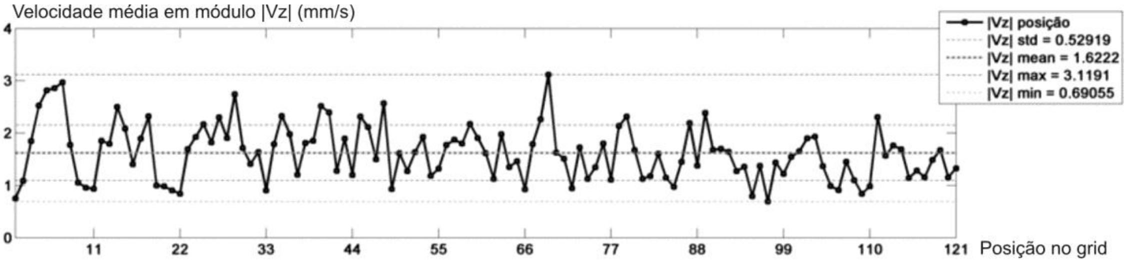

Figure 16 - Results for the grid oscillating at 2.5 Hz

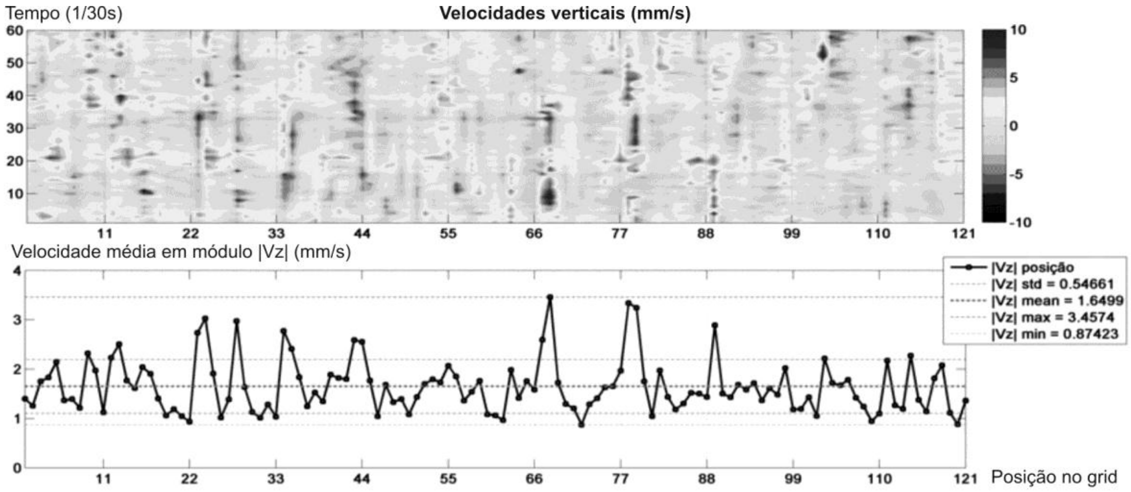

Figure 17 - Results for the grid oscillating at 2.67 Hz

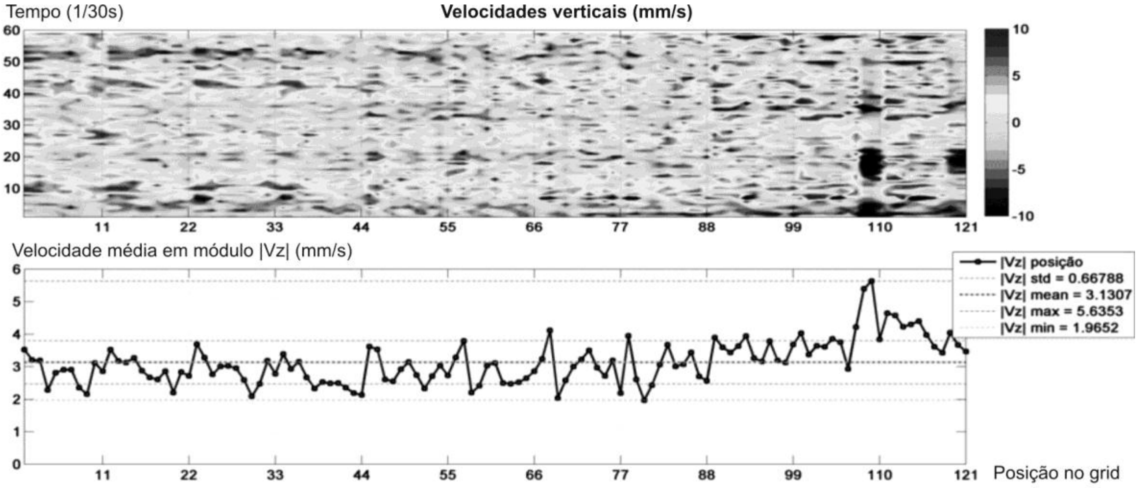

Figure 18 - Results for the grid oscillating at 3.0 Hz

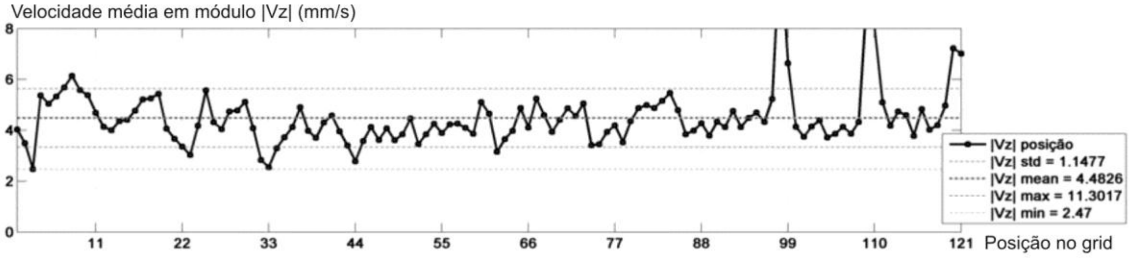

Figure 19 - Results for the grid oscillating at 3.33 Hz

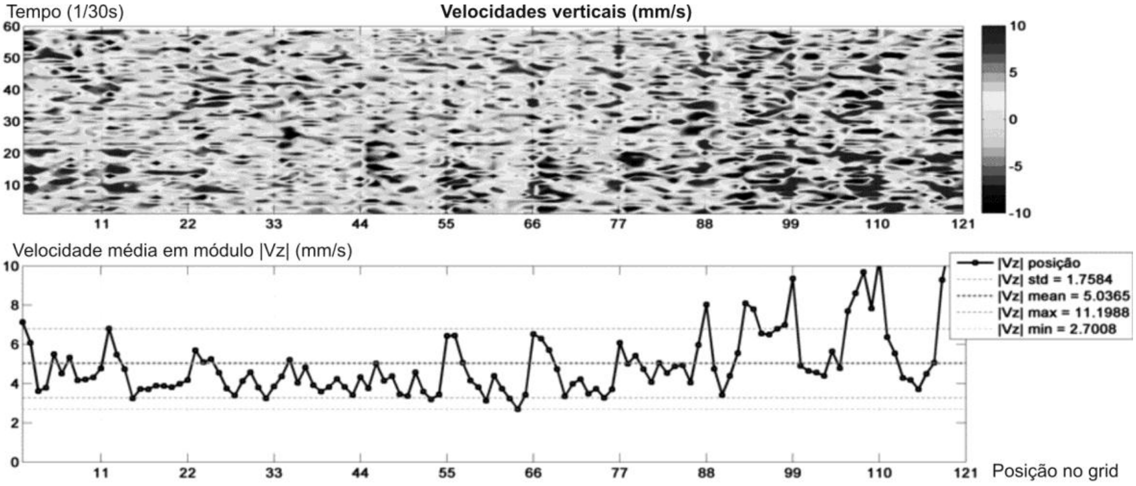

Figure 20 - Results for the grid oscillating at 3.67 Hz

5. Conclusions

The development of this system was directed for applications used in technological laboratories and also didactic demonstrations. It can be noticed its applicability to flow measurements with low turbulence level.

The use of non-dedicated cameras and continuous emission lasers for images acquisition granted its application on varied types of flows but restricted to the limits imposed by the devices and its acquisition capacity about the effects provoked by the particles velocity.

The S-PIV-3D system is a tool with high explanation power especially that related to the studies on the interactions with solid contours and also measurements of low turbulence flow like a water surface oscillation.

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References

Alkislar, B. M.; Krothapalli, A.; Lourenço, L. M. (2003). **Structure of a screeching rectangular jet: a stereoscopic particle image velocimetry study**. J. of Fluid Mechanics. Vol. 489, pp. 121-154. 13

Cicca, G. M.; Iuso, G.; Spazzini, P.G.; Onorato, M. (2002) **Particle image velocimetry investigation of a turbulent boundary layer manipulated by spanwise wall oscillations**. J. of F. Mechanics. Vol. 467, pp. 41-56.

Dong, S.; Karniadakis, G. E.; Ekmekci, A.; Rockwell, D. (2006). **A combined direct numerical simulation–particle image velocimetry study of the turbulent near wake**. J. of Fluid Mechanics. Vol. 569, pp. 185-207.

Elisinga, G.E.; Van Oudheusden, B.W.; Scarano, F. (2005). **The effect of particle image blur on the correlation map and velocity measurement in PIV**. In: Optical Engineering and Instrumentation, SPIE Annual Meeting, Paper 5880-37, 31 July - 4 August 2005, San Diego, California, USA, 14 pp

Jansen, K. D. (2004). **Flow Measurements**. Journal of Brazilian Society of Mechanics Science and Engineering. Vol. XXVI, N. 4. pp. 400 – 419.

Okamoto, K.; Nishio, S.; Kobayashi, T.; Saga, T.; Takehara, K. (2000). **Evaluation of the 3D-PIV Standard Images - PIV-STD Project**. Journal of Visualization. Vol. 3, Nº 2, pp. 115-123.

Petracci, A.; Doome, C. W .H.; Westerwell, J.; Lecordier, B. (2003) **Analysis of Stereoscopic PIV Measurements using Synthetic PIV Images**. In EUROPIV-2 Workshop – Zaragoza, Spain. 11p.

Pu, Y. & Meng H. (2005). **Four-dimensional dynamic flow measurement by holographic particle image velocimetry**. Applied Optics. Washington, USA. Vol. 44, Issue 36, pp. 7697-7708

Raffel, M.; Willert, C. Wereley, S.; Kompenhans, J. (2007) **Particle Image Velocimetry – A Pratical Guide**. Second Edition, New York: Springer Verlag. 448 p. 14 Sengupta, T. K.; Lim, T. T.; Sajjan, S. V.; Ganesh, S.; Soria, J. (2007). Accelerated flow past a symmetric aerofoil:experiments and computations. J. of Fluid Mechanics.Vol. 591, pp. 255-288.

Smith, B. L. & Glezer, A. (2002). **Jet vectoring using synthetic jets**. J. of Fluid Mechanics. Vol. 458, pp. 1-34.

Szeliga, M. R.; Roma, W. N. L. (2004). **Computer vision system for measuring turbulence and correlation with reaeration of water bodies**. Engenharia Sanitária e Ambiental, v. 9, n. 1, p. 30 – 44. ISSN 1413-4152. Published in Portuguese.

Szeliga, M. R.; Roma, W. N. L. (2009) **Reaeration Studies with Particle Image Velocimetry - S-PIV-3D System**. Engenharia Sanitária e Ambiental, vol.14, n.4, pp. 499-510. ISSN 1413-4152. doi: 10.1590/S1413-41522009000400010. Published in Portuguese.

Tao, B.; Katz, J.; Meneveau, C. (2002). **Statistical geometry of subgrid-scale stresses determined from holographic particle image velocimetry measurements**. Journal of Fluid Mechanics. Vol. 457, pp. 35-78.