

COMPUTATIONAL VISION SYSTEM FOR TURBULENCE MEASUREMENT AND CORRELATION WITH THE PHENOMENUM OF REAERATION

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Abstract

Bodies of water receiving wastewater have their dissolved oxygen decreased. The recovery of oxygen concentration occurs, mainly, through the mass transfer across the air–water interface and the process is increased by the surface turbulence. The measurement of the surface turbulence level is important for the determination of the natural reaeration capacity of these bodies of water. The method developed in this work consists on acquiring and computational processing the digital images of incidence and reflection of a laser beam on the surface flow. By using special algorithms as perspective correction, image threshold, determination of point of incidence and reflection and calculation of coordinates are obtained geometric data of the surface flow, by which the average vertical velocities and the amplified surface can be determined. These parameters are directly related with the turbulent intensity of the surface flow. With a Difference Finite Method the surface flow is simulated, reproducing important data of deformation of the surface. Through a graphic model these data are related to the reaeration coefficient K_2 for estimation of the water body's natural depuration.

Keywords: Natural Depuration, Reaeration, Turbulence measurement, Computational vision.

1. Introduction

The natural reaeration process of receiving water bodies of sewers involves the transfer of mass through the interface air-water. The demand for oxygen, resulting from the bacteriological action on the biodegradable organic matter can be supplied, or not, depending on the intensity with that the transfer phenomenon of oxygen occurs through the surface of the water body.

Quantitatively, the transfer of surface mass can be defined through transport equations that use the coefficient of gaseous transfer K_L , and more specifically, the transfer of oxygen, through the reaeration coefficient K_2 . Those coefficients are influenced by several factors as temperature, pressure, air humidity, wind and especially the turbulence in the surface. The turbulence plays an important part in the reaeration process, or by the insert of advectives components in the transfer, by the enlargement of the contact surface between the water and the atmosphere or by the renewal of the surface layer.

The study of the turbulent intensity helps in the obtaining of models that aid the process of administration of hydrographic basins on stipulating minimum conditions of previous treatment in discharges of sewers, as background for Studies of Environmental Impacts and other procedures related with the monitoring of the quality of water.

After the determination of the reaeration coefficient K_2 , for a given situation of water body, it is possible to evaluate the necessary time to a certain demanding of oxygen load has its level reduced to tolerable conditions. With the definition of the

degradation time of the load, it is also possible to calculate the length of intolerable effects in the water body.

The machine vision system for turbulence measurement on the flow surface consists on the acquisition and processing of digital images of the incident and reflecting laser beam on the surface flow at 30 pictures per second. This system doesn't introduce any mechanical element on the flow, thus it doesn't interfere on the surface oscillation.

The background to obtain the image is composed by the laser beam, the water surface and a horizontal screen; the laser reaching obliquely the surface determines the incidence point and it is reflected by the surface and reaches the horizontal screen, determining the reflection point. The acquisition of the images is accomplished through a digital camera positioned vertically over the turbulence generation system and connected to a personal computer through a "fire wire" interface.

The resultant file is processed in software which consists on the adaptation of a coordinate system and the obtaining of points of incidence and reflection for each digital image in the generated file.

The geometric calculation on the obtained coordinates defines the equation of the reflected ray straight line, which combined with the equation of the incident ray, results the equation of the normal line to the surface, at incident point. The normal line generates the tangent plan to the surface in the measurement point and, from the intersection of this plan with a fixed vertical axis, the vertical coordinate of surface point.

Considering the sequence of pictures, with a well defined time interval, and the displacements of the surface, it is easy to get the "instantaneous" vertical velocity of surface oscillation. The space accumulated divided by the accumulated time results in an absolute medium velocity of vertical oscillation. With longitudinal and transversal inclinations of the tangent plan it is possible to calculate the angular velocity with which the surface oscillates according to vertical plans in those directions.

The inclination data, together with the level of the flow are used in the propagation of the deformations verified in the measurement point. The information is associated to a mesh of finite differences that generates surfaces with deformation similar to the verified in the measurement point. This generated surface is used as a replacement of the original one and it permits to calculate the superficial area enlargement due to the turbulence.

Considering the sequence of surfaces generated by the system, the volume moved between each surface and its predecessor can be calculated. This volume divided by the interval of time results in a flow rate, which was denominated "Displacement Flow Rate".

The facilities in the laboratory are constituted by the production and image acquisition system and by the turbulence generation system composed by an oscillating grid on a prismatic tank.

The experiments were run by different types of oscillating grids and rotation speed, and several parameters related to surface turbulence were measured besides the experimental determination of the reaeration coefficient K_2 .

2. Bibliographical Revision

Reaeration studies in the Engineering School at Sao Carlos - EESC - USP, started with GIORGETTI & GIANSAANTI (1983) using soluble probes to evaluate the intensity of turbulence close to the surface in running water and correlating the results with the reaeration coefficient.

SCHULZ (1985) produced turbulence with liquid jets and correlated the coefficient of reaeration using the analogy with the dissolution of soluble probes of NaCl crystals close to the surface. BARBOSA (1989) used the technique of gas tracer and by the coefficient of desorption of the ethylene obtained correlations with the reaeration coefficient in tanks with agitation by rotating blades.

BARBOSA (1997) in the continuity of those studies used the technique of gas tracer in the determination of parameters of quality of water in natural courses. SCHULZ (1990) related the coefficient K_2 with the diffusivity establishing criteria for the proportionality with the agitation.

An optical method of evaluation of the surface turbulence (Optical Probe) was developed by ROMA (1988). In the work "Measured of parameters of surface turbulence and its interrelation with the reaeration coefficient", Roma introduced the idea of obtaining the level of oscillation of the free flow surface through the relationship between the oscillation and the signal captured by a photo transistor submerged and illuminated by an incandescent light.

The luminous intensity is converted in electric signal whose tension is registered and associated to the velocity of surface deformation. The device was tested experimentally in laboratory using a tank of oscillating grids for artificial production of turbulence, obtaining correlations between the turbulence measures and the reaeration.

CARREIRA (1994) proceeded to similar experiments using a tank with turbulence generated by rotating blades obtaining strong correlations on the turbulence signals of the photo transistor and the reaeration coefficient. ROMA (1995) using data of the Optical Probe investigated the surface deformation due to the turbulence determining the proportionality between the surface deformation and the luminous contribution to the optical sensor.

MELLO (1996) developed experiments on the oscillating grids tank and using the Optical Probe established geometric relationships for the deformed surface and correlated the surface deformation and the reaeration. SILVEIRA (1997) proposed models of calibration for the Optical Probe through experiments using the propagation of waves in channels, measuring the deformations and comparing the results with the signals obtained by the Optical Probe.

MIRANDA (2000) using the Optical Probe accomplished studies of the correlation between the turbulence data and the coefficient K_2 in the frequency domain. PEREIRA (2002) correlated turbulence parameters close to surface with the reaeration coefficient through photographic technique.

SZELIGA & ROMA (2004) obtained a graphic model for correlation between surface turbulence and the reaeration coefficient. SZELIGA & ROMA (2009) using the technique of Particle Image Velocimetry obtained an equation for the reaeration coefficient with data of velocities of vertical oscillation of free surface flow in a tank with oscillating grids.

RIGHETTO (2008) developed an oscillating grid tank for turbulence production and research about the reaeration coefficient.

The pioneers in the use of systems of turbulence generation by oscillating grids were ROUSE & DODU (1955) that researched the turbulent process of mixture using an interface liquid - liquid. FORTESCUE & PEARSON (1967) studied the turbulence developing what was called Model of the Great Whirls.

THOMPSON & TURNER (1975) used the system of oscillating grids in the study of the turbulent structure. Studies related with the frequency of oscillation of the grids and the surface turbulence were developed by HOPFINGER & TOLY (1976), complementing the work of THOMPSON & TURNER. These researchers used the Hot Film Anemometer to measure the turbulence in layers close to the surface.

3. Methodology

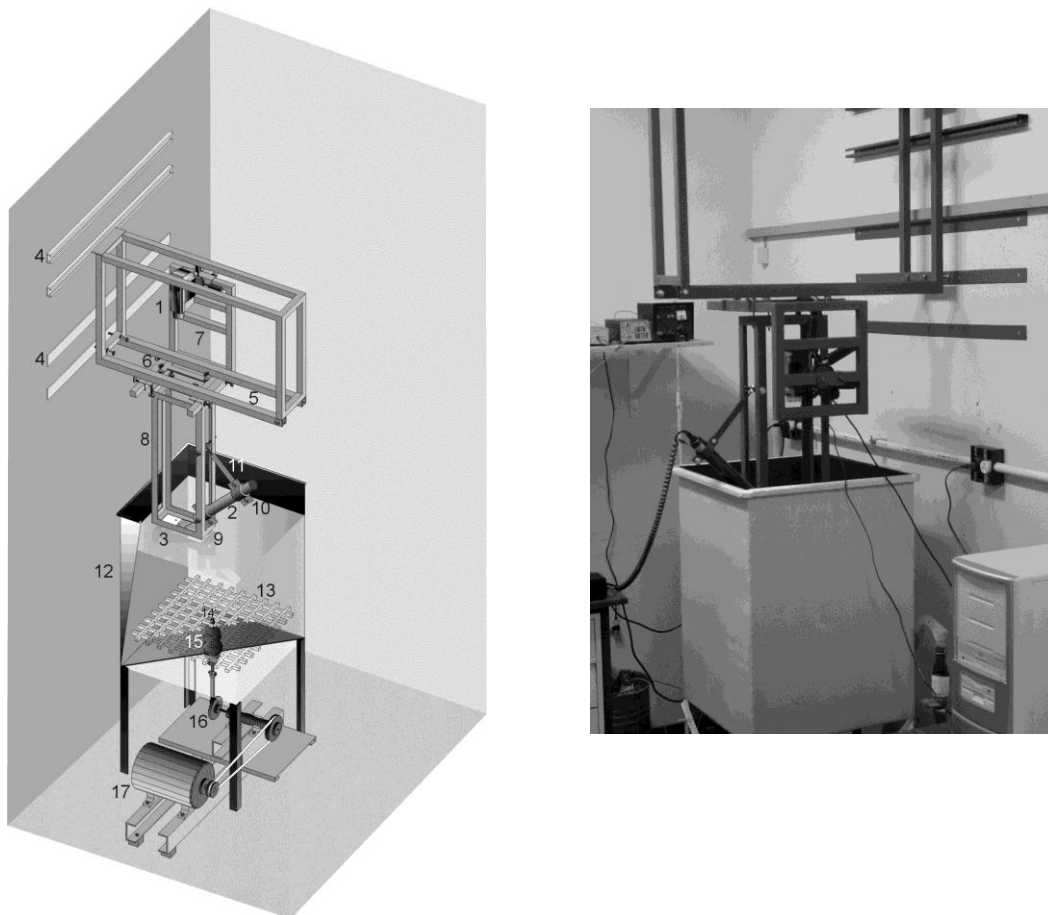


Figure 1 –Oscillating grid tank and supports for the measurement system.

The system is composed by a devices support set, turbulence generation, hardware and software for obtaining and visualization of results. At Figure 1 a general view of the facilities is shown. The production and acquisition devices of images are installed in a metallic support set. The support was designed to guarantee an appropriate positioning of the digital camera (1), the centralizing laser (2) and the projection screen (3), besides providing mobility to the set making possible the measurement in different positions.

The support set is coupled to horizontal guides (4) fixed on the wall allowing traverse mobility. The multiple guides fixed at different levels make possible vertical

mobility for the support set. The mechanical design of the support set was think for level adjustment and three way mobility using two sustentation rails (5), connection tray (6), camera support (7) and the laser support (8). The projection screen (3) is fixed on the base of the laser support. The laser (2) unit is supported by a "pivot" (9), a handle (10) and adjustment system (11) for the inclination angle. The turbulence system contains the steel tank (12), the oscillating grid (13) sustained by a central rod (14), lubricated and wrapped up (15) to avoid oil contamination. The vertical oscillation is produced by a rod-crank mechanism (16) driven by a direct current electric motor (17) powered by a variable power supply to allow variation of the rotation speed.

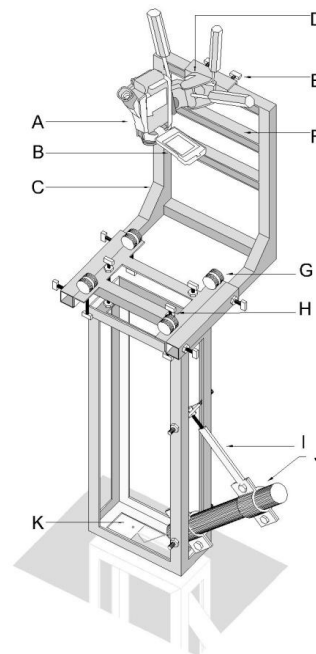
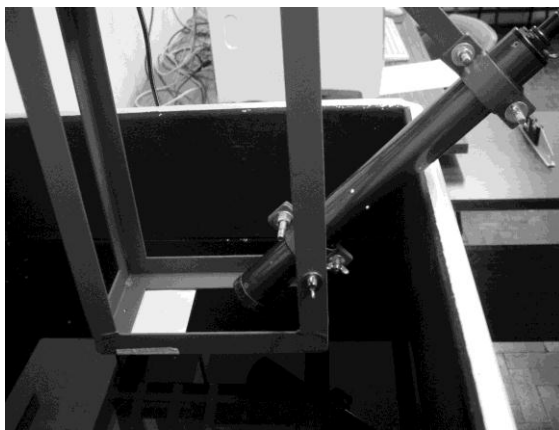


Figure 2 – Detail of the laser unit and projection screen and support of devices. A – Digital camera; B – Lateral viewfinder; C – Camera support; D – Tripod basis for camera; E – Support lock; F – Slips for camera settlement. G – Fitting pulleys in the rail; H – Regulation screws; I – Adjustment stem; J – Laser Unit; K – Projection screen

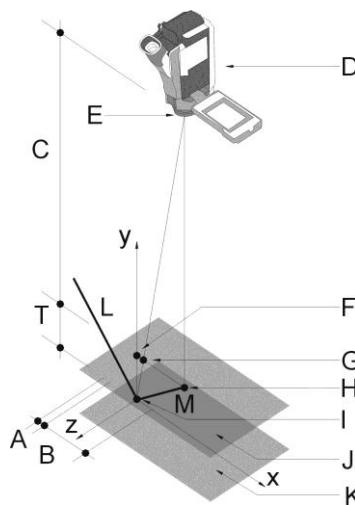


Figure 3 – Geometry of the incidence, reflection and correction of the perspective distortion. A – Correction in the direction GH; B – Length of the segment GH; C – Height of the optical center; D – Camera; E – Optical center; F – Point - image corrected; G – Point - image; H – Center of the image; I – Real point (incidence); J – Plan of the screen; K – Plan of the water surface; L – Incident ray; M – Reflected ray; T – Height of the projection screen;

A picture of the laser unit and of the projection screen as well as a representative illustration of the supports devices are shown in Figure 2. The coordinate system, whose origin is situated in the incidence of the laser beam, and the geometric elements used for perspective correction, are shown in Figure 3.

A typical image (Figure 4), obtained in the data acquisition consists on a dark background and two illuminated areas. On the left appears the incidence area and on the right the reflection area on a neutral and relatively homogeneous background. The images are converted to 8 bits depth, 256 gray scale and resolution of 360 x 240 pixels. In the image processing the coordinates of incidence and reflection coordinates are obtained with a image threshold operation and a sweeping on the image matrix to identify the areas, separate the background and calculate the geometric center of each one.

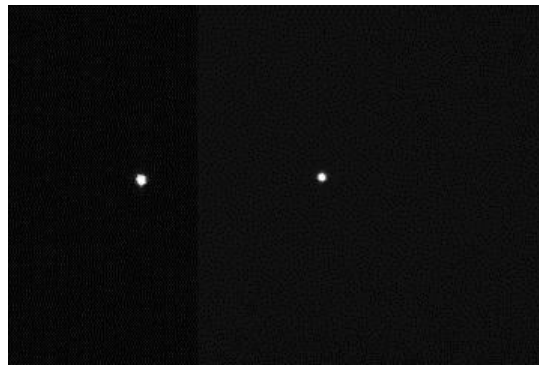


Figure 4 – Typical image.

The threshold operation doesn't implicate in the loss of information concerning to the gray level of each pixel. Each position of the binary matrix, that has value 1, has the gray level preserved in the other matrix and taken into account in the calculus of the coordinates of the incidence and reflection points.

Being admitted that the intensified region is relative to the center of the light beam, it is important to take into account, in the calculus of the coordinates, the intensity of each pixel belonging to the region of the image. In the Figure 5b, the definition of the region is shown after the threshold of the image. They are the internal pixels, with superior intensities to the chosen threshold, that influence the values of the relative coordinates to the region. The gray levels, for the 8 bits images, vary among values of 0 (black) and 255 (white). Those levels work like "weights" in the calculus of the coordinates through a weighted average. Thus, according to the distribution of intensities, the coordinates x and z that represent the incidence or reflection, located in the region and with tendency for the area of more intense pixels as appears in the Figure 5c.

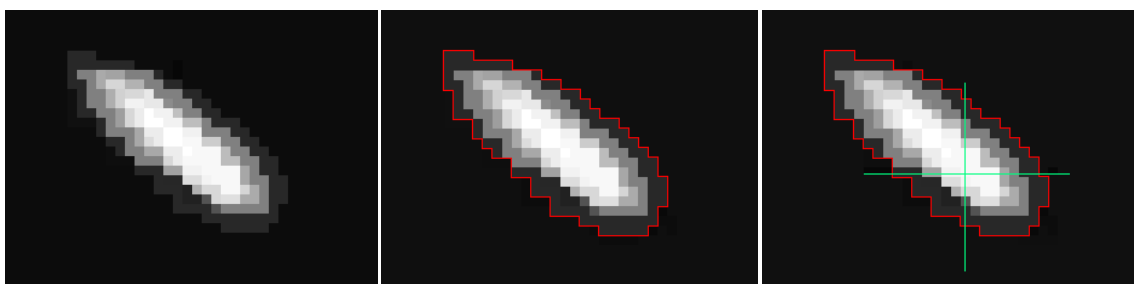


Figure 5a – Region.

Figure 5b – Region detecting.

Figure 5c – Weighted center.

The reflection point is in the plan of true greatness of the system and the incidence point has its coordinates corrected in function of the perspective distortion. The files, containing 1060 pictures on average, have about 35 seconds of time length.

An indexed variable keeps the values of the coordinates of incidence and reflection of each picture to use in the geometric processing. In this stage, after the equations of the line of the reflected ray and normal line to the surface had been obtained, it is defined, at each instant, the tangent plan to the surface at the measurement point. The intersection of that plan with the y axis of the system of coordinates (Figure 6) determines a point whose displacement is obtained to each instant.

This displacement divided by the interval of time results in an instantaneous vertical velocity of oscillation. The space accumulated divided by the accumulated time defines an absolute medium velocity. Alternatively also it proceeds to the calculation of the root mean square velocity - V_{RMS} - which consists on the square root of the sum of the squares of the instantaneous velocities divided by the number of samples.

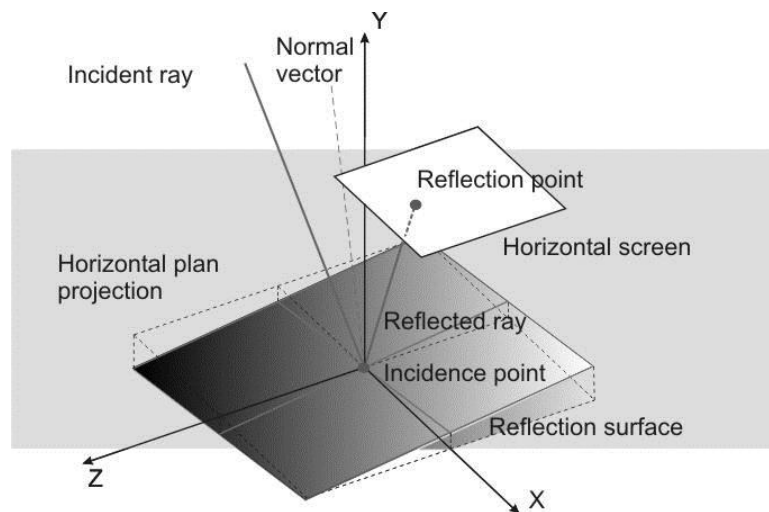


Figure 6 – Outline of the incidence and reflection lines and the tangent plan to the surface of the flow at the incidence point.

The successive inclinations of the tangent plan to the surface, according to the x and z directions, determines the variation of the angle of the surface in the measurement point. The angular velocity is calculated at each instant, and the medium absolute angular velocity of the flow is calculated along the total time.

The steepness, together with the quotas of level of the measurement point, leads to the calculation of the superficial enlargement through a numeric process of finite differences that result in the propagation of deformations. The method uses the numeric algorithm SOR - Successive Over Relaxation - applied to the first order differential equation and the level quotas in order to, iteratively and recursively, spread values to the neighboring elements. In that process, the knots of the finite differences mesh receive "properties", of level and inclination, interacting the readings of the current picture, of the previous and of the subsequent ones.

Three-dimensional surfaces are generated with current characteristics of the verified in the measurement, creating an equivalent surface to the real flow. The surfaces areas are calculated through the sum of the areas of the cells of the mesh of finite differences and that value is divided by the area of the projection on the plan xz,

producing an enlargement factor. The mesh of results contains 400 cells equivalent to a plane area of 400 mm^2 .

Another form of calculation of the vertical velocity of oscillation is the determination of the intersection of the deformed surface with the y axis. The oscillation of this intersection drives a traveled space that divided by the time determines an absolute medium velocity. It is verified, from the experimental data, that the speed calculated by this method and by the intersection of the tangent plan with the y axis doesn't present significant differences for flows with vertical oscillations of small amplitude. However, with the increase of the amplitude, the current result of the calculation for the deformed surface presents larger errors.

Between a surface and another, exists a volume displacement. It is possible to calculate the volume associated to a certain surface through the prismatic elements resulting from the projection of the cells of a finite differences mesh on the plan xz. For each surface the associated volume was calculated and their difference defined a volume displacement that divided by the interval of time resulted in a flow rate.

The absolute medium flow rate, designated as "Displacement Flow Rate" became an important parameter for analysis, since it results, simultaneously, from the deformation levels, from the vertical velocities and from the vertical amplitude of oscillation. Figure 7 presents an example of the representative finite differences mesh of the deformed surface of the flow. Composed by 3600 cells, just the results of the 400 central cells are taken in advantage and shown in the results. The form as it results from the computational program includes the axes of the coordinates system, the incident and reflected rays, the intersection points and several visualization modalities.

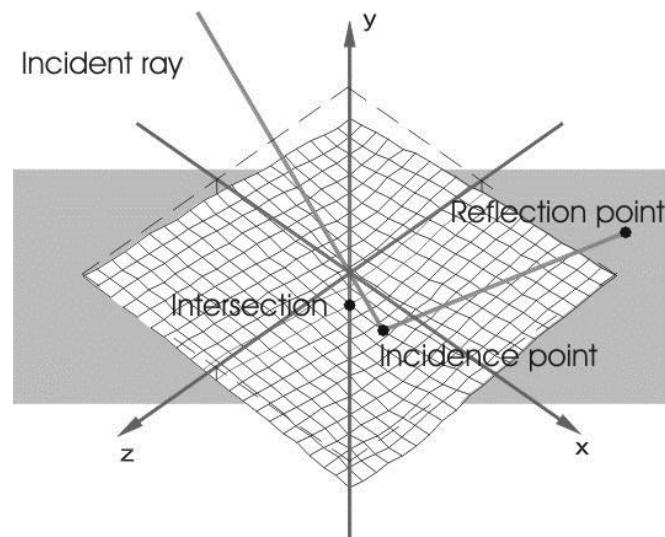


Figure 7 - Finite Differences Mesh

The computational program developed exclusively for this system, in the Visual Basic language under Windows platform, is composed by several stages, including adjustment of the system of coordinates, processing of images, geometric processing, propagation of deformations, alternative calculations for interpolations, graphic and numeric outcome.

Each stage is processed in an addressed sequence and several procedures are interactive, providing visual information on the physical and geometric context of the flow through graphic interface. It is possible to visualize, in three dimensions, with a varied range of alternatives, the oscillation of the tangent plan to the surface along the

time, all the coordinates of the main involved graphic elements, the instantaneous velocities and the averages along the time through interactive graphs.

Several visualization resources are available for the surfaces generated in the propagation of the deformations, where also visualization windows were included in 2D for the iso-lines maps. The results are presented in spreadsheets and interactive graphs where access is made to the generic and individualized information, as values of spaces, times, speeds, tendencies, averages, confrontations and comparisons, in windows where the movement of the mouse cursor provides the events.

In several phases of the program it is possible to export data files for be printed or verified in electronic spreadsheets. As it is treated of a prototype program several analysis tools were included in the intention of aiding the understanding of the results in a process where the user defines the level of detail of the exhibition of calculations and results.

4. Computational Processing

Initial stage. Adjust of the coordinates system

The adjustment of the system of coordinates occurs with the aid of a picture obtained through a static rehearsal. In that rehearsal is proceed a scene without movement of the surface. The incidence and reflection points are taken for origin and alignment of the system of coordinates. In this stage the user with the thresholding tools establishes the criteria for separation between the image background and the incidence and reflection areas. The Figures 8 and 9 contain reproductions of the initial modules of the computational program.

Image processing

In the screen of image processing, after the load of the file generated in the acquisition, the coordinates of incidence and reflection are obtained, frame by frame, and the results are presented in the displays. With the Figure 10 is shown the screen of the module of image processing and the necessary elements for operation.

Geometric processing

In this stage are obtained the coordinates of several points of interest for the Optical System and the calculated values are shown, frame by frame, in displays in the screen of the geometric processing module. Also the profile of the incidence and reflection are shown with the plan xz and plan xy . After the processing all the values which define the surface oscillation, can be revised, frame by frame, with the use of the exhibition buttons. The Figure 11 is the module screen reproduction.

Oscillation module

In the screen of the oscillation module appears the visualization window of the tangent plan to the surface where reproduces, along the time, the oscillation and the positioning of the geometric elements. There are several available ways of elements visualization and legends, including visualization in real time, camera position and zoom with controls in the menus and in the mouse movement. It is also included the interactive

graph of the instantaneous velocities, absolute medium velocity and quadratic medium velocity V_{RMS} . The visualization of the graph is integrated into the window of the tangent plan and the positions are altered with the movement of the mouse pointer. The Figure 12 contains a reproduction of the oscillation module.

Propagation module

In the screen of the propagation module it is shown the window of numeric processing for propagation of the deformations and visualization of the deformed surface in 3D, in "shade" way or in "wire frame" way, with camera angle and zoom available to the user. Also is found the window of visualization 2D of the surface iso-lines map and traverse and longitudinal profiles, besides the operation controls and displays. The information of quotas of levels and coordinates are presented with the movement of the mouse pointer and the geometric elements are available for visualization through the menus. The colors associated to the surfaces reflect the quota y of the knots of the surface mesh and the deformation thickness can be evaluated by the palette of colors used in each surface and with aid of a specific palette display. With the Figure 13 is shown the screen of the module.

Outcome

After the module of propagation of the deformations the final results can be accessed in form of spreadsheets, interactive graphs and summaries, however, in specific modules, other information will be able to be processed, as calculation of positions and speeds for interpolations, histogram of speeds and the divergent of the vertical velocity with results supplied in graphic and numeric displays. The Figure 14 is the screen reproduction of the spreadsheet and interactive graphic.

The screenshot shows the 'Sistema Óptico Para Turbulência Superficial' software interface. It features a 3D schematic of an optical setup on the left, a menu of options in the center, and a parameter adjustment panel on the right. The interface includes a status bar at the bottom with the time '17:16' and date '27/9/2002'. Annotations with arrows point to specific elements, categorized into steps and optional features.

Step 1 Optional: Alteration of the quota of the screen – T – in mm. Click in OK for

Step 2 Optional: Alteration of the height of the camera – C – in mm. Click in OK for confirmation.

Step 3 Obligatory: Link for opening of the picture file.

Step 4 Obligatory: Link for the window of the histogram image for definition of the threshold. Optionally the threshold can be chosen directly through the rolling control below in that window.

Step 5 Obligatory: Link for calculus of the incidence and reflection coordinates with the still picture.

Step 6 Obligatory: Link for adjustment of the system of coordinates to the points of the still picture.

Step 7: Button of finalization of the stage. It becomes available after effectuation of the obligatory steps.

Optional features:

- Use of default values just for tests
- Enhance of the regions with the option Zoom.
- Use of manual adjustment just for tests
- Zoom - Options of visualization of the image and regions.
- To turn off or draw the axes for image observation.
- Window of visualization of the image, axes, regions and calculated points.
- Zoom in
- Zoom extends
- Zoom window
- Alternative: Threshold direct choose.
- Zoom out
- Zoom previous
- Zoom pan
- Status Bar. Indicates the functions of the pointed elements.

Figure 8 – Screen of the initial module of the Optical System computational program.

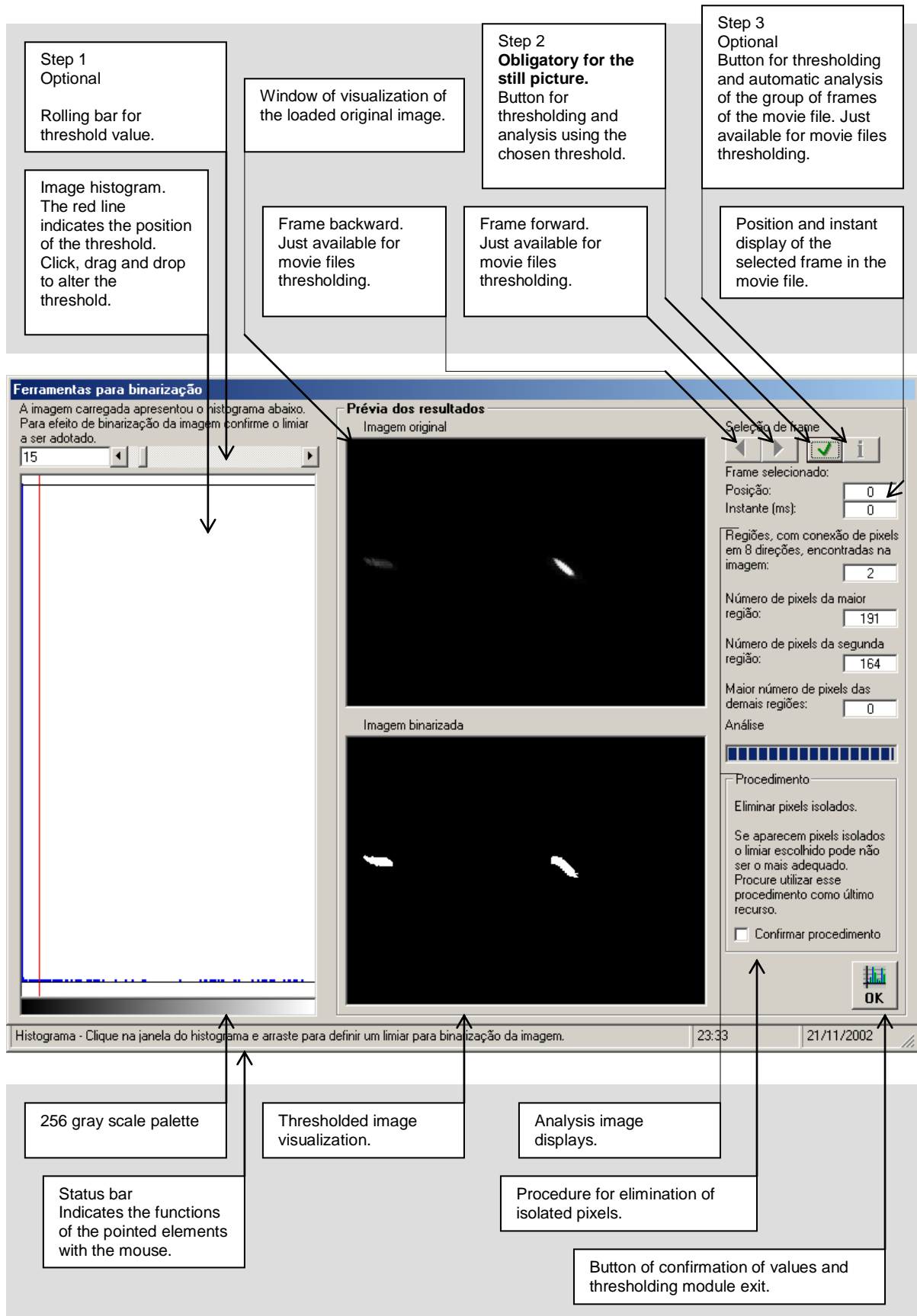


Figure 9 – Screen of the thresholding module.

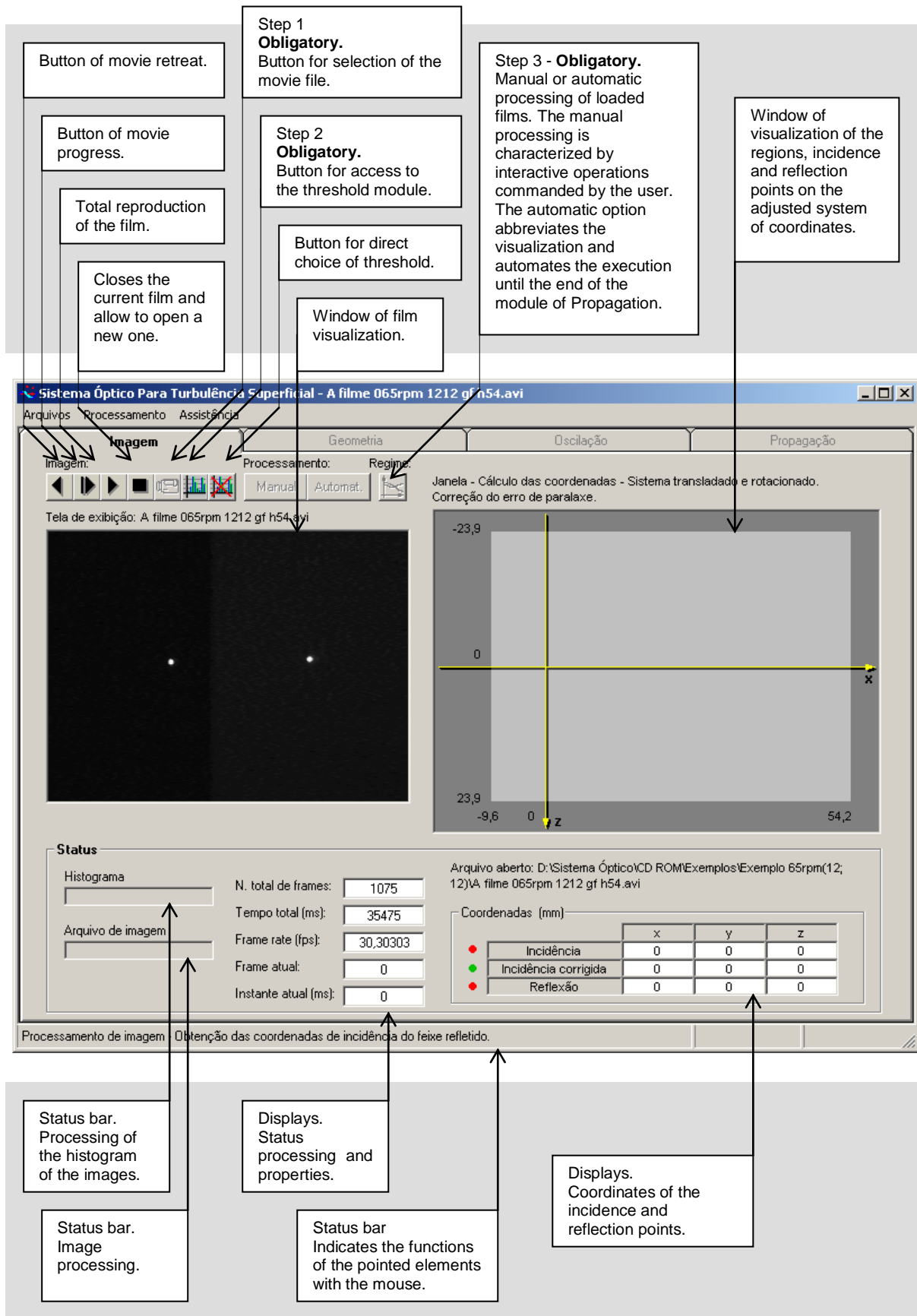


Figure 10 – Screen of image processing module.

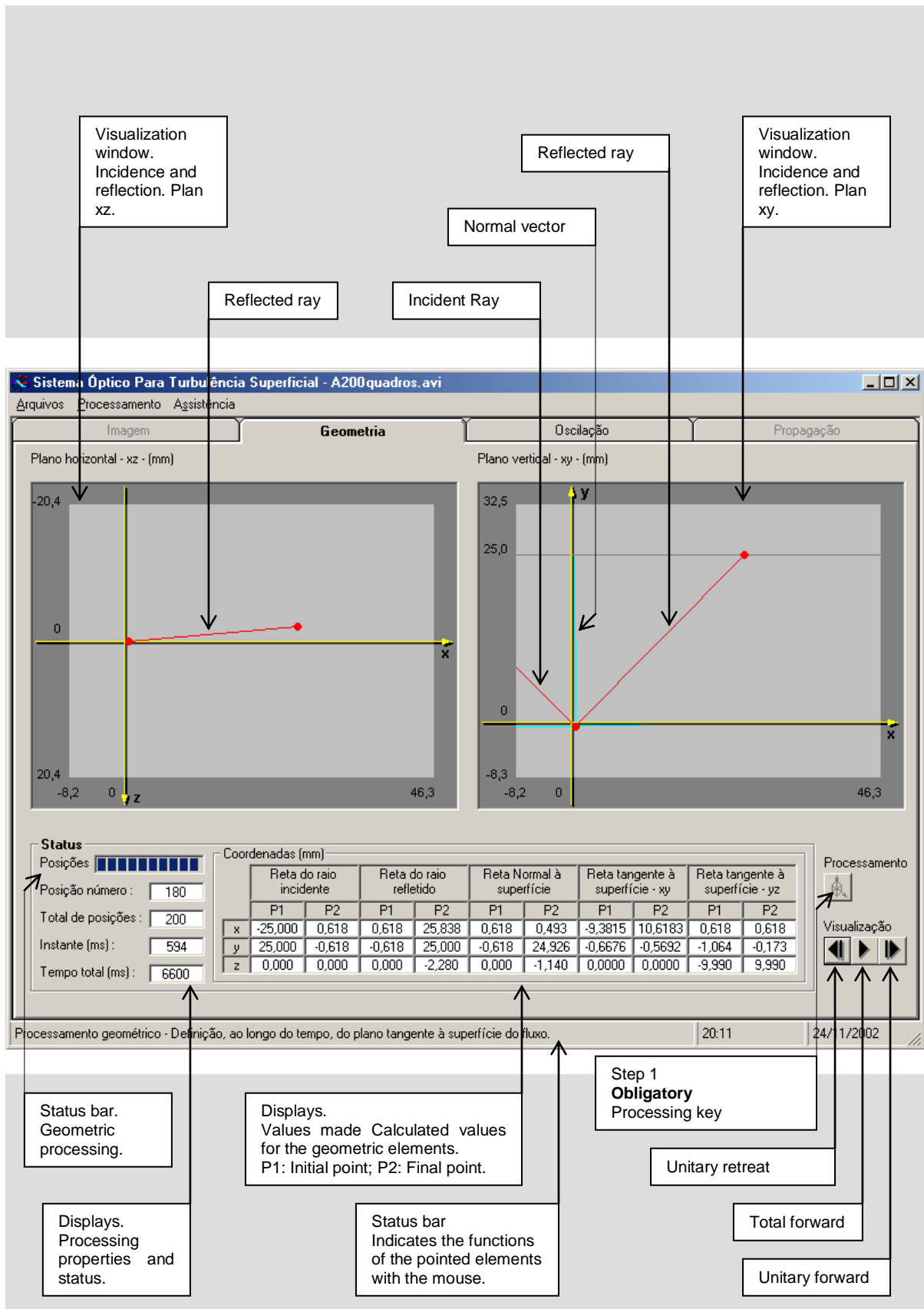


Figure 11 – Geometric processing module.

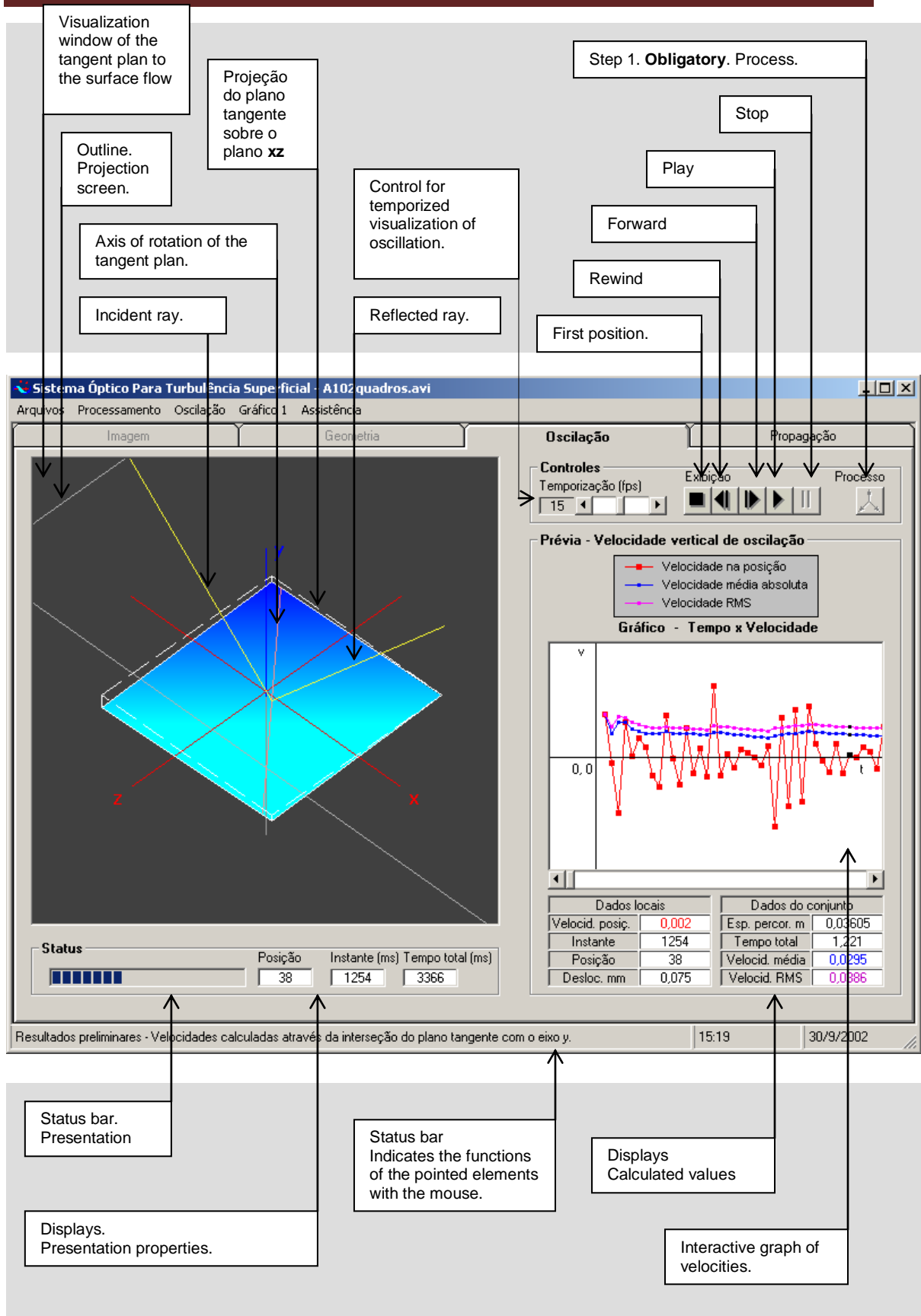


Figure 12 –Oscillation module screen.

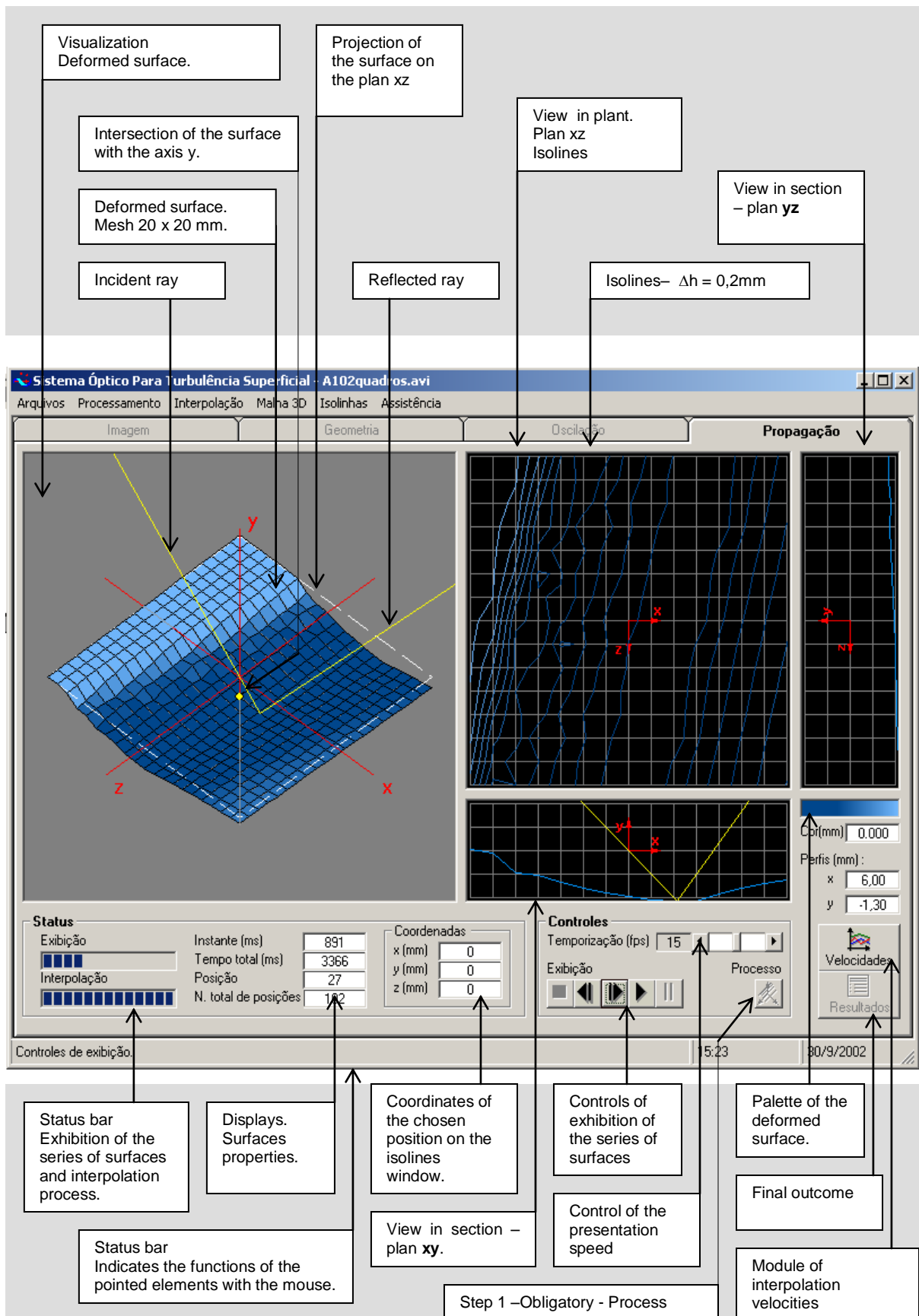


Figure 13 – Propagation module screen.

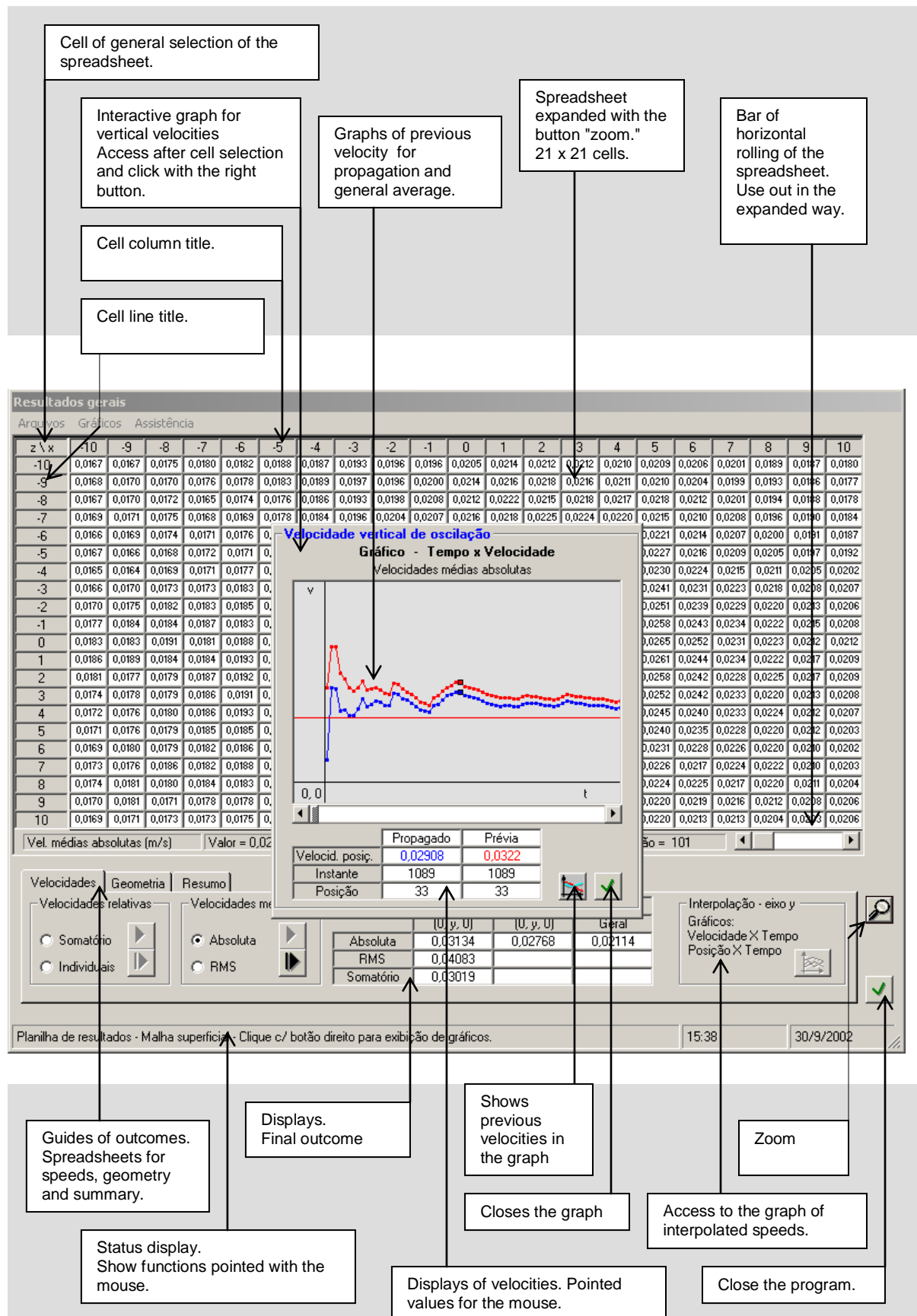


Figure 14 – Screen of results and interactive graph.

5. Conclusions

The outcome of Computational Vision System for Turbulence on the Surface demonstrated enough adaptation to the measurement objectives. Satisfactory answers were obtained regarding the speed of acquisition of data and regarding the precision in the obtaining of distances, that reach significant values around thousandth in second and of the millimeter hundredth respectively in this system.

The measured values for the velocities of surface oscillation of the flow and of the angular speed, presented agreement with the energy supplied to the system through the movement of the oscillating grids. The evaluation of the surface deformation, obtained by the system, was capable to identify the way of deformation through the type of oscillating grids and oscillation imposed to the grids. In that case was defined an "identity" for the flow.

That identity bases on measured characteristics that are registered in form of vertical velocities, angular velocities and flow rate of displacement. For the case of a measurement in field, if occurs repetition of characteristics, the flow will be recognized and its capacity of absorption of oxygen can be determinate.

The development of Computational Vision System for Turbulence on the Surface, in that phase, corresponded to a device adapted for specific conditions of laboratory. In that situation exists control some conditions that govern the system as the characteristics of the supports, digital camera, illumination, process of static calibration with the rehearsal of null rotation, software of the system and environmental conditions.

The operation in field situations depends, still, on considerable development in terms of procedures and adaptations to the inherent conditions of the environment. It is necessary support set with micrometric adjustment, appropriate facilities to guarantee the reliability of the measurements, protections for the electronic equipments, a new calibration system to avoid the static rehearsal, adaptation of the software for obtaining of results in real time and others providences.

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References

CARREIRA, M. F. (1995) **Relationship between the mass absorption coefficient KL and surface turbulence parameters obtained by optical methods**. Dissertation submitted to the School of Engineering of Sao Carlos, Sao Carlos: EESC – USP. 188p. Published in Portuguese.

COULSON, J. M. & RICHARDSON, J. F. (1979) **Chemical Engineering**. Oxford: Pergamon Press. 468p.

FORTESCUE, G. E. & PEARSON, J. R. (1967). **On gas absorption into a turbulent liquid**. Chem. Eng. Sc. Pergamon Press. P. 1163 – 1176.

HOPFINGER, E. L.; TOLY, J. A. (1976) **Spacially decaying turbulence and its relation to mixing across density interfaces**. J. Fluid Mechanics, p 155 – 175.

MELLO, E. D. (1996) **Optical system for evaluation of the coefficient of reaeration in surface water bodies**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP. 150p. Published in Portuguese.

MIRANDA, L. M. (2000) **Study of surface deformation generated by turbulence in the air-water interface, in the frequency domain, and its correlation with the coefficient of reaeration**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP, 125p. Published in Portuguese.

PEREIRA, C. E. (2002) **Study of turbulent parameters and their relationship with the reaeration coefficient using the photographic technique**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP, 192 p. Published in Portuguese.

RIGHETTO, M. M. (2008). **Development and calibration of a reaeration tank equipped with oscillating grid**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos, EESC – USP. 174p. Published in Portuguese.

ROMA, W. N. L. (1988) **Measurement of surface turbulence parameters and its interrelation with the coefficient of reaeration**. Thesis of Full Professor submitted to School of Engineering of Sao Carlos. Sao Carlos: EESC –USP. 74p . Published in Portuguese.

ROMA, W. N. L. (1995) **Surface deformation measurement with optical sensor and correlation with reaeration coefficient**. In: International Simposium on Air – Water Gas Transfer. Heildeberg, Germany.

ROUSE, H.; DODU, I. (1955) **Turbulent diffusion through a discontinuous density**. La Houille Blanche, 10: p. 522-581. Published in French.

SILVEIRA, P. E. (1997) **Development of a device for the measurement of deformations on the surface of a liquid**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP, 88p. Published in Portuguese.

SCHULZ, H. E. (1985) **Investigation of the mechanism of reoxygenation of water flow and its correlation with the level of turbulence near the surface -I**. Dissertation submitted to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP. Published in Portuguese.

SCHULZ, H. E. (1990) **Investigation of the mechanism of reoxygenation of water flow and its correlation with the level of turbulence near the surface - II**. PhD thesis presented to the School of Engineering of Sao Carlos. Sao Carlos: EESC-USP. Published in Portuguese.

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.

THOMPSON, J. S.; TURNER, J. S. (1975). **Mixing across an interface due to turbulence generated by an oscillating grid**. J. of Fluid Mechanics. 67: p. 349 – 368.