INTERACTION FLUID-STRUCTURE STUDY BY ACQUISITION OF SIGNALS AND IMAGES PROCESSING

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Abstract. *This paper determines experimentally the action of a fluid in a submerged structure using strain gages to compare it with theoretical data. It also obtains the velocity field of a fluid using digital images processing when the presence of a body causes the formation of vortex. A thin aluminum flat plate submerged in a flow of water in a rectangular channel was used as structure. The velocity profile of the fluid was drawn as well the drag and lift coefficients and Reynolds number were calculated over the height of the plate. These results allow us to obtain the strain that the plate is subject and its theoretical deformation. An assembly of four strain gages, was put on the plate, two of each side of the plate, forming a complete bridge of Wheatstone where it was applied a tension of 20V (constant). The deformation of the plate was obtained from the potential difference measured between the terminals of the assembly. Vortex were produced by the action of the plate over the fluid and visualized in a clear acrylic channel utilizing Velocimetry by Images of Particles (PIV). The crossed correlation functions of the corresponding functions of two images were obtained in different instants by a CCD video camera and the velocity field was obtained by the method of the high density of traced particles distributed in the flow.*

Keywords: interaction fluid- structure; extensometer; particles images velocimetry (PIV); vortex

1. Introduction

Second Goldstein, 1965, the first theoretical deduction of a formula for the drag was provided by the so-called theory of free stream-lines, developed, for flow past a flat plate, by Kirchhoff and Rayleigh according to the methods used by Helmholtz for two-dimensional jets, and extended by Levi-Civita and others to the case of curved rigid boundaries. According to this theory there is, in two-dimensional flow past a flat plate, for example, a mass of fluid at rest behind the plate separated from the stream by two streamlines springling from the edges of the plate. The velocity is discontinuous across these streamlines, which are therefore the traces of vortex-sheets. The velocity just outside the "free" streamlines is constant, and equal to the velocity U of the undisturbed stream. The pressure in the stagnant fluid is constant and equal to p_o, the pressure at infinity. This theory has considerable theoretical, but very little practical importance, its results being largely in disagreement with the results of observation in real fluids of small viscosity. Thus, for two-dimensional motion past a flat plate at right angles to the stream, the theoretical result for the drag coefficient is 0,880 while the measured value is nearly 2. The discrepancy arises largely from the fact that there is actually a defect of pressure, or suction, at the rear, the pressure being much less than p_o, and similar features are present in other typical cases.

In other important respects the theory is widely at variance with reality, since behind a bluff obstacle in a stream the observed motion either is an irregular, eddying one, or for two-dimensional motion at certain Reynolds numbers has, for some distance behind the obstacle, the appearance of a double trail of vortices with opposite rotations. Even if a motion with vortex-sheets, be supposed set up in an inviscid fluid, it would not persist, since it would be unstable. The notion that the stream leaves the plate at the edges is, however, valuable and in accordance with reality; and a vortex-sheet (more accurately, for real fluids, a thin vortex-layer) does being to be formed from the edges of the plate. But this vortex-sheet or layer is not fully develop either in a real or an inviscid fluid; it curls round on itself, and something much more in the nature of concentrated vortices is formed.

The double row of vortices can be idealized for an inviscid fluid, so that each vortex is supposed concentrated along a line at right angles to the plane of the motion. Kármán have studied the resulting arrangement. It appears that such a double row of vortices could keep its configuration unchanged, and would not be unstable for any slight displacements of the vortices parallel to themselves, only if the vortices in one row are opposite the points half-way between the vortices in other row, and if h/a = 0,28, as in a Fig. (1). A double row of this type is called a Kármán vortex-street, which would move, relative to the fluid, parallel to itself with a velocity u depending on the strength of each individual vortex. The vortex-street may be regarded as an idealization of the conditions behind a bluff obstacle in a stream; and on this basis a theory of drag on the obstacle may be constructed by Lamb, 1932, Rosenhead, 1929 (Goldstein, 1965).

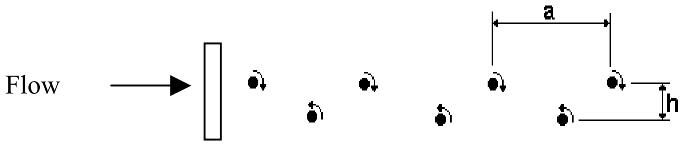


Figure 1. Kármán vortex-street.

Other authors, as Schilichting, 1968, that carried out the experiment using a cylinder as obstacle, Achenbach and Heinecke (1981) and De Carlo (1984), researched the formation of vortex provoked in the flow using a flat plate.

The objectives of this work are determine experimentally: a) the action of the stream of the fluid in a submerse structure using extensometers and to compare it with theoretical data; b) the velocity field of the stream when the presence of a body provokes the formation of vortex by the digital images processing method.

2. Fundaments of the interaction fluid - structure

When there is relative movement between a solid body and a fluid in which it is sunk, the solid is submitted to a resultant force F due to the action of the fluid. The nature of the forces that act are: the shear force, provoked by the friction between the fluid and the body and the force due to the pressure, provoked straightly by the distribution of pressure at the object. The resultant force F can be decomposed in the perpendicular and parallel components to the direction of the motion. The parallel component is the drag force, F_D, given by Eq. (1):

$$F_D = {}^1\!/_2 . C_D \rho V^2 A \tag{1}$$

where:

C_D = drag coefficient, function of the Reynolds number
ρ = density, kg/m^3
V= fluid velocity, m/s
A= flat plate area, m^2

The resultant drag force is the sum of pressure and friction drag (when the sunk body is not perpendicular to the stream). The perpendicular component to the flow motion is the lift force, F_L, determined by Eq. (2):

$$F_L = {}^1\!/_2 . C_L \rho V^2 A \tag{2}$$

where:

C_L = lift coefficient, function of Re number and the attack angle.

The strain analysis in a submerged body is based in the determination of the maximum normal flexion strain, σ_{max}, acting on the submerged body. This strain, when the plate is flat, is given by Eq. (3):

$$\sigma_{max} = \frac{M \cdot c}{I} \tag{3}$$

where:

c = distance to the neutral line = $t/2$ (t is the plate thickness), m;
I = Moment of inertia, m^4 (Eq. 4)
M = flexor maximum moment, N.m (Eq. 5)

$$I = \frac{b \cdot t^3}{12} \tag{4}$$

$$M = F_D \cdot h\!/_2 \tag{5}$$

where:

h = height of the flat plate (Fig. 2);
b = width of the flat plate (Fig. 2).

By replacing Eqs. (1), (4) and (5) into Eq. (3), we obtain Eq. (6), which supplies the maximum strain due to the drag coefficient and the characteristics of the plate and the flow.

$$\sigma_{max} = \frac{3 \cdot C_D \cdot \rho \cdot V^2 \cdot h^2}{2 \cdot t^2} \tag{6}$$

Equation (7) gives the Re_h number:

$$Re_h = \frac{V \cdot h}{\upsilon} \tag{7}$$

where:

ν is the cinematic viscosity of the water at 20^{o} C.

When $Re_h > 1000$, C_D becomes independent of the Reynolds number. It is only function of the geometry, i. e., the aspect ratio, *b/h*, according to the below Fig. (2), [Fox et al., 1998].

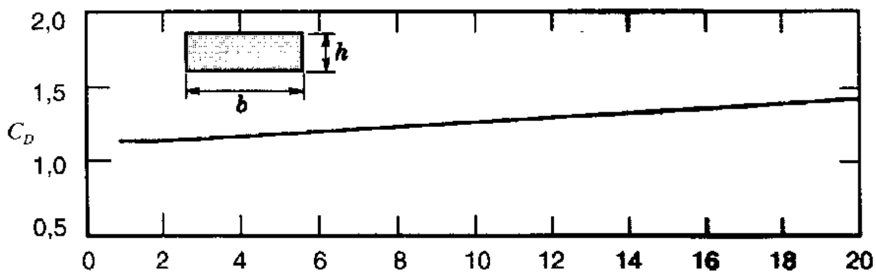


Figure 2. C_D as function of the aspect ratio, *b/h,* [Hoerner, 1965].

The plate deformation follows from the maximum calculated strain, ε_o, is given by Eq. (8):

$$\varepsilon_O = \frac{\sigma_{\max}}{E^*} \tag{8}$$

where E* is the module of elasticity of the flat plate material.

3. Experimental Methodology

A thin aluminum flat plate submerged in a flow of water in a rectangular channel was used as structure to determine experimentally the action of a fluid in a submerged structure. An assembly of four strain gages was arranged on the plate, two of each side of the plate, forming a complete bridge of Wheatstone where it was applied a tension of 20V (constant). Figures (3) to (5) show the rectangular channel and the plate position.

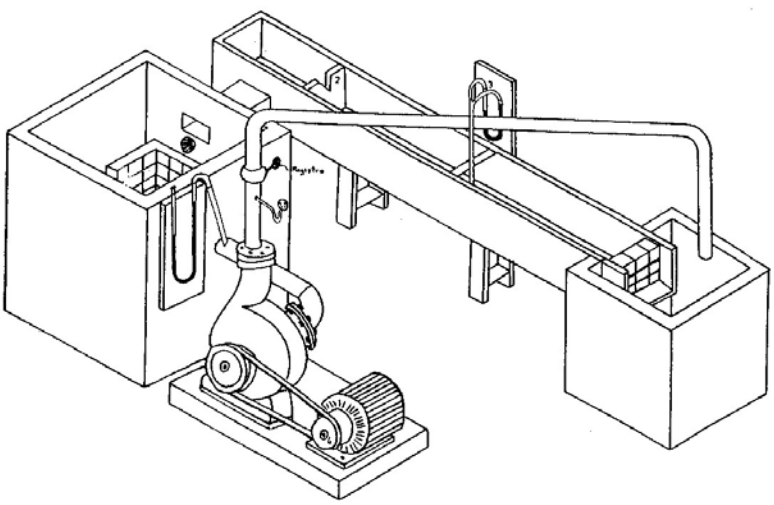


Figure 3. Rectangular channel used in the experiment.

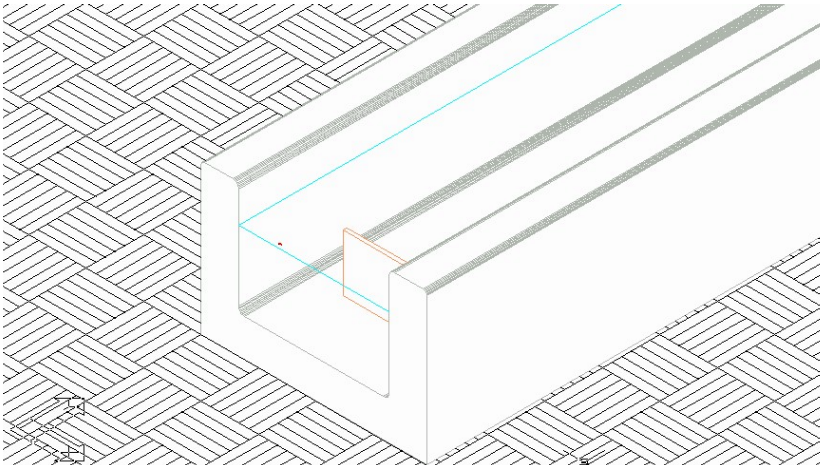


Figure 4. Position of the plate plan in the channel.

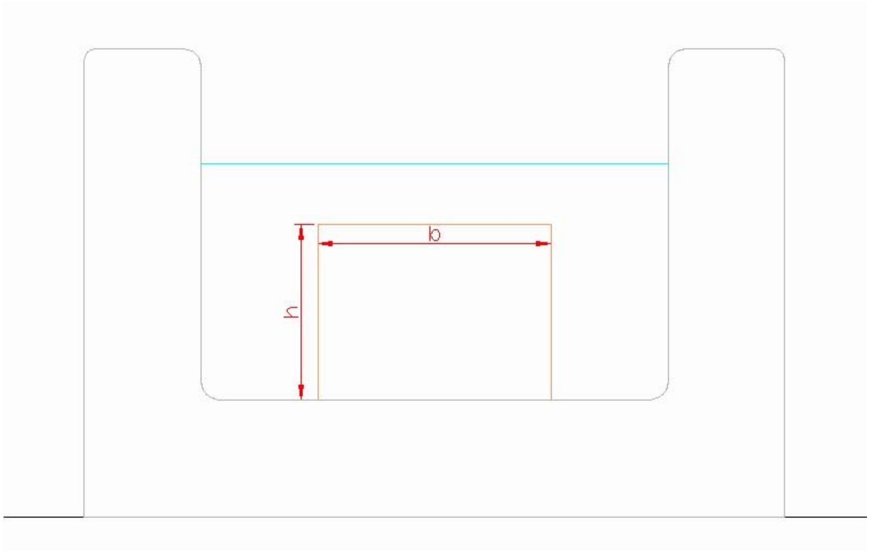


Figure 5. Frontal view of the plan of the plate in the channel.

The dimensions of the flat plate are given by the height, *h*, equals to 0.20m, the width, *b*, equals to 0.20m and the thickness, *t*, equals to 0.0005 m. Since the aspect ratio of the flat plate, b/h, is equal to 1, C_D is equal to 1.18 according to Fig. (2).

Figure (6) shows the arrangement of four strain-gages forming a complete Wheatstone bridge and located at 0.015m from the point where the plate is fixed.

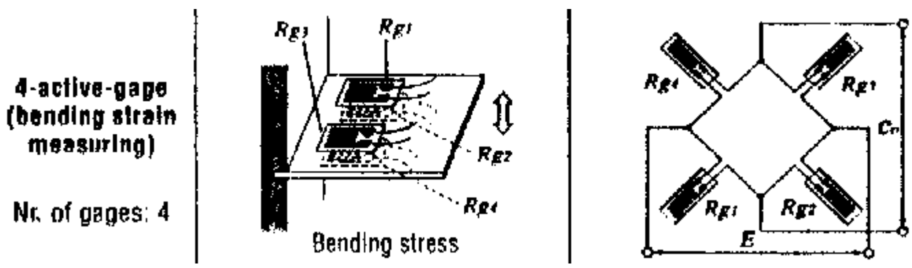


Figure 6. Arrangement of four strain gages forming a complete Wheatstone bridge.

The strain gage selected was KFC –2 – C –11 with resistance of 120± 0.3 Ω (KYOWA, 2002). The experimental deformation is given by the below Eq. (9) and σ_{max} is given by Eq. (8) (Section 2)

$$e_0 = K_S \cdot \varepsilon_0 \cdot E \tag{9}$$

where:

ε_o = specific deformation [$\mu\varepsilon$]

e_o = potential difference obtained in the output (mV)

E = potential difference applied in the input (V)

K_s = strain gage constant = 2.07 ± 1%

A tension source feeds the bridge and the answer is read using a signal acquisition plate [Advantech, 1995]. When the plate deforms, the resistances of the strain gages vary proportionally, a signal in mV is well-read in the acquisition plate, transformed in digital signal and stored in the computer, where is treated.

4. Images particles velocimetry

The velocity field of fluid acting on the flat plate was obtained by the approach of particles images velocimetry (PIV), described by Almeida, 1997. Figures (7) and (8) illustrate the assembly in the acrylic tank.

Figure 7. Picture from the assembly to determine the velocity fields.

A lightning produced by the laser source is transformed in a plan of small thickness after passing through the cylindrical lens. The moving fluid is lightened by the not pulsated laser plan incident in the side of the acrylic tank, lightening the traced particles. To determinate the vortex wake was utilized a monochromatic CCD camera that acquires 30 images by second equipped with lens of opening F = 4 mm and resolution of 768 X 494 pixels. The CCD video camera is positioned perpendicular to the stream and records the motion of the particles, which follow the fluid motion. The visualized images are captured and stored in the microcomputer. Successive images determinate the velocity field of the particles generated due to the vortex and the drawing of theirs paths. The studied stream is of water in the liquid phase and the traced particles are powder of glitter. The crossed correlation function of the corresponding functions to two images obtained in different instants is calculated and the approach of high density of traced particles distributed in the fluid is used to determinate the velocity field.

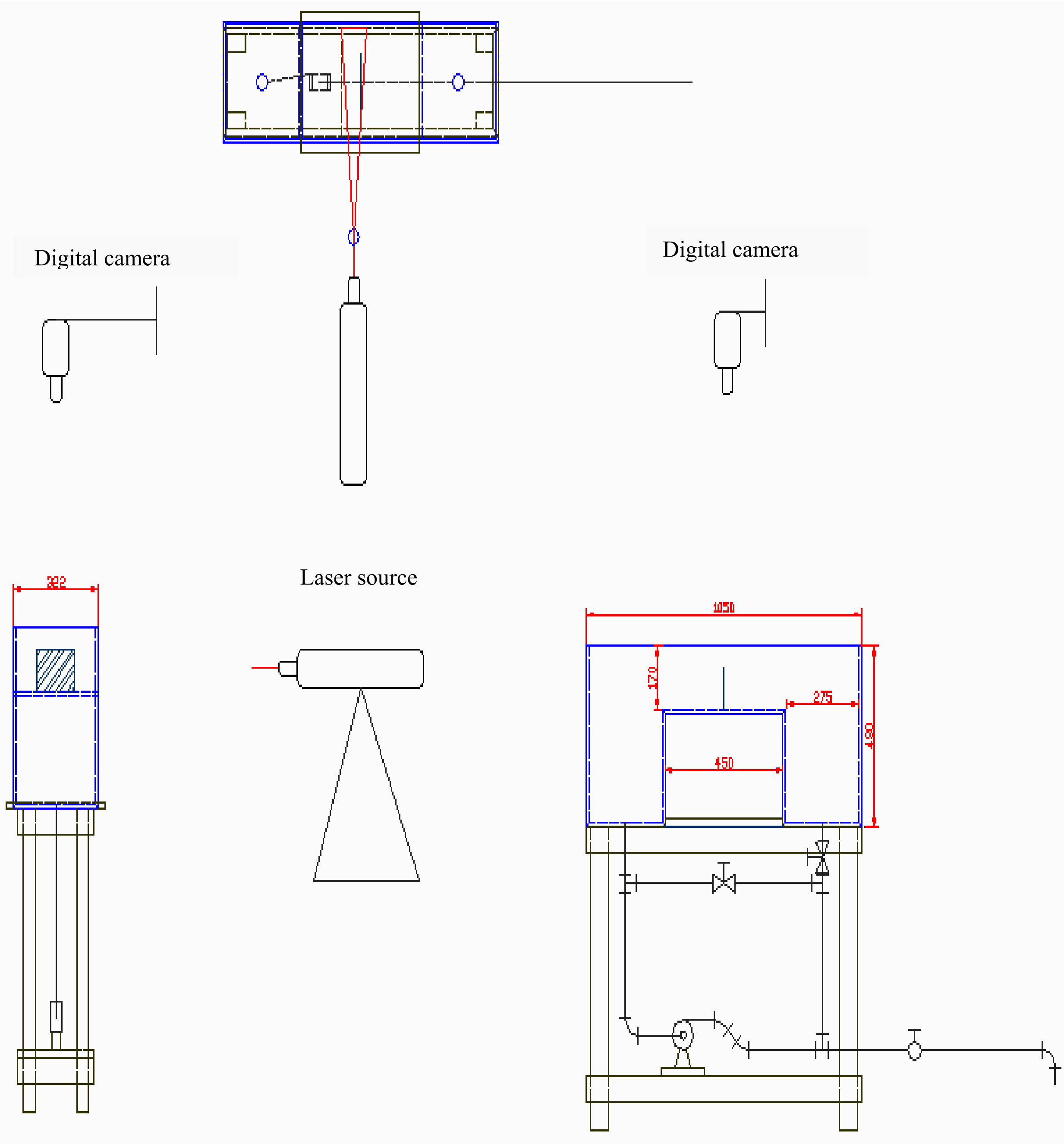


Figure 8. Assembly view for obtaining the velocity fields.

5. Analytical results

The analytical results were calculated according to Section 2. Table 1 shows the results obtained using an aluminum plate 2014-T6 with module of elasticity E* equals to 73.1GPa.

Table 1. Analytical Results

V (m/s)	F_D (N)	M (N.m)	σ_{max} (MPa)	ε_o ($\mu\varepsilon$)
0.07322±0.0061	0.1258	12.58	1.509	21.557
0.12847±0.0260	0.3867	38.67	4.640	66.286
0.17039±0.0220	0.6820	68.20	8.184	125.914

The velocity (V) in the channel was obtained experimentally, by accompaniment of a light buoyant body. The uncertainty of all experimental variables was calculated according to BIPM, 1997.

6. Experimental results

According to Section 3, the signal of potential output difference from the bridge of Wheatstone, e_o, was acquired and it was calculated the deformation, ε_o, and the strain, σ_{max}, by using Eq. (9) and Eq. (8), respectively.

Figures (9) and (10) show the behavior of the flexion strain due to the drag of pressure, as function of the time, for fluid velocity in the channel of 0.07322 m/s and 0.170 m/s, respectively.

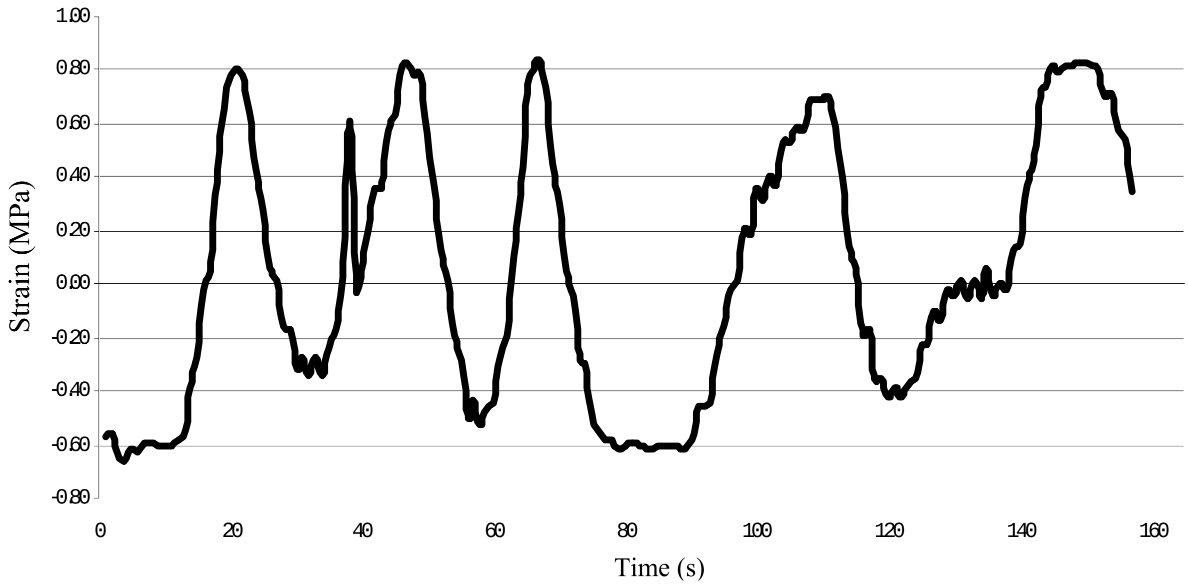


Figure 9. Behavior of the flexion strain due to the drag of pressure as function of the time, for fluid velocity in the channel of 0.07322 m/s.

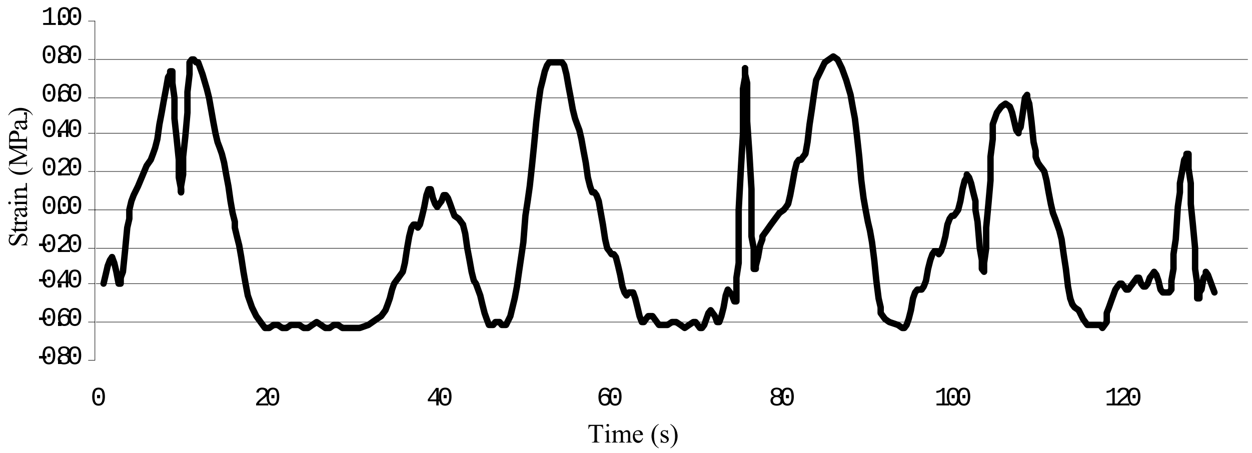


Figure 10. Behavior from the flexion strain due to him drags of pressure, in function of the time, for fluid velocity in the conduit of 0.170 m/s.

7. Results of particles images velocimetry (PIV)

Figure (11) shows a visualized image captured according to the procedure of the section 4. Figures (12) *a* and *b* show the velocity field obtained by the approach from the correlation crossed applied between 2 images captured during a time-flag equals to 0.1s, and the theoretical situation that the velocity field should occur.

To obtain the velocity vectors were used the following parameters in the PIV program (Almeida, 1997):

45 vectors in the horizontal direction; 30 vectors in the vertical direction;

base region of 6 pixels x 6 pixels; search region of 12 pixels x12 pixels;

Δt of 0.1 s;

calibration factor of 0.58 mm/ pixel;

minimum correlation coefficient of 0.95 and vectors scale of 2.

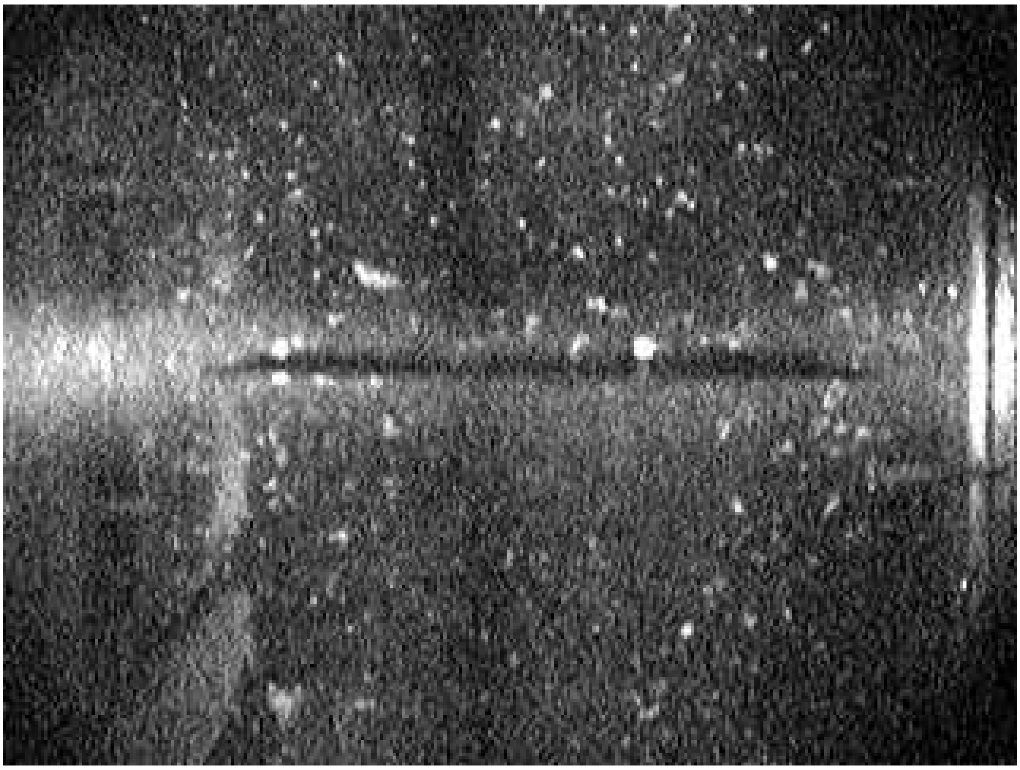
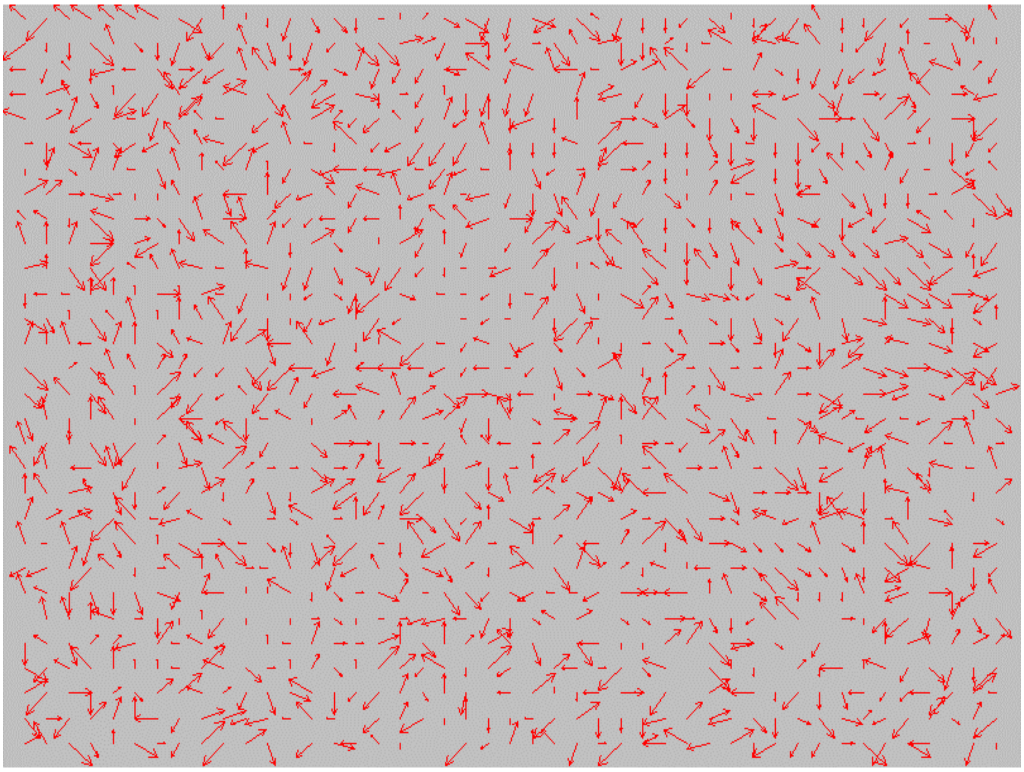
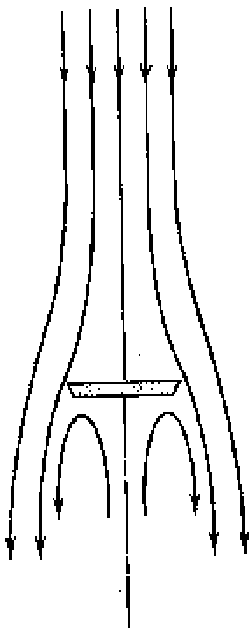


Figure 11. View of captured image.





a) b)

Figure 12. a) Velocities fields obtained and b) theoretical phenomenon.

A phenomenon occurred that at least was unexpected when we performed the velocimetry tests. When someone imagines a stream perpendicular to a flat plate, it is expected to occur the bifurcation of the fluid and the generation of vortex according to Figure (11) b. What really happened was that the vortex formed after the plate had sufficient velocity to cause a reflux in the stream. In the videos carried out, sequences of images exist that show perfectly that particles come back to the former seçtion of the plate, forming a significant vortex and without symmetry of the stream. This phenomenon shows that the ratio between the width of the plate and width of the channel has a significant effect on the stream. The phenomenon would be minimized or extinguished using a narrower plate.

8. Conclusions

By analyzing the results showed in Figures (9) and (10) we can see that the curves found for the strain (σ_{max}) correspond to those presented by the vectorial component of velocity in the turbulent regime. The calculated strain should be proportional to the square of the velocity component in the normal direction to the plate, according to Eq. (6); therefore, it should have a medium component as well an alternated one, as in the study of fatigue materials.

The values of the strain (σ_{max}) calculated using the theoretical methodology (section 5) present deviation of approximately 40% to 90% comparing to the experimental results (section 6). The more probable explanation refers to the drag coefficient, C_D. As the difference between the width of the plate and the width of the channel is small, the plate produces a significant effect in the stream, invalidating the drag coefficient supplied by the graphic showed in Fig. (2). The boundary layers of the lateral walls of the channel also cause a large influence in the stream.

In the image captured and in the velocity fields obtained in the tests by particles images velocimetry (PIV) (see Figs. (11) and (12)), we can see the existence of velocity in opposite direction of the stream. This velocity is generated by the vortex formed in the posterior size of the plate and it creates a drag force of pressure in the opposite direction of the stream, which is also cyclic and tends to compensate the component of the drag in the direction of the stream.

In subsequent works it will be studied the interaction fluid-structure for slender plates, diminishing the relation between the width of the plate and the width of the channel. A distributed load will also be calculated using arrangements of strain gages in several places of the flat plate.

9. References

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