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Determination of air and hydrofoil pressure coefficient by Laser Doppler Anemometry

Slavica S.Ristić * **Mirjana A.Puharić** †
Marina M. Kutin ‡ **Dušan R.Matić** §

Abstract

Some results of experiments performed in water cavitation tunnel are presented. Pressure coefficient (Cp) was experimentally determined by Laser Doppler Anemometry (LDA) measurements. Two models were tested: model of airplane G4 (Super Galeb) and hydrofoil of high speed axial pump. These models are not prepared for conventional pressure measurements, so that LDA is applied for Cp determination. Numerical results were obtained using a code for average Navier-Stokes equations solutions. Comparisons between computational and experimental results prove the effectiveness of the LDA. The advantages and disadvantages of LDA application are discussed. Flow visualization was made by air bubbles.

Keywords: water tunnel, LDA, airplane G4, hydrofoil, numerical simulation, Cp, flow visualization

*Institut Goša, Milana Rakica 35, 11000 Belgrade, Serbia, e-mail: s1avce@yahoo.com
†Institut Goša, Milana Rakica 35, 11000 Belgrade, Serbia
‡Institut Goša, Milana Rakica 35, 11000 Belgrade, Serbia
§MTI, Belgrade, Serbia

1 Introduction

Nowadays worldwide, various experimental and numerical methods [1-5] are used for airfoils or hydrofoils Cp determination. Besides the conventional methods for Cp determination, through measurements of pressure distributions on models surface by tips and pressure transducers, (using scanivalves or electronically scanned pressure sensors, smart sensors, miniaturized devices, pressure sensors based on electro active materials, balk or saw sensors, optical fiber tip pressure sensors and so on) non-contact methods are implemented more and more. Most frequently used methods are interferometry (classical or holographic), LDA, PIV, pressure sensitive paints, micro sensors and so on. These methods do not require models with small holes on the surface and do not cause disturbances in the flow.

The tests illustrate how one component LDA could be used for Cp determination, based on velocity vector measurements in the immediate vicinity of the model surface, and pressure calculations, from the velocity distribution using Bernoulli's law [1,2]. The method assumes that the fluid is incompressible and inviscid.

The aim of the first part of experiments is to measure the velocity, angle of incidence and Cp distribution at the moment of cavitation inception on the pilot cabin and on the upper surface of the G4 model wing, at the place where the sweep angle is changed.

The goal of the second part is, besides Cp measurements, to provide an experimental dataset which will be used for flow simulation (boundary conditions and turbulence are established using LDA). A code for solving the average Navier–Stokes equations was employed on structured grids in order to obtain the main features of the complex two-dimensional turbulent flow around the tested model. A particular emphasis is given to the unsteady, turbulent flow behind hydrofoil at 25° angle of incidence.

2 Description of test equipment

2.1 Water tunnel

Water cavitation tunnel (WCT) is continuous, closed circuit, a reverse-type facility, used for testing of: hydrodynamic characteristics of various ships and projectiles (like torpedoes), optimal shapes of aircraft and projectiles, cavitation phenomena, flow around various aeronautical and non-aeronautical objects and models. Velocity of the flow in the range 1 to 10.0m/s can be achieved in the test section.

Reynolds number is up to 10 million/m, run time unlimited. Test section is closed, tetragonal, 500 x 450 mm and 700 mm long [6,7].

2.2 Laser doppler anemometer

Laser Doppler Anemometry is an optical method that becomes one of the most suitable methods for measurements of the velocity vectors distribution in large number of technical problems.

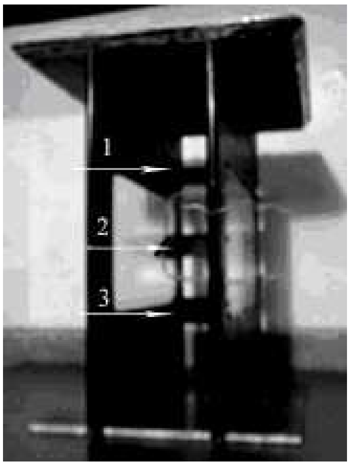
Laser Doppler Anemometer, used in the experiments, is a one-component system with 15mW He-Ne laser, λ=633nm (figure 1a) [6, 8]. The focal length of front lens is f=1200mm, the angle between the laser beams 20^o. The probe volume has Gaussian intensity profile and parameters: dx=0.88mm, dy=0.88mm, dz=12mm. The calibration constant is C=17.29 m/s MHz and N f=49. The optimized measuring volume was obtained based on adjustments of the LDA system with a calibrated spinning disc. Off axis forward measurement mode is used. The computer controlled traverse system moves the measuring point. Figure 1. illustrates some details of the used equipment: LDA system beside water tunnel (1a), test section and G4 airplane model (1b), model of hydrofoil grid out of WCT test section c) hydrofoil and laser beams in the test section (1d). Depending on the measuring conditions, the acquisition time for LDA measurements ranged between 0.1 to 3 s.

The LDV system was calibrated with a reference velocity from a spinning disk. Bias error in this calibration is introduced through uncertainty in disk rotational speed, disk radius, and the linear regression fit of the calibration curve. Based on the manufacturer's specified values, the maximum calibration bias in the LDV velocity measurement is $\pm$1.0%.

In the presented test, the total uncertainty interval for the laminar flow without cavitation was less then 1% for mean velocity, and around 3% for mean velocity in turbulent parts of the flow. These values include inaccuracies due to measurement technique, positioning of measure volume, wind tunnel fluctuations, traverse system vibrations, etc.

(a)

(b)



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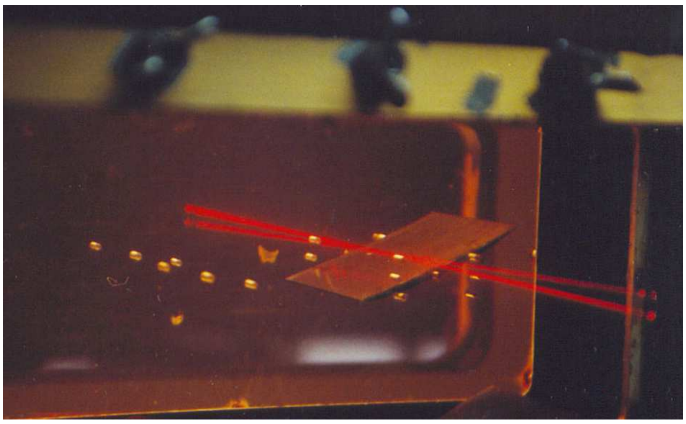


(d)

Figure 1: Some details of experimental setup, a) WCT and 1D LDA, b) WCT test section and G4 model, c) model of hydrofoil grid out of WCT test section and d) central hydrofoil in WCT test section at incidence angle of 25^o and laser beams

2.3 Test model description

The model of airplane G4 (Super Seagull) is made of aluminum alloy, in the scale 1:30. Model is supported in the test section by a tail sting mounted on a mechanism by which desired angles can be achieved. The model G4 wing span is 329 mm, the model fuselage dimensions: length 408 mm including probe and 378 mm excluding probe; height 143 mm; tail plane span 132 mm.

The model of straight grid comprises of three hydrofoils with 100 mm span (Al based alloy, type WH.3.1354), located at the distance of 84 mm each other. They are two-dimensional and mounted between two vertical plexiglas plates at incidence angle of 0^o or 25^o (Figure 1c). The measurements are made around central hydrofoil (Figure 1d). Top and bottom hydrofoils are positioned to provide inter-profile impact. The flow was from right to left [9].

Figure 2. shows the scaled drawings of G4 airplane model (fig.2a) and modified hydrofoil model (made in the scale 1:5) of centrifugal pump, produced by Foundry and centrifugal pump manufactory "Jastrebac", Nis, Serbia (fig.2b).

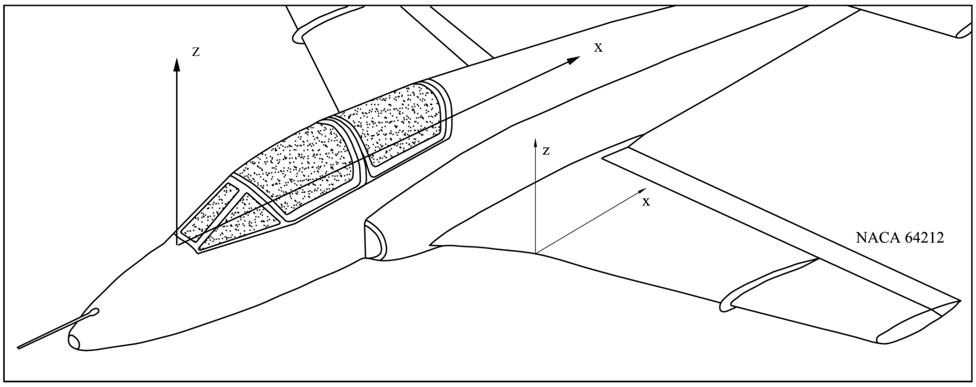
Models are produced on programmable milling machine CNC.

3 Experiments

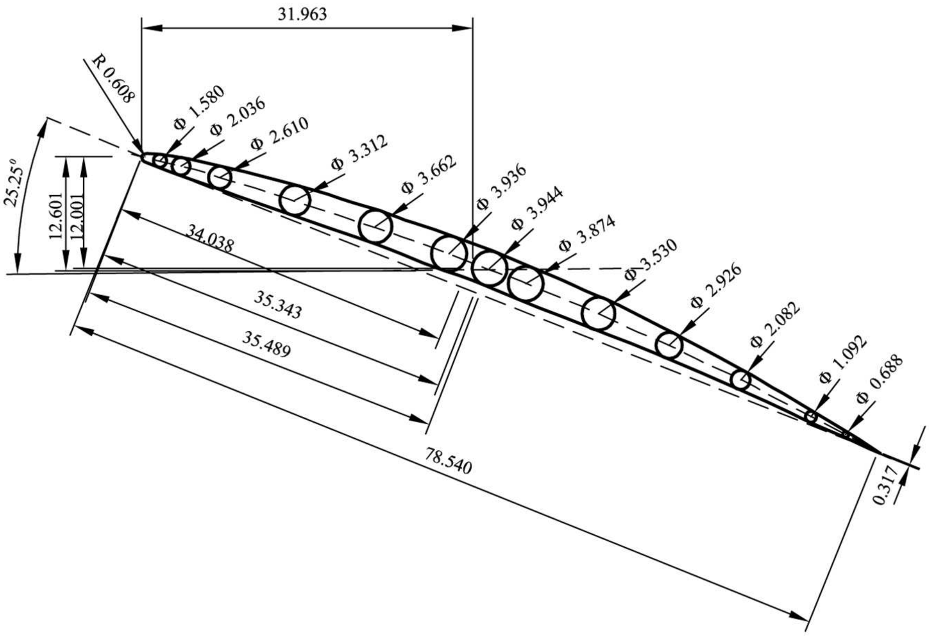
Experiments were consisted of three parts:

- calibration of the water tunnel includes velocity measurements with LDA and primary measuring system (PMS), based on measured difference between static pressures in two cross-sections of the water tunnel described in the [5,6].
- LDA measurements around G4 and hydrofoil models, and
- flow visualization

The horizontal velocity component is measured first; the vertical one is measured after LDA optical module rotation by 90° (in the same points where horizontal component has been measured). The velocity of undisturbed flow has been in the range of 1 to 10.0 m/s, and models incidence



(a) G4 airplane



(b) hydrofoil

Figure 2: Scaled drawings of tested models

angle of 0^o to 25^o [9]. LDA measures mean value of flow velocity based on approx. 900 samples in each point. The seeding centers for LDA measurement are the air bubbles in the water and there is no need to add any other particles. The measurement points were 1mm up the model surface. In order to make accurate near-wall velocity measurements, it is critical that the distance from the wall to the center of the measurement volume be held constant at a desired value.

The cavitation inception conditions were obtained by visual inspection of the flow field illuminated by a stroboscopic light. The angle of incidence for cavitation inception was determined by progressive increase of the incidence angle until cavitation was visible. At that moment LDA measurements were made.

Flow visualization was made with atmospheric air bubbles, which were injected with suction pipe placed about 1m in front of the hydrofoil model. Test section of water tunnel and model were illuminated with two spotlights of 200W each. In the previous experiment the aniline dyes, suctioned with special piping system from the external tank, were used for flow visualization [10,1]. The dye solution was made of purple aniline dye and alcohol.

4 Numerical simulation

Numerical simulation of the flow through a straight profile grid is made using the Fluent 6.1 program [12]. Solutions for the Navier–Stokes equations are obtained using the Reynolds average solutions technique (RANS). A profile grid of the axial pump is modeled with the Unigraphics 18.0 program. The geometry of the body was exported to Gambit 2.0 software for basic geometry modeling and computational grid generation. Geometry is modeled for grid profile angles, corresponding to the angles in the experiment 0^o and 25^o. The size of the grid that was used in simulations of the flow is the same as the size of the model that was used in the experiments in the water tunnel. The whole geometry was scaled 1:3. The computational grid density and its distribution were chosen to satisfy the following requirements: good representation of the body geometry; satisfactory values of the local Reynolds number y+; good representation of the areas of the computational space outside the boundary layer, in which large gradients of some flow variables are expected.

The boundary conditions corresponded entirely to the state in the water cavitations tunnel during the experiment (LDA measurements of velocity and turbulence). For the definition of the boundary conditions, the turbulence level in the area in front of the hydrofoil grid, measured during the experiment, was very useful. Depending on the grid profile angles, the number of elements in the generated computational grids varied in the range from 285.000 to 386.000. The number of elements in the computational grids increased with the increase of the incidence angle of the hydrofoil. The $k-\varepsilon$ standard model for turbulent stresses was used for 0^o incidence angle, and the $k-\varepsilon$ realizable model, for 25^o. Converged solutions for integral quantities of interest were obtained after 550 iterations for 0° angle of incidence and mass residuals equal to 10^{-5}. In the case of non stationary flow (25°), mass residuals were 10^{-4}, and 20 iterations are used for each temporal sequence. Enhanced boundary functions are used for the turbulent boundary layers.

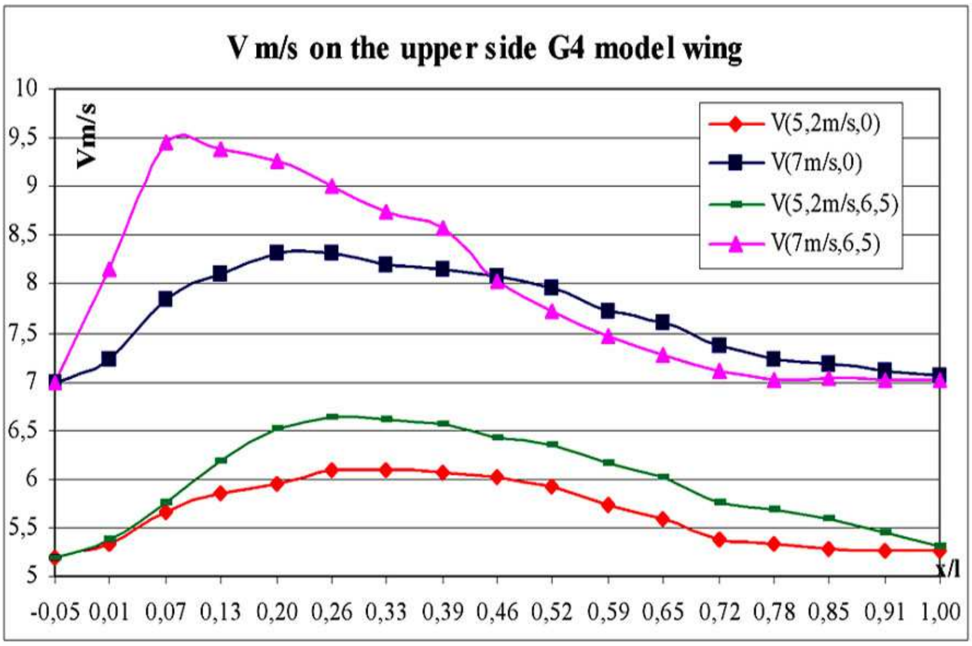
5 Analysis of results

The tunnel calibration results are given in [7]. The velocity distribution in the plane perpendicular to the tunnel axis is homogenous beyond the boundary layer (the measured thickness of the boundary layer is 9 mm). The turbulence level is satisfactory and is within the interval of 0.5 to 1.2%.

5.1 Cp around model G4 wing

The measurement of vector velocity on the upper, suction, surface of the G4 model wing is carried out in the plane of the sweep angle change (fig 2a).

The main aim was to detect the free stream velocity and the angle of incidence when the cavitation appeared on the leading edge. The cavitation was not noticed at the velocity of V_∞=5.2m/s (Figure 3a). The increase of V_∞, generally decreases the local pressure coefficient (Figure 3b) and hence increases pressure gradients. The cavitation occurred on the leading edge at V_∞=7.2 m/s and incidence angle $\alpha 6.5^o$, which is analog to the shock wave appearance after supersonic flow in the air.



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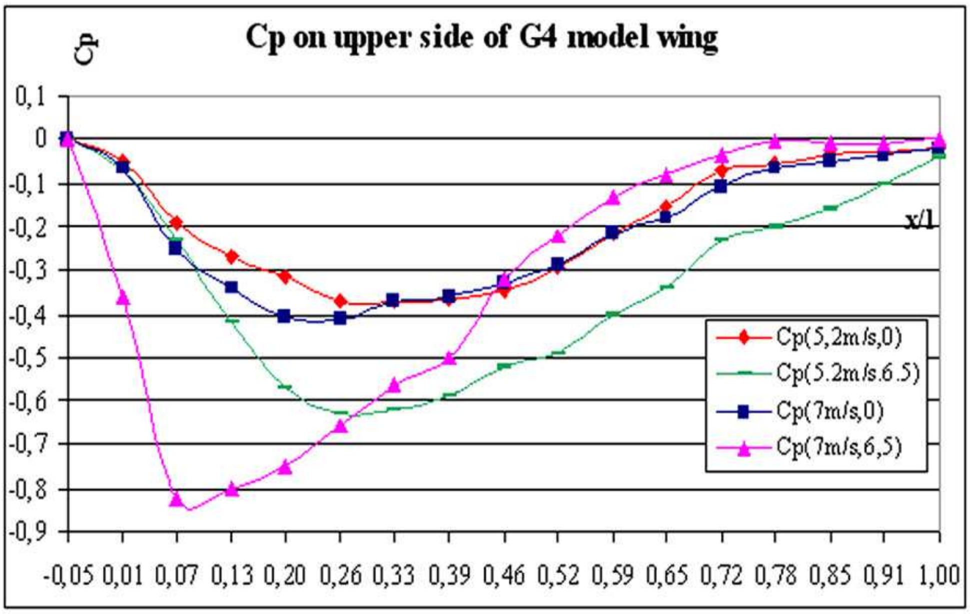


(b)

Figure 3: Velocity **(a)** and Cp distribution **(b)** for G4 model wing upper, suction, side with NACA 64212 airfoil

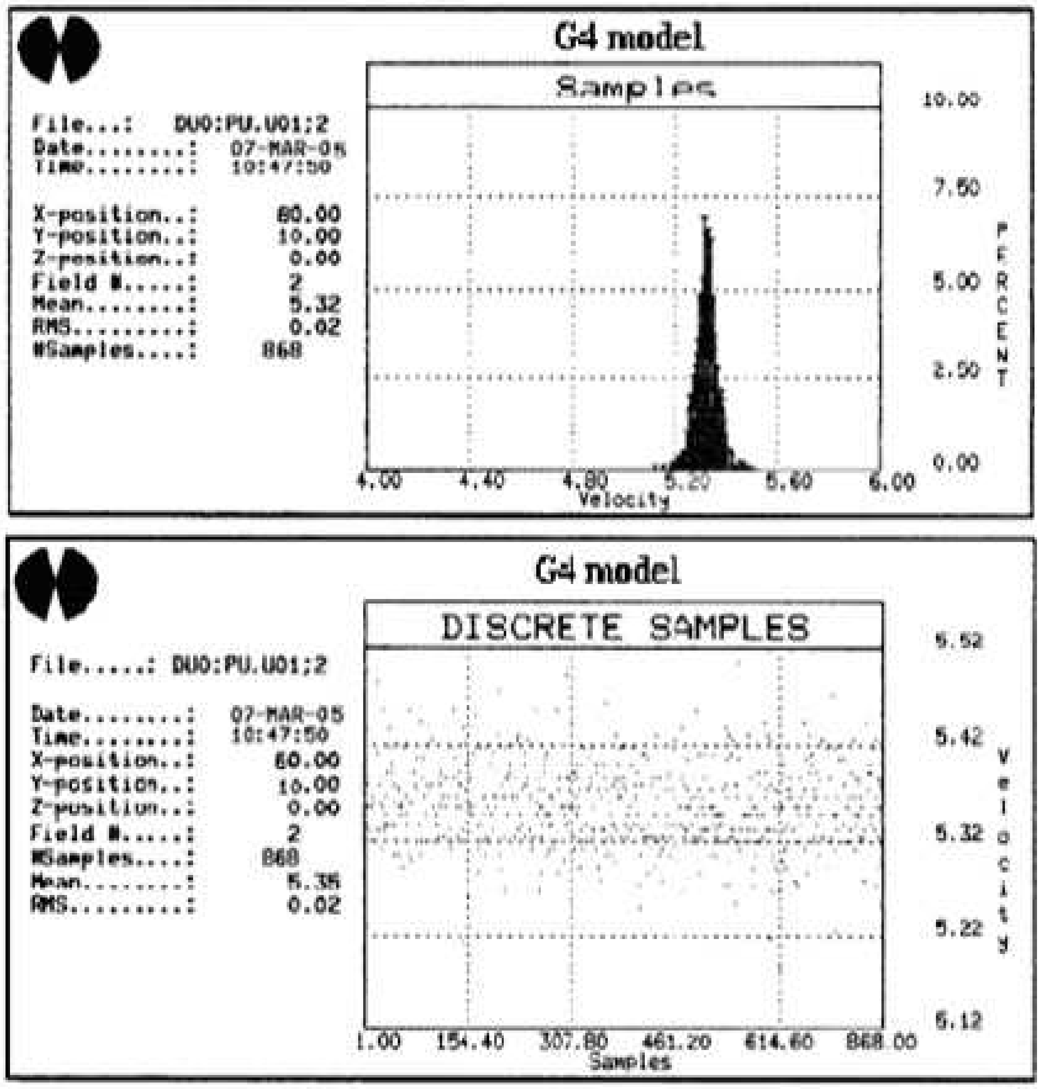


Figure 4: Histogram and discrete sample of velocity measurement at the point x/l=0.01, V_∞=5.2m/s, $\alpha = 0^o$

Figure 3 illustrates the measurement performed at the point x/l=0.01, V_∞=5.2m/s, $\alpha = 0^o$, on the suction wing side. The time necessary for data acquisition by LDA was 0.11s. The main value of velocity was calculated using 868 measured values. The discrete simples for velocity (4b) were scattered around main value. The RMS is 0.02. It means that the values of main velocity are distributed in the interval (5.32±0.02)m/s. These results are expected, because the flow around airfoil, in that point,was laminar and stationary.

The values of RSM became bigger at the moment of the cavitation inception and reach the value of 0.11. The flow in this moment was not steady and laminar, the measured value of main velocity vector can be reported as V_m= (9.52 ±0.11) m/s.

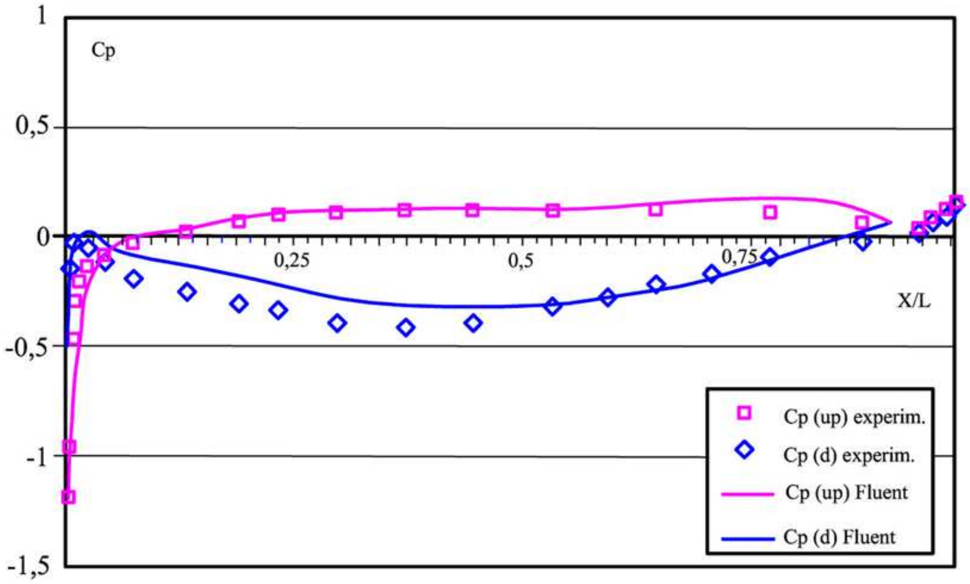
5.2 Cp distribution around hydrofoil

The vector diagrams and Cp distribution around hydrofoil for incidence angle of $\alpha = 0^o$ and 25^o and V_∞=5.32 m/s are illustrated in Figures 5 and 6.

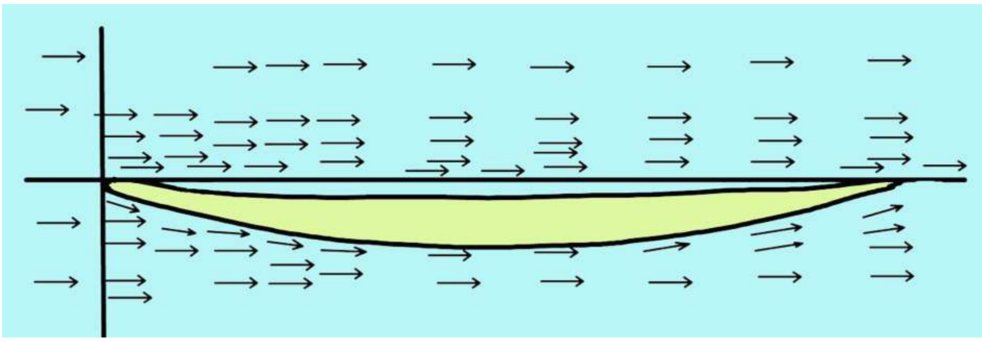
Flow around hydrofoil for incidence angle of α=0° is stationary. The agreement of the experimental and numerical results for Cp is very good (Fig.5a). During the experiments, the suction side of hydrofoil was down, the pressure one was upper.

Figure 6 illustrates the experimental and numerical results for Cp, when the hydrofoil was positioned at incidence angle α =25°. Flow around hydrofoil for that angle was unsteady and turbulent (particularly on the suction hydrofoil side), thus the diagram of Cp was alternated accordingly to the flow. Numerical diagram for Cp in Figure 6a gives the average values. LDA measures the average value of velocities from the recorded light scattering signals. It means that the calculated values for Cp are average,too. Depending on seeding in the measurement volume, the acquisition time was 0.03 to 5s. The difference between experimental and numerical Cp diagrams for suction side of hydrofoil is evident.

Path line colored by velocity magnitude (m/s), for different times is presented on Figure 7. Figure 8 shows experimental values for velocity vector distribution around central hydrofoil and path lines colored by velocity magnitude (m/s), in t=0.061s. Numerical flow lines (t=0.061s and t=0.15s) and experimental ones obtain by flow visualization with air



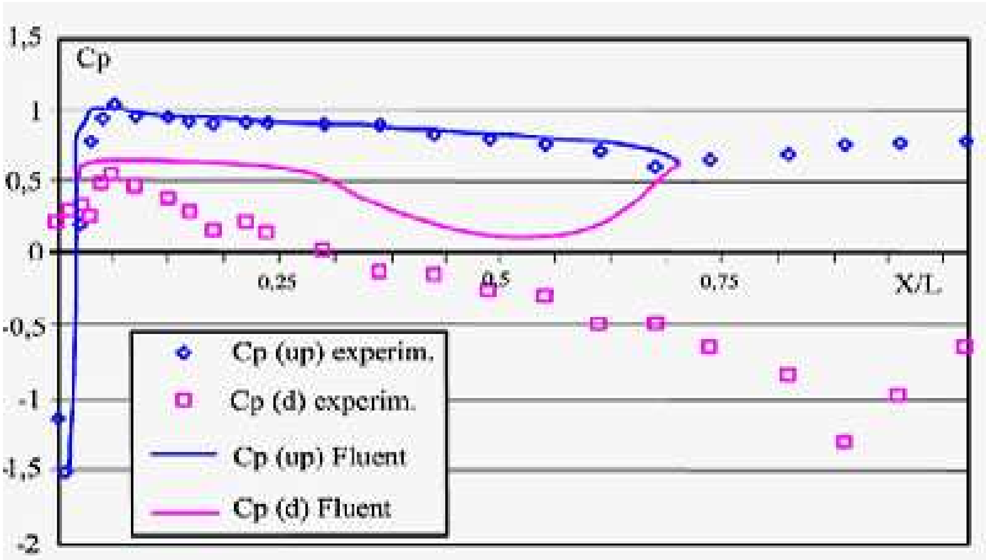
(a)



(b)

Figure 5: Experimental and numerical results for hydrofoil flow positioned at $\alpha = 0^0$, V_∞=5.32 m/s, (a) experimental and numerical distribution of Cp and (b) experimental vector velocity distribution

bubbles are given in Figure 9. Velocity vectors should be tangent of path lines.



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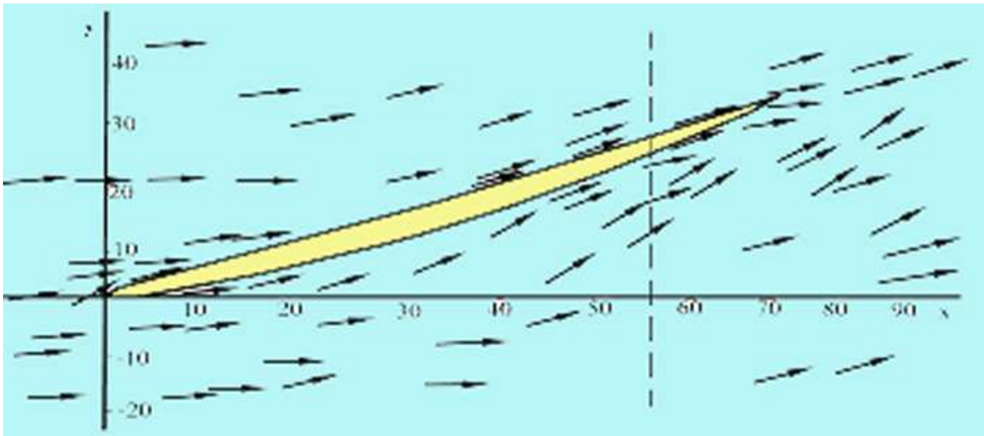


(b)

Figure 6: Experimental and numerical results for flow around hydrofoil positioned at $\alpha = 25^o$, V_∞=5.32 m/s, **(a)** Cp experimental and numerical and **(b)** experimental vector velocity distribution

The visualization results indicate that the flow lines, obtained with Fluent 6.1 at t=0.15s, correspond well with air bubbles visualization streamlines (Figure 9b).

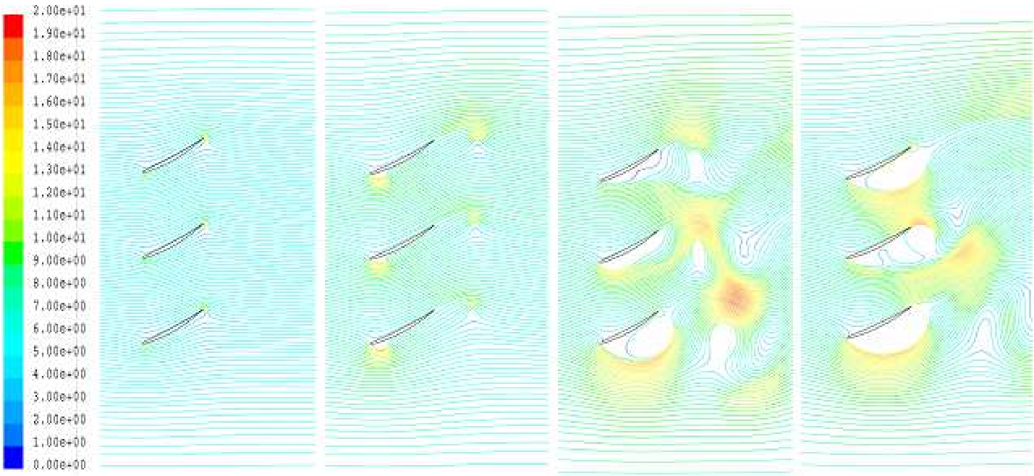


Figure 7: Path line colored by velocity magnitude (m/s), for different times ($t = 0.001s$, $t = 0.01s$, $t = 0.1s$, $t = 0.149s$) and $V_\infty = 5.32m/s$.

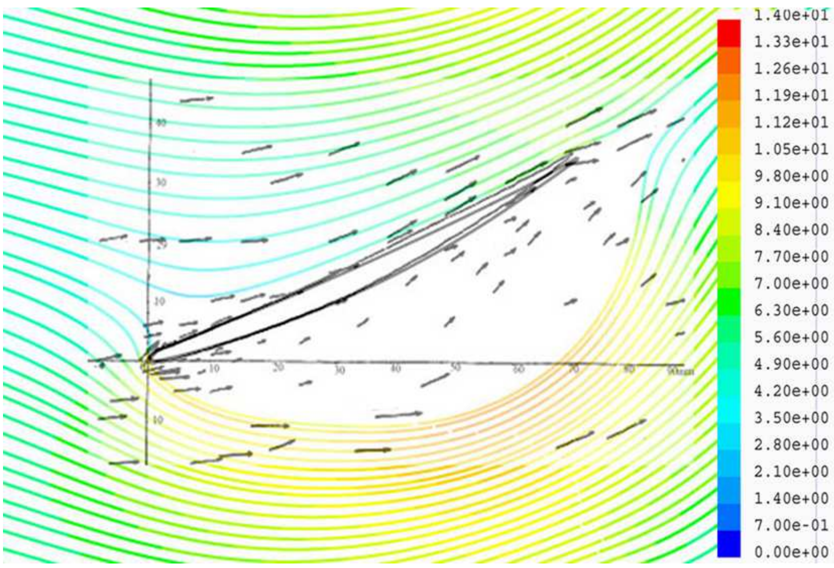
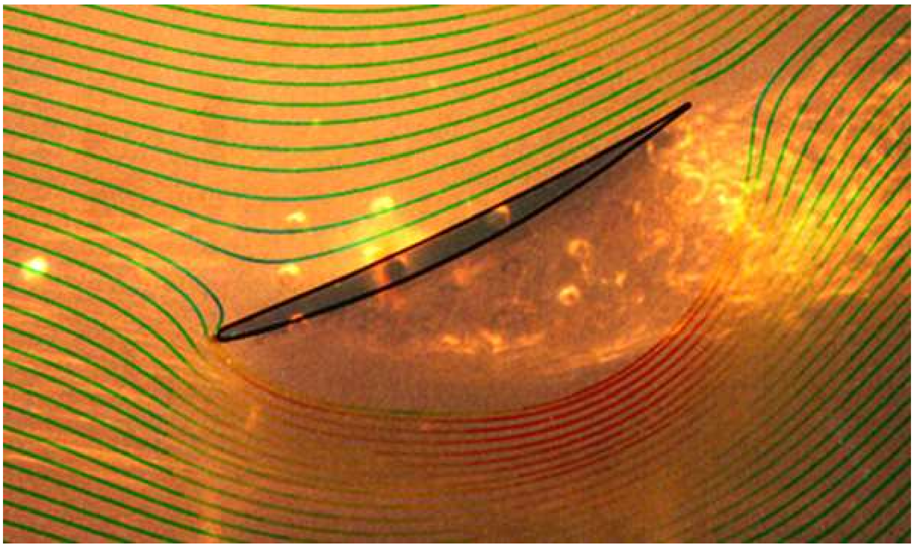
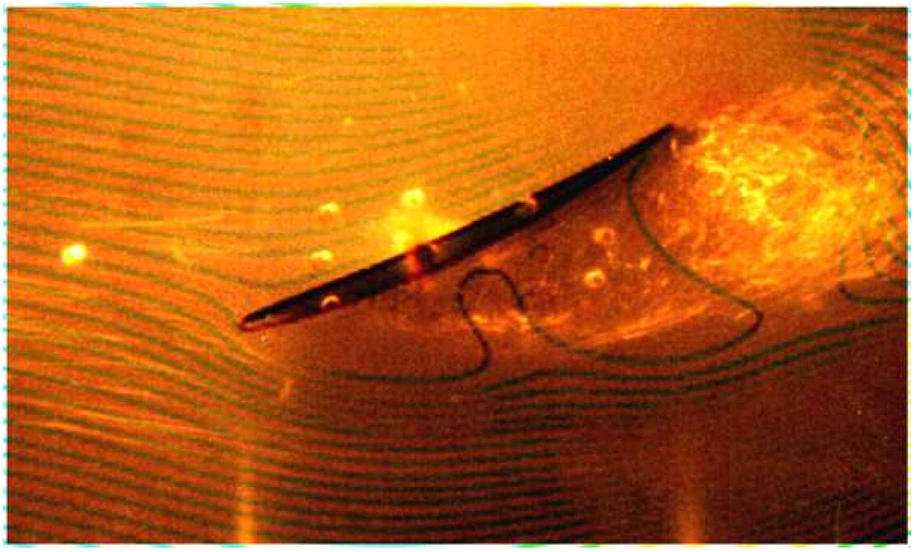


Figure 8: Path lines colored by velocity magnitude (m/s), t=0.061 s, and experimental values for velocity vector distribution around central hydrofoil, V_∞=5.32 m/s.



(a)



(b)

Figure 9: Simultaneously presentation of flow visualization with air bubbles and numerical simulation path lines at the time t=0.061s **(a)** and t=0.15s **(b)** after the flow beginning, V_∞=5.32 m/s

6 Conclusion

It has been shown how Cp, or pressure distribution, on models surface can be obtained by relative simple one component LDA system without special preparation of the models for pressure measurement. The experience shows that LDA has many advantages compared to the classical methods, but there are some practical problems related to seeding, optimization of LDA configurations and measured volume positioning for some complex flow, minimizations of S/N ratio and elimination of vibrations. The homogeneity,damages and stresses of glass windows, may produce light refraction and dislocation within the measured volume, which must be taken into account during flow velocity measurements. Optical visibility of flow is required. One of the largest disadvantages of LDA for large scale experiments is the time and effort required to map out a large portion of the flow field around and behind the models of interest, because the LDA is the one point measurement technique.

The experimental and numerical results for Cp distribution are compatible for steady flows, but there are some divergences for unsteady ones. The flow with cavitation is the example of typical unsteady flow and in that case other methods are more applicable. The flow visualizations and numerical simulations have been also performed, and the obtained results are mutually compared. The presented experiments confirm that it is very useful to use simultaneously various experimental methods and to compare experimental and numerical results.

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Određivanje koeficijenta pritiska Cp za aero i hidro profil Laser dopler anemometrijom

U radu su prikazani rezultati eksperimentalnih istraivanja u vodenokavitacionom tunelu, u kojima je određen koeficijent pritiska (Cp) pomoću laser dopler anemometrije (LDA). Ispitana su dva modela: model aviona G4 (Super Galeb) i model hidroprofila lopatica brzohode osne pumpe. Ovi modeli nisu pripremljeni za klasična merenja raspodele pritiska, pa je za određivanje Cp korišćena LDA. Numerička simulacija je izvrena softverskim paketom na bazi usrednjenih Navije - Stoksovih jednačina. Upoređenje između numeričkih i eksperimentalnih rezultata potvrđuje efikasnost LDA metode. U radu se razmotraju prednosti i nedostaci primene LDA. Vizualizacija stujanja je izvrena mehurićima vazduha.

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