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Field measurements in a flow around a hydrofoil: some preliminary results

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***Abstract* – This work reports the first results of an experimental study aimed at investigating the flow field modified by a hydrofoil NACA 0012 immersed in a water current. The velocity measurements were carried out at the Hydraulic Laboratory of the DICATECh (Polytechnic University of Bari, Italy) using an ADV (Acoustic Doppler Velocimeter) and a PIV (Particle Image Velocimetry) system, in order to reconstruct the flow field and the turbulence characteristics.**
We obtained instantaneous and average velocity vector maps, as well as instantaneous streamlines maps, in the streamwise direction, in vertical frames located both upstream and downstream of the hydrofoil. Furthermore, the vertical velocity profiles in some selected sections were also examined. The analysis of the acquired data was also performed in the frequency domain. The principal results show that the velocity profiles obtained with the PIV and ADV are comparable and that the frequency of vortex shedding downstream of the hydrofoil is in agreement with Strouhal's theoretical relationship.

I. INTRODUCTION

The study of solid objects immersed in a Newtonian fluid flow is of great interest. As an example, we can refer to means of transport such as cars, planes, submarines, or boats, for which it is necessary to assess the forces transmitted by air and/or water during their motion. The problem solutions can be searched numerically or experimentally.

The present paper shows the first results of the analysis of a uniform flow field modified by the presence of a NACA 0012 hydrofoil in a Newtonian fluid, obtained through an experimental investigation. The NACA 0012 hydrofoil is used in most common aeronautics and hydraulics applications. It has been studied for a long time, essentially because of its symmetrical and handy shape, which allows to obtain fairly generalizable results. We chose it because a more detailed knowledge of the downstream flow field is still desirable. Furthermore, we can refer to results of previous research [1,2,3,4] to test our experimental and measuring apparatus. We developed the survey through the two-dimensional reconstruction of the motion field generated by the profile. Based on previous research [1,2,3,4], we also analyzed the cyclical frequency of the vortices that detach downstream of the hydrofoil, the type of vortices generated and the interaction they have with the surrounding flow, thus providing generalizable results.

II. EXPERIMENTAL EQUIPMENT

The experimental installation consists of a 24.40 m long channel, with a cross rectangular section of 0.40 m wide and 0.50 m high. The lateral walls and the bottom surface of the channel are constructed of Plexiglas, as shown in Fig. 1.

Fig. 1. Channel detail

The outlet and the inlet structures of the channel are connected to a hydraulic circuit, allowing a continuous re-circulation of constant discharges. To create a smooth flow transition from the upstream tank to the flume, a set of stilling grids are installed in the upstream tank to dampen inlet turbulence. The channel is equipped with a side-reservoir spillway with adjustable height in order to maintain a constant and uniform water head. An upstream and a downstream movable gate (made of Plexiglas) are used to define the flow depth and mean velocity in the channel. At the downstream end of the channel, the water is intercepted by a rectangular reservoir which was 3 m long, 1 m wide and 1 m deep, equipped with a triangular weir (V-notch sharp crested weir) to measure the channel flow rate. The time-averaged bulk velocity of the current was between 1.8 and 2.8 m/s, corresponding to a flow rate between $1.92 \cdot 10^{-3}\, m^3/s$ and $3.39 \cdot 10^{-3}\, m^3/s$. The relevant tailwater levels in the channel were between 37.5 cm and 38 cm [2].

To examine the upstream and downstream velocity profiles, a 3D sidelooking ADV (Acoustic Doppler Velocimeter) measurement system was used (Fig.2), together with its acquisition software. The ultrasonic frequency of the ADV was 10 MHz. It was used with a velocity range equal to ± 10.0m/s, a velocity accuracy of ± 1 %, a sampling rate of 100 Hz, a sampling volume of vertical extend of 5.5 mm and a time of acquisition of 2 minutes. A 15 db signal-to-noise ratio (SNR) and a correlation coefficient larger than 70 % are recommended by the manufacturer for high-resolution measurements. The acquired data were filtered based on the Tukey's method and the bad samples (SNR < 15 db and correlation coefficient < 70 %) were also removed.

Measurements were carried out along the longitudinal plane of symmetry of the channel, to minimize the effect of the walls. A PIV (Particle Image Velocimetry) system by Dantec was also used to measure the velocity components in some selected vertical frames close to the hydrofoil.

The PIV system was composed of: a FlowSense EO 4M-32 camera with Nikon 60 mm lens (Fig.3); the Dantec Dual Power 135-15 dual-cavity laser powered by a Litron LPU550; the synchronization and connection devices for the various components; the DynamicStudio analysis software.

All the tests were carried out were conducted with a NACA 0012 hydrofoil with a 5 cm chord and inclined 20° (Fig.4).

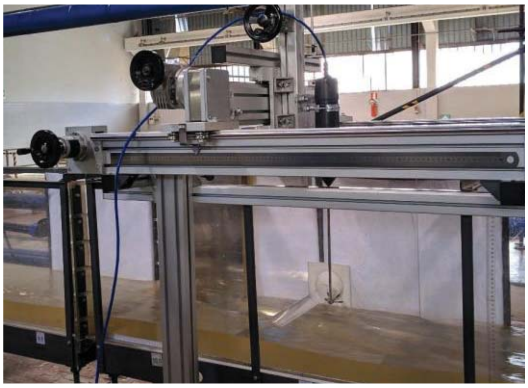

Fig. 2. Channel with 3D ADV

Fig. 3. Acquisition camera

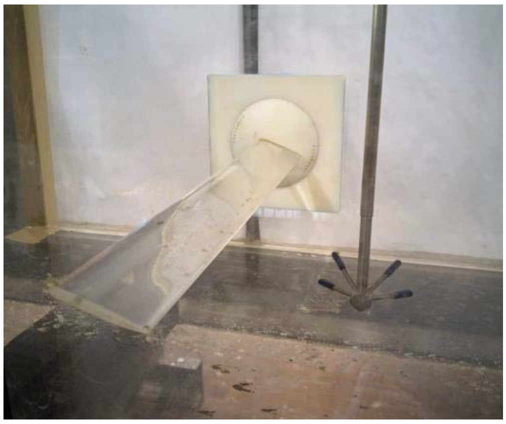

Fig. 4. NACA 0012 hydrofoil and sidelooking ADV located downstream

III. RESULTS

The acquisition started when the flow in the channel was steady, that is when all the perturbations induced in the transitory phase have dissipated.

The Reynolds number based on the hydrolfoil chord was between 640 and 1130, the Reynolds number of the flow was between 6400 and 11300, i.e. the flow in the channel was turbulent.

A. *Average velocity profile and frequency analysis with ADV*

Immediately downstream of the hydrofoil four points were selected for the study, respectively at 5, 10, 15 and 20 cm from the hydrofoil, in which the velocity frequencies were analyzed with the FFT algorithm (Fig. 5). The power spectra of the local velocity components along the horizontal direction (*u* component) and along the vertical direction (*v* component) of the measurement points are shown in the figures below (Figs. 6÷13).

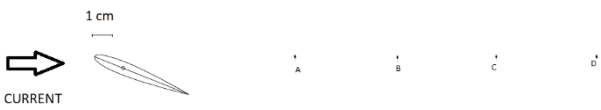

Fig. 5. Measurement points for the frequency analysis.

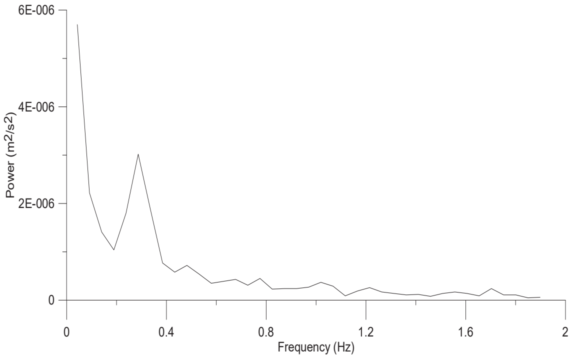

Fig. 6. Power spectrum of the u velocity component at point A.

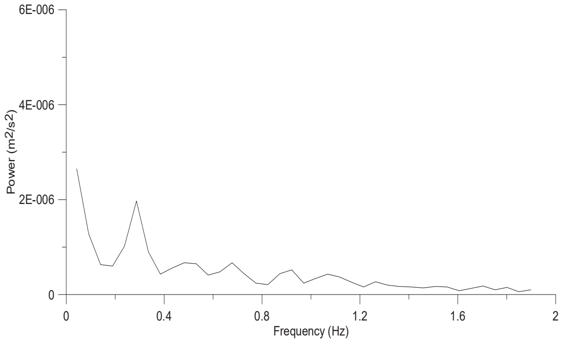

Fig. 7. Power spectrum of the u velocity component at point B.

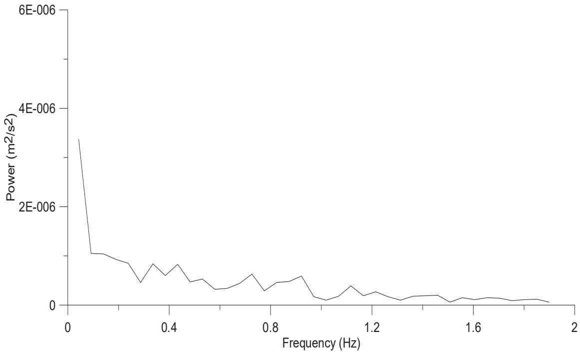

Fig. 8. Power spectrum of the u velocity component at point C.

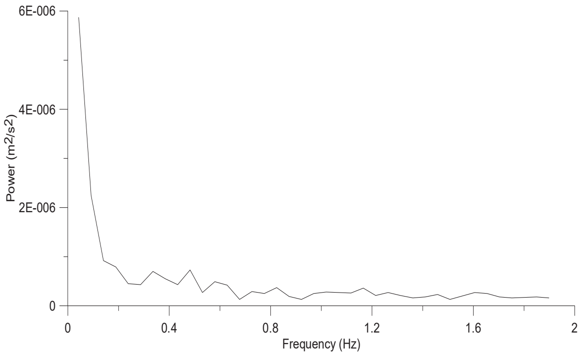

Fig. 9. Power spectrum of the u velocity component at point D.

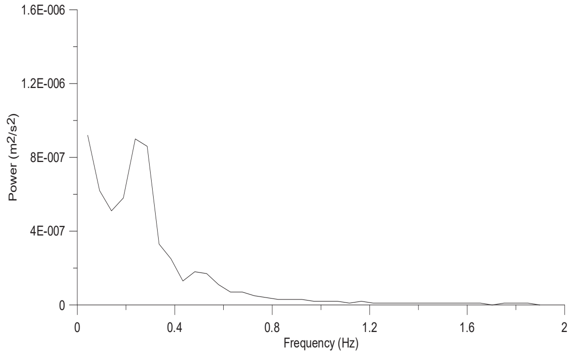

Fig. 10. Power spectrum of the v velocity component at point A.

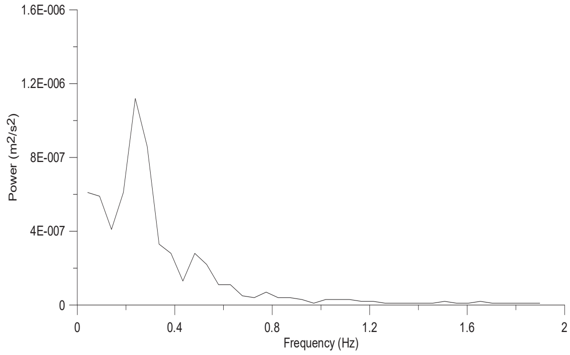

Fig. 11. Power spectrum of the v velocity component at point B.

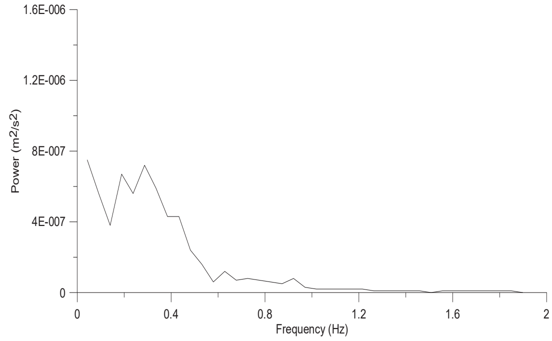

Fig. 12. Power spectrum of the v velocity component at point C.

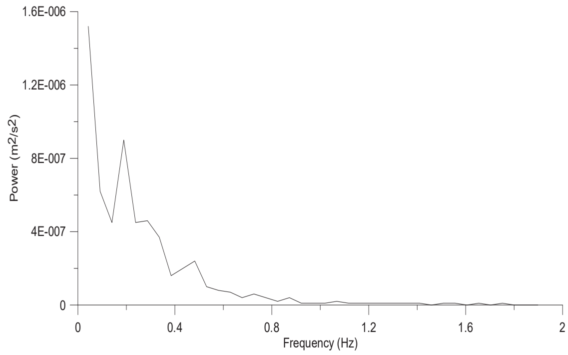

Fig. 13. Power spectrum of the v velocity component at point D.

These measurements were carried out in the test characterized by: flow rate of $3.39 \cdot 10^{-3}\ m^3/s$, average velocity of 0.0226 m/s, Reynolds number corresponding to the profile equal to 1130 and Reynolds number in the channel equal to 11300. The frequency analysis shows the presence of two main peaks in all the spectra, one at the zero frequency and the other one at around 0.29Hz for the u velocity component and at 0.24 Hz for the v velocity component. As expected, the first peak is the highest, due to the average velocity component. Instead, the second peak is due to the periodicity of the vortices which detach behind the hydrofoil. The Strouhal relation provides a theoretical frequency of vortex shedding equal to 0.26 Hz, approximately equal to the average frequencies of the *u* and *v* velocity components. Furthermore, the power of the spectrum decreases with increasing distance of the investigated point from the wing profile, in fact the vortex energy is dissipated with distance.

To detect how the hydrofoil modifies the velocity field, the u-component velocity profile was assessed in the undisturbed current and downstream of the hydrofoil at a horizontal distance of 5 cm from its neutral point.

The results are here shown for the test characterized by: flow rate of $2.84 \cdot 10^{-3}\ m^3/s$, average velocity of 0.0188 m/s and Reynolds number respectively based on the hydrolfoil chord and in the channel of 940 and 9400. The profiles and the relative standard deviation are shown in Figs.14÷17.

It is evident that upstream the undisturbed current has the typical logarithmic shape, while downstream a strong reduction of the *u* velocity is highlighted at the level of the hydrofoil, as expected.

In the flow region upstream of the hydrofoil the turbulence index (obtained as the ration between the standard deviation of the fluctuating velocity components and the local time-averaged velocity) is about equal to 12%, except for the area close to the bottom, due to wall turbulence. For the downstream profile, a similar situation is observed, but in addition there is an increase in turbulence at the hydrofoil level due to the detachment of the boundary layer and consequent vortex wake.

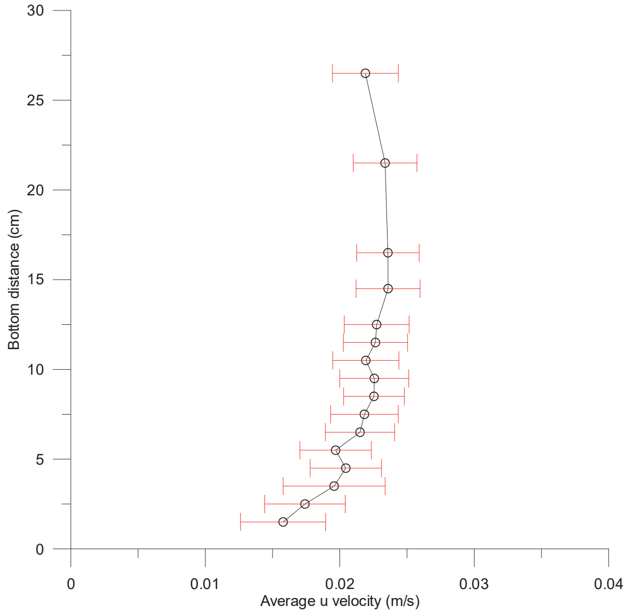

Fig. 14. Time-averaged u velocity component of the undisturbed current

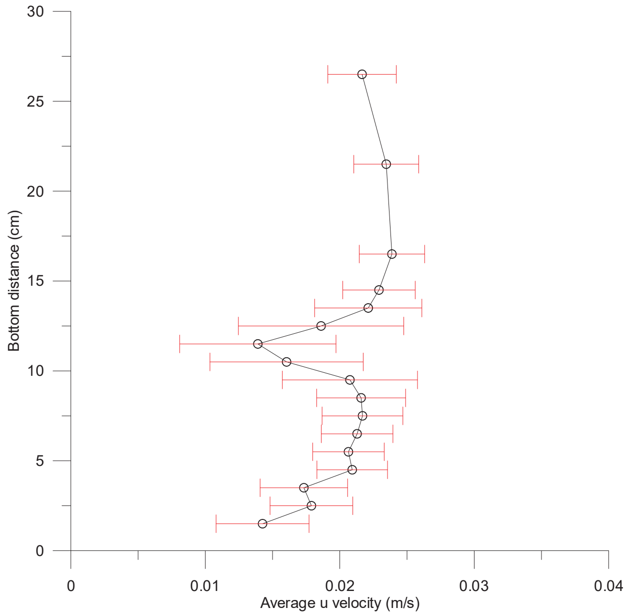

Fig. 15. Time-averaged u velocity component at a horizontal distance of 5 cm from the hydrofoil

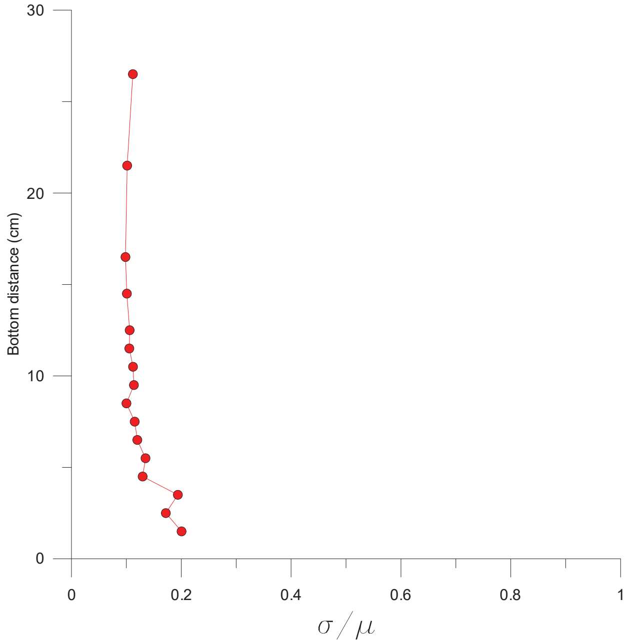

Fig. 16. Relative standard deviation of the upstream profile.

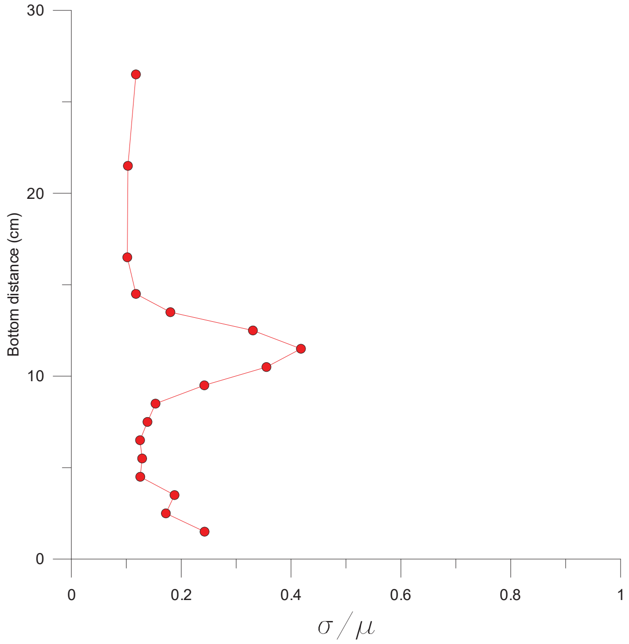

Fig. 17. Turbulence index in the vertical section at 5 cm from profile

B. Flow field and velocity profiles obtained by PIV

Six PIV acquisitions were carried out downstream of the profile, partially overlapping each other, to extend the investigated field, because the single acquisition captures an area of approximately 58x58 mm (Fig. 18).

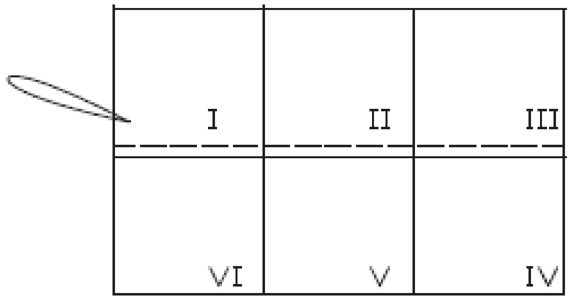

Fig. 18. Position of acquired frames

A series of vector maps were obtained, representing the velocity field of the acquired area. Fig. 19 and Fig. 20 display respectively an example of an instantaneous and an average velocity vectors map, assessed in frame I.

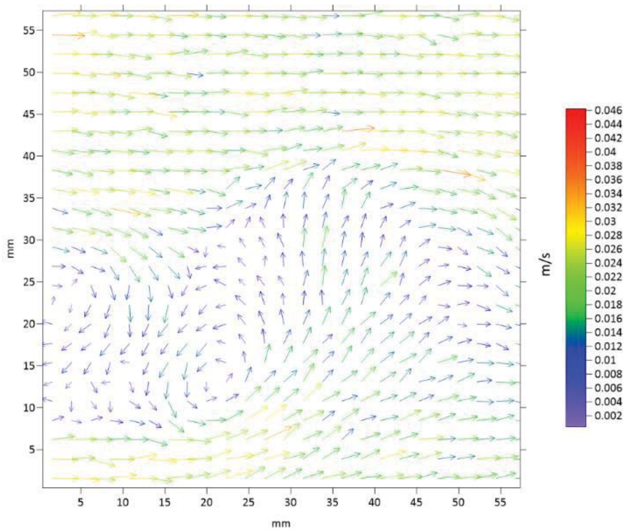

Fig. 19. Instantaneous velocity vector map.

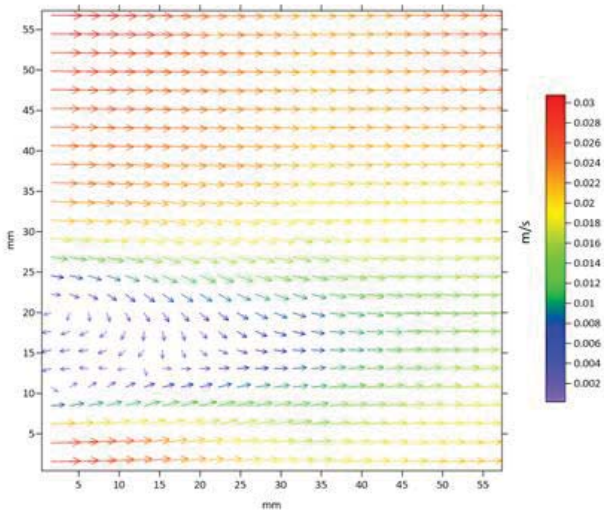

Fig. 20. Time-averaged velocity vector map.

Processing the velocity maps, the vorticity map was deduced, where the lines are tangent to all velocity vectors in the various points (Fig. 21). We note that the vorticity is characterized by the alternating presence of clockwise and counterclockwise vortices.

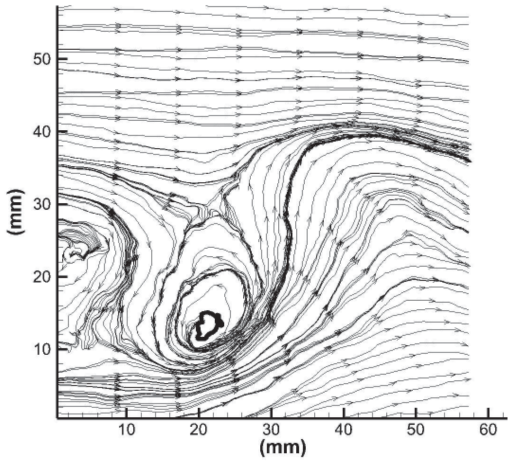

Fig. 21. Vorticity map.

Finally, we compare the average velocity profile measured with the ADV at 5 cm downstream of the hydrofoil (in point A) with the same profile as extracted by the PIV frame, referring to the same test condition. Notably, flow rate of $2.93 \cdot 10^{-3}$ m^3/s, average speed of 0.0193 m/s, Reynolds number based on the hydrolfoil chord of 965 and Reynolds number in the channel equal to 9650.

The two profiles are plotted in Fig. 22, where an almost complete overlap is evident.

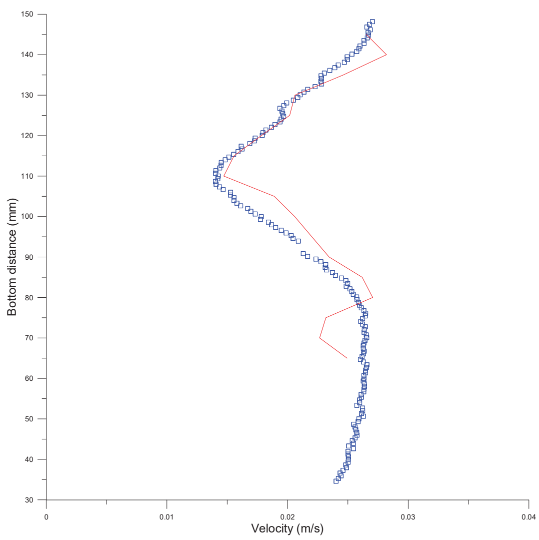

Fig. 22. Comparison between PIV speed profile (squares) and ADV speed profile (line)

IV. CONCLUSIONS

The object of this work was to analyze and reconstruct the motion field around a hydrofoil immersed in water. To do this we used two instruments, an ADV and a PIV. The first allows punctual and direct measurements, allowing to obtain high precision and accuracy. It allows very high frequency measurements, useful for analysis in the frequency domain of periodic phenomena. On the other hand, it is necessary to keep the correlation very high for long acquisition periods and is not suitable to investigate many points. The PIV allows faster measurements, multiple post-acquisition processing and allows the reconstruction of large portions of field of motion, freezing the speeds of all points at the same time. However, it has a lower acquisition frequency, requires careful calibration and considerable computing power.

The velocity profiles extracted through the PIV have a relative standard deviation of the order of 18% in the lower turbulence area, comparable to that obtained under the best conditions of the measurements by ADV.

PIV analysis of the motion field downstream of the profile highlights the presence of Von Karman vortices, characterized by an alternate detachment of vortices moving downstream and transported by the flow. This phenomenon is typical of the subcritical regime with Re between 60 and 5000, as in the simulations conducted. Furthermore, the theoretical frequency of vortex shedding is quite similar to those measured in the experimental tests.

V. CITATIONS AND REFERENCES

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