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DRAG ESTIMATION BY WAKE SURVEY PERFORMED MEASURING VELOCITIES AND MEASURING TOTAL AND STATIC PRESSURES

Luciano Amaury dos Santos
Petrobras Transporte S/A, Rua Felipe Musse, 803 – São Francisco do Sul – SC, Brasil, 89.240-000
e-mail: luciano.santos@petrobras.com.br

Ana Cristina Avelar
Instituto de Aeronáutica e Espaço – CTA, Praça Mar. Eduardo Gomes, 50 – São José dos Campos – SP, Brasil, 12.228-904
e-mail: anacristina@iae.cta.br

Matsuo Chiseaki
Instituto de Aeronáutica e Espaço – CTA, Praça Mar. Eduardo Gomes, 50 – São José dos Campos – SP, Brasil, 12.228-904
e-mail: matsuo@iae.cta.br

Olympio Achilles de Faria Mello
Instituto de Aeronáutica e Espaço – CTA, Praça Mar. Eduardo Gomes, 50 – São José dos Campos – SP, Brasil, 12.228-904
e-mail: oamello@iae.cta.br

Abstract. *Drag estimation by wake survey is a experimental technique specially useful for measuring the drag of airfoils at low angles of attack, since the low drag present in such situations may be difficult to measure with balances designed for measuring higher loads associated with the stalled airfoil. The technique is based on the balance of the momentum in the free-stream direction performed over a control volume that encircles the airfoil, and is developed essentially for two-dimensional flows. Although far from the airfoil the static pressures are equal to that of the free-stream and the wake velocity profile would be sufficient for the drag estimation, so far from the airfoil the uncertainty in the momentum deficit calculation that will lead to the drag may become too high. In the present work, using theoretical considerations and experimental results (obtained using PIV and simple Pitot-static tube measurements) attention is called to the difficulties of the drag estimation by wake survey based purely on velocities measurement and to the advantages of the technique based on dynamic and static pressures measurement.*

Keywords. *drag measurement, experimental aerodynamics, wind-tunnel, Pitot-static tube, PIV.*

1. Introduction

The drag estimation by wake survey is based on the *x*-momentum balance over a control volume like that depicted in Fig. (1).

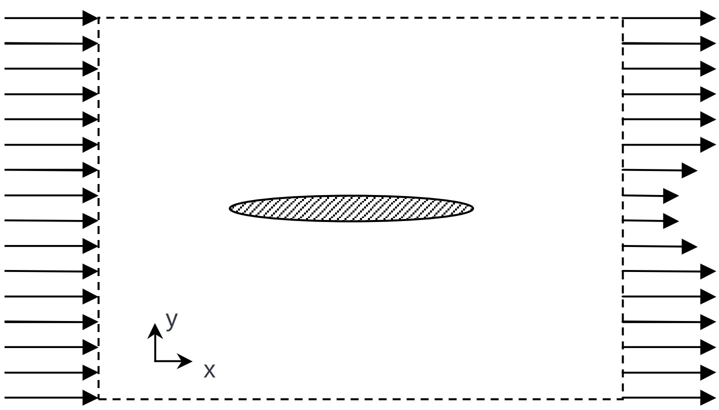

Figure 1. Control volume for drag estimation by momentum balance.

The flow is assumed to be two-dimensional and the control surface must be placed as far from the body as necessary to make the momentum transport through the surfaces perpendicular to the *y* direction unimportant and to make the hypothesis of uniform flow upstream of the body realistic. In principle, the downstream part of the control surface could be placed close to the body. It is not common, however, to have at the same time, information about the directionality of the flow and about the static pressure, both needed for the integration of the momentum flow over a surface where the vertical velocity component may be significant. The simple Pitot-static tube, for example, does not provide information about the flow directionality. A velocity measurement system, like the Particle Image Velocimetry (PIV), by its turn, does not provide information about the local static pressure profile. Far downstream the body, the flow can be assumed parallel and the static pressure becomes constant. But at such distances the wake itself may be difficult to detect as it spreads in the vertical direction and its velocity profile becomes more and more uniform since one falls in the old difficulty of measuring a small difference of relatively large quantities. Going downstream is not so much a problem for bluff bodies or airfoils at high angles of attack, but at least since Betz (1925) *apud* Schlichting (1975) techniques based on total and static pressures measured **close** to an airfoil trailing edge have allowed good drag estimation also for slender wing profiles at small angles of attack.

The most easy technique to use for drag estimation based on total and static pressure measurements made close to the trailing edge is due to Jones (1936). It is based on the Bernoulli equation to relate the measurements conducted close to the trailing edge to the quantities far downstream the body that are accounted into the momentum balance. The results obtained using this technique are compared with those obtained using velocities measured with PIV at some distances behind a NACA 0012 airfoil.

1.1. The momentum balance

The *x*-momentum balance performed over the control volume in Fig. (1) may be expressed mathematically as

$$\frac{d}{dt}\int_V \rho\, u\, dV + \oint_S \rho\, \hat{n}\cdot\vec{V}\, u\, dS = \oint_S \hat{n}\cdot\tilde{T}\cdot\hat{i}\, dS + \int_V b_x\, dV - D \tag{1}$$

where V is the control volume, S is the control surface area, defined as the perimeter indicated by a dashed line in the figure multiplied by some width W, ρ is the fluid specific mass, $\vec{V}$ is the local velocity vector, $\hat{n}$ is the external unitary vector locally normal to the surface S, u is the velocity component in the x-direction, $\tilde{T}$ is the stress tensor, b_x is the body force per volume unit acting on the fluid in the x-direction, dV is the control volume element, dS is the control surface area element and D is the force in the x-direction exerted by the fluid on the airfoil represented by the hashed area in Fig. (1).

It must be used, now, the steady and two-dimensional flow hypothesis, but it should be kept in mind that, for a turbulent flow, this means that time-averaged quantities do not vary in time or in the third (z) direction. The body forces will be neglected and it will be assumed that all the important contributions of the stress tensor will be those due to its spherical part, the pressure p. With these assumptions one obtains

$$\langle D\rangle = \left\langle \oint_S (p\, \hat{n}\cdot\hat{i} - \rho\, \hat{n}\cdot\vec{V}\, u)\, dS \right\rangle \tag{2}$$

where the angle brackets are used to denote time averaging.

Now supposing that the control surface is a rectangular prism with a cross section like that shown in Fig. (1), that its sides are far enough from the body, in such a way that there is no flow across its ceiling and floor and that along its downstream face the momentum flow is uniform (equal to ρU_∞^2), and that the specific mass and the pressure are uniform along all the control surface, one obtains

$$\langle D\rangle = \left\langle W\rho\int_{-\infty}^{\infty}(U_\infty^2 - u^2)\, dy \right\rangle = W\int_{-\infty}^{\infty}\rho\left(\left\langle U_\infty^2\right\rangle - \left\langle u^2\right\rangle\right)dy \tag{3}$$

The integration is performed only over the downstream face of the control volume, which is extended above and below the airfoil y-position until the specific momentum flux on that surface equals U_∞^2 making the integrand null. An interesting point to be observed here is that connecting two total pressure tubes to a low-pass filtering differential pressure meter like an U-tube one can measure directly the integrand at the right hand side of the Eq. (3). The angle brackets will be dismissed for the remaining of this paper, but the time averaging needed for turbulent flows must be remembered.

Usually some subtleties of the turbulent flow are disregarded and the mass conservation is used to rewrite Eq. (3) in terms of a velocity deficit as

$$D = W\rho\int_{-\infty}^{\infty} u(U_\infty - u)\, dy \tag{4}$$

where the integration is performed only over the downstream face of the control volume that is extended, above and below the airfoil trailing edge level, far enough to reach positions where the integrand becomes null.

1.2. The technique due to Jones

The central idea in the technique due to Jones (1936) for drag estimation is to consider the existence of streamlines connecting the points of the control volume downstream face discussed in the preceding subsection to points of a plane located near to the airfoil trailing edge. This plane, where the measurements are performed, is supposed to be nearly normal to the flow at the measurement points. Disregarding any loss of total pressure and compressibility effects along these streamlines one would have $u = \sqrt{u_m^2 + \frac{2p_m}{\rho}}$, where the subscript *m* denotes quantities measured on the plane near the airfoil trailing edge. Substituting this in Eq. (4) and nondimensionalizing the result, one obtains

$$C_D = \frac{2D}{\rho U_\infty^2 A} = \frac{2W}{A}\int_{-\infty}^{\infty} \frac{u_m}{U_\infty}\left(1 - \sqrt{\frac{u_m^2}{U_\infty^2} + \frac{2p_m}{\rho U_\infty^2}}\right) dy_m = \frac{2W}{A}\int_{-\infty}^{\infty} \sqrt{\frac{h_m - p_m}{H_\infty}}\left(1 - \sqrt{\frac{h_m}{H_\infty}}\right) dy_m \tag{5}$$

where A is the characteristic area of the airfoil, h_m is the total pressure at the plane near the airfoil trailing edge, p_m is the static pressure at the same plane, H_∞ is the free-stream total pressure and dy_m is the element of distance along the trace of the plane near the trailing edge on the symmetry plane of the two-dimensional flow.

In spite of the approximations involved in its derivation, Eq. (5) is known to produce good results, even in turbulent flows. The measurements of h_m and p_m, however, must be performed out of any recirculation bubble. This equation was developed for incompressible flows, but there are extensions of it available for high speed subsonic flows (see Pankhurst and Holder, 1965).

2. Experimental apparatus

The experiments were performed, in a closed-circuit, open test section subsonic wind tunnel, named TA-3. The outlet of its contraction, and the inlet of its diffuser are circular. The wind tunnel contraction outlet has a diameter of 0.65 m and the test section is 0.97 m long. A 13 hp motor produces a maximum velocity of 40 m/s through the test section. The turbulence intensity of the empty wind tunnel is around 0.3% at 30m/s. The NACA 0012 airfoil model was made of wood and had a chord length of 20 cm and 1 m of span.

The technique due to Jones can not be applied when only velocity measurements are available. To use this technique, measurements of static and total pressure where performed using the pair of static-Pitot tubes, that appear in Fig. (2). One of these was measuring the pressures at the wind-tunnel contraction outlet, upstream and above the airfoil. The other was attached to a height gage in such a way that it could be displaced vertically within 5 hundredths of a millimeter precision, downstream the airfoil trailing edge.

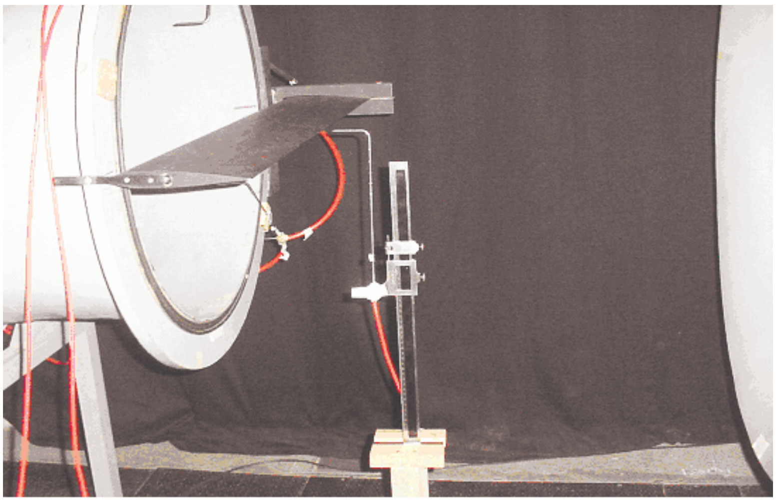

Figure 2. The NACA 0012 airfoil model positioned at the TA-3 wind-tunnel with the Pitot-static tubes.

The inclined liquid column manometers used to measure the differences between static and total pressures, and to measure the dynamic pressure at the wind-tunnel contraction outlet, are shown in Fig. (3).

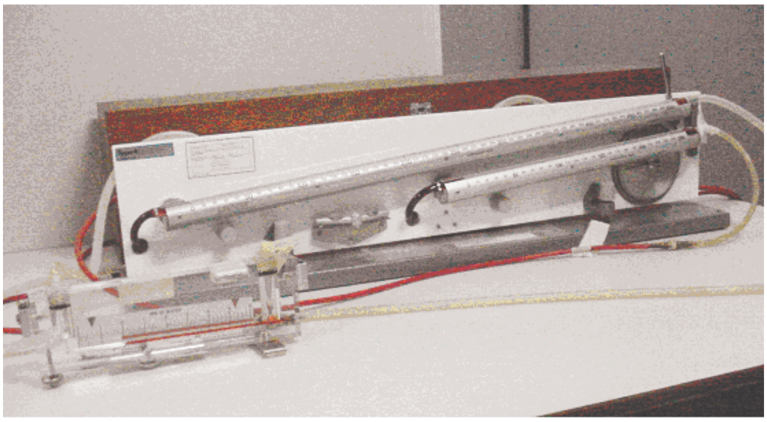

Figure 3. Inclined liquid column manometers used.

In Fig. (4) a detail of a wake survey rake used in the 3 × 2 m^2 test section of the TA-2 wind tunnel is shown. TA-2 is the largest CTA wind-tunnel. The ruler also shown in the picture is 20 cm long. The small metallic tubes are total pressures probes, and the bigger L-tube with round nose is a static pressure probe, that has four holes in its perimeter to allow some misalignment between the probe and the flow. There are 91 Pitot tubes and 6 static pressure probes along the length of the rake. The Pitot tubes and the static pressure probes are less spaced in the center of the rake, that must be aligned with the center of the wake, and more spaced near the rake tips. Since the nose of the static pressure probes is aligned with the Pitot tubes openings, and the static pressure holes must be 6 diameters downstream the probe nose, the static pressures are taken a few centimeters downstream the points where the total pressures are taken. This rake was not used in the experiments reported in this paper, but is shown here as an example of equipment used for wake surveys in industrial experiments.

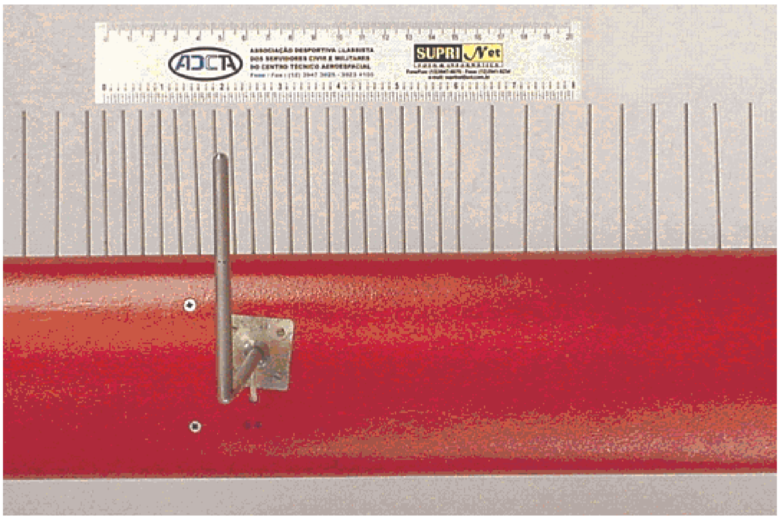

Figure 4. Detail of a wake survey rake built for a 2 m in height closed test section.

A schematic representation of the experimental set up for PIV measurements is shown in Fig. (5), it was used a Dantec Flow Map PIV System. As indicated in this figure, the laser source was fixed on an aluminum trail that was on the ground. A vertical laser light sheet was created using a 90^o mirror unit and light sheet optics with thickness adjuster.

The flow was seeded with theatrical fog (polyethylene glycol water-solution) generated by a Rosco Fog Generator, which was placed inside the wind tunnel diffuser. A protective black shelter was placed around the test section in order to avoid dangerous laser reflections and avoid the interference of environment light in the measurements. The laser light source was a 200 mJ dual pulsed Nd:Yag laser, built by New Wave Research, Inc. The PIV images were recorded with two digital HiSense 4M cameras (built by Hamamatsu Photonics, Inc.) with Nikkor f# 2.8 lenses with 105 mm of focal length. The measurement process was synchronized and controlled by a Flow Map System Hub and the FlowManager software produced by Dantec Dynamics, Inc. The two digital cameras were placed on Dantec Scheimpflug Camera Mounts fixed on an aluminum trail supported by a positioning device, as shown in Fig. (6)

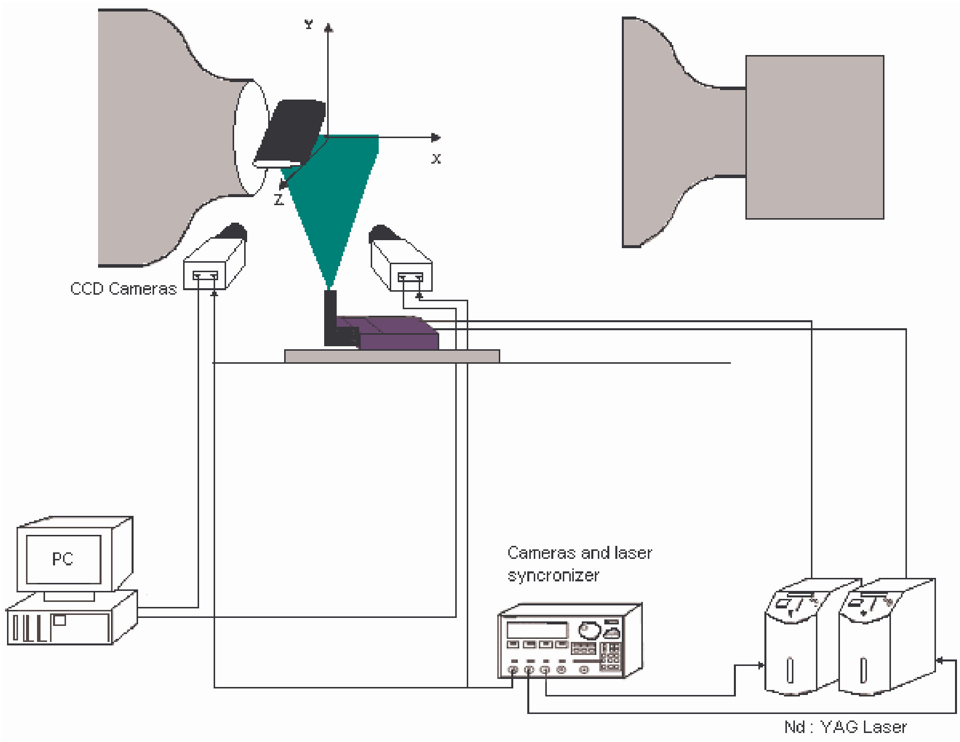

Figure 5. Schematic representation of the PIV setup.

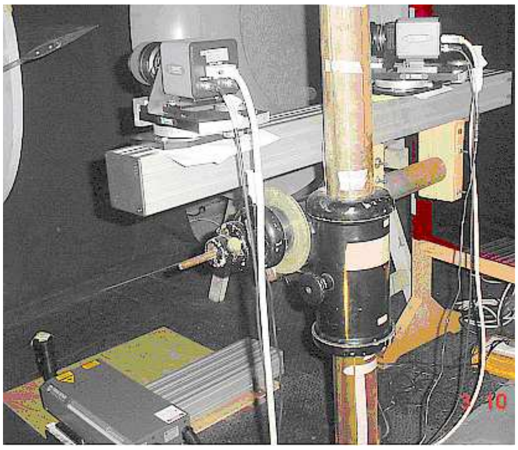

Figure 6. The PIV cameras supported on a mechanical positioning device.

3. Results and discussion

In Figs. (7) and (8) total and static pressure profiles obtained traversing the airfoil wake at distances of 12.5 mm and 48 mm downstream of its trailing edge are shown. The Reynolds numbers based on the airfoil chord were of 4.43×10^5 and 4.47×10^5 in the experiments corresponding to each of these figures. A correction was need for zeroing the difference between the total pressure measured by the Pitot tube in the wind-tunnel contraction outlet and by the Pitot tube used to traverse the wake when the latter was far outside the wake. Albeit this, the results seem to be pretty satisfactory. Using this data to obtain approximately the right hand side of Eq. (5) and performing the integration by the trapezoidal rule the values of 0.0082 and 0.0081 for the C_D are obtained. These values are not far from the approximately 0.0065 found in the literature (Abbot and von Doenhoff, 1959, Fig. 66 at the page 150) for the NACA 0012 with smooth surface at this Reynolds numbers range. As shown at the page 463 of the same reference, for a higher Reynolds number, the roughness of the surface can increase the drag coefficient to nearly 0.01.

Some restrictions could be made to the static pressure measurements shown in Figs. (7) and (8) for two main reasons. The first is that the static pressure holes are about 3 cm downstream the Pitot tube nose, so the static pressure profile shown in Fig. (7) may be more appropriate for use with the total pressure profile shown in Fig. (8) – the drag coefficient obtained with this pair of profiles is approximately 0.0080 (a little bit closer to the literature value for the airfoil with smooth surface). The second reason is that no wind-tunnel calibration was performed to quantify the gradients of static pressure that can occur between the outlet of the contraction, where the reference Pitot-static tube was placed, and the middle of the test section, where the wake survey was performed. This is linked to the general subject of wind-tunnel interference effects (see, e.g. Pankhurst and Holder, 1965, p. 378). Some other questions that deserve more study and are certainly important also for the drag estimation based on velocity profiles regard the errors inherent to the numerical integration procedures and the choice of the integration limits, since using real measurements the integrand never becomes exactly zero.

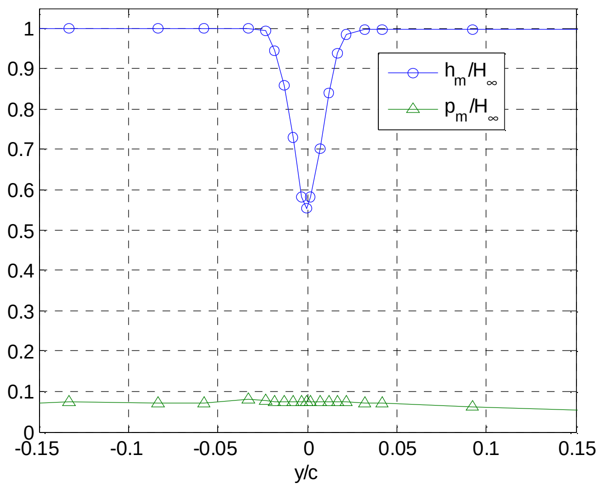

Figure 7. Total and static pressure profiles obtained with the Pitot-static tube placed 0.0625 chord downstream of the airfoil trailing edge.

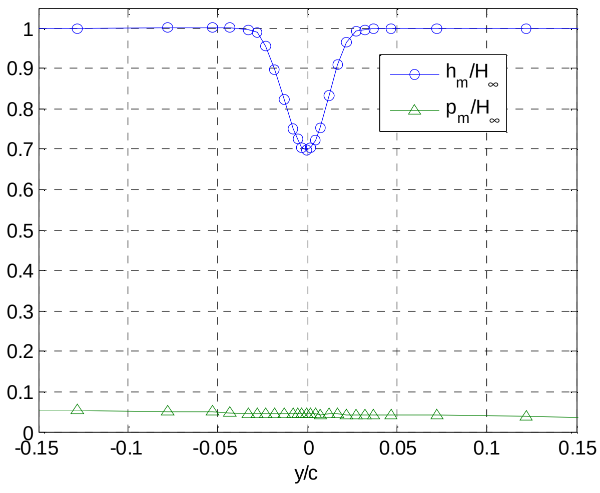

Figure 8. Total and static pressure profiles obtained with the Pitot-static tube placed 0.24 chord downstream of the airfoil trailing edge.

In Fig (9) the velocity profile obtained by PIV one chord downstream the airfoil trailing edge is shown. The drag coefficient, calculated by a nondimensionalized version of Eq. (4) obtained using this profile is 0.0096, a value that could be regarded as reasonable for the experiment Reynolds number (4.79×10^5) if the airfoil surface is considered rough. But, besides being substantially (21 %) larger than the values obtained with the Pitot tube, if one takes a value for the free-stream velocity 0.1 % larger than the one chosen (by looking to the velocity profile) in the former calculation, the drag coefficient changes to 0.0102 (a 6.25 % increase). The question is that the estimation of drag based in velocity profiles measured relatively far from the airfoil trailing edge is more sensitive to measurement errors than the estimation based on total and static pressure profiles measured close to that edge.

There are some reasons for the increased sensitive to errors of the drag estimation based on velocity profiles. One of these reasons is that, in a practically incompressible flow, the total pressure is constant outside the boundary layers and the wake. So it is much easier to identify the free-stream total pressure than to identify the free-stream velocity that is affected by the potential flow around the airfoil. Consequently, it is easier to identify the wake region looking to a total pressure profile than looking to a velocity profile.

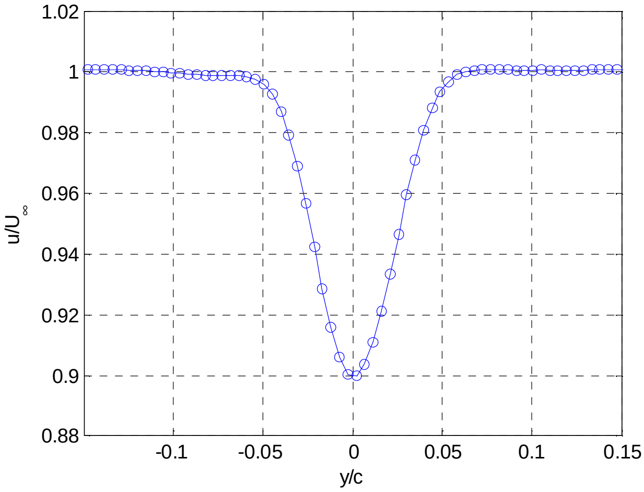

Figure 9. Detail of the velocity profile 1 chord downstream of the airfoil trailing edge obtained by PIV.

The wider velocity profile shown in Fig. (10), that extends outside of the uniform jet that is in the core of the test section, is presented to make clear the difficulty of identifying the free-stream velocity. The boundaries of the jet affect the velocity near the wake and contribute to this difficulty.

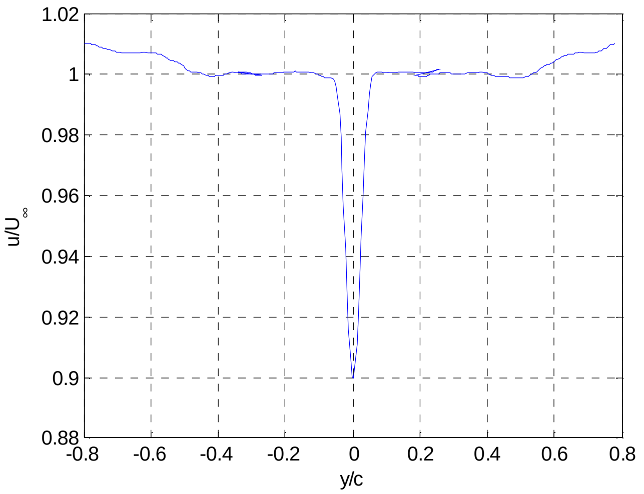

Figure 10. The velocity profile 1 chord downstream of the airfoil trailing edge obtained by PIV changing the vertical position of the cameras in order to sweep the most uniform part or the wind-tunnel jet .

In Fig. (11) it is shown a velocity profile obtained in an experiment a bit different from those that generated the results presented before, in this paper. As can be deduced from the asymmetry of that profile, the airfoil was at a small positive angle of attack. The Reynolds number was smaller (1.3×10^5) and the profile was taken closer to the airfoil trailing edge (20 mm, that amounts to 0.1 chord, downstream of it). Performing the integral in the Eq. (4) only in the region where the velocity was smaller than that attributed to the free-stream, the value of 0.015 was obtained for the drag coefficient. This coefficient is expected to increase as the Reynolds number decreases in the range bellow 10^6 and so the obtained value is not bad. But the choice of the free-stream velocity and even the use of Eq. (4) are now very difficult to justify. So close to the airfoil trailing edge there is no uniform velocity outside the wake, but a region of accelerated flow as can be seen in Fig. (11).

An also important reason for the drag estimation based on a velocity profile measurement to be more sensitive to measurement errors than the estimation based on total and static pressure profiles is that the total pressure fall associated to a wake is larger than the corresponding velocity fall, even if the velocity and pressure profiles are taken at the same distance of the trailing edge. Notice that one must divide the quantities by their free-stream values in order to make them comparable. The difference in the relative falls happens because the total pressure is roughly proportional to the square of the velocity. And one should not forgot that the known techniques allowing the use of measurements performed close to the trailing edge (where the velocity fall is larger) are based on total and static pressure measurements.

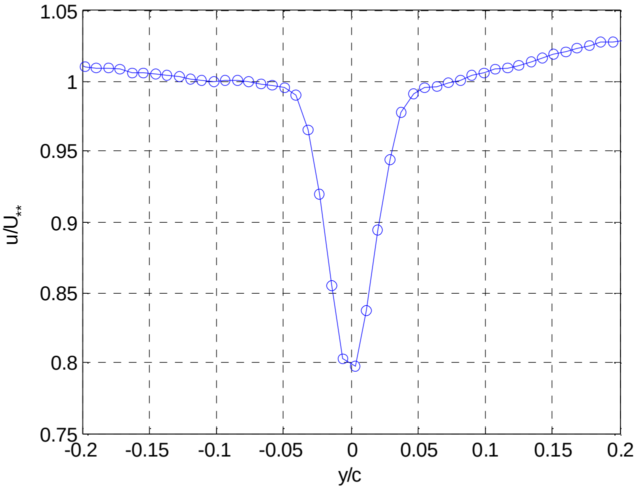

Figure 11. The velocity profile obtained by PIV 0.1 chord downstream of the airfoil trailing edge.

The averaging properties of total and pressure measurements can also be seen as an advantage of their use. The tubes connected to the Pitot tubes and static pressure probes act as low-pass filters, averaging in time the pressures that are transmitted. And the averaged values measured by a Pitot-static tube in a turbulent flow, like that expected in most wakes, are not directly associated with the mean velocity, as noted by Ower and Pankhusrt (1977). The mean total and static pressures can be easily linked to the momentum flow and this seems to be an important reason for the lack of considerations regarding turbulence during the development of a technique applied to turbulent flows does not have bad consequences. A filtering process, and a momentum flow calculation, may be applied to velocity measurements. This is easier to do using a hot-wire anemometer or LDV than using PIV. But, even considering the eventual difficulty of tilting the Pitot tubes and static pressure probes, or the rake if one is afforded, for aligning them with the flow behind an airfoil at a non-null angle of attack or with high-lift devices deployed, the techniques based on total and static pressures seem preferable.

4. Conclusion and future work

The theoretical and experimental evidences found in the present study revealed several advantages of the use of total and static pressure measurements, instead of velocity measurements, for drag estimation by wake survey. Even so the present authors intend to use velocity measurements for such estimation in situations where the instrumentation for performing efficient total and static pressure measurements are not available. For this reason they will continue to investigate the consequences of this use of velocity measurements, in particular measurements by PIV.

5. Acknowledgement

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