EVOLUTION OF A FIVE-HOLE PROBE CALIBRATION NEAR A WALL

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ABSTRACT

Five-hole probes (5HP) are a common tool for measurements of the velocity in turbomachinery studies. In those applications, the spaces are confined, which drives the probes to get close to walls. The proximity of the wall affects the behavior of the 5HP. The wall-related evolution of the calibration of two hemispheric L-shaped 3D printed five-hole probes is investigated in a low speed wind tunnel. 2D Particle Image Velocimetry (PIV) and pressure measurements were carried out. The wall proximity causes the probe to measure that the flow goes away from the wall whereas the boundary layer causes the probe to feel that the flow direction is towards the wall.

NOMENCLATURE

5HP :	five-hole probes
BL :	boundary layer
PIV :	particle image velocimetry

INTRODUCTION

Five-hole probes are a useful tool in turbomachinery measurements. They can be designed to be robust [1] and don't require optical access. However, some problems are encountered when using them in this setting [2]: their big size in the turbomachine veins affects the flow; they interact with nearby surfaces; the flow is different from the calibration flow which affects the way the data should be interpreted. In particular, near the walls of the vein, the probe blocks the flow and changes its direction [3]. The boundary layer on the wall adds complexity to the situation.

The tunnel used is the L-12 wind tunnel in von Karman Institute for Fluid Dynamics (VKI), that can reach Mach 0.05 at ambient temperature and pressure. The base probe of this work is inspired by a probe used at SAFRAN on the BEARCAT project, that has a diameter of 4mm. The probes used for this experiment are scaled up and have a diameter of 8mm and 16mm. The objective was to reduce the relative size of the boundary layer to limit its effects on the data. Investigation in the boundary layer are carried out during another experiment. A flat plate with a sharp bevel was mounted in the test section to obtain a wall with a small boundary layer.

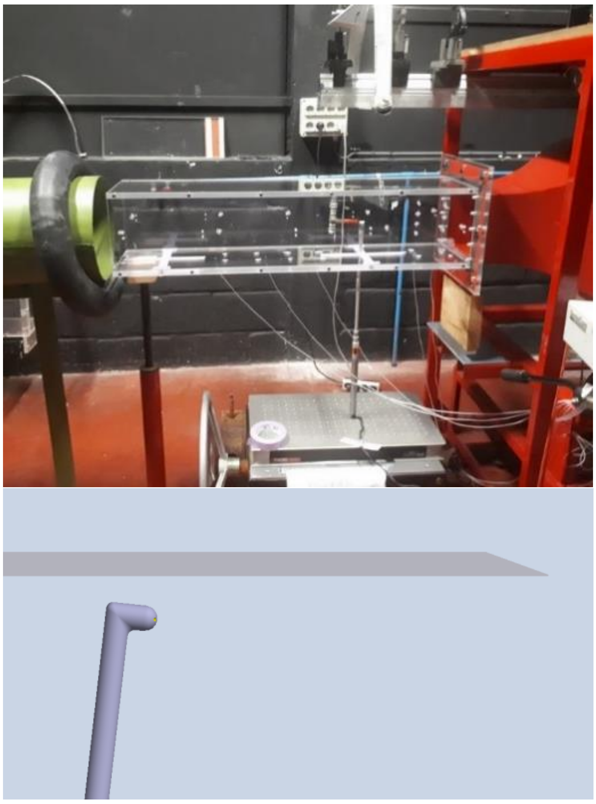


Figure 1 : Photo of the test section and digital mock-up of the experiment. The probe moves vertically towards the flat plate in gray. The flow comes from the right.

The calibration coefficients were measured at different distances from the flat plate, at two locations downstream the start of the flat plate to vary the boundary layer thickness. At the first location, 200 mm downstream the start of the plate (downstream position), the boundary layer was expected to be 5.5 mm thick, assuming it was turbulent. At the second location, 8.4 mm from the start of the plate (upstream position), the boundary layer was expected to be 2.6 mm thick, half the other thickness.

The ideal probe used ideally would measure the same flow direction as it gets closer to the wall, whereas according to the literature review [3] the presence of the probe near the wall deflects streamlines away from the wall. The shear in the boundary layer deflects streamlines to the wall and counteracts the wall proximity effect. Thus, even if the flow without the probe is parallel for example, the probe is going to measure a non-parallel flow. It is therefore important to quantify these two effects on the 5HP.

The probe head was moved from halfway between the flat plate and the bottom of the test section to contact with the flat plate. This represents 6 to 0.5 diameters for the 8mm probe and 3 to 0.5 diameters for the 16mm probe. The spatial resolution of the traverse was increased from half a diameter 6 diameters away from the plate to 0.1 diameter close to the plate. PIV measurements were made every 5 probe position. At each probe position, orientation and height, the pressure data from the five probe holes, the static pressure on the test section wall and total pressure in the settling chamber were simultaneously acquired. The probe hole pressure sensors were +-250 Pa LBA bleed sensors from SensorTechnics. The static pressure was acquired on a +-86 Pa Validyne sensor, and the total pressure on a +-220 Pa Validyne sensor. The LBA sensors were calibrated using the wind tunnel as the constantly renewed pressure source and a Druck DPI610 250 Pa calibrator. The Validyne sensors were calibrated with the Druck DPI610 250 Pa calibrator. The ambient pressure and temperature were noted twice a day from the VKI atmospheric pressure service and a room thermometer.

Figure 2 : the two probes used for the experiment. The heads were 3D printed and assembled with the masts in VKI.

The traverses were made with different positions of the probe to calculate the calibration coefficients:

Traverse	Pitch	Yaw
1	0	0
2	0	10
3	10	0
4	10	10
5	-10	0
6	-10	10

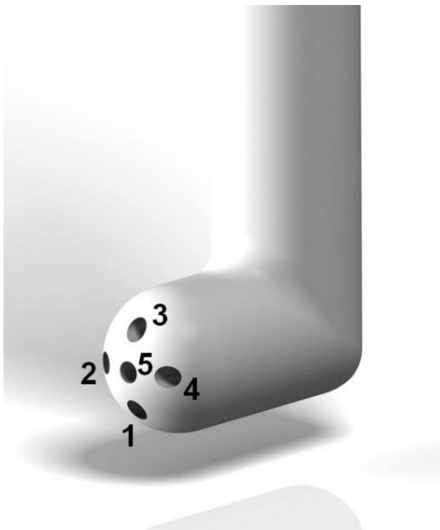
An earlier calibration of the probes showed sufficient symmetry on each side of 0° of yaw to only investigate positive yaws. As the probe is not symmetrical pitch-wise, negative and positive pitches were studied.

The pitch and yaw calibration coefficients are defined as follows, overlined p being the mean pressure of the side holes:

$$k_{yaw} = \frac{p_4 - p_2}{p_5 - \overline{p}}$$

$$k_{pitch} = \frac{p_3 - p_1}{p_5 - \overline{p}}$$

The numbering of the holes is the following:



A summary of the experiment is presented in Figure 3.

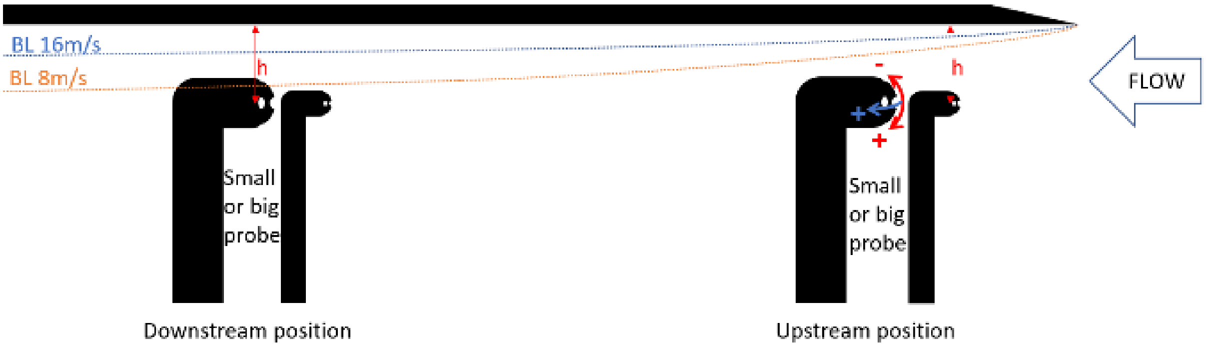


Figure 3: illustration of the different probe positions in the experiment

RESULTS AND DISCUSSION

Firstly, no hysteresis was found when getting closer or further from the wall.

Here, we observe two types of cases: the cases where the wall proximity effect and the boundary layer effects contributions are clear, because they start at different points in the traverse or because one is much stronger than the other and the cases where the analysis was harder due to the entanglement of the phenomenon.

One situation was striking among the first type of cases: with the 16mm probe, at the upstream location and for the highest speed, the boundary layer was thin enough for its effect to kick in too late to change the measurements noticeably. This situation was used as a reference to extract the boundary layer effect from other cases. In those cases, the pitch and yaw coefficients are monotonous and evolve faster as the probe gets closer to the wall, as seen in Figure 4 and Figure 5 in red. In most cases, there was a slow decrease, then a surge in pitch coefficient and then a new decrease as the probes got closer to the plate, as in Figure 4 in blue and Figure 6. The surge seems to happen sooner with the small probe and at the downstream position, where the boundary layer is thicker. The ratio of the boundary layer effect to wall proximity effect changes dramatically from case to case. The sooner the boundary layer meets the probe, the more predominant its effect is.

A decreasing pitch coefficient means that the stagnation point on the probe is moving towards the hole closest to the wall. The probe measures that the flow is diverging more from the wall. The largest change in pitch coefficients amount as much as 7° variation in pitch, according to the calibration far from any wall.

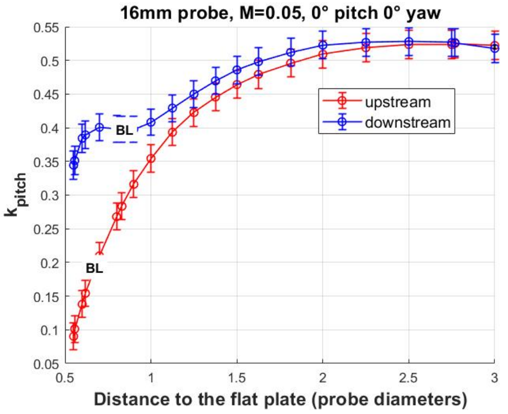


Figure 4: pitch coefficient comparison for 0° pitch and 0° yaw with the 16mm probe

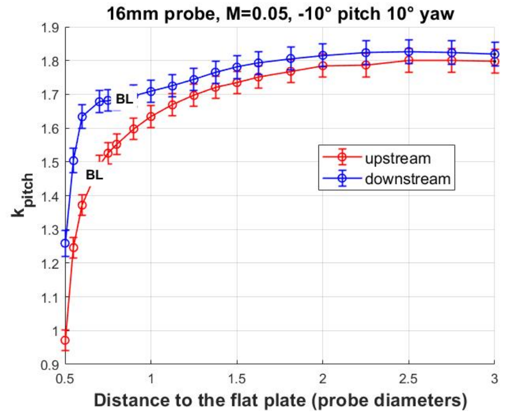


Figure 5: pitch coefficient comparison for -10° pitch and 10° yaw with the 16mm probe

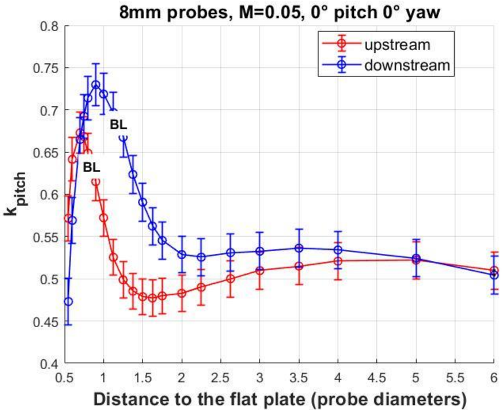


Figure 6: pitch coefficient comparison for 0° pitch and 0° yaw with the 8mm probe

In Figure 4 and Figure 5, the red curve is from the reference case, the comparison between upstream and downstream gives the boundary layer component of the error in pitch coefficient, displayed in Figure 8 and Figure 7. The boundary layer increases the perceived pitch. It fits with the effects of shear flow described by Bailey [3] and Appukutan [4]: the shear makes the probe sense a flow going in the opposite direction of the gradient.

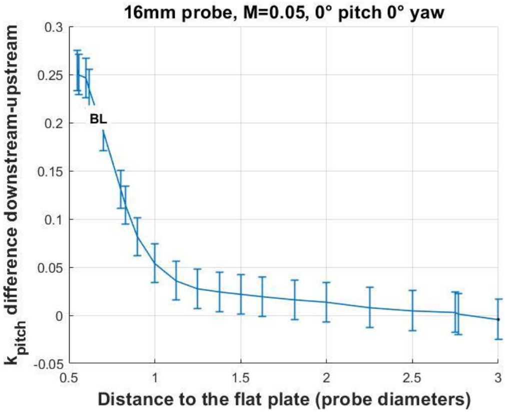


Figure 7: BL component in pitch coefficient for 0° pitch and 10° yaw

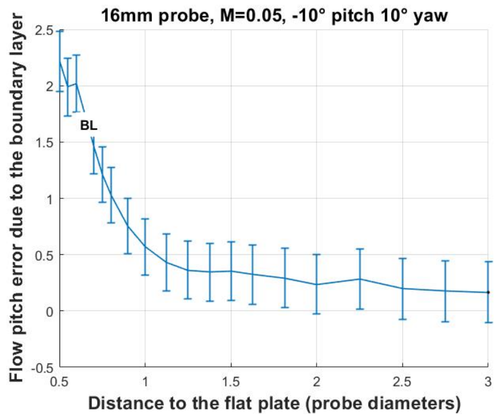


Figure 8: BL component in pitch coefficient for -10° pitch and 10° yaw

When the yaw is 0, it is almost unaffected, as can be seen in Figure 9, but it is affected by the wall proximity when the probe is placed at a non-zero yaw. Little asymmetries in the probe geometry or flow and uncertainty in the yaw setting can explain the yaw coefficient offset from zero in the 0-yaw case. The closest the probe is to the wall, the more the yaw is overestimated. The upstream-downstream comparison in Figure 11 and Figure 13 show that the boundary layer further increases the yaw coefficient error. The yaw error reaches 5° in the most extreme cases. The contribution of the boundary layer is, in those cases, two to three times weaker than the wall proximity contribution on these specific cases. This has to be assessed on the whole data corpus.

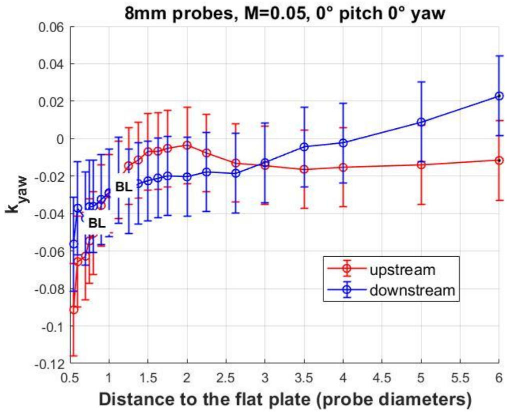


Figure 9 : yaw coefficient comparison for 0° pitch and 0° yaw

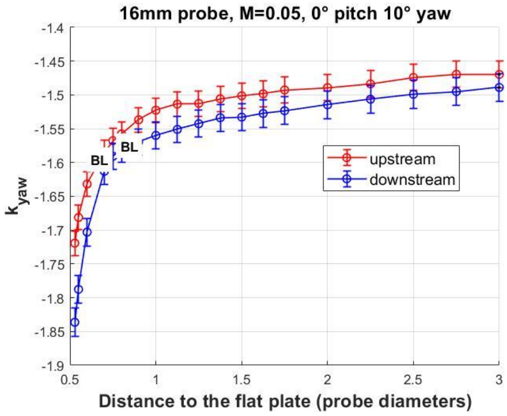


Figure 10: yaw coefficient comparison for 0° pitch and 10° yaw

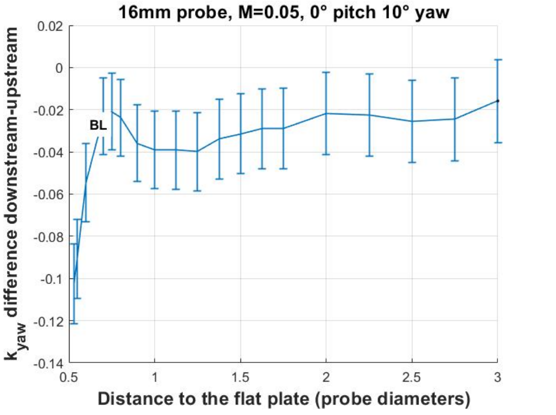


Figure 11: BL component in yaw coefficient for 0° pitch and 10° yaw

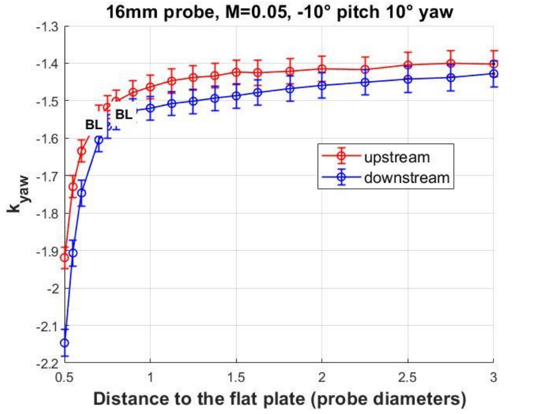


Figure 12: yaw coefficient comparison for -10° pitch and 10° yaw

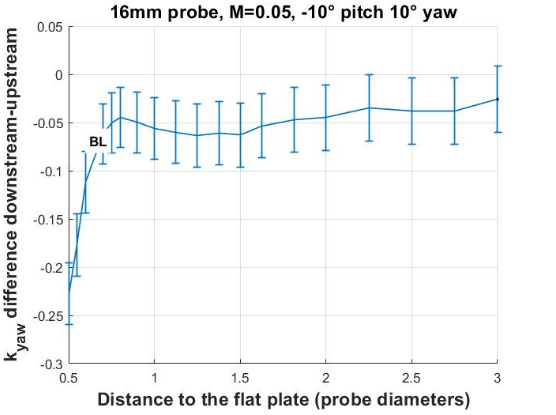


Figure 13: BL component in yaw coefficient for -10° pitch and 10° yaw

The evolution of the pressure coefficients can be broken down in their hole pressure components. Figure 14 shows that, for the dashed lines corresponding to the traverse with almost no boundary layer, P1 (the pressure of the hole closest to the wall) increases with wall proximity while P3 (the pressure of the hole furthest from the wall) keeps decreasing. This means that the stagnation point moves towards the hole closest to the wall as the probe gets closer to the wall. It corresponds to a flow diverging from the wall mentioned in [3]. We can see with the solid lines, corresponding to the downstream case with a thickest boundary layer, that the boundary layer drives a drop in pressure 2, 3, 4, 5 but a stabilization of P1 after the wall proximity has started affecting the pressures. The pressure drop in P1 due to the boundary layer is fought by the wall proximity which ultimately makes P2 rise again. This shows that the top hole is the place where the two error sources interact the most, and that the study of individual hole pressures brings additional information to the study of the pressure coefficients.

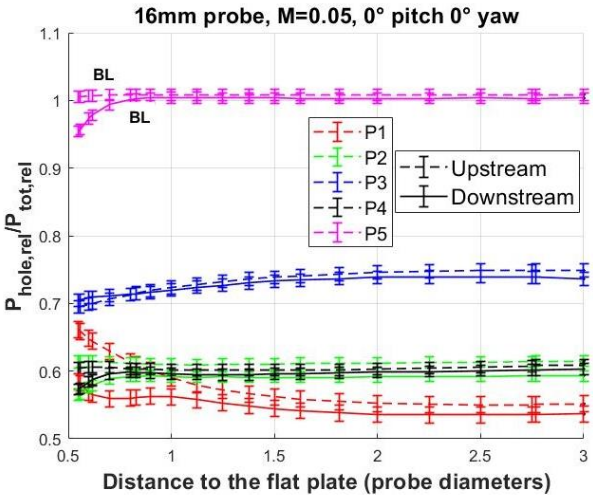


Figure 14: pressure evolution in the five holes for the case of Figure 4. The BL indicators have been only left on the center hole curves for visibility

The start of the pitch spike seems to correlate with the entrance of the top of the probe in the boundary layer. It correlates well in the traverses using the 16mm probe. However, it does not account for the start of the boundary layer effect in all cases. A better indicator is being searched. It is possible that it should take into account the probe boundary layer thickness as well as the probe diameter and the wall boundary layer thickness. It is also possible that the two probes have an effect on the boundary layer thickness as they get closer to the wall, of different intensity from one probe diameter to another. The PIV data will help answer this question thanks to flow information around the probe, a better knowledge of the boundary layer during the traverse and the acceleration between the probe and the wall.

Figure 15, Figure 16 and Figure 17 show the perceived flow yaw and pitch in the test section reference during several traverses with different probe positions. As the flat plate flow is parallel to the plate, the measured yaw and pitch in the test section reference should be 0 whatever the position of the probe and its distance to the flat plate, which means the curves should be a dot staying on (0°,0°). The black dots around (0.25°, -1°) are the start of the traverses. 3 diameters away from the wall. “BL” shows where the probe is entering the theoretical BL and the symbols "2", "1", ".6" and ".5" signal the distance between the probe and the wall in probe diameters. 0.5d is contact with the wall. Every curve should start and stay at (0°, 0°) if there was no boundary layer or wall proximity effect. The bigger the error, the bigger the extent of the curve. We can make several observations on this representation:

• The beginning of the curves seems to be centered around (0.25°, -1°) instead of (0°, 0°). It could be caused by the flow being not exactly parallel to the flat plate or an error in setting up the probe;

• Between the start and 2d distance, the coefficients evolve very little;

• It seems to be possible to simplify the curves in two regions by two straight lines of different slopes: one outside and one inside the boundary layer effect zone;

• When the boundary layer starts between 0.7d and 0.5d, it doesn't have enough room to influence the yaw and the pitch coefficients significantly.

• Both effects seem weaker or more complementary with low speed flows;

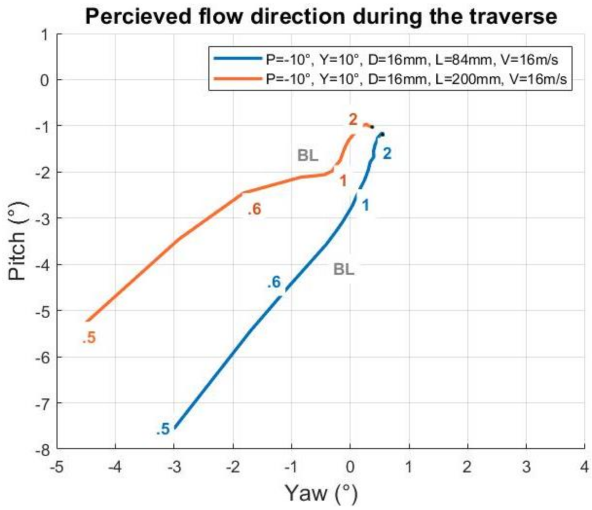


Figure 15: perceived direction with -10° pitch and 10° yaw

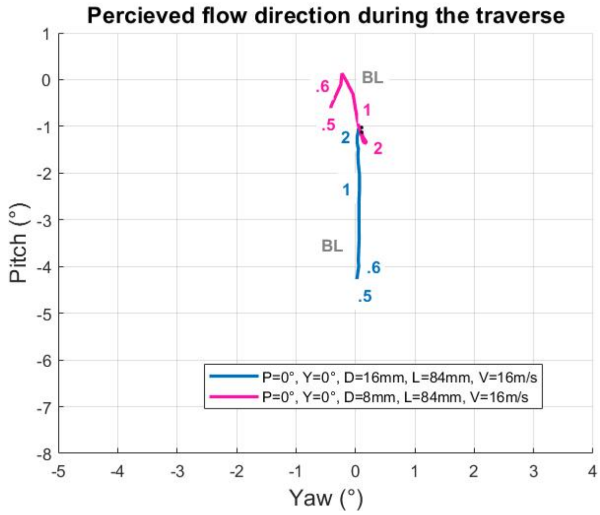


Figure 16: perceived direction with vertical probes

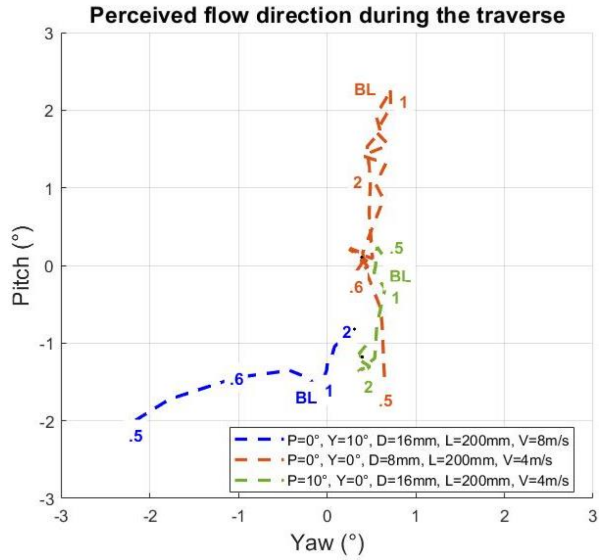


Figure 17: perceived direction for low Mach numbers

The PIV data has not been fully post-processed yet. Some pictures pairs only roughly were roughly analyzed to check whether the data quality was satisfying. The goals of the PIV analysis are to

• Know how the flow field is in absence of the probe;

• Measure the deflection of the stagnation point streamline;

• Have a value of the actual velocities measured by the probe;

• Understand better the local flow at the center, up and down probe holes.

In Figure 18, we can see a strong acceleration between the probe and the flat plate. The acceleration could explain the drop in the pressure at the top hole and the increase of the pitch coefficient seen in Figure 14 and Figure 4.

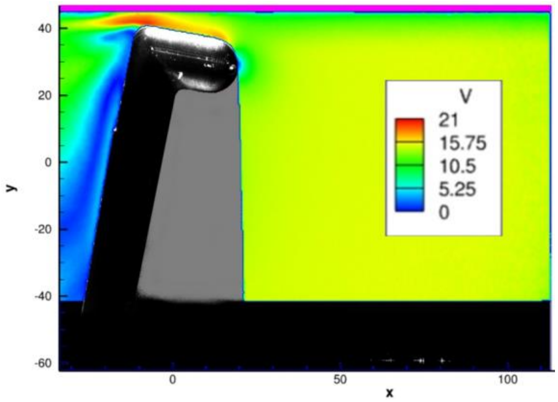


Figure 18: contour of the velocity magnitude with the 16mm probe, 1 diameter away from the flat plate (purple) in the downstream position, with -10° pitch. The gray area is the shadow of the probe since the laser sheet came from above.

The current findings for these experiments are that there is an effect of the wall proximity distinct from the boundary layer effect, that can be isolated in some cases. The probe measures a pitch diverging from the wall as it gets closer to the wall but the boundary layer has the opposite effect. The two effects are in competition regarding pitch measurements and can compensate in some cases. These findings are coherent with the work of Bailey [3]. In cases with yaw, the proximity of the wall increases the perceived yaw. The boundary layer has a smaller effect on the yaw measurement compared to the wall proximity in the cases where the two effects were possible to isolate. We saw that the boundary layer effect is stronger in most cases. The diversity of comparative amplitude and area of effect between the two error sources implies that two separate corrections are necessary. The data shows that a prior knowledge of the boundary layer characteristics could be necessary to apply boundary layer effects corrections. In that case, CFD simulations of the measured flow would be complementary to the 5HP acquisitions.

The magnitude of these two phenomena and their interaction will be analyzed further thanks to the PIV post-processing and the results of other experiments, that were conducted in the same test section with the same probes, are processed. One of those experiments is about the boundary layer effect away from the wall and will help understand the results of the experiment subject of this document.

The coming work about the data from this campaign is to:

• Study how kyaw and kpitch as functions of the yaw and pitch evolve near the wall;

• Investigate the individual behavior of the hole pressures;

• Post-process the PIV data to compare our data to measure the displacement of the stagnation point streamline and compare it to the results of Bailey [3] and have local information about the flow around the holes;

• Use CFD to decouple wall proximity and boundary layer effects thanks to slip wall conditions;

• Account for the distance between the probe holes as described in the article by Ligrani [5].

The experimental conditions are far from engine conditions. We are planning on using CFD to assess whether the low-Mach conclusion can be extended to high subsonic flow. Later on, we will be able to suggest and test wall proximity and shear corrections for this probe geometry.

ACKNOWLEDGMENTS

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