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USE AND CALIBRATION OF 5-HOLE PRESSURE PROBES TO MEASUREMENT OF AIRFLOW VELOCITY

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Abstract

Multi-hole probes are simple and robust device to measurement of flow velocity magnitude and direction in wide range of angles of attack – up to 75°. They become popular as they may be easily use to measurement of unknown flow velocity, while optical methods, like PIV or LDA, require some knowledge about the flow for proper setting of measurement devices. Multi-hole probes are also more lasting in comparison with CTA hot-wire probes, which may be damaged by a dust.

A multi-hole probe measures air pressure with one pressure tap on its tip and a few (usually 2, 4, 6 or more) taps on conical or semispherical surface of the probe tip. Based on measured pressures, some non-dimensional pressure coefficients are calculated, which are related to flow velocity direction (i.e. two angles in Cartesian or spherical coordinate system) and magnitude. Finding relations between these parameters is relatively complex, which for years was limiting application of multi-hole probes.

The article summarizes methods of multi-hole probes calibration and use, which may be classified as nulling and non-nulling methods or – with other criteria – as global and local methods. The probe, which was presented in the article, was the 5-hole straight probe manufactured by Vectoflow GmbH and calibrated in the stand designed and manufactured at the Institute of Aviation. The local interpolation algorithm has been used for calibration, with some modifications aimed on mitigate of mounting uncertainty, which is related with the non-alignment of flow velocity direction and probe axis

Results of calibration showed that the accuracy of presented methodology is satisfactory. The standard measurement uncertainty was assessed for 0.2° for the pitch angle and yaw angle, which is better than accuracy declared by the probe's manufacturer (1.0°). The measurement uncertainty of the flow velocity is approximately 0.12 m/s, similarly like in manufacturer's data.

Keywords: *aerodynamic measurement, turbomachinery, measuring devices, flow direction measurement, multi-hole probes*

1. Introduction

A common issue in the applied aerodynamics is measurement of flow direction or flow velocity vector. To perform such measurements, various instrumentation may be applied. Typically used devices are e.g. multi-component CTA (Constant Temperature Anemometry) probes and optical systems like PIV (Particle Image Velocimetry), LDA (Laser Doppler Anemometry) etc.

Another possibility, which recently gains its popularity, are multi-hole pressure probes. These devices have many advantages. In comparison to optical methods, they are more flexible to use (no strict requirements for their location, no preliminary knowledge about measured flow is necessary) and do not require visibility for the light source. In comparison with CTA hot-wire probes, multi-hole probes are more lasting (insensitivity for a dust, higher temperature etc.), more easy to maintenance and less sensitive for the air temperature change. Moreover, their application is relatively cheap – the probe requires only a few pressure transducers and postprocessing/logging device. A drawback of such probes is that a measurement can be taken in one point at the time; to obtain a spatial distribution of the velocity; one should increase number of probes or implement a traversing system (which in line requires a steadiness of measured flow).

2. Methods of use

Regardless of applied method, the measurement of flow velocity is based on measurement of static pressure in each pressure tap of the probe. Usually a set of non-dimensional coefficients is calculated, which in line are used to obtain velocity magnitude and direction (i.e. two Cartesian or spherical angles) using calibration results. Most popular definition was given by Krause and Dudzinski [11]:

$$Cp_{\alpha} = \frac{P_1 - P_3}{P_5 - \overline{P}}, \tag{1}$$

$$Cp_{\beta} = \frac{P_2 - P_4}{P_5 - \overline{P}}, \tag{2}$$

$$Cp_{total} = \frac{P_5 - P_{total}}{P_5 - \overline{P}}, \tag{3}$$

$$Cp_{static} = \frac{\overline{P} - P_{static}}{P_5 - \overline{P}}, \tag{4}$$

where:

$P_1 - P_4$ – pressure measured on peripheral pressure taps,
P_{total} – total pressure (measured independently),
P_{static} – static pressure (measured independently),
P_5 – pressure measured on a tip of probe,
$\overline{P}$ – quasi-dynamic pressure, given by equation:

$$\overline{P} = \frac{P_1 + P_2 + P_3 + P_4}{4}. \tag{5}$$

This set of coefficients, however, is valid in limited range of angle of attack (up to 30°, according to [17]). For higher angles, the flow separation on the leeward side of the probe appears and the stagnation point shifts from the tip pressure tap towards one of peripheral taps (Fig. 1). It may result with some singularities in equations (1)-(4).

To solve the problem of singularities, some improvements were suggested. For example, Pissasale and Ahmed [14] suggested to slightly extending the range of angle of attack by including dynamic pressure (multiplied by a scale factor) and static pressure, instead of quasi-dynamic pressure $\overline{P}$. However, more effective solution was proposed by Gallington [5], who suggested to omit the leeward pressure tap measurement (which is taken in the flow separation area) and to take into account only the measurement from the pressure tap, which measured the maximum pressure, and from neighbouring pressure taps.

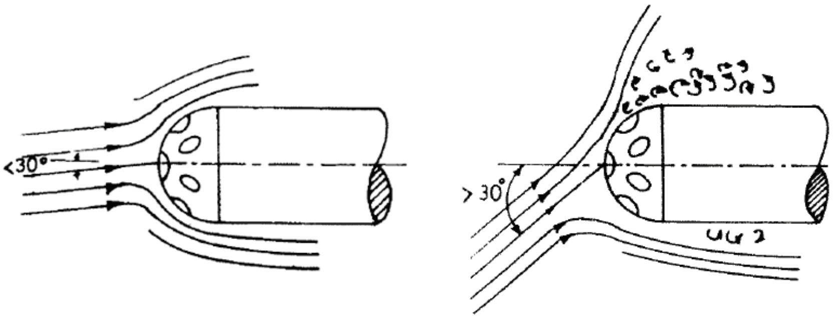

Fig. 1. The flow around probe tip for low (left) and high (right) angle of attack [17]

Coefficients defined by Gallington concerned a 7-hole probe. Variations of these equations for a 5-hole probe can be found in the literature, i.e. in the paper of Johansen et al. [9]:

$$Cp_{\Theta} = \frac{P_i - P_5}{\bar{P}}, \tag{6}$$

$$Cp_{\Phi} = \frac{P^+ - P^-}{\bar{P}}, \tag{7}$$

$$Cp_{\text{total}} = \frac{P_i - P_{total}}{\bar{P}}, \tag{8}$$

$$Cp_{\text{static}} = \frac{\bar{P}}{P_{total} - P_{static}}, \tag{9}$$

where:
P_5 – pressure measured on a tip of probe,
$\overline{P}$ – quasi-dynamic pressure, given by equation,
P_{total} – total pressure (measured independently),
P_{static} – static pressure (measured independently),

$$\overline{P} = P_i - \frac{P^+ - P^-}{2}. \tag{10}$$

Pressure coefficients, regardless of their definition, allow calculating magnitude and direction of investigated velocity vector. This step seems to be crucial for measurement quality and easiness, while various methods of measurement and its postprocessing are defined in the literature. In most general way, two approach may be classified:

- nulling,
- non-nulling.

In first approach, one of Cartesian angles measured by the probe should be set to zero by proper placing of the probe. Such approach allows simplifying probe's equations to single variable function. However, this approach requires possibility of probe's rotation along one of its axis, which may be impossible due to mechanical constrains (common in turbomachinery, where the space is limited). Moreover, proper placing of the probe requires previous measurements of the flow direction, which enlarges time and cost of the tests. These disadvantages caused that the nulling approach has rather historical meaning – a progress in computational methods caused by the computers alleviated the meaning of probe's equations simplification.

The opposite approach is the non-nulling one. In this case, the probe may be placed in any position along the flow velocity – a limitation is the range of probe. Due to this feature, multi-hole probes are so universal and flexible to use. A disadvantage of this approach, however, is that results of calibration must be obtained as functions of three variables (velocity magnitude and direction, given by Cartesian angles or spherical angles).

A classic way to solve a problem of the probe's calibration is to find a matrix equation, which bounds measured pressures (or nondimensional coefficients, calculated from these pressures) and velocity vector. It may be named as global approach, while the governing equation is valid globally, i.e. in whole range of parameters. This approach was applied among others by Morrison et al. [12], who have expressed flow velocity parameters (i.e. magnitude, pitch angle and yaw angle) using third-order polynomials or polynomial ratios. Similar solution was used recently by Georgiou & Milidonis [6]. Instead of polynomial approximation, Reichert and Wendt [15] used Taylor series to find set of 7 coefficients and Fingersh & Robinson [4] suggested method based on neural-networks using Levenbergh-Marquadt optimization, because linear interpolation methods and bi-cubic spline interpolation failed due to the nature of their data.

The complexity of finding a governing equation of the probe is a significant limit of global approach. What is more, this task becomes even more difficult when higher angles of attack should be included. As it was mentioned, in this case the nature of the flow around the probe changes, which requires a different way of calculation the pressure coefficients.

To solve this issue, Bryer & Pankhurst [2] divided the area around the 5-hole probe tip into one low angle zone and four high angle zones. Each zone defined possible directions of flow velocity and a selection of zone could be made by identifying, which pressure tap measures the highest pressure (which means that this pressure tap is the closest one to the stagnation point). Relations between pressure coefficients and flow velocity direction were obtained for each regime separately, using polynomial curve fitting.

Division of the area into independent zones, proposed by Bryer & Pankhurst, triggered a development of the local approach. In this case, mathematic relations between velocity parameters and measured pressure coefficients are valid in a limited range (locally). It allows applying a low-order polynomial, based on only a few calibration points. Such an approach was used i.e. by Reditionis et al. [16], who proposed to divide each zone (defined as suggested Bryer and Pankhurst) into smaller ones. Each of these zones was investigated independently to find governing equations and, as a result, to calculate measured flow angles and velocity magnitude.

A different way was proposed by Ziliac [18], who used local spline-based Akima interpolation directly from calibration points, instead of approximation of relations between pressure coefficients and velocity parameters as a mathematic formula. This approach allowed to reduce time and effort of calibration postprocessing and improved its accuracy, while uncertainty of approximation was not included. Similarly, Venkateswara Babu [17] used a locally obtained 2-nd degree polynomial functions of pitch coefficient and yaw coefficient, and Johansen et al. [9] simplified the algorithm by the use of linear interpolation (plane equation).

In presented article, a local non-nulling approach has been implemented, based on Johansen et al. [9]. In this case, one finds three calibration points (closest to the measurement point in 2D coordinate system of Cp_α and Cp_β) that create a triangle, inside which lies the measurement point. Selected calibration points define a plane in coordinate system, for example, Cp_α, Cp_β, α. Based on this plane and measured values of Cp_α and Cp_β, the pitch angle is obtained. In the same way the yaw angle β is calculated, as well as static pressure coefficient and total pressure coefficient, which are used to calculate total and static pressure and the Mach number of the flow.

3. Calibration setup

The calibration of multi-hole probes was conducted on the stand, which was developed at the Institute of Aviation. The stand is an open-jet, open circuit wind tunnel, with nozzle diameter of 0.25 m. Maximum available Mach number is over 0.90. The wind tunnel is supplied with air by external pneumatic installation. The Mach number is calculated with equation:

$$M = \sqrt{5 \cdot \left(\left(\frac{P_{t\_g} + P_{s\_a}}{P_{s\_a}} \right)^{\frac{2}{7}} - 1 \right)}, \tag{11}$$

where:

P_{t_g} – stagnation pressure, measured in stabilisation chamber of the wind tunnel (gauge value),

P_{s_a} – ambient pressure, measured outside of the flow (absolute value).

The stagnation pressure was measured by WIKA P30 gauge pressure transducer with pressure range of 1.0 bar and measurement uncertainty of 0.05% FS. The ambient pressure was measured by WIKA P30 absolute pressure transducer, with pressure range from 0.8 to 1.6 bar and measurement uncertainty of 0.1% FS. Both pressure transducers were connected to National Instruments CompactRIO unit, which was postprocessing and logging results.

A calibrated probe was mounted to the stand with rotating arm, which position (pitch angle, yaw angle, and transverse shift) was set by three electric motors, which were controlled by the NI CompactRIO unit. The pitch angle and the yaw angle may be changed in range of 45° with an uncertainty of 1 arcmin and 2 arcmin, respectively.

Fig. 2. The calibration stand

To verify the calibration procedure, a set of 10 probes Vectoflow 5HP-16mih8 has been calibrated. Each probe was the 5-hole straight probe with conical tip. Lenght of probe was 400 mm, its maximum diameter was 15 mm and its tip diameter – 3 mm. According to producer’s catalogue, the measurement uncertainty is below 1.0° for pitch angle and yaw angle and about 0.1 m/s for velocity magnitude.

Probe pressures were measured by 5 single-channel gauge pressure transducers WIKA S20 with pressure range of 0.4 bar and measurement uncertainty of 0.1% FS. All pressures were logged with the NI CompactRIO unit.

Fig. 3. The tip of calibrated probe

The calibration of each probe was conducted for the flow velocity of 100 m/s, which corresponds to Mach number of 0.3. Range of both pitch angle and yaw angle was ±7°.
During calibration, two sets of data have been collected:

- database points – measurements for equidistant grid of α, β (with the step of 0.5°),
- test points – 80 random combinations of α and β, different from database points.

The test points were used to calculate flow velocity magnitude and direction (i.e. pitch angle and yaw angle). A comparison of these values and given ones allows obtaining an information about measurement accuracy.

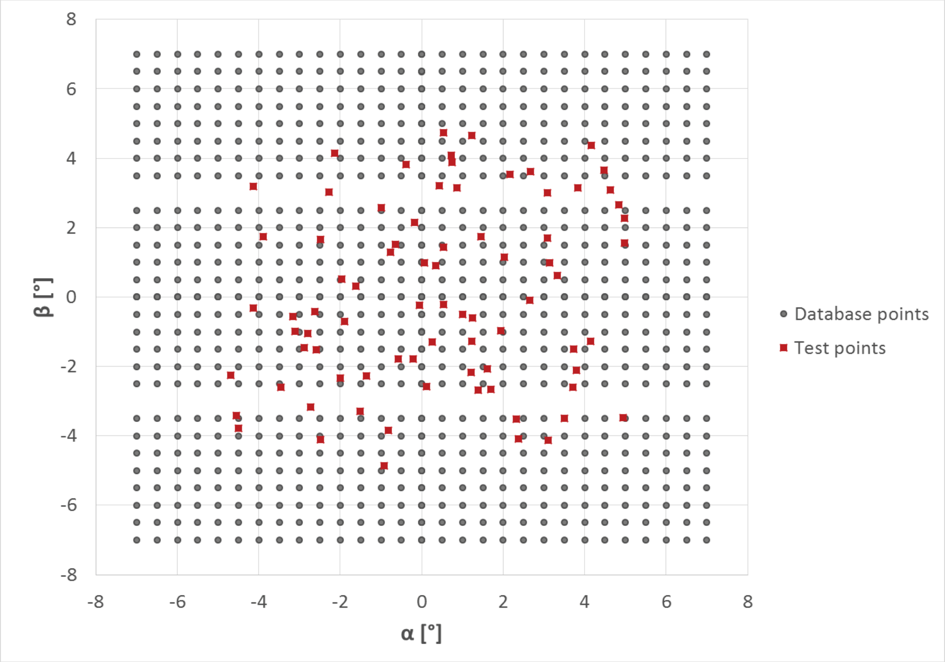

Fig. 4. Database points and test points

3. Calibration results

A pitch angle, yaw angle and flow velocity, calculated for each probe for the test points were compared with reference values, measured by the calibration stand. Based on differences between respective values, mean error and standard deviation of the error were calculated (Fig. 5 and Fig. 6).

Results presented in Fig. 5 include a modification of the procedure, aimed on minimise the uncertainty of probe alignment. To achieve it, the calibration was performed also for 'inverted' position of the probe, i.e. the probe was rotated of 180° along its axis. Relations of $Cp_\alpha(\alpha)$ and $Cp_\beta(\beta)$, plotted for normal and inverted position and for $\beta=0$ and $\alpha=0$ respectively, intercepted for specific values of pitch angle and yaw angle. For these values, it is assumed that the probe is aligned with the flow direction, and thus one should subtract these values from pitch and yaw angle. As a result, the difference between results for 'normal' and 'inverted' position decreased significantly, as it has been presented in Fig. 7.

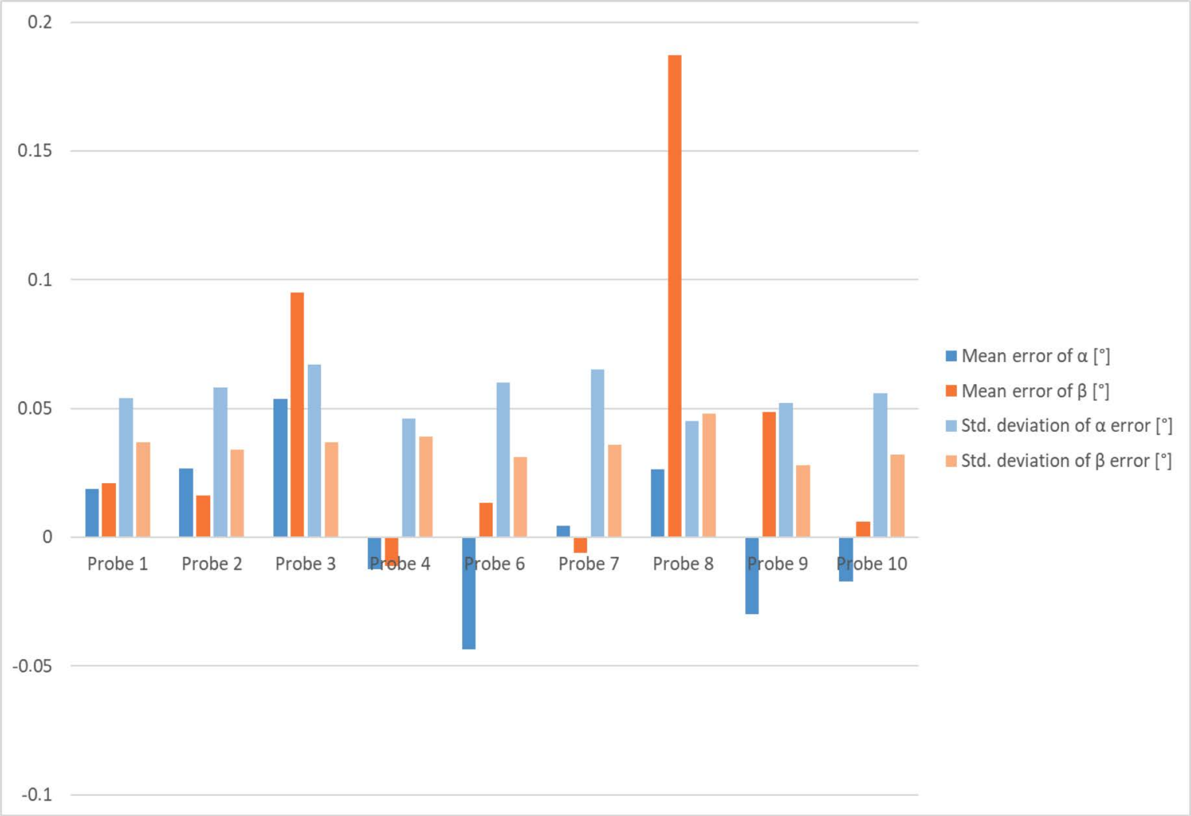

Fig. 5. Mean and standard deviation of pitch angle and yaw angle error

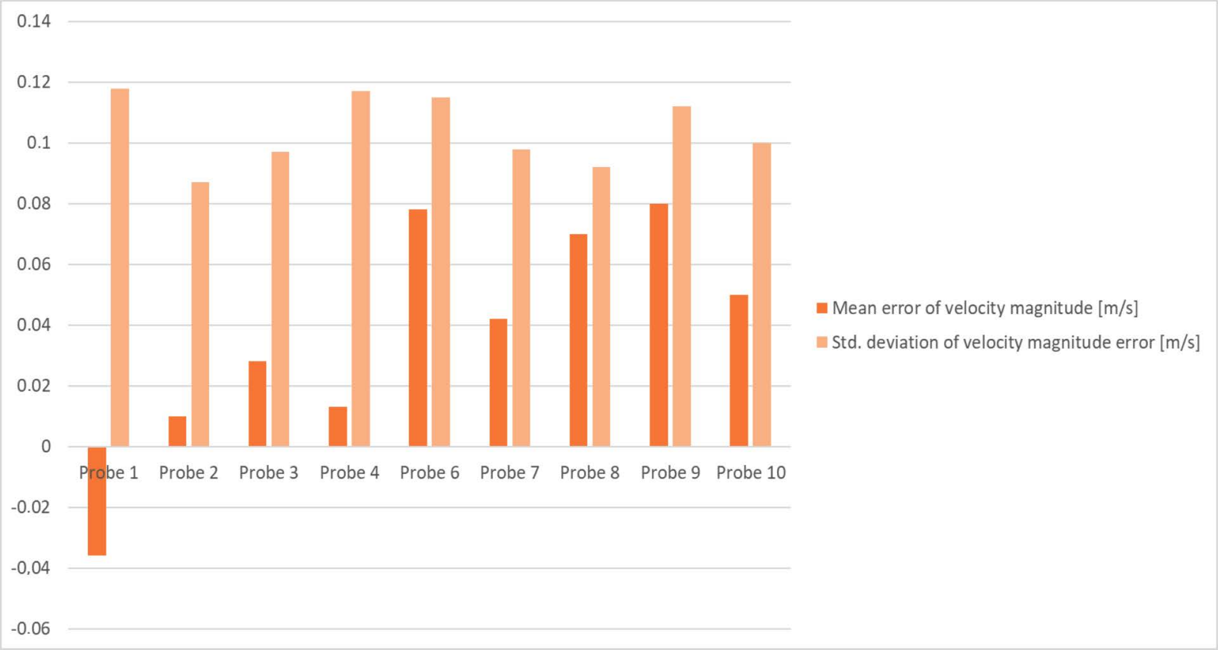

Fig. 6. Mean and standard deviation of flow velocity magnitude error

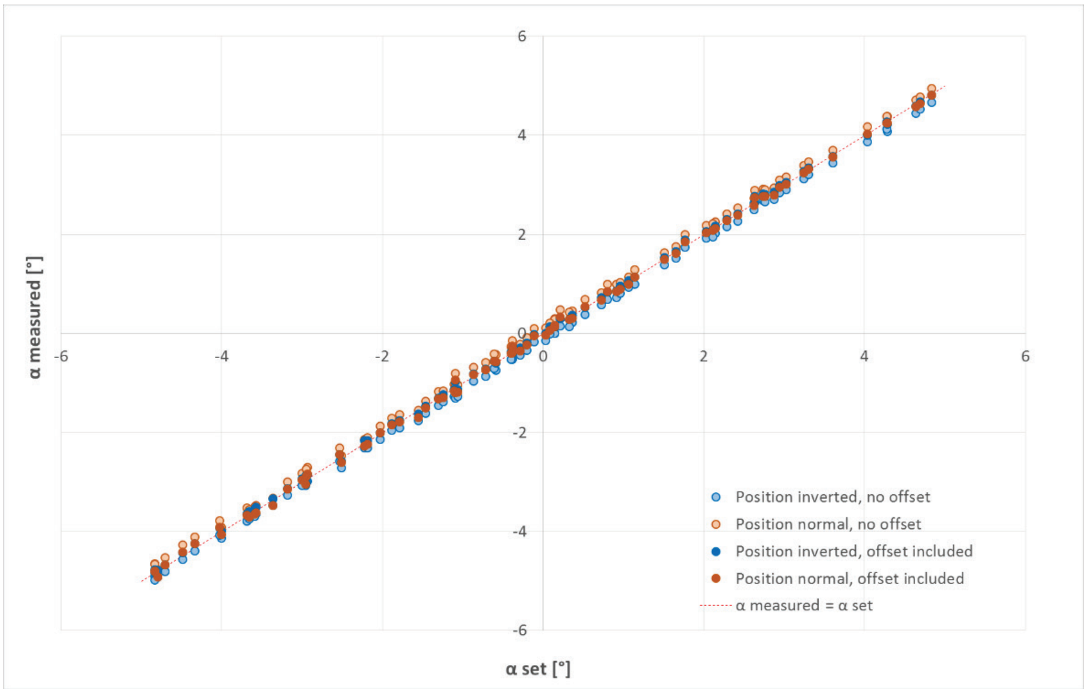

Fig. 7. Effect of the offset of pitch angle

4. Conclusion

Results of calibration presented in the article are satisfactory. The standard measurement uncertainty (assessed based on mean value and standard deviation of measurement error) for both pitch angle and yaw angle is approximately 0.2°, which is significantly less than the uncertainty declared by probe's manufacturer (1.0°) [19]. In the assessment the probe number 8 was not neglected, despite in this case the mean error of yaw angle was surprisingly high (about 0.18°); it is probably related with high variation of the flow speed during Itcalibration. should be noted that the modification of calibration procedure, i.e. including 'normal' and 'inverted' positions, gave satisfactory results. Maximum value of mean error of pitch angle (for the whole set of calibrated probes) decreased from 0.45° to 0.21°. For the yaw angle, the improvement is even better: maximum value of mean error decreased from 0.92° to 0.21°.

It has to be noted that the calibration was performed for constant velocity of 100 m/s. An influence of the velocity for the measurement uncertainty is planned to be investigated in next step of the work. It is also foreseen to analyse the impact of difference of speed between calibration conditions and measurements conditions.

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