Guidelines on the Calibration of Solid Anemometers Part 1: Pitot Static Tubes

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Flow

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Guidelines on the Calibration of Solid Anemometers
Part 1: Pitot Static Tubes

Purpose

This document has been produced to ensure traceability in air speed calibration by using solid anemometers. The Purpose of this first part is to outline the basic technical requirements for the calibration of Pitot Static Tubes (PSTs). It provides the users with the fundamental information necessary for establishing and applying calibration procedures.

Content

1 INTRODUCTION

The purpose of this EURAMET Calibration Guide is to outline the basic technical requirements for the calibration of Pitot Static Tubes (PSTs) for accredited or non-accredited calibration laboratories and for Accreditation Bodies.

The Guidelines provide the users of Pitot Static Tubes with the fundamental information necessary for establishing and applying calibration procedures.

This Guideline applies to all Pitot Static Tubes, independent of the tube shape.

2 REFERENCE DOCUMENTS

- ISO 3966:2008: Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes
- IEC 61400-12-1 (2017): Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines
- ISO 17713-1:2007: Metrology – Wind measurements – Wind tunnel test methods for rotating anemometer performance
- ISO 7194:2008: Measurement of fluid flow in closed conduits – Velocity-area methods of flow measurement in swirling of asymmetric flow conditions in circular ducts by means of current-meter of Pitot static tubes

3 SYMBOLS AND DEFINITIONS

Symbol	Quantity	Dimensions	SI unit
K	coefficient of calibration	-	-
$v_{display}$	displayed velocity of the Pitot tube	LT^{-1}	m s^{-1}
v_{PST}	measured velocity of the Pitot tube	LT^{-1}	m s^{-1}
$v_{reference}$	reference velocity	LT^{-1}	m s^{-1}
Δv	velocity difference of reference and device under test	LT^{-1}	m s^{-1}
Δp	differential pressure measured by the Pitot tube	$ML^{-1}T^{-2}$	Pa
ε	expansibility factor	-	-
$(1-\varepsilon)$	compressibility correction factor	-	-
ρ	density of the fluid	ML^{-3}	kg/m^3

4 GENERAL COMMENTS

The calibration is performed in a wind tunnel where the velocity is measured with a reference instrument. The purpose of the calibration is then to determine either the velocity deviation (Δv) between the reference and the Device Under Test (DUT) or the calibration coefficient (K_{PST}) of the Pitot Static Tube according to the Equation (1) or (2), respectively. The velocity deviation (Δv) or calibration coefficient (K_{PST}) must be determined over the whole calibration range.

$$\Delta v = v_{PST} - v_{reference} \quad (1) \qquad K_{PST} = \frac{v_{reference}}{v_{PST}} \quad (2)$$

where

v_{PST} is the measured velocity by the PST (m/s),

$v_{reference}$ is the reference velocity measured by the reference device (m/s).

This Guideline is applicable for different types of Pitot Static Tubes as outlined in Section 4.1. Section 4.2 describes how to determine the required fluid density.

4.1 Types of Pitot Static Tubes (PSTs)

4.1.1 PST with a measurement of a differential pressure

The primary measurement of a Pitot Static Tube is a differential pressure. The measured differential pressure is related to the velocity through the equation:

$$v_{PST} = (1-\varepsilon) \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad (3)$$

where

v_{PST} is the calculated velocity by the PST (m/s),

ρ is the fluid density (kg/m^3),

Δp is the differential pressure measured between the high and low pressure holes of the Pitot Static Tube (Pa),

$(1-\varepsilon)$ is the compressibility correction factor as defined in ISO 3966:2008 Section 8.2.

4.1.2 PST with a measurement in units of velocity

The Pitot Static Tube is considered as a complete measuring instrument, if it is connected to a pressure transducer whose measurement is directly converted and displayed in units of velocity. Then, v_{PST} is replaced by $v_{display}$ in the calibration result according to Equation (1) or (2).

$$v_{PST} = v_{display} \qquad (4)$$

where

v_{PST} is the velocity indicated by the device, corrected for actual conditions of temperature, pressure and humidity,

$v_{display}$ is the velocity output of the device display.

Either the actual value for the fluid density is determined according to Section 4.2 or predefined conditions are assumed to convert the differential pressure measurement into units of velocity. In the second case, a correction must be applied according to Equation (5).

4.1.3 Special Types

Pitot Static Tubes with no measurement device

In this case choose a differential pressure instrument with an appropriate measuring range and sufficiently high accuracy. Then the instruction given for a PST with a measurement of differential pressure must be followed [see Section 0].

Pitot Static Tube with analog output

An analog output can be specified for a PST with a measurement in units of velocity or of a differential pressure. If an analog output is used then the additional uncertainty contribution to the uncertainty budget must be considered. There can be a significant difference in the uncertainty budget if using current or voltage measurements due to the shunt-resistance.

4.2 Determination of the Fluid Density

For the determination of the fluid density, the ambient conditions (atmospheric pressure, temperature and humidity) must be recorded. For each calibration point a mean density value of the measurement time must be determined and the corresponding uncertainty must be specified. The formula for the determination of the fluid density must be disclosed. In the case of air, the formula presented in reference [1] must be used. Additionally, it may be necessary to apply corrections according to Section 4.3.

4.3 Corrections for Operating Conditions

4.3.1 PST pressure and temperature corrections

If there is no option for changing the predefined temperature, pressure and humidity values, then it should be noted that the displayed velocity is not in actual conditions but in predefined conditions. The following correction must then be applied to convert the display value to the actual reference value:

$$v_{PST} = v_{display} \cdot \sqrt{\frac{\rho_{display}}{\rho_{actual}}} \qquad (5)$$

where

v_{PST} is the velocity indicated by the device corrected for actual conditions of temperature, pressure and humidity,

$v_{display}$ is the velocity output of the device display,

ρ_{actual} is the fluid density in actual conditions,

$\rho_{display}$ is the fluid density in predefined conditions.

4.3.2 PST with density measurement in evaluation unit

If the temperature, pressure and humidity values are measured by the evaluation unit then usually the velocity value is displayed in actual conditions. Thus, the displayed values can be directly compared to the reference value according to Equation (4).

5 CALIBRATION PROCEDURE FOR PILOT STATIC TUBES

5.1 Preliminary Operations

The following instructions should be followed when installing the instrument:

- Place the PST at an appropriate location in the wind tunnel where a stable and homogeneous flow profile is achieved, e.g. a location with a low turbulence degree and a velocity value that is stable over time.
- Place the PST in such a position as the high pressure hole is facing the flow. In the case of a symmetrical device (Pitot type S for example), if the position is not indicated, choose one and indicate it on the tube.
- The relevant placement position of the PST is the total pressure hole,
- Take special care to the alignment of the tube. Usually, the influence of a misalignment of a PST related to the flow direction is only partly specified in data sheets. Therefore, orientation dependent measurements must be done and the resulting error must be considered in the uncertainty budget.

Prior to the calibration, the following data shall also be recorded:

- the identification parameters of the reference instrument and of all the instruments used for measuring the output signal,
- the identification parameters of the device to be calibrated. An identification number should be indicated on the PST.

5.2 Calibration

The calibration can be performed with simultaneous or sequential measurements of the reference and the pitot static tube. At each calibration point, the following data should be recorded:

- the velocity indicated by the reference instrument (or the elements necessary for calculating the measured velocity),
- the indication of the instrument to be calibrated, which is according to the case:
    - the indication of the differential pressure instrument connected to the PST,
    - the indication of the instrument connected to the PST in case of complete measuring instrument (in m/s, electric unit, pressure unit, …)
- the air temperature, static pressure, humidity measurements in the wind tunnel for the fluid density calculation
- for sequential measurement, the stability of the flow profile over time must be recorded. In the case of high fluctuations, either corrections must be applied with modification of the uncertainty budget or simultaneous measurements must be performed.
- for simultaneous measurement, the reference and the PST cannot measure at the same position. A typical laser measurement position is upstream and off axis (see Figure 1).

  The flow profile causes different velocity values at the Laser Doppler Anemometer (LDA) and PST measurement position which must be corrected in the context of the position correction.

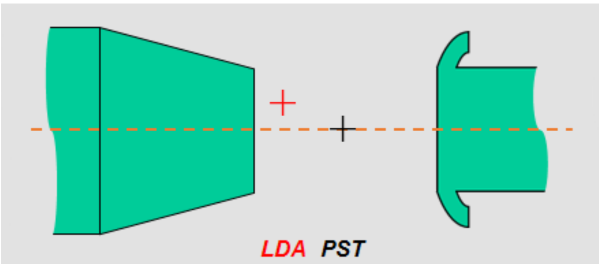

Figure 1: Typical LDA and PST measurement position indicatedwith the red and black cross, respectively.

Placing the PST at the measurement position has an influence on the flow profile at the LDA measurement position, the so-called “blockage effect”. This effect must be evaluated and can be either corrected or considered in the uncertainty budget. An example is given in Appendix A.

6 EVALUATION OF MEASUREMENT UNCERTAINTY

The principal components to be taken into account for the evaluation of the uncertainty of the calibration result for a PST are:

- uncertainty of the reference instrument in the conditions of use,
- uncertainty due to repeatability,
- uncertainty of the measuring instruments used during the calibration (differential pressure manometer or transducer and multimeter),
- uncertainty of the fluid density calculation [1, 2], taking into account:
  - uncertainty of the measuring instruments (temperature, pressure, humidity)
  - uncertainty of the formula used; for air density the uncertainty determination must be done as described in [1, 2]
- uncertainty due to the PST under test (blockage effect, misalignment, pressure measurement)

The measurement procedures of the calibration laboratories should describe how the contributions to the uncertainty budget resulting from these components are determined.

7 REFERENCE INSTRUMENT

Laser Doppler Anemometer (LDA) or a Pitot Static Tube (PST) can be used as a reference instrument. To get the uncertainty in the range of 0.5 % to 0.8 % (k=2) for the entire calibration a Laser Doppler Anemometer must be used as the reference.

PSTs are often only usable as a reference instrument with a larger uncertainty in the range of 0.8 % to 1 % (k=2). The lowest value of velocity is then often limited to the range and accuracy of the differential pressure instrument that is used.

If other reference meters are used, then this will result in higher measurement uncertainties. These uncertainty values might be too large to use the system for the intended application.

The lowest uncertainties (below 0.8% (k=2)) are only achievable under the following conditions:

- Using LDA as the reference
- Consideration of the compressibility contribution with respect to the uncertainty budget
- Profile measurement (influence of the DUT on the flow profile) and determination of the uncertainty contribution due to the blockage effect
- Applying position correction in case of simultaneous measurement
- Alignment measurement
- Determination of density

8 EXPRESSING SCOPE OF CALIBRATION

The scope declared by a laboratory for calibration of solid anemometers, especially Pitot Static Tubes, should state the following parameters:

- Measurement range
- Measurement uncertainty within the entire range
- Ambient conditions (pressure, temperature, humidity)
- Type of probes

9 CALIBRATION CERTIFICATE

Together with the general requirements of the ISO/IEC 17025 standard, the calibration reports for PSTs should include this minimum information:

- Facility description
- Type of reference
- Description of the calibration procedure
- Description of the Device Under Test (DUT)
- Calibration results can be depicted either as reference and the PST value separately or as reference and deviation (Δv) between the reference and the Device Under Test (DUT) or as reference and calibration coefficient, K.
- Measurement uncertainty
    - In the case of a PST, the stated measurement uncertainty is the uncertainty either of the calibration coefficient of PST or of the measurement of v_{PST} (see Section 0).
    - In the case of a PST with a display, the measurement uncertainty corresponds to the uncertainty of the measurement chain after applying Equation (4) (see Section 0), if necessary.
    - The uncertainty values should be given with a maximum of two significant figures. The excessive number of digits should be rounded according to Section 7.2.6 of reference [3].
    - The stated measurement uncertainty must contain the uncertainty of the calibration facility.
- Additional information can be provided such as:
    - Position of the PST regarding the flow.
    - If statement of compliance with a specification is made, these should identify which clauses of the specification are met or not met.
    - Indication of any malfunctioning or anomaly detected.

10 REFERENCES

[1] Davis R.S., Equation for the Determination of the Density of Moist Air (1981/91), Metrologia 1992, 29, 67-70

[2] Picard A., Davis R.S., Gläser M. and Fujii K., Revised formula for the density of moist air (CIPM-2007) - Metrologia 45 (2008) 149–155

[3] JCGM 100: 2008, Evaluation of measurement data — Guide to the expression of uncertainty in measurement

APPENDIX A: Example of position and blockage correction for a smaller sized wind tunnel

For smaller sized wind tunnels it is recommended that a position and blockage correction is done. A schematic view of the measurement section is shown in Figure 2. The LDA measurement position is selected at a position where the influence of the DUT on the flow profile is minimal.

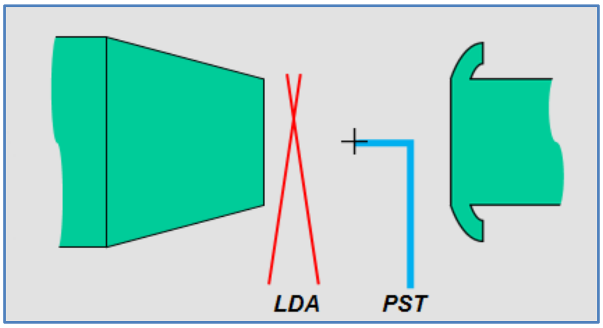

Figure 2: Schematic view of the measurement section of a windtunnel with indicated LDA- and DUT-position (PST)

In the following sections an example calculation for the position and blockage correction is presented. It is recommended that the basic principles for the corrections are followed.

Position Correction

For each specified velocity two measurements should be taken. The velocity is determined at the LDA and the DUT measurement position without changing the set reference velocity. From these values a correction factor is calculated as was done, for example, in Table 1. For the final calibration, the reference velocity must be corrected with this position correction factor.

Table 1: Example for position correction factor of a wind tunnel with 255 mm diameter; velocity measurement at the LDA (position 1) and at the DUT (position 2) position

specified velocity [m/s]	velocity [m/s]		correction factor
	position 1	position 2	
1	0.968	0.973	1.0053
1.5	1.471	1.479	1.0055
2	1.961	1.969	1.0040
2.5	2.457	2.473	1.0067
3	2.961	2.985	1.0079
4	3.957	3.996	1.0096
4.5	4.452	4.500	1.0108
5	4.944	4.995	1.0104
10	9.904	10.011	1.0108
15	14.888	15.043	1.0104
20	19.831	20.018	1.0094
25	24.830	25.068	1.0096
30	29.822	30.080	1.0087

Blockage Correction

For the blockage correction, the influence of a Device Under Test (DUT) on the flow profile must be determined in advance. Therefore, the flow profile is recorded along the LDA x-position (see Figure 3) with and without the PST mounted in the measuring section. Thereby either a velocity shift along the whole cross-section (Figure 4 left) or a combination of a velocity shift along the cross-section and an offset (Figure 4 right) can be detected depending on the size of the DUT.

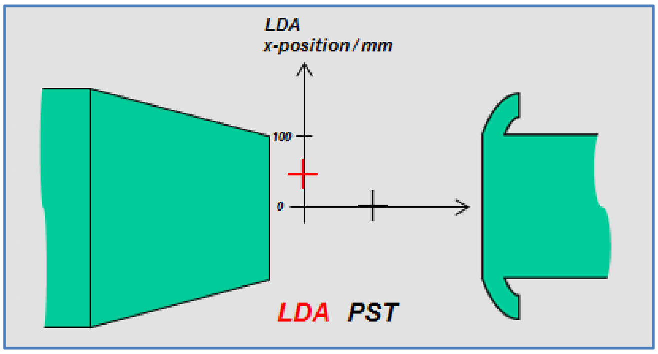

Figure 3: Schematic view of the definition of the LDA x-position

Figure 4 shows flow profiles for different sized DUTs as an example. During calibration the LDA measurement position is at 80 mm x-position (off axis) and the DUT is located at 0 mm x-position (on the axis) but at a different cross-section.

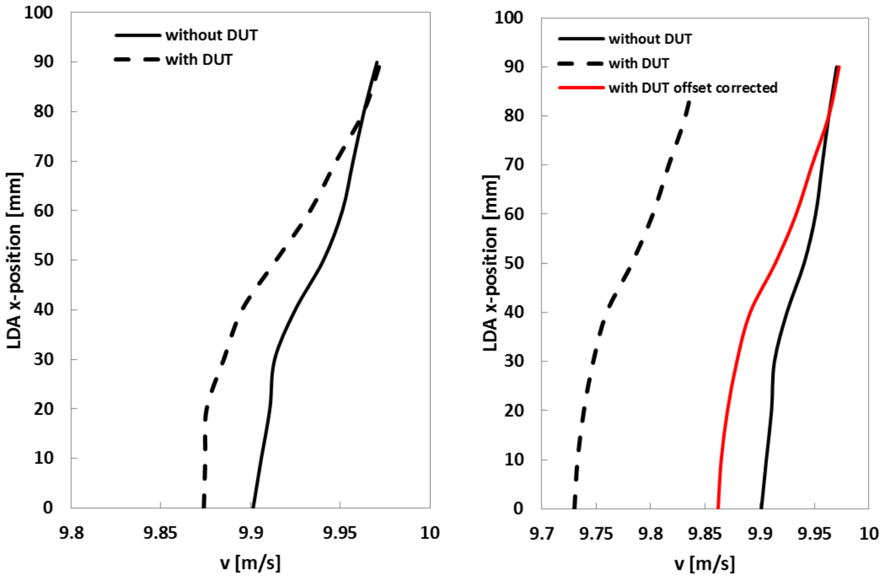

Figure 4: Flow profile measured along the cross-section at the LDA x-position. Solid black line: without DUT, dashed black line: with DUT, red line: with DUT offset corrected. Flow profile (left) with a velocity shift at the DUT position and no influence at the LDA measurement position (case 1), (right) with velocity offset along the whole cross-section and a remaining velocity shift at the DUT position (case 2); LDA x-position represents the distance perpendicularly off axis

For the case 1 (Figure 4 left) there is no difference of the flow profiles at the LDA measurement position. At the DUT position (0 mm x-position) a velocity shift with the borders 9.873 m/s and 9.9 m/s is determined which must be added as a squared distributed uncertainty contribution to the entire uncertainty budget.

For the case 2 (Figure 4 right), an offset between the solid black line and the dashed black line is determined at the LDA measurement position (at 80 mm x-position). The flow profile with the DUT is corrected with respect to this offset and the remaining velocity shift with the borders 9.862 m/s and 9.901 m/s at the DUT position is determined and must be added as a squared distributed uncertainty contribution to the entire uncertainty budget.

During calibration the LDA is measuring according to the red line, thus the offset correction need not be done for the calibration results and makes no contribution to the uncertainty budget. The calculated uncertainty contributions of the two cases are shown in Table 2.

Table 2: Example calculation of the blockage uncertainty contribution of the two flow profiles shown in Figure 4

	velocity measurement [%]	
	Case 1	Case 2
Offset at the LDA x-position of 80 mm	0	1.32
Velocity shift at the DUT position	0.27	0.39
Blockage uncertainty contribution (squared distributed contribution of the velocity shift at the DUT position)	0.16	0.23

APPENDIX B: Example of a calibration certificate

National Metrology Institute

####
calibration mark
mmyyyy

Logo of the Institute

Calibration Certificate

Object	Pitot Static Tube
Manufacturer	Manufacturer
Type	Typ
Serail number	S/Nr.: SerNr
Customer	Adr_1 Adr_2 Adr_3 Adr_4
Order No.	KA000000
Number of pages of the certificate	14
Date of receipt	dd.mm.yyyy
Date of calibration	dd.mm.yyyy

This calibration certificate documents the traceability to national standards, which realize the physical units of measurements according to the International system of Units (SI).
The user is obliged to have the object recalibrated at appropriate intervals.

This calibration certificate may not be reproduced other than in full. Calibration certificates without signature and seal are not valid.

Seal	Date	Authorized person	Person in charge
	dd.mm.yyyy	Signature	Signature

Description of object to calibrate

Pitot Static Tube

Measurement results

Position	*Reference air velocity*	*Output value*	*Output value air velocity*	*Corrected output value air velocity*	*Deviation from reference value **	*Expanded measurement uncertainty*	*Density of air*
#	m/s	unit to be selected	m/s	m/s	m/s	m/s	kg/m³
1							
2							
3							
4							
5							

** Either the deviation (Δv) between the reference and the Device Under Test (DUT) or the coefficient (K_{PST}) of the Pitot Static Tube according to the Equation (1) or (2), respectively, can be specified.*

Measurement values of unit under test were corrected to standard air density

Standard density of air: ρ_0 = 1.29167 kg/m^3

Pressure: p_0 = 1013.25 hPa

Temperature: T_0 = 273.15 K

Relative Humidity: U_w = 45 % rh

Density of moist air: $\rho = \frac{pM_a}{ZRT}\left[1 - x_v\left(1 - \frac{M_v}{M_a}\right)\right]$

Output Configuration: ###

Calibration conditions

Calibration pressure: (### ± #) hPa

Calibration temperature: (##.# ± #.#) °C

Relative humidity: (## ± #) % rh

Position of the anemometer (center sensor): Center wind tunnel

Supply voltage: ### VDC

Load resistor: ### Ω

Ambient temperature: (## ± #) °C

Calibration procedure

According to internal procedures, the calibration is performed in a device to achieve a constant, homogeneous and low turbulence air flow as comparison measurement with a laser Doppler anemometer. The reference air flow is provided by wind tunnel with open measurement volume and a circular cross section of air flow of ### mm diameter.

Measurement uncertainty

The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of approximately 95 % for normal distribution.

The standard uncertainty was determined according the “Guide to the Expression of Uncertainty in Measurement (BIPM, IEC, IFCC, ISO, IUAPC, IUPAP, OIML)” and to the document EA-4/02.

The measured values and the deviations from the reference values were calculated as mean values from more than 100 single measurements of the reference and more than 10 measurements of the unit under test in a time period of at least 10 s.

Remarks

Measurement results as found

Position	*Reference air velocity*	*Output value*	*Output value air velocity*	*Corrected output value air velocity*	*Deviation from reference value **	*Expanded measurement uncertainty*	*Density of air*
#	m/s	unit to be selected	m/s	m/s	m/s	m/s	kg/m³
1							
2							
3							
4							
5							

** Either the deviation (Δv) between the reference and the Device Under Test (DUT) or the coefficient (K_{PST}) of the Pitot Static Tube according to the Equation (1) or (2), respectively, can be specified.*

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