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DESIGN AND CALIBRATION OF A PITOT STATIC TUBE FOR AN EDUCATIONAL SUBSONIC WIND TUNNEL

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Abstract. In order to instrument the educational subsonic wind tunnel, a Pitot-static tube was designed and calibrated for measuring airflow velocities. The tunnel's test section has an area of 0.25 m^2 and a velocity range of up to 15 m/s , facilitated by its 3 HP motor, allowing for aerodynamics studies on scaled F-SAE and AeroDesign models. The objective of this work is to determine the actual flow conditions in the test section, including the velocity profile, average velocity, volumetric flow rate, Reynolds number, and static pressure of the airflow stream. The Pitot-static probe was designed and constructed in accordance with the international ISO Standard 3966:2008, aiming to minimize intrusion into the flow. The uncertainties in velocity measurements were determined following the Brazilian NBR ISO Standard 5168. The construction methodology involved dividing the Pitot probe into three main parts: an ellipsoidal profile with a parallel orifice serving as the total pressure outlet, an inner tube as an extension of the pressure channel, and an outer tube with six holes perpendicular to the airflow for static pressure measurement. These parts were constructed from steel to ensure rigidity and quality, involving machining and welding processes. To facilitate the measurement of the velocity profile within the wind tunnel section, a vertical movement system was designed. The probe calibration was performed at multiple velocities, with three runs at each velocity to assess repeatability. Pressure readings were measured using a differential pressure sensor, along with an Arduino microcontroller that provided velocity values displayed on an LCD screen. The velocity uncertainty of the Pitot-static tube was determined to be 3.4% when compared with measurements obtained using a digital anemometer. Thus, this level of uncertainty indicates that the Pitot-static tube is a valuable tool suitable for didactic purposes.

Keywords: Pitot tube, subsonic wind tunnel, velocity profile, pressure sensor, arduino.

1. INTRODUCTION

Pitot tubes are widely used in several applications, such as HVAC (Heating, Ventilation, and Air Conditioning) systems, aerospace, aviation, automotive industry, process industries, environmental monitoring and research and development areas. A Pitot static tube is a tubular device consisting of a cylindrical head attached perpendicularly to a stem allowing measurement of a differential pressure from which the flow rate of the fluid in which it is inserted can be determined. It is provided with static pressure tapping holes (drilled all around the circumference of the head at one or more cross-sections) and with a total pressure hole (facing the flow direction at the tip of the axially symmetrical nose of the head, ISO, 2008).

ISO 3966 currently provides guidelines and specifications for Pitot tubes. It specifically focuses on Pitot static tubes used for the measurement of fluid flow in closed conduits. ISO 3966 addresses key aspects related to the design, installation, and maintenance of Pitot static tubes. Additionally, the standard describes the calculation procedures for determining local velocities based on measured differential pressures and for integrating velocities to calculate flow rates. It serves as a reference for ensuring accuracy and consistency in the use of Pitot tubes for flow measurement purposes.

The main purpose of this work was to design a Pitot tube to determine the airflow conditions, such as mean flow velocity, velocity profile, mass flow rate, and Reynolds number, in the rectangular cross-section of the test section of an educational open-circuit subsonic wind tunnel, as shown in Fig. 1. The tunnel test section has an area of 0.25 m^2 and operates in a velocity range of up to 15 m/s , driven by a 3 HP motor, to facilitate aerodynamics studies on scaled F-SAE vehicles and aero design models.

2. LOCAL VELOCITY AND MASS FLOW RATE MEASUREMENTS

The local velocity of the airflow at a certain point inside the test section of the wind tunnel is computed by considering the conservation of energy in a inviscid, incompressible fluid at steady flow. Thus, the assumptions allow for the applica-



Figure 1. Open-circuit subsonic wind tunnel at the State University of Western Paraná (UNIOESTE). Contraction (1), settling chamber (2), test section (3), diffuser (4) and fan (5).

tion of the Bernoulli equation between two points that lie on a streamline that begins far upstream of the tube and comes to rest in the mouth of the Pitot tube as shown in Fig. 2.

$$v = \alpha \sqrt{\frac{2(p_o - p_s)}{\rho_{air}}}, \quad (1)$$

where p_o is the stagnation pressure, p_s is the static pressures and ρ the density of the fluid. The coefficient α is the calibration factor of the Pitot tube (ISO, 2008). Equation (1) is applicable in this work since the maximum achievable velocity in the wind tunnel is 14 m/s, which results in a Mach number lower than 0.3.

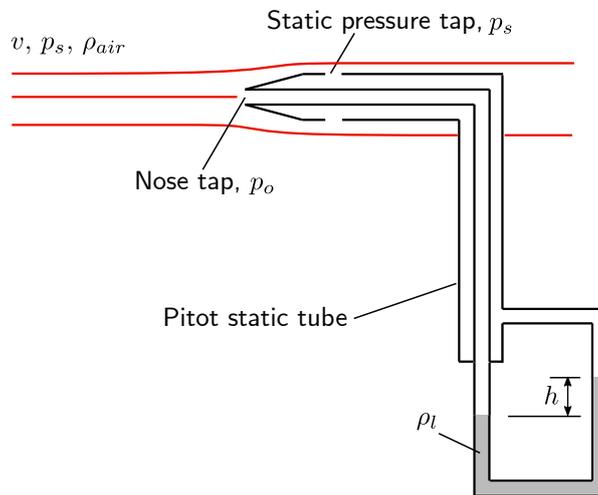


Figure 2. Schematic of a Pitot static tube.

The local fluid velocities are obtained by measuring multiple points that are positioned along a straight line passing through a known square shape cross-section with an area A in the wind tunnel's test section. The measurement data can be fitted to an algebraic curve, which can then be manually integrated across the square shape cross-section to determine the volumetric flow rate (\dot{V}) in m^3/s or the mass flow rate (\dot{m}) in kg/s when multiplied by the fluid density (ρ).

$$\dot{m} = \int_A \rho u(z_o, y) dA, \quad (2)$$

where $u(z_o, y)$ represents the velocity profile that varies along the y -axis, measured at an axial position z_o in the flow direction inside the test section of the wind tunnel.

3. DESIGN AND MANUFACTURE OF PITOT-STATIC TUBE

The Pitot-static tube constructed in this work was fabricated using a stainless steel tube with an outer diameter $d_o = 14$ mm and an overall length $L_P = 280$ mm. The Pitot tube consists of three primary components: an ellipsoidal head and two concentrically mounted tubes, namely an inner tube and an outer tube, as shown in Fig. 3. The ellipsoidal head, which measures a diameter $d_i = 2$ mm and a length $L_h = 26$ mm, has been specifically designed, as described in ISO (2008), to accurately measure the total pressure of the flow at the test section.

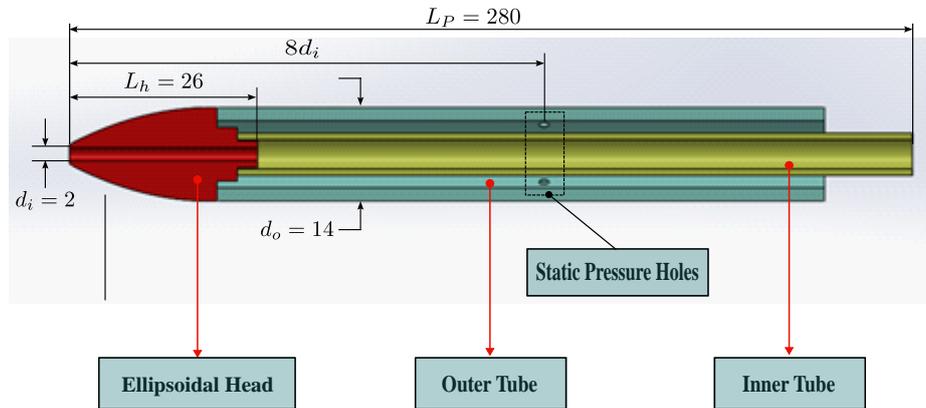


Figure 3. Main components of the Pitot-static tube.

In the figure, the ellipsoidal head has been machined to be coupled with both the inner and outer tubes using microplasma welding. Additionally, six holes with a diameter of 1.5 mm were created at a distance of $8d_i$ from the ellipsoidal head and are evenly spaced around the perimeter of the outer tube. These holes have been incorporated to measure the static pressure of the flow. The final design of the Pitot-static tube is shown in Fig. 4. These three components work together to enable the Pitot-static tube to measure both total pressure and static pressure, which are essential parameters in fluid flow analysis and calculations.

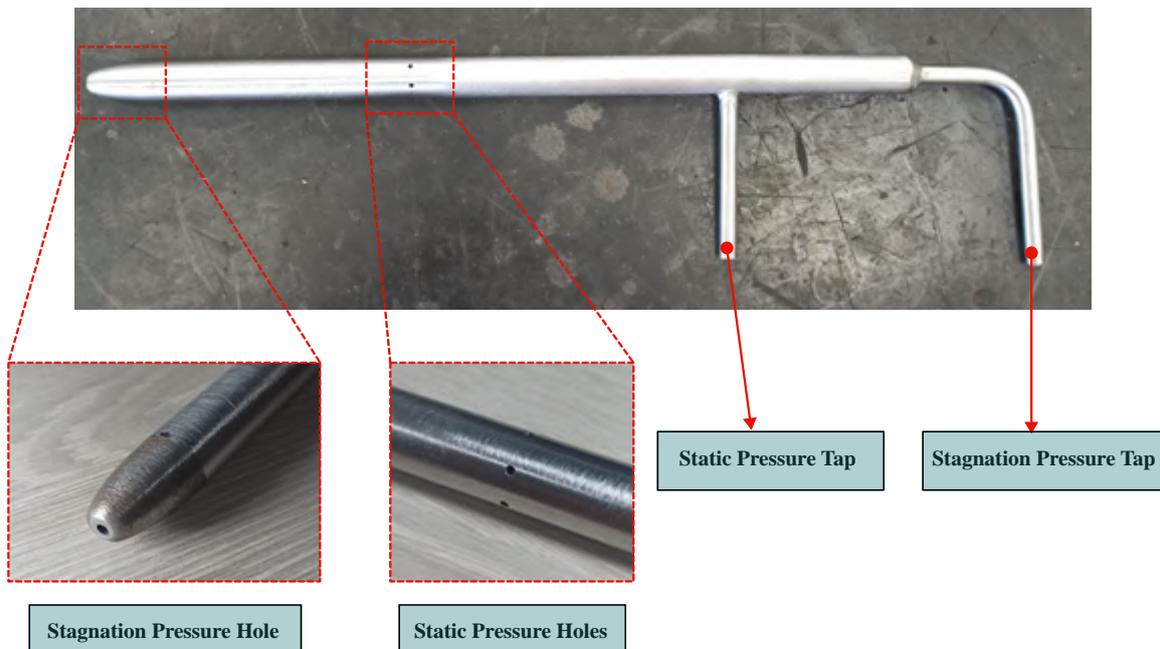


Figure 4. Final design of the Pitot-static tube.

Figure 5 shows a fixation system that was manufactured using 3D printing for the purpose of fixing and moving the Pitot-static tube. This system allows for vertical movement of the instrument, facilitating velocity measurements at

different points within the test section.



Figure 5. Fixation system to facilitate the vertical movement of the Pitot-static tube within the test section.

4. PRESSURE MEASUREMENT AND VISUALIZATION

For the measurement of total or static pressure in the Pitot-static tube, a differential pressure sensor type MPX5010DP was utilized. This electronic component enables pressure measurements within the range of 0 kPa to 10 kPa. To acquire and process the data, the sensor was connected to the Arduino electronic prototyping platform. Furthermore, an LCD display was employed for visualizing the local flow velocity. Figure 6 presents a schematic of the electronic project for pressure measurements in the Pitot-static tube.

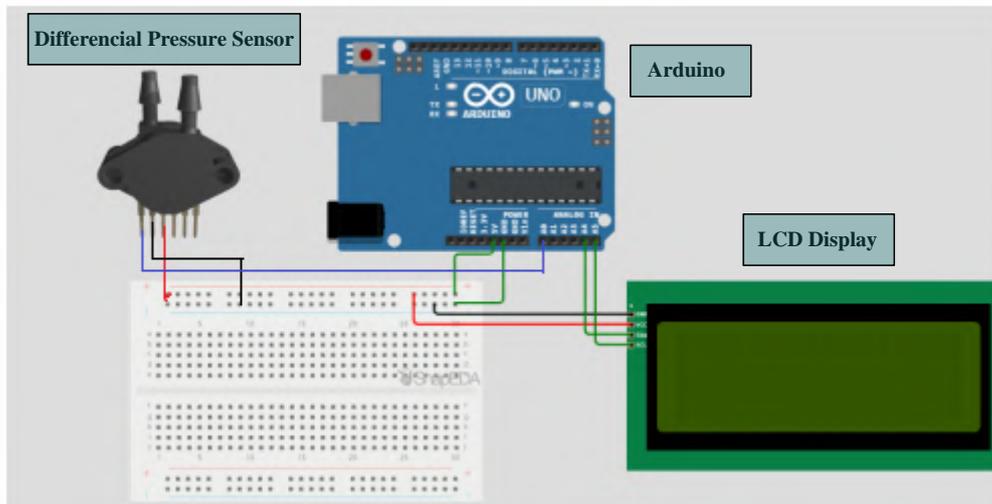


Figure 6. Schematic of the electronic project for pressure measurements in the Pitot-static tube.

5. CALIBRATION OF THE DIFFERENTIAL PRESSURE SENSOR

To calibrate the MPX5010DP differential pressure sensor, pressure is manually applied to the sensor using a surgical syringe containing air inside. The pressure read by the sensor is compared with the pressure obtained from a U-tube manometer that uses water as the manometric fluid. The difference between these two measured values represents the uncertainty in pressure measurement of the sensor (Malaquias et.al., 2012). Thus, the sensor calibration is performed by obtaining a calibration curve that relates the pressure measured by the sensor to the pressure measured by the U-tube manometer as shown Fig. 7. The curve fitted predicts the measurements with a confidence interval (for 95 % coverage) of $\pm 0.75 \%$.

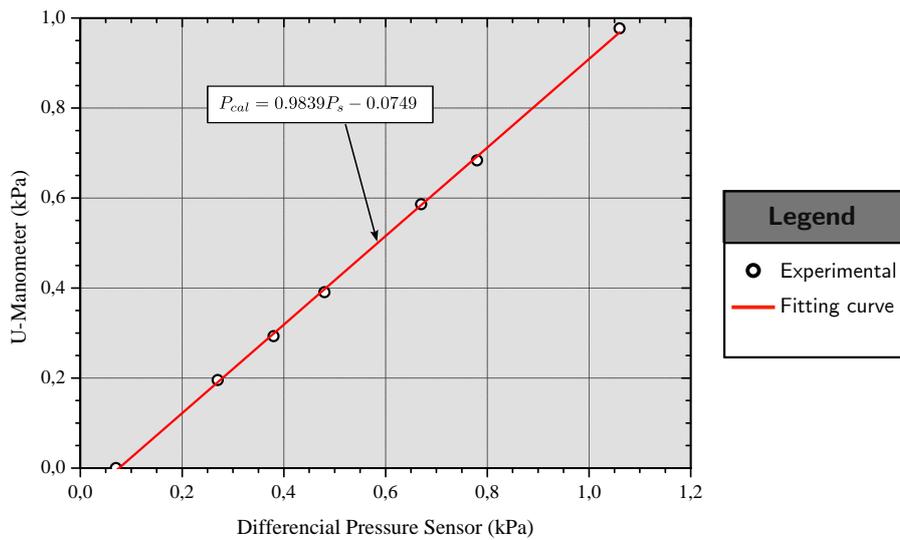


Figure 7. Calibration curve for differential pressure sensor.

6. RESULTS

A total of 10 points were measured along a vertical line of the rectangular cross-section of the wind tunnel using the Pitot-static tube and a portable digital anemometer model AD-250. Throughout the tests, the air temperature and atmospheric pressure remained approximately constant at 25 °C and 101.325 kPa, respectively. The height of the conduit in the measuring cross-section was 240 mm measured from centerline to the tunnel wall, and the distance between measuring points was set to 30 mm. A preliminary normalized velocity profile using the Pitot-static tube is shown in Fig. 8.

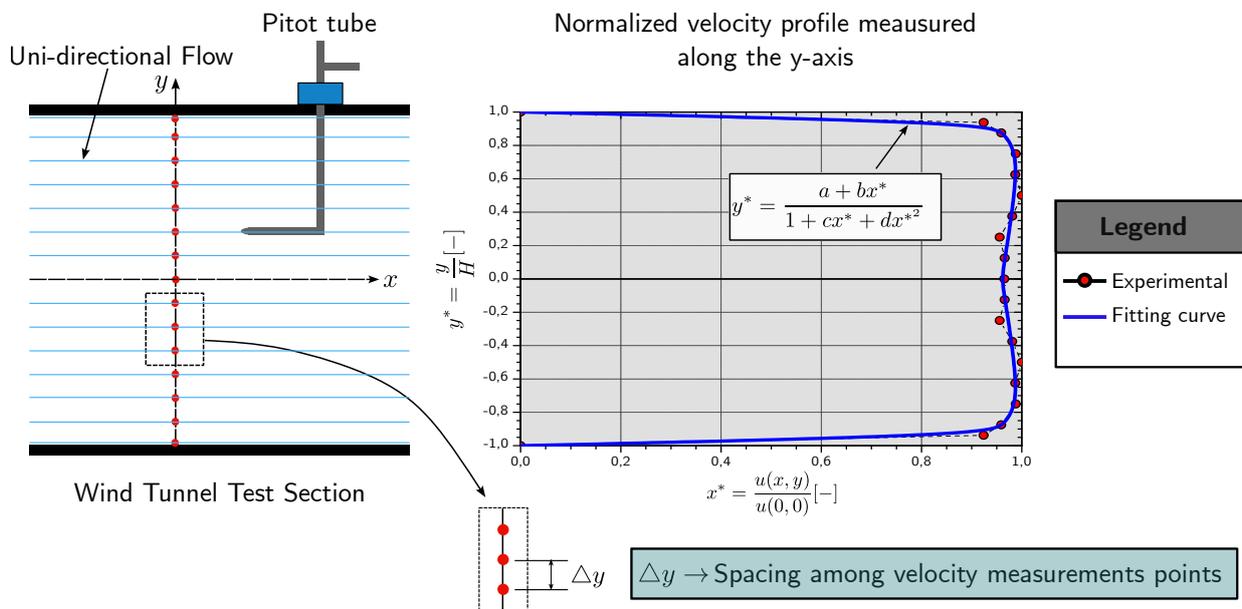


Figure 8. Experimental velocity profile measured using the Pitot-static tube.

In the left side figure, a representative schematic shows the positioning of the Pitot-static tube at various locations along the cross-section of the test section. As air enters the tube, both total pressure and static pressure are measured. The difference between these pressures enables the calculation of local velocity. The measurements reveal a velocity profile typically characterized by a relatively constant velocity across the entire cross-section of the test section. The airflow

tends to be more uniform, resulting in less pronounced velocity variation along the height of the tunnel. However, it is important to note that slight variations in the velocity profile must have occurred due to boundary layer effects on the walls and flow irregularities in the test section. These variations can be accounted for by taking multiple measurements at different positions within the test section and averaging the results to obtain a more representative velocity profile. In this work, only three sets of measurements were performed.

Figure 9 presents a comparison between the normalized velocity profiles obtained from the Pitot-static tube and the digital anemometer. It can be observed that the measurements obtained with the anemometer result in a velocity profile that is more uniform and flat compared to the Pitot-static tube. These differences can be attributed to the methods used by the instruments to measure the local flow velocity. The Pitot-static tube measures the local velocity at a stagnation point of the flow, while the anemometer calculates an average velocity based on the airflow passing through a measurement region with a circular area of approximately 35 mm in diameter. Additionally, the anemometer is capable of damping small fluctuations in flow velocity, which helps maintain a nearly constant value for the local average velocity.

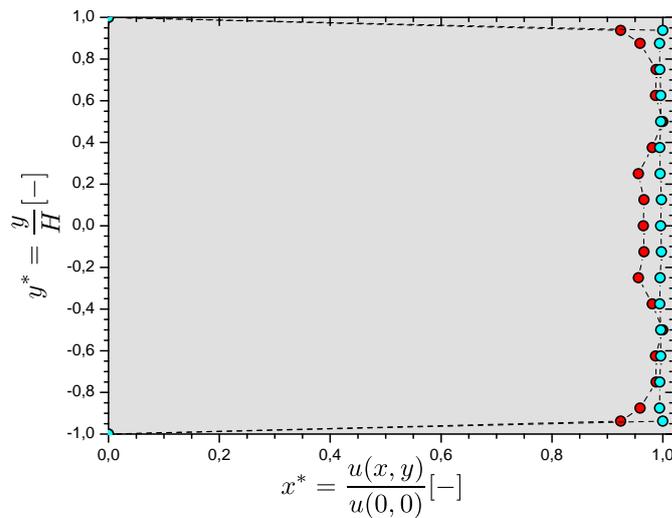


Figure 9. Comparison of the velocity profiles obtained by the Pitot-static tube and the anemometer

To determine the flow characteristics within the test section, Table 1 summarizes the values of volumetric flow rate, mean velocities, and Reynolds number obtained using the Pitot-static tube and the anemometer. The results indicate a turbulent regime for the internal flow within the test section. Furthermore, the Pitot-static tube yields a volumetric flow rate that is 3.41% lower than the value obtained by the anemometer. Besides, according to the results from Vanzo (2017), a mean velocity of 13 m/s was obtained in the wind tunnel, facilitated by a 3 HP motor with a nominal rotation speed of 1135 rpm.

Table 1. Values of volumetric flow rate, mean velocities, and Reynolds number for Pitot-static tube and the anemometer.

Variables	Pitot	Anemometer
Volumetric flow rate (m ³ /s)	3.34	3.46
Mean velocity (m/s)	13.37	13.84
Number Reynolds (-)	438297	453770

7. CONCLUSIONS

The design and construction of a Pitot-static tube for measuring flow velocities in a subsonic wind tunnel for educational purposes is a common and valuable approach in experimental aerodynamics. The Pitot-static tube allows for the measurement of air flow velocity with low uncertainty by utilizing the pressure difference between the total pressure (captured at the front end of the tube) and the static pressure (captured at the side openings of the tube). This enables the acquisition of accurate information about the air velocity in the wind tunnel. By comparing the preliminary results obtained with the Pitot-static tube to the velocity profile measured by a digital anemometer, it is possible to evaluate the reliability of this device. Small discrepancies were observed in the velocity profile, indicating the need to assess possible sources of error and perform additional calibrations of the Pitot-static tube. As a result, further measurements are currently being conducted to complete this academic research project.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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