Analysis of the airflow in the TA-2 subsonic wind tunnel

M L C C Reis¹,², M S Souza¹, M C C Araújo³

¹Instituto de Aeronáutica e Espaço, Pr. Mal. Eduardo Gomes, 50, CEP 12228904, Brasil.
²Instituto Tecnológico de Aeronáutica, Pr. Mal. Eduardo Gomes, 50, CEP 12228901, Brasil.
E-mail: marialuisamlccr@iae.cta.br

Abstract. Tests are being carried out at the TA-2 wind tunnel to obtain the velocity and pressure distributions at the test section. The airflow conditions must be known to fulfil the required accuracy of tests. A rake composed of Pitot tubes was used to measure local static and total pressures of the flow. The test section region considered here is related to the transverse central area. The estimated parameters are velocity and pressure coefficient. Uncertainties associated with these parameters are evaluated according to metrological standardisation. Calibration curves are supplied using the least squares fitting. Results revealed a gradient in airflow parameters.

1. Introduction
Wind tunnels are aerodynamic laboratories used to simulate the condition encountered by a body immersed in the flow. They are built in a great variety of configurations in terms of size and airflow regimes according to industrial and research needs [1].

The TA-2 is a subsonic facility located at the Aerodynamics Division of the Institute of Aeronautics and Space. It has a closed circuit and the test section is 2.10 m high, 3.30 m wide and 3.20 m long. The TA-2 wind tunnel has contributed to design optimization of aeronautical vehicles developed by the Brazilian industry and to the analysis of the flow around structures subject to wind loads such as offshore platforms, buildings and automotive vehicles.

Experimental aerodynamicists are primarily concerned about the uniformity of the airflow at the wind tunnel test section. Ideally, a test section should be free of gradients and turbulence. As these conditions are difficult to achieve in practice, tests are carried out periodically to calibrate the flow.

According to the international aerodynamic community, the calibration procedure of a wind tunnel depends on the type of tests conducted in the facility [2]. Reference [3] classifies four calibration categories: 1) calibration to correct the parameters which are measured in one location and are transferred to another point of the circuit; 2) analysis of experimental data repeatability employing standard models of the type wing/body/tail; 3) surveys to determine flow parameter uniformity; and 4) evaluation of the impact caused by changes in the circuit, hardware or test technique.

This study is concerned with the third category. Although the whole campaign encompasses also the evaluation of the boundary layer thickness and the turbulence level of the airflow, the results presented in this paper are related to the analysis of the velocity, $V$, and the pressure coefficient, $C_p$, distributions at the inner area of the TA-2 test section. A rake consisting of 15 Pitot tubes was

¹ To whom any correspondence should be addressed.
employed. The uncertainties associated with the estimated parameters were evaluated by using the law of propagation of uncertainty. Least squares fitting is used to supply calibration curves.

The knowledge of the distribution of the airflow field parameters helps to plan the test of aerodynamic models at the wind tunnel regarding accuracy, precision and uncertainty requirements. Information supplied by this campaign can be used to circuit improvements and represent a basis for the development of methodology for wall interference corrections.

2. Methodology

The test campaign analyses the distributions of the flow velocity and the flow pressure, measured at 25 positions of the TA-2 test section (figure 1a). The x axis represents the wind direction and is positive downstream of the flow. The y axis is the horizontal position and the positive direction is from left to right, when the observer is facing the airflow. The height from the floor is the z axis. The origin of the coordinate system (x, y, z) = (0, 0, 0) is located at the center of the test section floor.

The velocity regimes considered in the tests are 30, 43, 60, 75, 86, 98 and 108 m/s, which corresponds to free stream dynamic pressures approximately equal to 50, 100, 200, 300, 400, 500 and 600 mmH$_2$O. The measured parameters are static temperature, $T$, and static, $p$, total, $p_0$, and dynamic, $q$, pressures.

The tests employ a rake composed of 15 Pitot tubes (figures 1b and 1c) to measure the local static pressure and the local total pressure. The Pitot tubes are located at 1982, 1851, 1720, 1590, 1459, 1329, 1198, 1067, 937, 806, 676, 545, 415, 283 and 153 mm from the test section floor. Free stream parameters of the airflow are measured by a Pitot tube and a thermometer located at the entrance of the test section. Pressure instrumentation is connected to the Pitot tubes to measure pressure signals. The mean and standard deviation of the temporal pressure signals obtained during the wind tunnel runs were estimated and considered in the uncertainty evaluation. The results presented in this paper are related to the central vertical plan, where $x = 0$ and $y = -120, -60, 0, 60$ and 120 mm (positions P11, P12, P13, P14 and P15, respectively).

![Figure 1. a) Scheme of the TA-2 test section floor where the rake is positioned. Unit: millimeter. The transverse central section corresponds to the positions P11, P12, P13, P14 e P15. b) Rake composed of 15 Pitot tubes. c) Rake positioned at P13 of the TA-2 test section.](image)

Pressure instrumentation was calibrated prior to the tests. Excel® sheets, MatLab® and LabView® codes were implemented for data acquisition and data reduction.
2.1. Mathematical modeling
The Bernoulli equation for the incompressible flow is used to calculate the local airspeed, $V$ [4]:

$$ p_0 = p + \frac{1}{2} \rho V^2 $$

which for our study results in:

$$ V = \left[ \frac{2( p_{\text{local}} - p_{\text{local}})}{\rho} \right]^{\frac{1}{2}} $$

In equation, $p_{\text{total}}$ is the total pressure and $p_{\text{local}}$ is the static pressure measured at the rake tubes. The airflow density is calculated by:

$$ \rho = \frac{p_{\infty}}{RT} $$

where:

- $p_{\infty}$ is the free stream static pressure measured at the entrance of the test section;
- $R$ is the gas constant equal to 287 J/(kg)(K); and
- $T$ is the temperature expressed in kelvin.

The pressure coefficient is defined by:

$$ C_p \equiv \frac{p - p_{\infty}}{q_{\infty}} $$

where $p$ is the local static pressure and $p_{\infty}$ and $q_{\infty}$ are the free stream static and dynamic pressures, respectively. For the present study, the numerator of equation (4) is measured by a differential sensor and the expression used to calculate $C_p$ is:

$$ C_p = \frac{\Delta p}{q_{\infty}} $$

2.2. Uncertainty Evaluation
The uncertainties associated with the pressure coefficient, $u_{C_p}$, and velocity, $u_V$, are evaluated by using the law of propagation of uncertainty [5]. For the case of independent variables, the combined standard uncertainty is the positive square root of:

$$ u_y^2 = \sum_{i=1}^{N} \left( \frac{\partial y}{\partial x_i} \right)^2 u^2(x_i) $$

where $y$ is the output quantity, the measurand [6], and $x_i$ are the input quantities.

Applying equation (6) to equations (2), (3) and (5) results in:
2.3. The curve fitting

The least squares method was applied to the local pressure coefficients, $C_p$, and local velocities, $V$, to supply calibration curves that represent the airflow behavior [7]. First order polynomials were fitted to the estimated parameters, i.e., the calibration curves are of the kind:

$$ y = a_0 + a_1 x $$

(10)

The law of propagation of uncertainty was also applied to equation (10) in order to obtain the uncertainty associated with the fitted curve. As the polynomial parameters $a_0$ and $a_1$ are correlated, the uncertainty of the output quantity $y$ is written as [5]:

$$ u_y^2 = (1)^2 u_{a_0}^2 + (x)^2 u_{a_1}^2 + 2u(a_0, a_1) $$

(11)

where the uncertainty of the input quantity $x$, $u_x$, was considered negligible and $u(a_0, a_1)$ is the covariance between $a_0$ and $a_1$.

The quality of the fit was evaluated by the chi-square quantity [8]:

$$ \chi^2 = \sum_{j=1}^{n} \left( \frac{y_{measured} - y_{fit}}{u_y} \right)^2 $$

(12)

A chi-square value approximately equal to the number of degrees of freedom indicates a good quality of curve fitting. The number of degrees of freedom is equal to the difference between the number of data points, $N$, and the number of parameters of the fitted curve to be estimated, $m$.

The reduced chi-square is expressed by:

$$ \chi^2 = \frac{\chi^2}{N-m} $$

(13)

where $N-m$ is the number of degrees of freedom of the curve fitting. A $\chi^2$ value approximately equal to 1 indicates a good fit. Departure from this condition reveals that either the chosen curve or the uncertainty assigned to data points is erroneous.

The standard deviation of the fit is:
3. Results and discussion

The airflow uniformity at the transverse area of the central region of the TA-2 test section is presented in this paper. Velocity distributions obtained with the rake located at P11 to P15 are seen in figures 2a to 2e. The velocity regime is related to the dynamic pressure $q = 300 \text{ mmH}_2\text{O}$, i.e., the nominal velocity is 75 m/s.

![Velocity distribution, V Blue P11](image1)

![Velocity distribution, V Blue P12](image2)

![Velocity distribution, V Blue P13](image3)

![Velocity distribution, V Blue P14](image4)

![Velocity distribution, V Blue P15](image5)

![Velocity contour.](image6)

**Figure 2.** Velocity distribution at the TA-2 transverse central section. Nominal velocity is 75 m/s.
The abscissa axis in figures 2a to 2e represents the velocity, \( V \) (m/s), and the ordinate axis represents the height of each Pitot tube from the floor, \( z \) (mm). Uncertainty limits of the fitted curve are also shown in figures 2a to 2e and correspond to a 68% level of confidence (equation (11)).

The results are grouped together and a graphic where the velocity is shown as color intensity is included to facilitate the visualization of the airflow uniformity at the transverse area of the central region of the TA-2 test section (figure 2f). One observes that the velocity is greater in the negative part of the horizontal axis nearer the floor. The difference between the maximum and the minimum velocity values, considering the uncertainty limits, is approximately 1 m/s. This velocity variation was considered acceptable regarding airflow uniformity requirements.

The calibration curve equations for velocity, \( V_x, \) and pressure coefficient, \( C_p, \) at position P13 are shown in Table 1, for all airflow regimes. The fitted function was the first degree polynomial because the pressure coefficient, \( C_p, \) at position P13 considered as \((x, y) = (0, 0)\) in figure 1a, the velocity decreases as we approach the test section ceiling. At P13, this behavior occurs for all airflow regimes. The fitted function was the first degree polynomial because the flow is expected to be uniform (equation (10)). Ideally, the airflow would be free from gradients and the \( a_1 \) coefficient value would be equal to zero in the calibration curve.

Table 1. Curve fitting results for velocity, \( V, \) and pressure coefficient, \( C_p, \) Position P13.

| Airflow regime \( q \) (mmH\(_2\)O) | Velocity \( V \) (m/s) | Pressure coefficient \( C_p, \) \( (\text{dimension one}) \) |
|---------------------------------|---------------------|----------------------------------|
| 50                              | \( V = 30.26(0.021) - 0.3(1.7) \times 10^{-2} z \) | \( C_p = -0.0073(0.0015) + 2.7(1.2) \times 10^9 z \) |
| 100                             | \( V = 43.07(0.07) - 0.0(0.6) \times 10^{-2} z \) | \( C_p = -0.0116(0.0020) + 21(17) \times 10^{-2} z \) |
| 200                             | \( V = 60.94(0.04) - 4(3) \times 10^{-3} z \) | \( C_p = -0.0119(0.0024) + 12(20) \times 10^{-3} z \) |
| 300                             | \( V = 75.30(0.03) - 72(28) \times 10^{-6} z \) | \( C_p = -0.012(0.003) + 11(25) \times 10^{-7} z \) |
| 400                             | \( V = 87.08(0.04) - 10(4) \times 10^{-7} z \) | \( C_p = -0.0120(0.0029) + 11(24) \times 10^{-8} z \) |
| 500                             | \( V = 98.10(0.03) - 99(25) \times 10^{-9} z \) | \( C_p = -0.0131(0.0029) + 11(24) \times 10^{-8} z \) |
| 600                             | \( V = 108.04(0.023) - 105(19) \times 10^{-10} z \) | \( C_p = -0.014(0.003) + 9(25) \times 10^{-11} z \) |

It was observed that at the position P13 considered as \((x, y) = (0, 0)\) in figure 1a, the velocity decreases as we approach the test section ceiling. At P13, this behavior occurs for all airflow regimes. The pressure coefficient, \( C_p, \) is negative, indicating that the local static pressure, \( p_s, \) is lower than the free stream static pressure, \( p_{\infty}, \) downstream of the test section entrance (equation (4)). The positive value of the \( a_1 \) parameter in the \( C_p, \) calibration curves means that the local static pressure approximates the value of the free stream static pressure as the height \( z \) increases.

Data reduction showed that the quality of the fitting quantified by equation (12) is not satisfied for all test configurations, when using standard deviations of the temporal signals obtained during the runs. Table 2 shows an example. The reduced chi-square values, \( \chi^2_v, \) were obtained by fitting the experimental velocity data measured at positions P11, P12, P13, P14 and P15. The velocity regime is related to \( q = 300 \text{ mmH}2\text{O} \) (nominal \( V = 75 \text{ m/s} \)). One observes that at P13 and P14, the uncertainty assigned to data points are underestimated, resulting in a reduced chi-square around 10, indicating that further investigation of the error sources must be carried out to describe the experimental errors.

Table 2. Reduced chi-square for least squares fitting applied to velocity data. \( q = 300 \text{ mmH}2\text{O}. \)

| Test section region | P11 | P12 | P13 | P14 | P15 |
|---------------------|-----|-----|-----|-----|-----|
| \( \chi^2_v \)     | 1.28| 2.43| 10.83| 12.88| 5.93|

The standard deviation of the fitting expressed by equation (14) gives an idea of the value that should be assigned to experimental data, provided that the fitted model is corrected [7]. Table 3 presents the uncertainties associated with the measured velocities, \( u_v, \) and the standard deviation of the fitting \( S, \) for \( q = 300 \text{ mmH}2\text{O}. \) At position P11, the uncertainties \( u_v \) are equal to 0.13 for all heights \( z \) and the standard deviation \( S \) is equal to 0.15; they are of the same order, and the quality of the fit is...
good \((\chi^2_\nu \text{ is around 1})\). The same applies to P12, where \(u_\nu = 0.11\) and \(S = 0.17\). On the other hand, \(u_\nu = 0.06\) and \(S = 0.20\) for P13, and \(u_\nu = 0.07\) and \(S = 0.24\) for P14, resulting in chi-square values 10 times greater than unity. The results for P15 are \(u_\nu = 0.07\) and \(S = 0.17\), and the value of \(\chi^2_\nu\) was considered good.

### Table 3. Comparison between uncertainty associated with data points, \(u_\nu\), and the standard deviation of the fit, \(S\). Airflow regime \(q = 300 \text{ mmH}_2\text{O}\).

| Region | P11 \((\text{m/s})\) | P12 \((\text{m/s})\) | P13 \((\text{m/s})\) | P14 \((\text{m/s})\) | P15 \((\text{m/s})\) |
|--------|-------------------|-----------------|-----------------|-----------------|------------------|
| height, \(z\) \((\text{mm})\) | \(S\) \((\text{m/s})\) | \(u_\nu\) \((\text{m/s})\) | \(S\) \((\text{m/s})\) | \(u_\nu\) \((\text{m/s})\) | \(S\) \((\text{m/s})\) | \(u_\nu\) \((\text{m/s})\) | \(S\) \((\text{m/s})\) | \(u_\nu\) \((\text{m/s})\) | \(S\) \((\text{m/s})\) | \(u_\nu\) \((\text{m/s})\) | \(S\) \((\text{m/s})\) |
| 1982 | 0.14909 | 0.17112 | 0.20083 | 0.23639 | 0.174434 |
| 1851 | 0.13201 | 0.11001 | 0.06118 | 0.06580 | 0.07183 |
| 1720 | 0.13182 | 0.10976 | 0.06099 | 0.06564 | 0.07177 |
| 1590 | 0.13202 | 0.10986 | 0.06103 | 0.06569 | 0.07176 |
| 1459 | 0.13180 | 0.10964 | 0.06091 | 0.06557 | 0.07164 |
| 1329 | 0.13215 | 0.10991 | 0.06101 | 0.06573 | 0.07179 |
| 1198 | 0.13174 | 0.10966 | 0.06086 | 0.06555 | 0.07158 |
| 1067 | 0.13125 | 0.10913 | 0.06064 | 0.06530 | 0.07129 |
| 937 | 0.13181 | 0.10962 | 0.06087 | 0.06555 | 0.07157 |
| 806 | 0.13200 | 0.10976 | 0.06095 | 0.06566 | 0.07168 |
| 676 | 0.13196 | 0.10967 | 0.06094 | 0.06564 | 0.07162 |
| 545 | 0.13154 | 0.10945 | 0.06078 | 0.06548 | 0.07151 |
| 415 | 0.13158 | 0.10945 | 0.06082 | 0.06552 | 0.07155 |
| 284 | 0.13173 | 0.10958 | 0.06088 | 0.06562 | 0.07177 |
| 153 | 0.13215 | 0.11009 | 0.06126 | 0.06621 | 0.07195 |

### 4. Conclusions

The uniformity of the airflow at the central region of the test section of the subsonic wind tunnel TA-2 was analysed. A series of 15 Pitot tubes arranged in a rake were used to measure the local static pressure and the local total pressure.

Calibration curves which represent the pressure and velocity characteristics of the airflow were supplied. The curves were obtained by fitting a first degree polynomial to the experimental data. Only the results for the central area are shown in this paper and the curves are related to the vertical axis.

The chi-square quantity obtained in the curve fitting was good for most of the tests, but further investigation of the error sources must be carried out to describe the experimental errors of some test configurations, as presented in tables 2 and 3.

Although gradients in velocity and pressure distributions were observed for all airflow regimes covered by the tests, the variations in velocity and pressure values were considered acceptable.

### 5. Acknowledgments

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### References

[1] Barlow J B, Rae Jr W H and Pope A 1999 *Low-Speed Wind Tunnel Testing* (John Wiley & Sons Inc.) p 713

[2] AIAA R-093-2003 Recommended Practice: *Calibration of Subsonic and Transonic Wind...*
Tunnels (American Institute of Aeronautics and Astronautics)

[3] Hudgins M S and Hergert D W AIAA 2005-4280 Methodology and Results from a Recent Calibration of the Boeing Transonic Wind Tunnel 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit (Tucson, Arizona, USA, 10-13 July 2005)

[4] Anderson Jr J D 2001 Fundamentals of Aerodynamics (New York Mc Graw Hill) p 892

[5] BIPM/JCGM 101:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement – GUM 1995 with minor corrections (Joint Committee for Guides in Metrology, BIPM, Metrologia, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML) p 120

[6] BIPM/JCGM 200:2012 International vocabulary of metrology – Basic and general concepts and associated terms (VIM) (Joint Committee for Guides in Metrology, BIPM, Metrologia, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML) p 91

[7] Press W H, Teukolsky B P T, Vetterling W T 1990 Numerical Recipes (Cambridge University Press) chapter 14 pp 547–565

[8] Bevington P R, Robinson D K 2003 Data Reduction and Error Analysis for Physical Sciences (New York Mc Graw Hill Higher Education) p 320