DETERMINATION OF TURBULENCE LEVEL IN THE TA-2 AERODYNAMIC WIND TUNNEL

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Abstract. An experimental investigation has been carried out at the TA-2 Aerodynamic Wind Tunnel test section of the Institute of Aeronautics and Space – IAE at Aerospace Technical Center – CTA. Preliminary results of turbulence intensity and velocity measurements were determined by using a computer-controlled constant-temperature anemometer system. Such results are presented in this paper and compared to previous turbulence sphere results. The main purpose of this work is to examine the behavior of the flow at TA-2 through the development and application of this technique, which will be integrated to other advanced technologies to give support to the aerodynamic tests carried out at this wind tunnel. Good agreements between velocity profiles measured with hot wire-anemometer and with pitot-static rake were observed. It was also observed that the turbulence intensity at TA-2 is low.

Keywords. *Turbulence Level, Hot- Wire Anemometer, Turbulence Sphere, TA-2 Wind Tunnel.*

1. Introduction

Hot-wire anemometer has been used extensively for many years as a research tool in fluid mechanics, and among other methods of fluid velocity measurement such as laser anemometry and pressure methods, it has become a leading method. It is also the instrument most widely used for fluctuations measurements. Some advantages of this instrument are that it has a much higher frequency response than pressure methods and it is less expensive than laser anemometry (Feier, 1997). It is capable of reading instantaneous values of velocity up to very high frequencies. Hence, it responds and is capable of measuring the turbulence fluctuations in the flow field. Hot-wire anemometer is based on convective heat transfer from a heating sensing sensor. In this method, a small, electrically heated element is exposed to a fluid medium to sense the fluid velocity. Because of the influence of the fluid velocity on the rate of heat transfer from the heated element to flowing fluid, the power input to the sensor provides a measure of the fluid velocity. The most well known thermal velocity probes are hot wire and hot film anemometers.

Variations between results of tests made in different wind tunnels at the same Reynolds number and between tests made in wind tunnels and in flight have indicated that same correction was needed for the effect of turbulence that exists in wind tunnels (Barlow *et al*., 1999). The turbulence at a given point is taken to be the ratio of the square root of the mean square of the deviations of the speed from its mean value to the mean value. At any point in the wind stream, the speed fluctuates with time about a mean value. The turbulence is the mean fluctuation taken in a definite manner and expressed as a percentage of the mean speed (Dryden and Kuethe, 1929).

This paper describes the experimental procedures and results from application of a computer-controlled constant-temperature anemometer system at the TA-2 wind tunnel test section of the Institute of Aeronautics and Space – IAE at Aerospace Technical Center – CTA. Both mean and turbulent velocity profile investigations by hot-wire anemometer are carried out and preliminary results are presented. Mean velocity profiles are compared to pitot-static rake measurements and turbulence intensity are compared to previous turbulence sphere results.

2. Fundamental data analysis

The turbulence intensity measurements were carried out by using a constant temperature anemometer (CTA), DANTEC StreamLine 90N10, with a one-dimensional hot-wire probe. The CTA works based on the fact that the probe resistance will be proportional to the temperature of the hot wire. The CTA consist of a bridge circuit that is set up by setting the adjustable resistor to the resistance you wish the probe and is leads to have during operation. A servo amplifier tries to keep the error voltage zero. It will adjust the bridge voltage such that the current through the probes heats it to the temperature, which gives the select resistance. When the probe is put in a flow, the fluid flowing over it will try to cool it. In order to maintain the temperature (resistance) constant, the bridge voltage will have to be increased. Thus, the faster the flow, the higher the voltage.

The hot wire responds according to King's Law:

$$E^2 = A + Bu^n \tag{1}$$

where E is the voltage across the wire, u is the velocity of the flow normal to the wire and A, B, and n are constants. King's evaluation suggest that $n = 0.5$, but the results obtained by Collis and Williams (1959) have demonstrated that a better curve fit can be obtained using $n = 0.45$, provided $0.02 < Re < 44$. At moderate velocities, the optimum value of n for a typical 5 μm tungsten hot-wire probe usually lies in the range 0.4 - 0.45. Attempts have been made to use the power-law relationship with $A = E_o^2$, where E_o is the voltage at zero velocity. Several investigators have shown that this results in n being a strong function of the velocity, which greatly complicates its use. It is recommended instead that A is treated as variable parameter ($A = 0.8\ E_o^2$) (Bruun, 1995).

Through King's Law, the hot-wire equation has been specified in the form $E = F(U)$. With this formulation, it is necessary to carry out an inversion process, $U = F^{-1}(E)$, in order to obtain the required velocity information. However, mathematically there is no reason why the hot-wire relationship should not be expressed in the form $U = F(E)$. George et al. (1981,1989) introduced a polynomial equation of the form,

$$U = A + BE + CE^2 + DE^3 + \ldots \tag{2}$$

Expressing the velocity U in a polynomial form of E has computational advantages since the required velocity, U, can be obtained directly from Eq. (1). This method was tested by Bruun (1995) and it was found that the curve fit is not so good as for the simultaneous solution of A, B and n for the simple power law of Eq. (2), but the best-polynomial-fit solutions compare favorably with the accuracy obtained for Eq. (2) using a variable n for the optimization. To achieve this accuracy, it is necessary to use either a full fourth-order polynomial in E or a third-order polynomial in E^2. In the present work the King's and polynomial Law were used to generate the calibration curve fit.

The hot-wire anemometer has an excellent frequency response. For this reason it can be used to determine transient velocity and flow turbulence. An instantaneous velocity, $u(t)$, can be divided into an average velocity, $\bar{u}$, and a fluctuating component u'

$$u(t) = \bar{u} + u' \tag{3}$$

The turbulence intensity can be determined by the root-mean square of u' divided by $\bar{u}$

$$\xi = \frac{\sqrt{\overline{u'^2}}}{\bar{u}} \tag{4}$$

Before the hot-wire anemometry, a turbulence sphere was the main method to measure the relative turbulence in a wind tunnel. It remains a very useful and easy way to characterize the turbulent environment in a tunnel and to check if there is an indicated effect following changes in the tunnel configuration or special installation that might affect the flow quality (Barlow et. al, 1999). Spheres are known to have a distinct critical Reynolds number above which the flow on the upstream face of the sphere is fully turbulent, causing the drag coefficient to drop abruptly. This occurs because the increase of the Reynolds number produces earlier boundary layer transition from the laminar to turbulent state, which in turns results in a smaller wake. The Reynolds number at which this transition occurs is strongly dependent on the degree of turbulence in the wind tunnel (Phoreman et al., 2000).

The critical Reynolds number as defined by either force or pressure measurements is then used to define a turbulence factor for the tunnel by comparing the tunnel's critical Reynolds number:

$$TF = \frac{385{,}000}{RN_{\text{tunnel}}} \tag{5}$$

Then the effective test Reynolds Number is defined by

$$RN_e = TF \times RN_{test} \tag{6}$$

where TF is the turbulence factor and RNc is the Reynolds number at which the measured drag coefficient passes trough 0.3 during transition from laminar to turbulent boundary layer flow. The turbulence factor is then related to the tunnel turbulence level using the relation obtained with hot-wire anemometry seen in Fig. (1).

The use of a turbulence sphere yields what may be thought of as an average value of tunnel turbulence. It does not give any information on the magnitude of the turbulence.

In the present work, the results of turbulence intensity obtained with hot wire anemometer were compared with previous measurements in the TA-2 wind tunnel with sphere of 30cm and 15cm diameter. The experimental tests were conducted following the procedure described by (Barlow et. al, 1999).

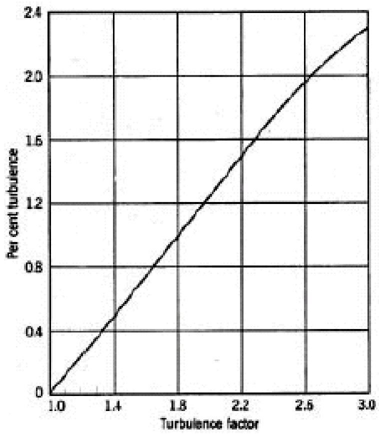


Figure 1 – Variation of turbulence factor with turbulence intensity from hot-wire measurements (Barlow et al., 1999).

3. Experimental Analysis

3.1 Calibration Procedures

The single hot wire sensor calibrations has been performed in an as-yet uncertified laboratory at IAE which will be re-structured to become a laboratory with controlled climatic conditions.

The hot-wire anemometer was calibrated using a DANTEC Calibration Module (90H01) and a separate Flow Unit (DANTEC 90H02) connected to this module. The calibration system is fully computer controlled and it has been used with CTA for automatic calibration procedure. The calibration module directs setup parameters from the PC to the Flow Unit. It samples the signals from the pressure and temperature transducers in the Flow Unit and transmits them via the Controller in the Frame to the PC. The jet exit velocity is then calculated in the StreamWare Application Software.

The Calibration system produces a free jet, where the probe is placed during calibration. It requires a normal pressurized air supply. The fixed velocity points distributed to the minimum and maximum velocity limits, respectively, are established with high accuracy by means of an internal pressure regulator. The settling chamber has flow straighteners, silencers and nets ensuring low turbulence at the nozzle exit.

The Calibrator is designed to provide multi-point calibrations. It works with compressed air and is able to set different velocity ranges depending on the nozzle selected. In the present experimental setup the one used was nozzle number II covering the range from 0.5 m/s to 120 m/s.

The single probe (DANTEC type 55P01) to be calibrated was placed in a probe holder mounted on the top plate of the Flow Unit with the probe axis in the direction of the jet as shown in Fig. (2). The tungsten wire in the center of the exit nozzle II is perpendicular to the flow and the prongs parallel with the flow. This holder allows proper positioning and alignment the probe.

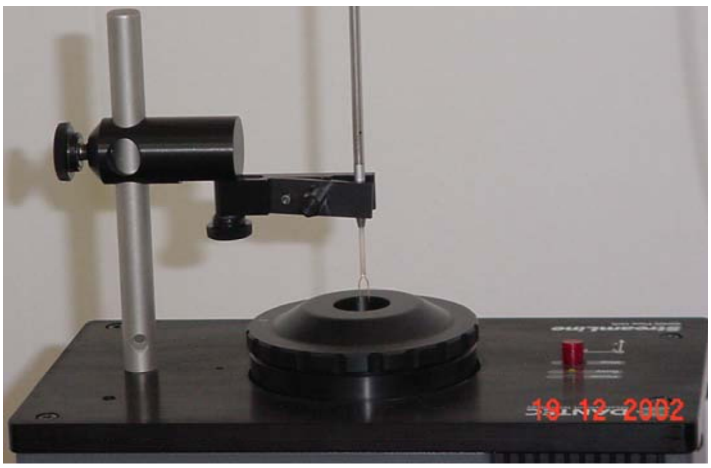


Figure 2 – Calibration Module with probe.

Through the StreamWare Application software, it was defined the hardware system configuration showed in Fig. (3) (probe, boards, frames, modules, external probes etc.) and how they are interconnected and also, set up the CTA module in use.

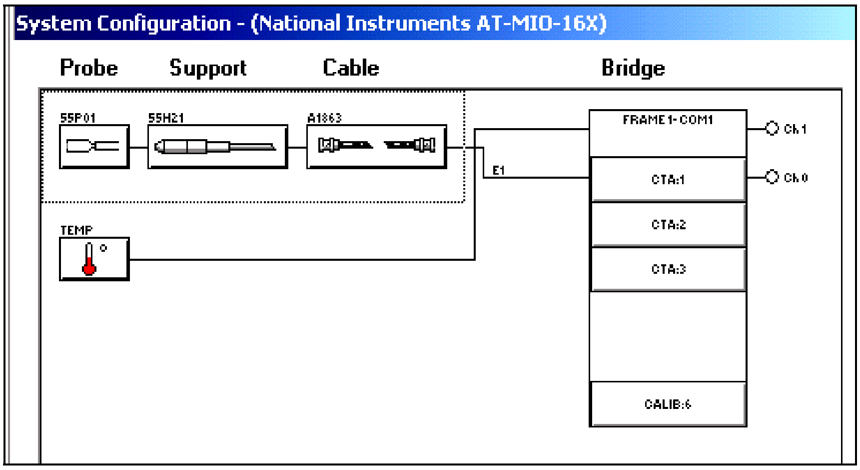
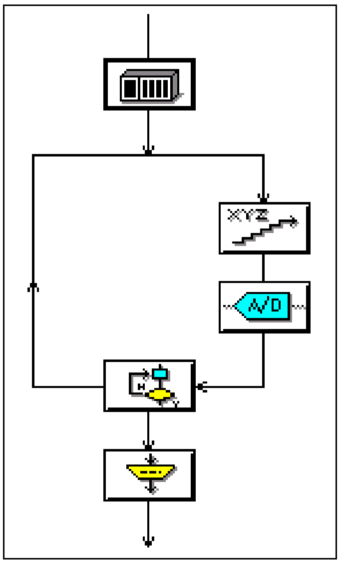


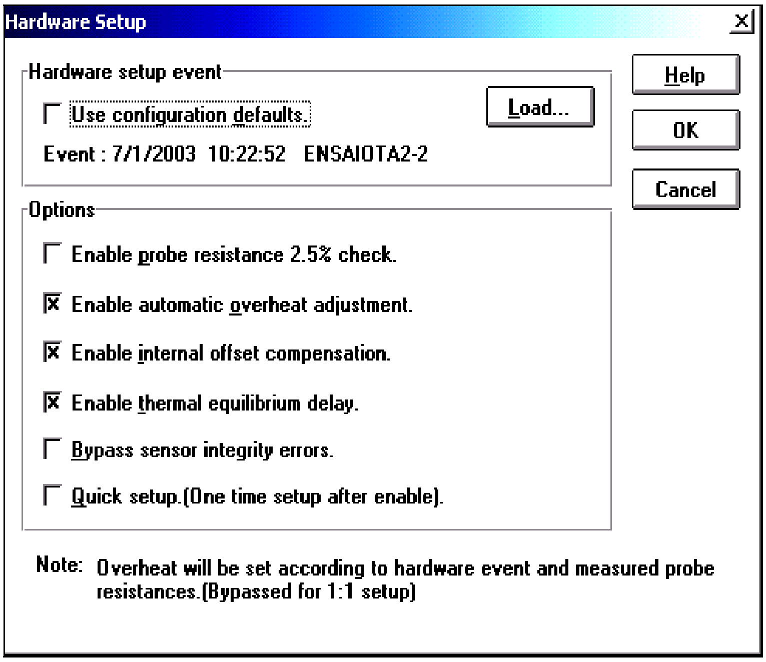
Figure 3 – The system configuration.

After the necessary hardware was installed and configured, the following procedures was carried out

1. The hardware setup event was carried out to the adjusted overheat ratio (static bridge balancing);
2. The automatic overheat adjust was enabled in the computer controlled anemometer via Stream_113 Software, as showed in Fig. (4) in which the probe cold resistance is measured, and the overheat is re-adjusted before calibration event and before to each data acquisition. This procedure was carried out because the temperature changes were expected on account of the probe could not be calibrated *in-situ*;



(a) Default Setup.



(b) Hardware Setup.

Figure 4 – Default and Hardware Setup.

3. The automatic velocity calibration event was carried out in which the velocity points were set and the transfer function was determined through Polynomial and Power Law curve fittings.

4. Conversion and data reduction event was defined to load the data acquired in TA-2 tests as shown in Fig. (5).

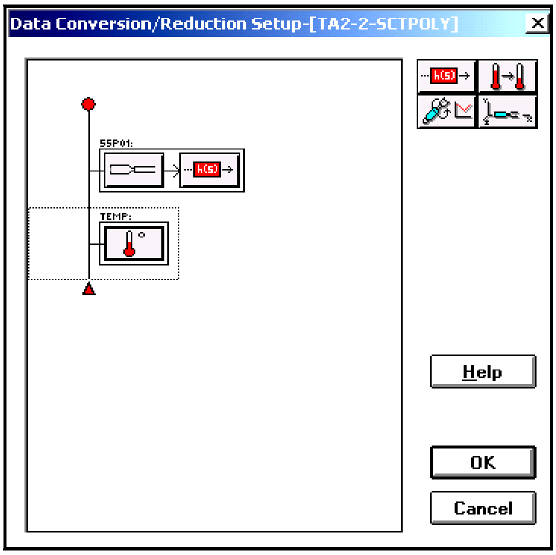


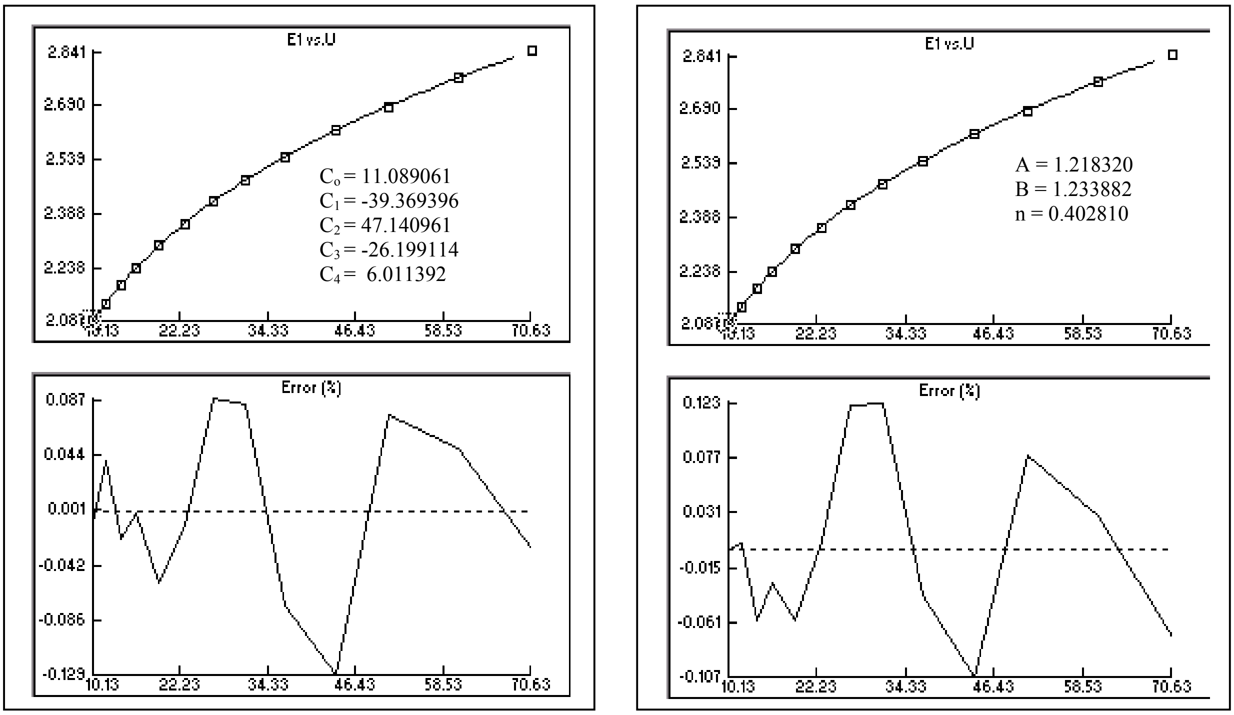
Figure 5 – Conversion and data reduction setup.

5. Default setup was configured to data acquisition and reduction / conversion as shown in Fig. (4a);

6. Data acquisition (sampling frequency and number of samples) was defined in default setup shown in Fig. (4a).

The velocity points were defined in a worksheet through the automatic calibration procedure. The calibration data was defined in a velocity range from 10 to 70m/s. After the calibration, a set of related values of CTA output voltage was obtained and the raw calibration data were stored in the datasheet .

The curve fit forms the basis for the conversion of probe voltages into calibration velocities, which define the transfer function. Figure (6) shows the polynomial curve fit of 4th order and the King's Law curve fit. The linearization errors for the curves are also shown in this figure.



(a) Polynomial Law. (b) King's Law.

Figure 6 – Polynomial and Power Law curve fit and the linearization errors for the curve fit selected.

3.2 Test Setup and Procedures

The tests with hot-wire anemometry and turbulence sphere tests were conducted in the Aerodynamic Wind Tunnel TA-2 of the Institute of Aeronautics and Space-IAE at Aerospace Technical Center – CTA. The TA-2 is a subsonic closed circuit tunnel. The test section measures 2.10 width and 3.0 m height. The 1600 horsepower motor allows a maximum tunnel flow speed of 500km/h. Forces and moments are measured by a six-component balance installed beneath the test section. Fig (7) represents the main dimensions of TA-2.

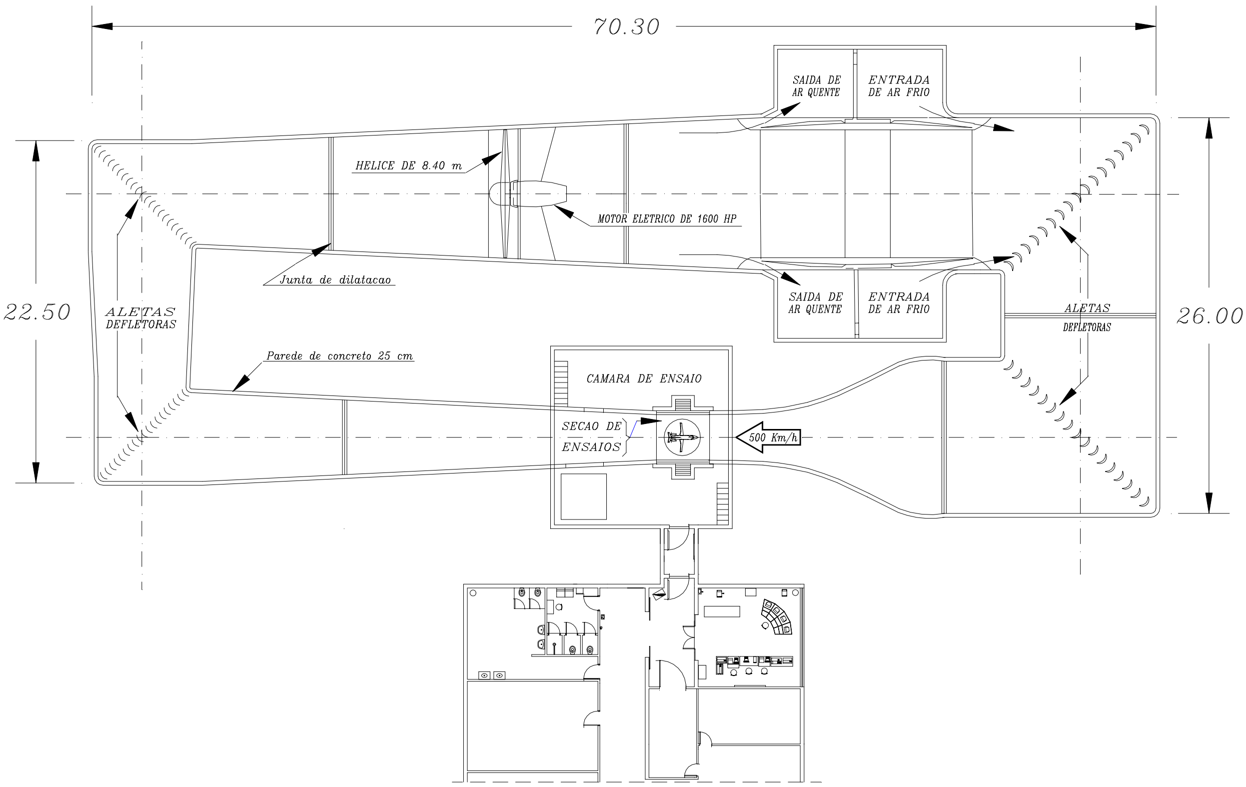


Figure 7 – Mean dimensions of TA-2.

Hot-wire calibration and tests in TA-2 were performed using a CTA with a single hot-wire probe. Data acquisition was done by a PC with a National Instruments AT-MIO-16X Data Acquisition board running Stream_113 Application software. The AT-MIO-16X is an eight differential channel or 16 single-ended, 16 bit, DAQ board set up for differencial acquisition mode over a maximum input A/D range of + or –10 Volts DC.

After probe calibration procedures, the tests in the wind tunnel and data acquisition were carried out in a different temperature with respect to the velocity calibration temperature. Pressure and temperature environmental conditions were measured in the TA-2 by an atmospheric pressure sensor (ASHCROFT 15PSI) and a thermocouple sensor (SALCAS PT100).

The tests were performed by using a standard Pitot tube to compare the velocity measurements with hot-wire anemometer. At TA-2 tunnel, there are two Pitot tubes fixed on the tunnel ceiling and positioned in front of the test section of which just one is used to data acquisition and processing and the other is used only for data validation. The single hot-wire sensor was placed in a probe holder mounted on the Pitot rake vertically positioned in the center of the wind tunnel. The hot wire with its holder was fixed in the center of the rake, and was carefully oriented along the flow direction. The rake location in the tunnel is shown in Fig. (8).

The wind tunnel air velocity was set using the dynamic pressure measurement from the Pitot tube. The air velocity range, in terms of the dynamic pressure reading, was from 16.3 to 310.1 mm water column. These dynamic pressure measurements were acquired by using STATHAM 2,5 PSI pressure sensors with National Amplifiers 1121 series. Data acquisition was done by a PC with a National Instruments AT-MIO-16X Data Acquisition board running LabWindows 4.1 software.

After the necessary hardware had been installed and configured at TA2 laboratory for single hot wire measurements and the Default Setup defined to acquisition data, the CTA output voltages and dynamic pressure measurements from standard Pitot tubes were acquired as simultaneously as possible.

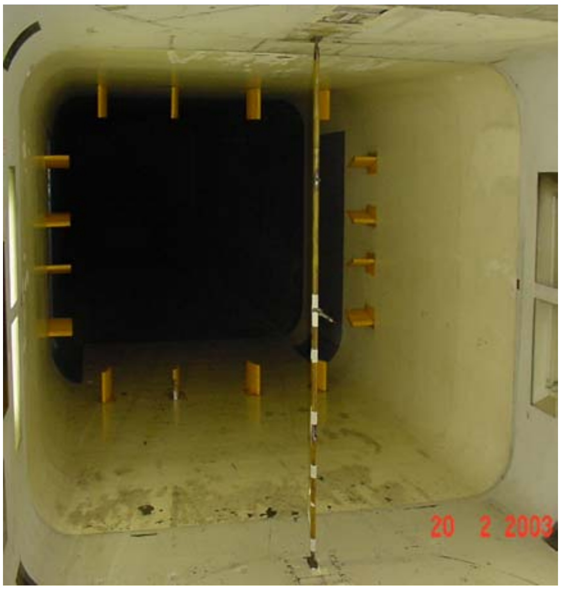


Figure 8 – Hot-wire anemometer at TA-2 wind Tunnel.

4. Results and Discussion

In Fig. (9) velocity measurements in the wind tunnel obtained from the TA2 Pitot tube and from the Hot-Wire anemometer are compared.

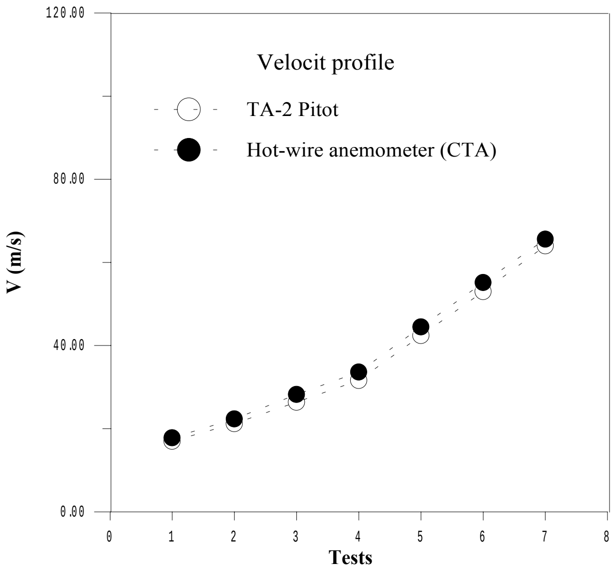


Figure 9 – Velocity measurements.

From Fig. (9) it can be noticed a good agreement between the velocity measurements obtained with hot-wire anemometer and Pitot tubes. Differences between the results were in all tests less than 2.5%.

Table (1) shows a comparison between the velocity obtained with the polynomial and Power Law curve fit.

Table 1 – Velocity obtained with the polynomial and Power Law curve fits.

	TA-2 Pitot		CTA - Polymial		CTA – Power Law		Ambient Conditions	
Tests	**ΔP (mm H_2O)**	**V (m/s)**	**V (m/s)**	**Dp (m/s)**	**V (m/s)**	**Dp (m/s)**	**ΔP (mm H_2O)**	**T (°C)**
1	16.6	17.0	17.8	0.0700	17.8	0.0701	724.8	27.0
2	25.6	21.2	22.3	0.0872	22.3	0.0874	724.0	27.2
3	39.6	26.4	28.1	0.0936	28.1	0.0937	722.8	27.5
4	56.9	31.6	33.6	0.1138	33.6	0.1138	721.3	27.5
5	101.8	42.4	44.6	0.1369	44.6	0.1368	717.3	27.6
6	157.9	53.0	55.3	0.1558	55.3	0.1556	712.3	27.7
7	227.8	64.0	65.6	0.2009	65.6	0.2005	706.0	27.7

As can be noticed from Tab. (1), there is no difference in the velocity results obtained from the two fittings. It can also be observed that the temperature variation along the tests was 0.7°C. It should be mentioned that the CTA calibration had been performed at a temperatures between 26.6°C and 26.9°C. Temperature variations play a significant role in CTA measurement accuracy. In this case, there are two options in accounting for temperature variations: the first one, used in the present work, is the overheat adjust, in which the overheat ratio is readjusted before calibration and before each data acquisition. The second option would be to apply a temperature correction. For that second option, the overheat ratio is adjusted once and left untouched during calibration and data acquisition; the temperature is measured during calibration and during the experiment and used to correct the anemometer voltages. In the present work, the temperature variation between calibration and experiment and during the actual experiment were on the order of a degree. For that kind of variation, the overheat adjust option may not have been effective in compensating for the temperature variation. This is a possible reason for the differences between the pitot and CTA velocity measurements. However, further investigation is needed in order to confirm that.

Table (2) and (3) show values of turbulence factor and turbulence intensity obtained with Sphere and Hot-wire anemometer, respectively.

Table 2 – Turbulence results with Turbulence Sphere.

V (mm H_2O)	Mean FT	Mean Turbulence Level
24	1.018	0.02
100	1.0125	0.01

Table 3 – Turbulence results with Hot-wire anemometer.

V (mm H_2O)	Mean FT	Mean Turbulence Level
25.5	1.24	0.30
101.8	1.25	0.31

In the tests with turbulence sphere, the turbulence factor, *TF*, was obtained from Eq. (5) and the turbulence level was obtained from Fig. (1). In the tests with hot-wire anemometer, the turbulence level was measured and the turbulence factor was obtained from Fig. (1).

As can be observed from the tables above, the turbulence level obtained with the hot-wire was considerably different from that obtained with spheres to the almost same dynamic pressure values. One of the possible reasons for this discrepancy in the results may be related to vibrations in the mounting structure of the probe. Another reason may be the reduced number of points in the calibration curve in the velocity range around the mean flow velocity.

In order to investigate the vibration effects on the turbulence results, additional tests were carried out using the one-dimensional probe in the TA-2 wind tunnel. In these tests, velocity tension data were acquired using a low pass filter of 1 KHz in the signal conditioner, acquisition rate of 2.5 KHz and number of samples of 4096. These tests were carried out without air flow (V=0). Figure 10 shows the velocity tension frequency spectrum, for this test. In this case, the only sources for the velocity tension signal would be zero-velocity signal (offset), which appears near zero frequency, and noise, which appears over the remaining spectrum.

Another test was performed in which the probe was again mounted in the TA-2 wind tunnel without air flow (V=0). This time, the mounting was excited so that a mild vibration would occur. The same data acquisition parameters as above were used. Figure 11 shows the velocity tension frequency spectrum for this test. In this figure, besides the high peak around zero frequency, a strong peak is noticed at 17 Hz. This peak should be associated with the natural frequency of the probe mounting set-up. Even though this test was performed without wind, one should expect that, when the same probe mounting set-up is subjected to wind, a vibration would occur around the same frequency. Such vibration would then contaminate the signal and consequently the turbulence measurement.

Figure 12 shows the velocity tension frequency spectrum with wind for the first test case in Tab. 1, i.e., V=17 m/s. This figure shows that a peak occurs around 17 Hz. This indicates that the turbulence intensity has been contaminated by probe mounting vibration. These tests do not provide enough information to filter out the effects of probe mounting vibration on the turbulence intensity, but they indicate that future turbulence measurements should be conducted with special care to avoid these vibration effects.

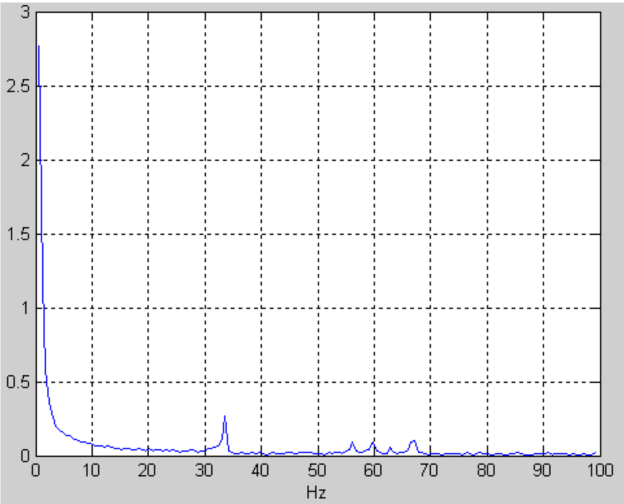


Figure 10: Velocity tension frequency spectrum without air flow.

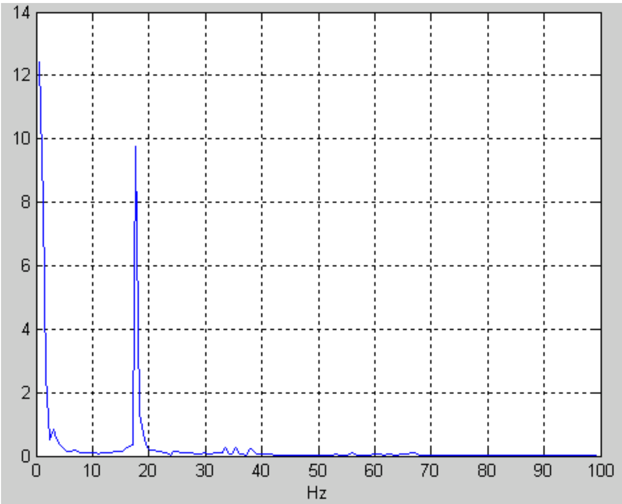


Figure 11: Velocity tension frequency spectrum without air flow after probe mounting excitation.

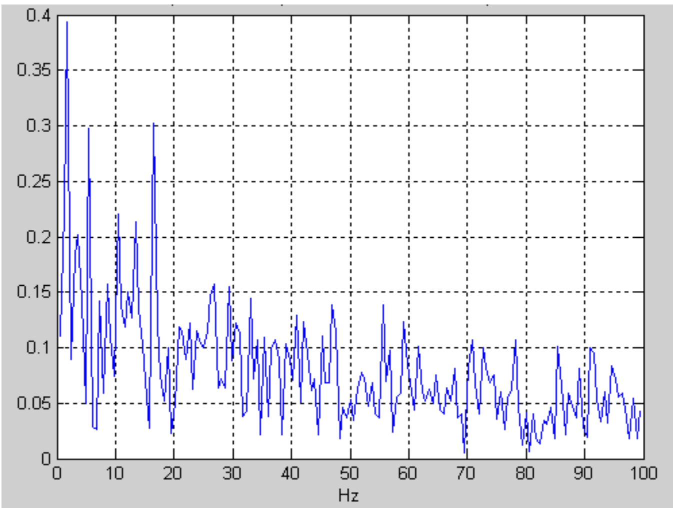


Figure 12: Velocity tension frequency spectrum with air flow (V=17 m/s).

5.Conclusions

An experimental investigation was carried out at TA-2 Aerodynamic Wind Tunnel test section and the preliminary results obtained suggest the following conclusions:

- Although the hot-wire anemometer could not be calibrated *in-situ,* the calibration equations showed low linearization errors, around 0.2%;
- With respect to the velocity measurements, reasonable agreement was verified between the values obtained from Pitot tubes and from the hot-wire anemometer. The temperature variation between calibration and experiment and during the actual experiment was of the order of a degree, thus the overheat adjust option, which was used in the present work, may not have been effective in compensating for the temperature variation. This is a possible reason for the differences between the pitot and CTA velocity measurements. However, further investigation is needed in order to confirm that;
- Regarding the turbulence intensity, the results obtained from previous sphere tests were very encouraging as they demonstrated the low turbulence level of the TA-2. However, significant differences were observed between these results and measurements obtained with hot-wire anemometer. There are some factors that may have been contributors to uncertainty in the turbulence intensity obtained with hot-wire anemometer. Among those, perhaps the most significant is probe mounting vibration. Additional tests showed that this effect may indeed have contaminated the turbulence intensity measurement.

6. Future work

This paper presents preliminary results from an ongoing investigation. Thus, the next steps are foreseen as follows:

- Carry out the hot-wire probe calibration *in-situ*. The most satisfactory arrangement is to calibrate the hot-wire probe in the facility in which the measurements are to be taken, since the disturbance caused by the probe and its holder and the interference of the geometry of the test facility will be the same during calibration and experiment;
- Because of the individual characteristics of each sensor, of the variations in the anemometer components and because of the variations in the fluid temperature, it is always necessary to perform a calibration each time the hot-wire anemometer will be used;
- Carry out the calibration using 10-30 points spaced evenly over the selected velocity range, as recommended by (Bruun, 1995);
- Re-evaluate the temperature compensation methodology;
- Investigate further the effects of probe mounting vibration and implement means to reduce its effects as much as possible.

7. Acknowledgements

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