VELOCITY PROFILE AND TURBULENCE INTENSITY MEASUREMENTS IN THE TA-2 WIND TUNNEL

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Abstract.
The Aerospace Technical Center (CTA) Aerodynamical Wind tunnel, TA-2, is going through modernization process, what has been possible through a partnership project in which CTA, EMBRAER, USP-EESC and FAPESP foundation are participants. The purpose of this paper is to present results of background turbulence measurements in the TA-2 wind tunnel, and also flow measurements carried out with Pitot tubes rake along vertical lines. These experiments has been conducted in order to evaluate the improvements in TA-2 test section flowconditions. The results of measurements in the empty wind tunnel showed a uniform velocity field and low intensities turbulence values.

***Keywords**: Turbulence Intensity, wind tunnel, Hot-wire anemometer, Pitot tubes*

1. Introduction

Wind tunnels are equipment designed to obtain airflow conditions, so that similarity studies can be performed with the confidence that the actual operational conditions can be performed (Witter and Möller, 2000). The TA-2 Wind tunnel, located at Aerospace Technical Center (CTA), São José dos Campos, is a closed circuit wind tunnel with a 2.1m x 3.0 m closed test section. A 1600 horsepower motor produces a maximum velocity of 500 km/h through the test section. A six-component balance installed beneath the test section allows the measurement of aerodynamic forces and moments on models positioned at varying pitch and yaw angles. The TA-2 wind tunnel has a 14:1 contraction ratio, which means that the wind speed increases by a factor of 14 as the air passes from the entrance of contraction to the entrance of the test section. This high contraction ratio allows a very low root-mean-square (RMS) value of velocity fluctuations in the test section. The main components of the TA-2 wind tunnel are represented in Fig. (1). TA-2 wind tunnel main customers are Embraer, the Brazilian Air Force, Aeroespacial industries, science and technology institutes and universities.

The TA-2 wind tunnel is going through a modernization process, which has been possible through a partnership project in which CTA, EMBRAER, USP-EESC and FAPESP foundation are participants. One of the goals of this project is the improvement of flow quality in the TA-2 test section. In order to accomplish this aim, the screen upstream of the contraction has been changed, the wind tunnel internal and external surfaces have been improved, and the propeller has been changed. In order to follow up the improvements, background turbulence and flow measurements have been carried out in the wind tunnel test section. The measurements presented in this paper were performed after the change of the screens and it will be repeated after the change of the propeller.

Turbulence can be described as the property of a flow in which the velocity at a given point varies erratically in magnitude and direction, and low turbulence intensity is an indicative of flow quality. Background turbulence in the TA-2 wind tunnel were investigated with a hot-wire anemometer system (Brumm, 1995), which is a popular instrument in fluid mechanics research since it can provide continuous signals of local velocity information as well as on turbulence properties. Because of the small size and low thermal inertia of the wires, the hot-wire anemometer can follow variation of wind speed at frequencies up to several kilohertz.

From the results obtained from the hot-wire anemometer experiments it could be conclude that, as expected, the TA-2 wind tunnel has low background turbulence intensity, around 0.1%. It will be presented also in this paper, results of some measurements performed with Pitot rakes in order to estimate the boundary layer thickness, which was found out to be around 10mm.

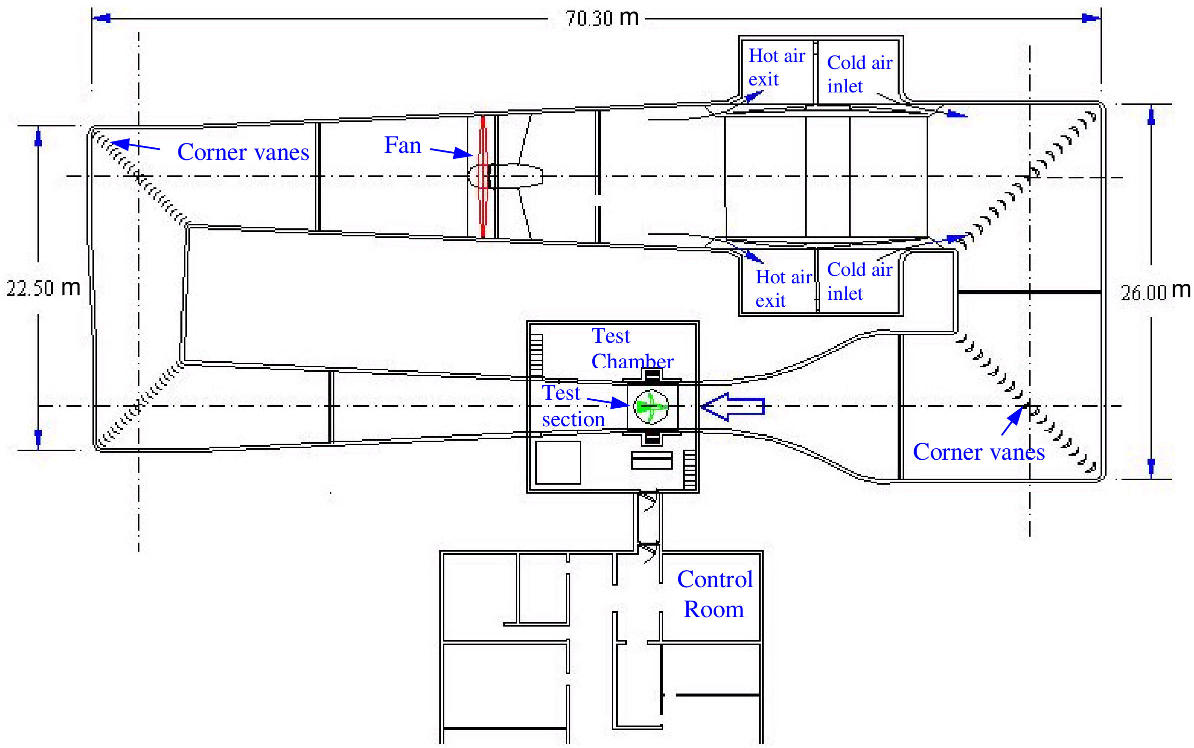

Figure 1 - TA-2 wind tunnel laboratory.

2. Experimental Apparatus

Velocity and turbulence intensities measurements were performed for values of free-stream velocity of 30m/s and 70m/s, and also some few measurements in the velocity of 100 m/s. These measurements were carried out in several positions along a vertical line in the center of the turntable, and also in other positions along the wind tunnel test section. Since there wasn't a computer controlled traverse system available, the TA-2 wind tunnel had to be turned off after finishing one punctual measurement in order to properly fit the probe holder and then to perform turbulence and velocity measurements in other position.

In the center of the turn table, in the location indicated by P1, in Fig. 2, it was carried out hot-wire anemometer measurements in the following distance from the ground: 5.5 cm, 8 cm, 11 cm, 13 cm, 16.5cm, 65 cm and 120 cm. It was carried out also some measurements in the positions indicated in Fig. 2 by P2, P3, P4 and P5 that are equally separated from the position P1 by 1m.

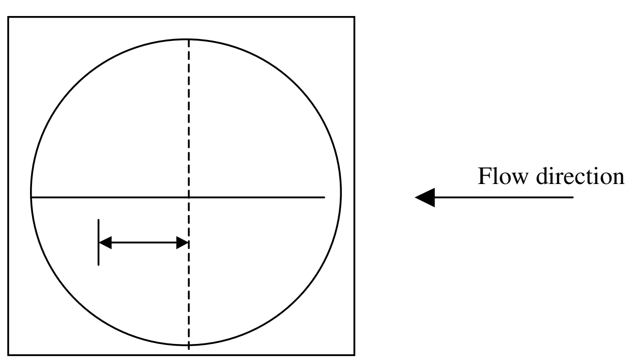

Figure 2 - TA-2 wind tunnel test section plant.

These last measurements were performed only with 50cm and/or 120cm from the ground. Each punctual measurement were done considering three samples, each consisting of 300000 observations of wind speed, were taking at a sampling frequency of 30 kHz.

Figures (3) and (4) show the holder used to fix the hot-wire anemometer probe and the temperature transducer sensor in the TA-2 wind tunnel test section. The hot-wire sensor was carefully oriented along the flow direction.

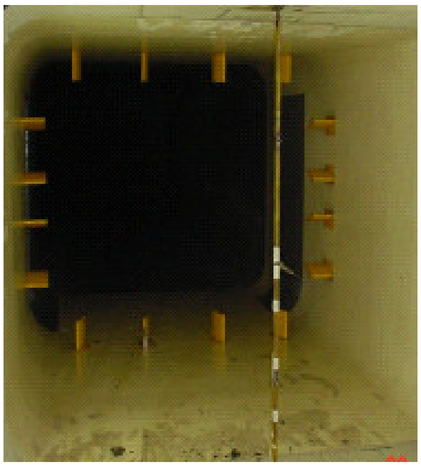

Figure 3 - TA-2 test section and probe holder.

Figure 4 - Hot-wire anemometer probe holder.

Mean velocity and background turbulence were measured using a hot-wire anemometer system consisting of a Dantec ´Streamline' frame, fitted with three 90C10 constant-temperature anemometry (CTA) modules and one 90H10 calibration module, which controls a 90H02 flow unit for calibrating probes. In the experimental tests performed, a one-dimensional hot-wire probe was used; hence, only one CTA module was utilized. The CTA module consists of a resistance bridge with electronic circuit that continuously adjusts the voltage across the wire in order to maintain its resistance constant. The voltage required to do this serves as a measure of the rate at which heat is being carried away from the wire by the air, and, hence, of the wind tunnel speed.

The CTA modules have a Signal Conditioner that is used to match the CTA bridge output voltage to the input range of the A/D converter board in the PC and also to perform filtering of the signal. It can be operated in both DC and AC mode. It contains an input *Offset* circuit that subtracts up to 10 Volts from the bridge output voltage with a resolution of 1 mV and a *Gain* function that amplifies the resulting signal up to 1024 times (Dantec StreamLine Manuals, 2000).

The AC voltage signal from the CTA was low-pass filtered (10 kHz) to reduce any high-frequency noise associated with the electronic circuitry, and a high-pass filter of 10Hz was used to remove any mean and low frequency components of signals before being digitized with a 12-bit A/D converter (National Instruments AT-MIO-16X 12 bits). The velocity values were obtained from the DC channel signals, once the mean voltage, which corresponds to mean velocity values were removed from the AC voltage signal. High gains, between 128 and 1024 were applied in order to improve the A/D converter resolution. Although, for background turbulence measurements it is recommended to use high-pass filter above 5Hz (Möller, 2000), a 10Hz high pass-pass filter was used because it is the lowest value allowed by the equipment model used. On the other hand, for the air flow minimum velocity measured, 30 m/s, second a length scales analysis (Tennekes and Lumley, 1974), and taking in account that the TA-2 test section height is 2.10m, the characteristic frequency that can be found is 15Hz, which is above the filtered values.

2.1 The hot-wire anemometer calibration procedure

Hot-wire anemometry is an indirect method; that is, it deduces instantaneous velocities from local heat-transfer information of the sensor. Hence, calibration versus reference velocity is necessary, and serves the purpose of establishing a transfer function between anemometer output voltages and the velocity acting on the probe. The accuracy of a hot-wire anemometer measurements are highly dependent on the calibration process. For the measurements carried out, it was used a Dantec 55P01 probe, Fig. (6), which has a single 5μm diameter platinum-plated tungsten wire, with copper and gold plating at the ends, isolating the active portion of the wire which is 1.25mm. A Dantec's software (V2.08), running on a Pentium 233 MMX controlled all aspects of the calibration process, setting up of the CTA module, and capture and conversion of samples of digitized measurements from A/D converter. The calibrator used, shown in Fig. 5, operates from a pressurized air supply and creates a low turbulence free jet, where the probes are placed during the calibration. The free jet velocity is calculated on basis of the pressure drop over its exit. It was not possible to perform the probe calibration *in situ,* because in the occasion that the measurements were carried out, there wasn't a suitable pressurized air supply system near the TA-2 wind tunnel test section.

Figure 6 - Dantec 55p01 Probe.

Figure 5 – Dantec StremLine Calibrator.

In order to minimize the influence of the differences in environment conditions during the calibration and measurements events in the TA-2 wind tunnel, several calibration curves were carried out. Two days were spent in the calibration process in order to obtain suitable transfer functions for different values of environment temperature. This way it was possible to choose the best curve during the measurement in the TA-2 wind tunnel. As recommended by Brunn (1995), the calibration curves were performed considering small velocity ranges, around 20 m/s and with number of points between 10 and 20. This procedure avoids temperature variation during the process. In addition, corrections were made to the signal to account for changes in temperature and density between the time the probe was calibrated and the time the measurements were made.

The probe calibrations were performed using a Dantec StreamLine calibration system, which consists of a calibration control module placed in the StreamLine frame and separate flow unit, which creates the free air jet used as the velocity reference, which has a flat, low-turbulence velocity profile. The flow unit contains a set of control valves, pressure and temperature transducers, and a settling chamber with an exchangeable exit nozzle that allows the air jet velocity varies from few cm/s up to Mach 1. A picture of the flow unit is presented in Fig. (2).

The calibration curve was adjusted using a power law relation, the king's Law (1914):

$$E^2 = A + Bu^n$$

Where E is the direct output from the anemometer, and A, B and n are calibration constants. According to Brunn (1995), at moderate velocity, the optimum values of n for a typical 5µm tungsten hot-wire probe, n lies in the range from 0.4 to 0.45. With basis on this information, all calibrations curves were carried out aiming to get a suitable n value. One of the calibration curve obtained is showed in Fig. (7).

Before the measurements in the TA-2 test section, it was carried out some turbulence measurements in the calibrator exit air jet in order to check the adequacy of the hot-wire anemometer calibration procedure, StreamLine software configuration and evaluation technique. The obtained results were compared with the ones provided by Dantec, the manufacturer. In order to get these results it was sent them the calibrator serial number. It was received from the manufacturer three measured values of air jet velocity, the correspondent turbulence intensity values and information about the calibration curve used. In order to do a proper comparison, the calibration performed here was done exactly according to the data provided by the manufacturer. Then, it was carried out only one calibration curve, between 5 and 60 m/s, for the three velocities values provided, shown in Tab. 1. As can be note form this table, good agreement was observed between the values provided from the manufacturer and the measured values, which is an indication that the hot-wire anemometer set-up used is suitable.

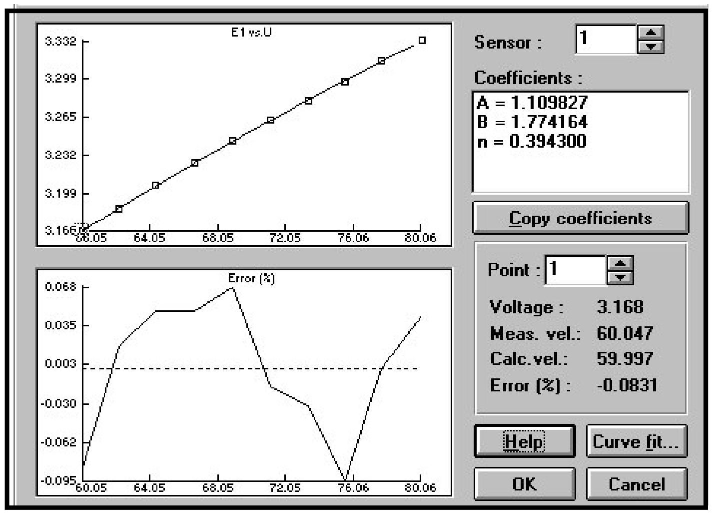

Figure 7 – Calibration curve.

Table (1) – Velocity and the correspondent turbulence intensity values in the calibrator air jet.

Values obtained from Dantec		Measured values	
Mean Velocity [m/s]	Turbulence Intensity [%]	Mean Velocity [m/s]	Turbulence Intensity [%]
7.21	0.103	7.50	0.11
14.63	0.091	14.19	0.089
28.09	0.283	28.91	0.26

After calibration the hot-wire anemometer system were taken to TA-2 wind tunnel, where the experiments were carried out. Pressure and temperature environmental conditions in the TA-2 were measured by an atmospheric pressure sensor (ASHCROFT 15PSI) and a thermocouple sensor (SALCAS PT100). The wind tunnel flow velocity was set using the dynamic pressure measurement from a Pitot tube that is fixed on the tunnel ceiling, in front of the test section. These last measurements were acquired using a STATHAM 2.5 PSI pressure sensor with National Amplifiers 1121 series. A PC with a National Instruments AT-MIO-16X board running Lab Windows 4.1 software was used to data acquisition.

Mean velocities profiles with the empty wind tunnel were obtained using the two Pitot rakes shown in Fig. (8) and Fig. (9). In both rakes the dynamic pressure in each position were obtained using a PSI Pressure transducer with 32 channels, model EPS-32HD. These experiments were carried out at the velocity of 70 m/s and 30m/s.

Figure 8 – Boundary Layer Pitot rake.

Figure 9 - Pitot rake.

The rake shown in Fig. (8), has 1 Pitot tubes, where the first 10 tub
the last ones 10cm. This rake was used for obtain the velocity distribu

showed in Fig. (9), has 15 Pitot tubes that are equally spaced 10cm from each other, and was used to get the velocity distribution beyond the boundary layer.

3. Fundamental Definitions

According to the classical work of Reynolds (1895), in a turbulent flow, the instantaneous velocity $u_i(t)$ can be decomposed into a mean flow, $\overline{U_i}$, and velocity fluctuations $u_i(t)'$, such as

$$u_i(t) = \overline{U_i} + u'_i(t)$$

Where,

$$\overline{U} = \frac{1}{T}\int_T u(t)dT$$

Then, the mean value of the velocity fluctuations is zero by definition. Hence, this fluctuation is quantified by its Variance, σ^2, defined as,

$$\sigma^2 = \overline{(u - \overline{U})^2}$$

It is often convenient to take the square root of the variance, σ, which is referred to as the standard deviation or the root mean square (RMS) value. Then, the turbulence intensity is defined by,

$$IT = \frac{\sigma}{\overline{U}}$$

4. Results and discussion

Results of turbulence intensity measurements along a vertical line, in the center of the turntable, in the position P1, are presented in Fig. (10). From the results presented in this figure, it can be notice that for distances greater than 16 cm (d/H=0.08), the turbulence intensity is almost constant and lies around 0.1%. The higher turbulence values were verified near the wall, as expected.

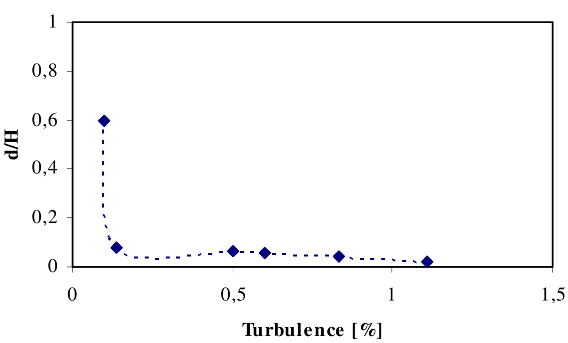

Figure 10 - Turbulence intensity variation with distance.

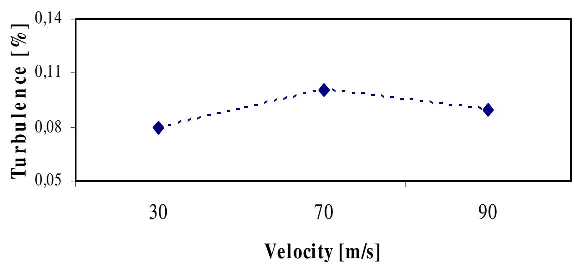

Figure 11 - Turbulence intensity variation with velocity.

Turbulence intensity values measured at different wind tunnel speed values are presented in Fig. (11). As can be noticed from this figure, no significant variation in turbulence intensity with velocity was verified. Although the experiments were very carefully conducted, this behavior may be an indicative that there is some noise avoiding the decrease of the turbulence as the wind tunnel velocity increases. Further investigations about possible noise source will be performed in the future.

Uncertainty analyses were carried out according to Jorgensen (2000) and it was verified that it is around 3% for a velocity sample.

Dimensionless velocity profiles for the mean velocity of 70m/s are presented in Fig. (12). These measurements were carried with the empty tunnel along a vertical line on the center of the turntable and in the positions indicated in Fig. (12), in a turntable plant view.

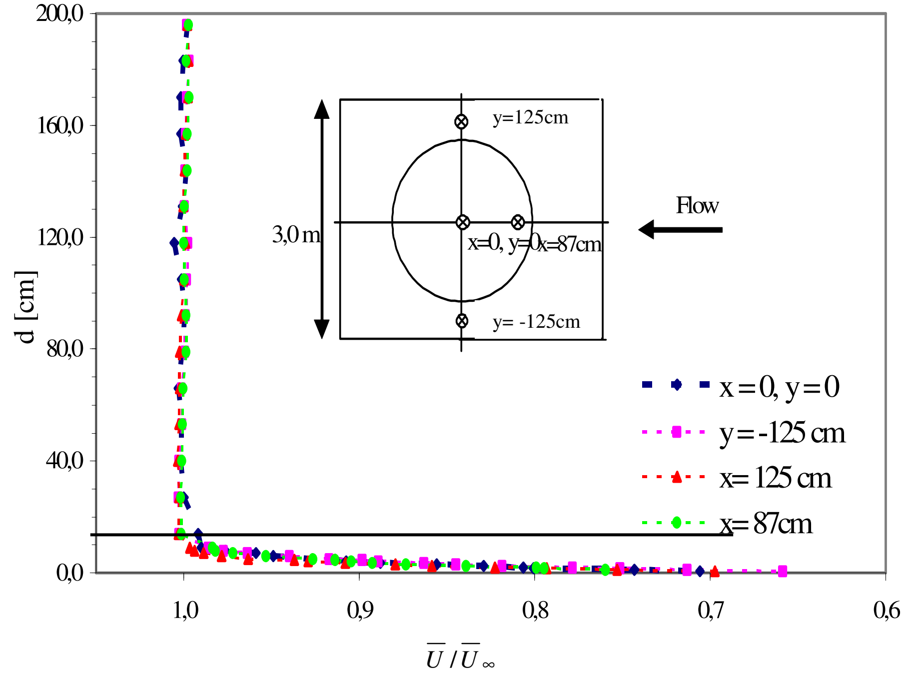

Figure 12 - Mean dimensionless velocity in the specified positions.

From the results presented in Fig. (12), it can be realized that the TA-2 boundary layer thickness is around 10mm. This boundary layer thickness value was verified also for other velocity values and positions inside and around the turntable. In locations near the lateral walls, although not shown in Fig. (12), it was verified an increase in the boundary layer thickness.

The power spectrums of hot-wire anemometer fluctuating signal, at wind tunnel speed of 70 m/s, is presented in Fig.(13) and Fig. (14). The frequency spectrums shown in these figures were obtained via Fast Fourier Transform, Doebelin (1976). Mean and standard deviation of the wind velocities were obtained from each signal of 10s duration. However, for spectral analysis, each signal was divided into 10 windows of 30000 data points. Altogether 10 sets of windows were used to obtain the average power spectrum. It can be noticed from Fig. (13), a clear region with a –5/3 declivity, characterizing the Kolmogorov's inertial range.

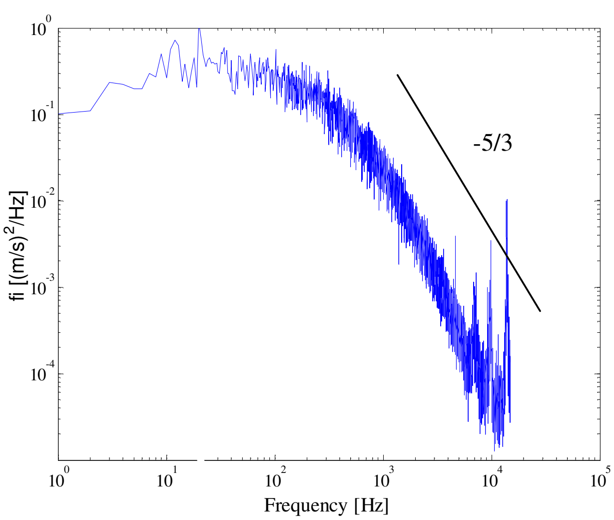

Figure 13 – Energy power spectrum - position P1.

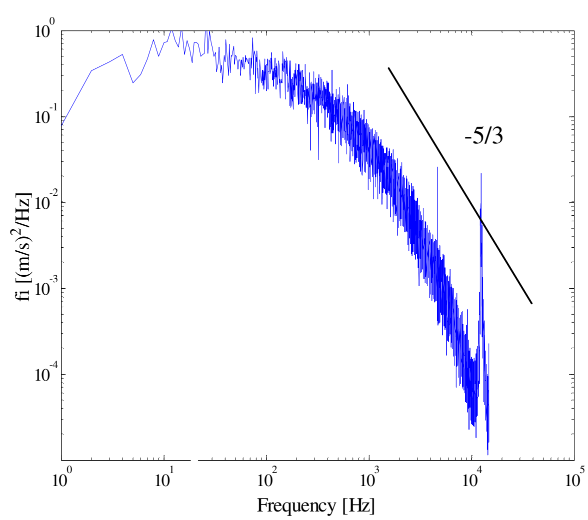

Figure 14 - Energy power spectrum – position P3.

5. Conclusions

The purpose of this research work was the evaluation of the TA-2 wind tunnel characteristics in order to follow up the improvements that have been taking place there. Measurements of velocity and turbulence intensities in the empty wind tunnel showed and uniform velocity field and low turbulence intensities. The results obtained indicate that the wind tunnel boundary layer around the turntable is around 10 cm. The results show also that the turbulence intensity beyond the boundary layer is approximately 0.1%, and around 1% inside it. Although these turbulence levels are very low, they should be regarded as ‘upper bounds’, since no significant variation of the turbulence intensity with increase in the wind speed, which suggest that the measurements can be affected by some kind of noise. Further investigations will be conducted as an extension of the present paper.

6. References

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7. Acknowledgements

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