COST Action TU1304 WINERCOST

Wind Energy Technology Reconsideration to Enhance the Concept of Smart Cities

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Short Term Scientific Mission Final Report

Topic **Experimental wind engineering in a VKI wind tunnel**

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Summary

This report describes the main activities carried out during my Short Term Mission (STSM) at the Von Karman Institute for Fluid Dynamics (VKI), in the Environmental and Applied Fluid Dynamics department , under the supervision of Prof. Jeoren van Beeck and Dr. Nicolas van Wyer. During the STSM I had the opportunity to improve my knowledge about the application of different measurement techniques to characterize the flow inside a turbulent boundary layer. My interest on these experimental techniques is related with the development of an integral boundary layer calculation model to calculate the flow on wind turbine blades. My main activity during the STSM was to collaborate in the characterization tests of the flow in a new wind tunnel's test section, performing hot wire velocity measurements and computing mean velocity profiles and integral length scales.

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1. Introduction

The aim of this Short Term Mission (STSM) was to gain knowledge about the application of different measurement techniques to characterize the flow inside a turbulent boundary layer.

As a research topic, I am especially interested in investigating the use of integral three dimensional boundary layer methods to simulate the flow over a wind turbine blade. These methods require a model for the velocity profile inside the boundary layer, which is expressed as two components: a longitudinal component aligned with the external flow direction and a crossflow component, defined in the transverse direction to the external flow. The crossflow component is generated due to transverse pressure gradients and to the rotation of the frame of reference. Empirical velocity profiles can be used to approximate the longitudinal and crossflow components, providing closure relations for the boundary layer equations. This formulation allows a significant reduction in the computational cost of the flow simulation, with great advantages for optimization and parametric studies.

In order to evaluate the applicability of different empirical velocity profiles and to validate important model assumptions regarding diffusive effects, it becomes particularly valuable to obtain a detailed description of the flow inside the three dimensional boundary layer. Optical measurement techniques and hot wire anemometry are especially useful for this purpose. The Von Karman Institute for Fluid Dynamics (VKI) has a worldwide recognition for experimental research in fluid dynamics and an extensive knowledge on advanced measurement techniques in this domain. During my two week STSM I had the opportunity to contact with some of these techniques and observe their application in tests undertaken at the VKI facilities.

My main activity consisted on measuring the velocity profile and turbulent integral length scales of the flow in the test section of a recently modified wind tunnel using a hot wire anemometer. This work was part of the characterization tests of the new experimental facility, projected at the Environmental and Applied Fluid Dynamics department of VKI by Dr. Nicolas Van de Wyer, with whom I worked in close cooperation during my STSM. As a very interesting complement to my main activity, I also had the opportunity to observe the application of optical measurement techniques in other tests carried out at VKI, namely the use of Laser-Induced Fluorescence (LIF) to detect turbulent structures on a boundary layer flow and the application of Phase Doppler Velocimetry (PDV) to characterize oil droplets for Particle Image Velocimetry (PIV) measurements.

This report describes the velocity measurement tests with the hot wire anemometer and presents some preliminary results that could be obtained in the very short period of the STSM.

2. Experimental setup

2.1. The wind tunnel facility

The tests were carried out in the L-2A low-speed wind tunnel facility, which has been specifically modified for aeroacoustic studies, by enclosing the diffuser and test section parts inside acoustically isolated chambers (Figure 1-a). It is an open circuit wind tunnel with a maximum flow velocity of 45 m/s and a very low turbulence level, as confirmed by the results presented in this report. The test section is a square duct with a 25 cm side, made of plexyglass providing optical access for future PIV measurements. A transition roughness band was installed at the end of the wind tunnel's contraction to get a turbulent boundary layer right since the beginning of the test section.


a) b)

Figure 1. Wind tunnel facility: a) view of the test section enclosed inside an acoustically isolated chamber; b) view of the hot wire probe installed inside the test section and wall pressure tap.

Figure 1-b) shows a close-up of the hot wire probe mounted inside the test section. The probe is centered in the horizontal direction of the test section and its vertical position is regulated by 1 mm steps. The velocity at the inlet is measured indirectly using a pressure tap at the lateral wall of the test section. The wall pressure is correlated with the inlet velocity by an eight order degree polynomial function, obtained in a previous calibration test, using as reference the velocity measured with a Prandtl tube. A thermocouple was also installed inside the test section to monitor the temperature during the tests.

The hot wire signal was acquired at a 51.2 kHz sampling rate, while the wall pressure and temperature signals were acquired at 1 kHz. All signals were recorded during a sampling period of 1 s.

2.2. Hot wire anemometer

To measure the longitudinal velocity profile in the test section a one component VKI hot wire anemometer was used. The wire was aligned along the direction perpendicular to the incoming main flow. Two different calibrations were performed: one at the outlet of a free jet and the other inside the wind tunnel's test section. The hot wire voltage was corrected for temperature variations using the expression:

$$E = E_{meas}\sqrt{\frac{T_{wire} - T_{ref}}{T_{wire} - T}}$$

where E is the corrected voltage, E_{meas} is the measured voltage, T_{wire} is the wire temperature, T_{ref} is a reference temperature, chosen as 293.15 K, and T is the measured temperature. The reference velocity U for the jet calibration was determined from the measurement of the static pressure at the inlet of the convergent nozzle, using the atmospheric pressure as reference. At this inlet, total and static pressures are practically of the same value so the measured pressure difference corresponds to the dynamic pressure $\mathrm{p_{dyn}}$, from which U is expressed as $\mathrm{U} = \sqrt{2\mathrm{p_{dyn}}/\rho}$. The density ($\rho$) was corrected for atmospheric pressure and temperature variations with negligible effect on U for the ambient conditions range of the tests. The calibration curves $\mathrm{U}(E)$ for the hotwire anemometer were obtained by applying a third order polynomial curve fit to the measured points, as Figure 2 illustrates.

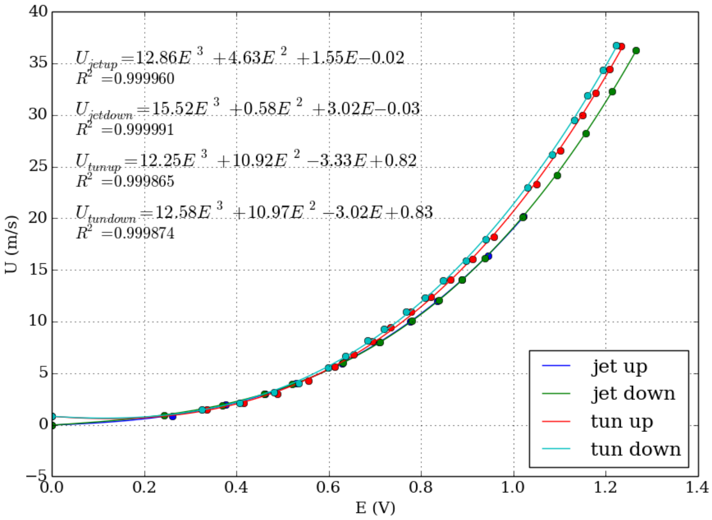


Figure 2. Hot wire anemometer calibration curves for the jet calibration ('jet') and wind tunnel calibration ('tun'). For each one, two sets of points were taken, corresponding to ascending ('up') and descending ('down') velocity sweeps.

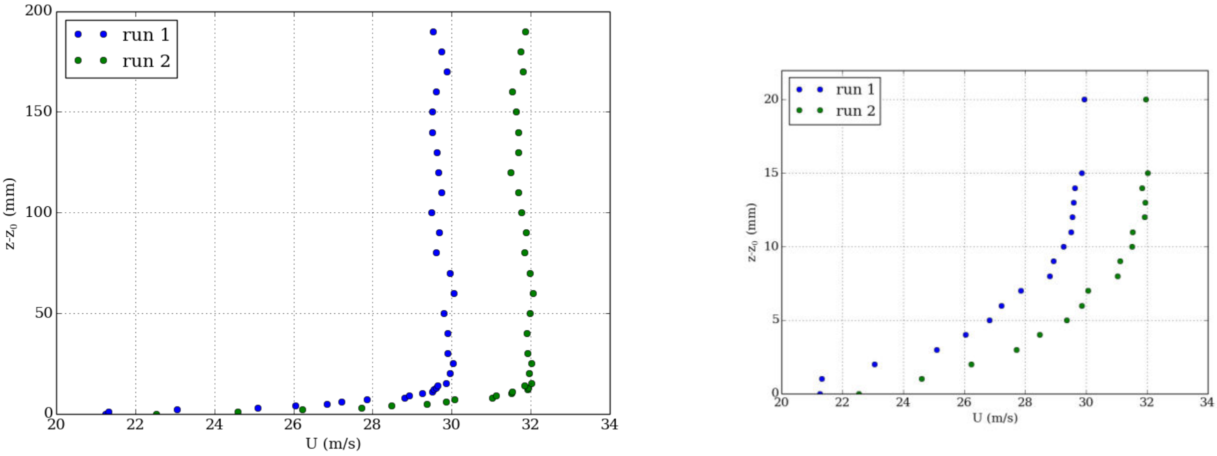
The characteristic response time (τ_r) of the system was measured at the limits of the velocity range of interest, corresponding to a frequency of response $f = 8.2$ kHz at 0 m/s, and $f = 15$ kHz at 38 m/s, given by $f = 1/(2.02\tau_r)$.

3. Results

3.1. Mean flow velocity profile

The velocity was measured at 35 positions along the vertical direction (z) of the test section. The probe's position closest to the wall (z_0) was not accurately determined but according to visual inspection it should be less than 1 mm from the wall. The z_0 position was kept the same for all tests within the uncertainty of the vertical positioning procedure.

Figure 3 shows the mean velocity profiles $U(z - z_0)$ obtained for two wind tunnel runs at different inlet velocities. The average value of the inlet velocity based on the wall pressure measurements is 27 m/s (*r.m.s* = 0.07) for run 1 and 29 m/s (*r.m.s* = 0.16) for run 2. These results are inconsistent with the velocity profiles plotted on Figure 3-a), that show a velocity at the center of the test section about 9 % higher for both runs. It was not possible to clarify the reason for these discrepancies by the end of the STSM, which should require further investigation. There was also some uncertainty regarding the temperature measurements that could not be appropriately taken into account in the calculations by the end of the STSM. Maximum temperature variations during the tests were low (0.9°C for run 1 and 1.8°C C for run 2) but the measured absolute values seem to be underestimated by about 2°C. The analysis of the present results should have these limitations in mind.



a) b)

Figure 3. Mean velocity profiles as a function of the relative distance to the wall, measured with respect to the probe's position closest to the wall (z_0): a) full measured velocity profile; b) detail of the boundary layer region.

Figure 3-b shows in more detail the measurements taken at a 2 cm distance from the wall, where a boundary layer profile can be clearly identified. These plots suggest that the thickness of the boundary layer at the probe's longitudinal position inside the test section should not exceed about 1.8 cm for both runs.

3.2. Turbulence intensity

The turbulence intensity (TI) is defined as $\mathrm{TI} = \sigma/\mathrm{U}$ where σ is the root mean square of the longitudinal velocity component $u = \mathrm{U} + u'$, U being the mean value and u' the turbulent fluctuations. Figure 4 shows TI, expressed in %, calculated for both runs. It can be seen that turbulence intensity is below 1 % from relative distances to the wall $(\mathrm{z} - \mathrm{z}_0) > 1.5$ cm, up until the highest measured positions inside the test section.

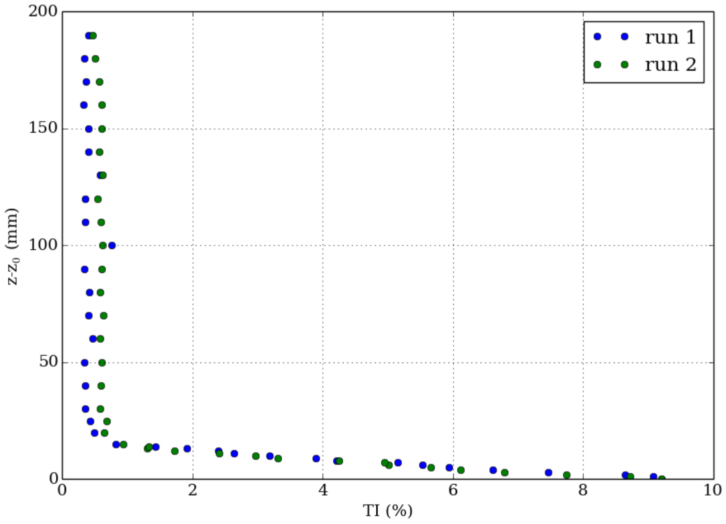


Figure 4. Turbulence intensity (%) as a function of the relative distance to the wall, measured with respect to the probe's position closest to the wall (z_0).

3.3. Integral length scales

The auto-correlation coefficient $R_u(\tau)$ was computed for several velocity measurements $u(t)$ taken at different $(\mathrm{z} - \mathrm{z}_0)$ positions, in each run. This coefficient expresses the correlation between the instant velocity measured at two times t and $t + \tau$, at a certain fixed position in the velocity field, and is expressed as:

$$R_u(\tau) = \frac{\overline{u(t)u(t+\tau)}}{\overline{u(t)^2}}$$

where the overbar denotes a temporal average. R_u is a useful indicator to detect the presence of turbulent structures in a flow and can be used to determine the turbulence integral time scale T_u. A good approximation for T_u is the value of τ where R_u crosses $1/e$ ~0.37. Using the frozen vorticity hypothesis, the integral time and length scales can be related through the mean local velocity (z) :

$$L_u(z) = U(z)T_u(z)$$

where L_u is the turbulent integral length scale[1].

Figures 5 and 6 show the autocorrelation coefficients computed for run 1 and run 2, at different measurement positions inside the boundary layer, for correlation time intervals $\tau < 4$ ms. In Figure 7 the corresponding integral length scales are plotted as a function of the relative distance to the wall. These results show that the turbulence is anisotropic in the internal part of the boundary layer, where L_u is one order of magnitude higher than the distance to the wall, suggesting a somewhat flattened structure of the eddies.

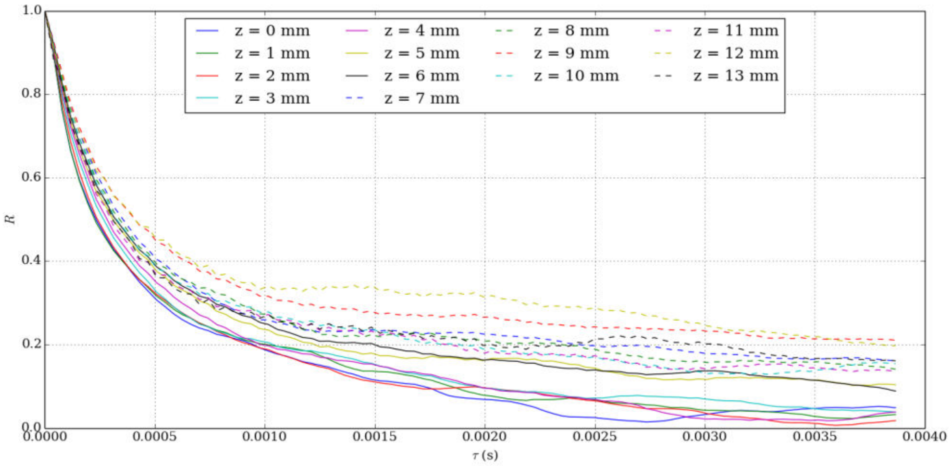


Figure 5. Auto-correlation coefficient as a function of τ for the measurement velocities taken at distances $(z - z_0)$ between 0 and 13 mm for run 1.

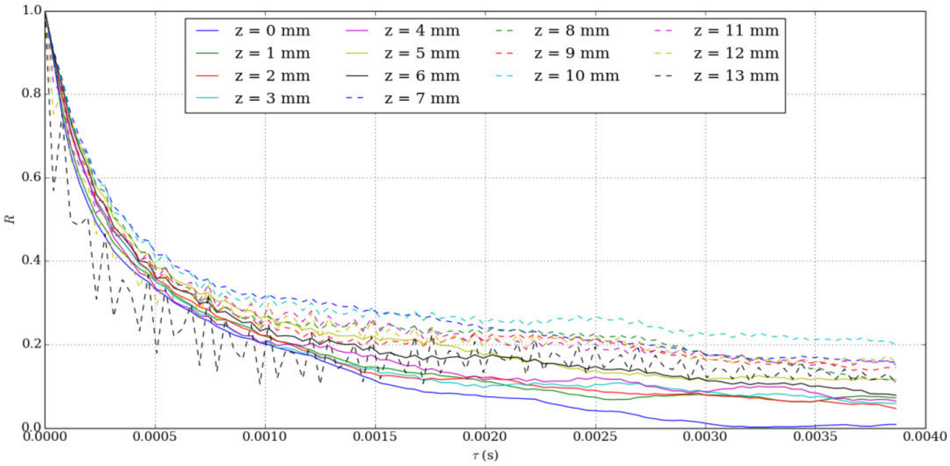


Figure 6. Auto-correlation coefficient as a function of τ for the measurement velocities taken at distances $(z - z_0)$ between 0 and 13 mm for run 2.

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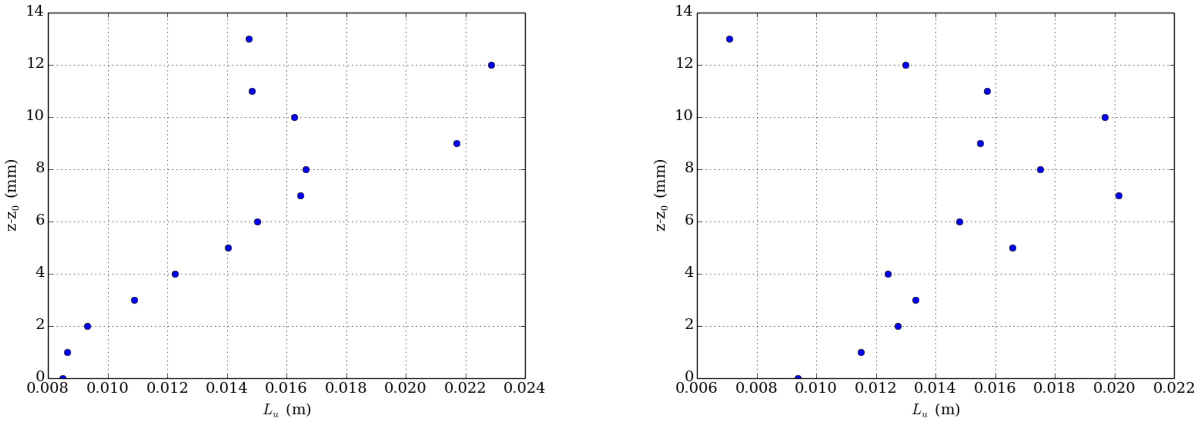
[1] A more detailed description of the auto-correlation coefficient and turbulent integral length scales can be found on the Project Report by Sofia Buckingham (Wind park siting in complex terrains assessed by wind tunnel simulations, 2010).



a) b)

Figure 7. Turbulent integral length scale as a function of relative distances to the wall $(\mathrm{z}-\mathrm{z}_0)$ computed for the measurement velocities of a) run 1 and b) run2, corresponding to positions inside the boundary layer.

Figures 8 and 9 show the autocorrelation coefficients computed for run 1 and run 2, at measurement positions along the full height of the test section, for correlation time intervals τ < 50 ms. It is clear the presence of a periodic influence in the velocity field that requires further examination. It should be interesting to investigate if the frequency of this perturbation is the same frequency of the wind tunnel's axial fan.

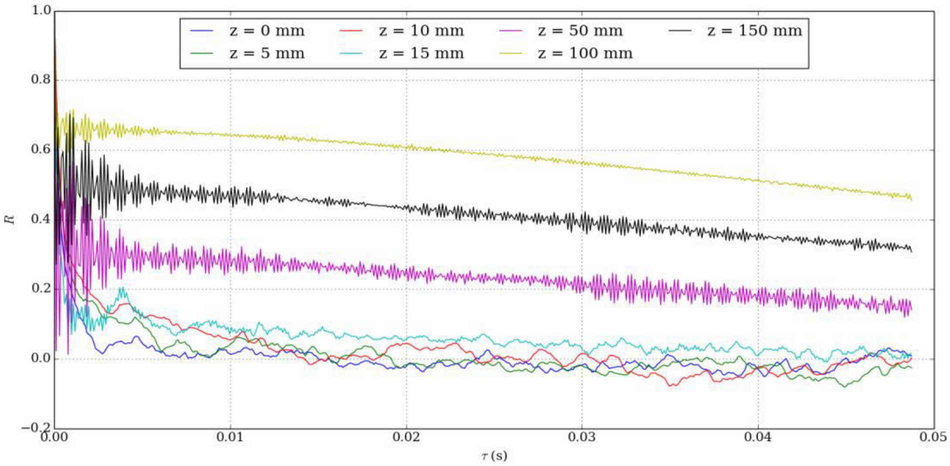


Figure 8. Auto-correlation coefficient as a function of τ for the measurement velocities taken at distances $(\mathrm{z}-\mathrm{z}_0)$ between 0 and 100 mm for run 1.

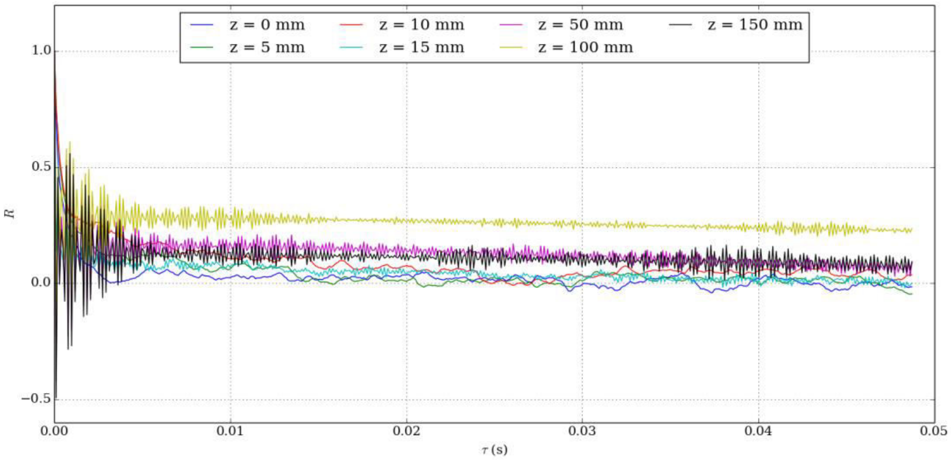


Figure 9. Auto-correlation coefficient as a function of τ for the measurement velocities taken at distances $(z - z_0)$ between 0 and 100 mm for run 2.

4. Conclusions

The present STSM was a valuable experience for my research activity in boundary layer flows and, more broadly, in wind engineering. It provided me with the opportunity of improving my knowledge about different measurement techniques, which I believe will be very useful for the development of an integral boundary layer calculation model that can be applied to wind turbine blades. Furthermore, during the STSM I established several important contacts in this field of expertise. I would like to express my gratitude to Prof. Jeoren van Beeck for being my host for this mission and also to Dr. Nicolas van Wyer for assisting me during my activities at the VKI. My appreciation extends to the TU1304 WINERCOST Action for providing me with this STSM opportunity.