LAB EXERCISE : WIND TUNNEL SIMULATION OF A NEUTRAL ATMOSPHERIC BOUNDARY LAYER

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For a fluid flowing adjacent to a solid surface, there is a "layer" of fluid next to the surface where, for a high enough Re number, the flow is nearly always turbulent, with the turbulence generated by the action of shear and/or buoyant convection. This layer adjacent to the surface, in which vertical mixing is especially important, is termed the boundary layer. In fact, turbulent boundary layers involving shear or buoyancy effects are a key feature of all bounded fluid flows at high Reynolds number.

In the case of the air in the atmosphere, the boundary layer has an important influence on the behavior of the atmosphere as a whole, and activities involving the representation of the atmosphere such as climate modeling and numerical weather prediction cannot succeed without the boundary layer being represented in some detail. The boundary layer is of particular significance to human activities and natural processes occurring on the Earth's surface. Here, prediction and understanding of the local environment requires an understanding of the boundary layer. In particular, the boundary layer is important for predicting a range of parameters such as the near surface wind and turbulence; daily maximum and minimum temperatures; visibility and fog; the dispersion of pollutants and other material.

In this lab exercise, passive devices will be used to simulate a neutral boundary layer in a wind tunnel. Measurements will be provided for cases with and without these devices and the task at hand will be to process the measurements and verify that the logarithmic law of the wall reproduces the measured velocity distribution [1]:

$$u(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_o}\right) \tag{1}$$

where (z) is the vertical distance from the wall, (u_*) is the friction velocity, (z_o) is the roughness length and (κ) is the von Karman constant (κ=0.4187).

Measurements in the empty wind tunnel have been performed at a sampling rate of 10 kHz using constant temperature hot wire anemometry (TSI IFA 300) and an automated traversing mechanism. This data is provided as a reference. During the course of the exercise, measurements will be performed with the passive boundary layer enhancement spires and roughness elements in place (Figure 1).

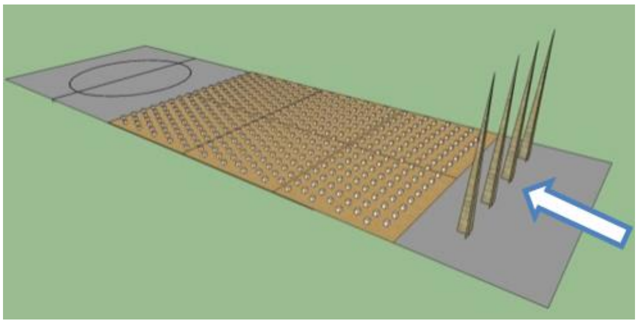

FIGURE 1 Roughness elements and boundary layer enhancement devices

Results of the measurements at each point are in the form of instantaneous velocity time series (u(z,t)). Since the sampling frequency is high (f=10kHz), the time series include information on turbulence fluctuation velocities and can be used to derive information about turbulence time and length scales, based on the autocorrelation function.

The autocorrelation of a single variable u(t) at two times t_1 and t_2 is defined as

$$\mathrm{R}(t_1, t_2) = \overline{u(t_1)u(t_2)} \tag{2}$$

where $\bar{\square}$ denotes a time average :

$$\bar{x} \equiv \frac{1}{T}\int_0^T x(t)dt \tag{3}$$

In the case of a statistically stationary process, the autocorrelation depends on the difference $\tau = t_2 - t_1$ but not on the actual instants of time, t_1 and t_2. So, we could also define the autocorrelation as

$$\mathrm{R}(\tau) = \overline{u(t)u(t+\tau)} \tag{3}$$

or, the normalized autocorrelation function as

$$\mathrm{r}(\tau) = \frac{\overline{u(t)u(t+\tau)}}{\overline{u^2}} \tag{4}$$

For time lag $\tau = 0$, the autocorrelation is r(τ)=1. It decays with increasing time lag. For the limit of very large time lags the autocorrelation function of velocity turbulent fluctuations converges to zero, since turbulence is a random phenomenon. This allows for the definition of an integral time scale Tu_x of turbulence:

$$Tu_x = \int_0^\infty r(\tau)\, d\tau \tag{5}$$

Based on the assumption that a flow disturbance travels with the mean velocity ($\bar{u}$), and using Taylor's "frozen turbulence hypothesis", the integral length scales can be determined from:

$$\mathrm{Lu}_x = Tu_x \cdot \bar{u} \tag{6}$$

Tasks :

a) Make two graphs comparing the vertical profiles of mean velocity and those of turbulence intensity for the measurements in the empty wind tunnel and those obtained with the boundary layer enhancement devices
b) Make a Table with
    a. the values of z_o, u_* for the velocity profile in the empty wind tunnel and the velocity profile obtained with the boundary layer enhancement devices
    b. your estimate of the boundary layer height in the two cases
c) Calculate the turbulence length scales for the measurements in the empty wind tunnel and those obtained with the boundary layer enhancement devices at 3 positions: close to the ground, far from the ground and something in between.
d) Compare and comment on the characteristics of the two measured boundary layers.

References

[1] P. J. Mason, D. J. Thomson (2015) "BOUNDARY LAYER (ATMOSPHERIC) AND AIR POLLUTION | Overview", Encyclopedia of Atmospheric Sciences (Second Edition), 220-226