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TURBULENCE SCALES SIMULATIONS IN ATMOSPHERIC BOUNDARY LAYER WIND TUNNELS

BY

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Abstract. The simulation of the air flow over models in atmospheric boundary layer tunnels is a research domain based on advanced scientific technologies imposed by the necessity of studying the turbulent fluid movements in the proximity of the Earth’s surface. The experiment presented herein is developed in the wind tunnel from the Laboratory of Structural Aerodynamics of the Faculty of Civil Engineering and Building Services in Iassy. Measurements necessary for the determination of the turbulence scales of the wind action in urban environment were conducted. The data obtained were processed and analyzed and interpreted with specific software. The results are used for a synthesis regarding the scales of turbulence of the model of flow and the actual accuracy of measurements. The paper presents some of the important elements of this synthesis.

Key words: wind tunnels, atmospheric boundary layer.

1. Introduction

Due to the extension of the world wide programs of testing on models in atmospheric boundary layer tunnels, the modern codes for designing to wind actions, among them Eurocode 1 being a good example, are able to asses in a highly accurate degree the various effects of these actions. Some different models of turbulent flow are now used in numerical simulations, but during the research studies these simulation are validated by tunnel testing measurements of the parameters integrated in the computation. High standards of the quality of the flow inside the tunnel are of capital importance in the pursuit of reliable data obtained via measurements. The simulation of a good flow is mainly characterized by spatial uniformity of velocity and pressure along with temperature steadiness and for this reason some quality indicators of the flow are essential/1/. Insuring the flow quality in an existing wind tunnel not only asses the impact of the design modifications but also sets optimum conditions for further numerical simulations of the air flow in atmospheric boundary layer tunnels. The spatial symmetry of the blow is put in evidence by velocity vectors

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parallel to the testing section line having a horizontal direction and constant magnitude and in the same time, lateral uniformity of the flow in the empty test section [2]. Reliable simulations in atmospheric boundary layer tunnels must respect laws consisting in a correct growth of the boundary layer and a good matching scale of modeling. Mean velocity profiles, turbulence profiles, power spectra and finally integral scales of turbulence give essential information on the fidelity of the model.

2. Experimental Conditions

2.1.Laboratory tests

The simulation of the growth of the boundary layer depends on the geometric characteristics of the wind tunnel, and many discussions were dedicated to when and how part-depth or full-depth simulations are sufficiently accurate to model the wind action for different terrain roughness levels and for different geometric and time scales [3]. It is then most important that during the modeling stage a way of estimating the scale factors independently of the simulated layer thickness must be found. Checking the fluctuating parameters of the simulation to be linearly scaled to the atmospheric data is a valid technique for both part-depth and full-depth simulations.

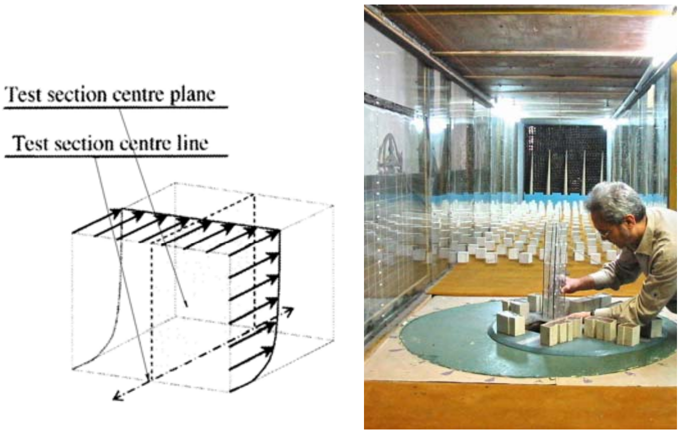

Fig. 1. – Flow inside an ABL tunnel: a- symmetry of the flow in the cross section of the tunnel/1/, /2/; b- inside view along the wind tunnel with a model of the building immersed in the boundary layer

In the Laboratory of Building Aerodynamics from the Faculty of Construction and Building Services a great number of tests had been run during the last decade, all of them in the wind tunnel SECO 2, an open circuit tunnel with a testing section of 1.4x1.4 m and 10 m length, able to reproduce the wind action in atmospheric boundary layer conditions.

2.2.Basics of Theoretical Analysis

The turbulence of the air flow is described by instantaneous wind speed as a function of space and time; three-dimensional expression of this function discarding the mean and the fluctuating component will look like

$$\begin{aligned} u(x,y,z,t) &= U(x,y,z)+u'(x,y,z) \\ v(x,y,z,t) &= V(x,y,z)+v'(x,y,z) \\ w(x,y,z,t) &= W(x,y,z)+w'(x,y,z) \end{aligned} \tag{1}$$

where the mean values of the projections *U*, *V*, *W* are the result of averaging on a certain interval of time the wind speed, respectively the fluctuating components (velocities) which describe the turbulence of the speed.

The turbulence scales of the instantaneous wind speed are the measure of the representative dimensions of vortices induced by the turbulence inside the mean stream of the flow. Their importance lies in the fact that they describe most clearly the dimensions of the turbulent eddies which “wrap” the obstacle-in our case the building at a certain time.

The determination of the turbulence spatial scales starts with the computation of the correlation functions of the fluctuating components, so they may be longitudinal, transversal and vertical. In general the characteristics of the flow are well defined if the inter correlation functions are determined for the mean stream wise components longitudinally and transversally. The correlation in time is determined with the known relationships

$$\begin{aligned} \rho_{u_i u_j}(\tau) &= \frac{R_{u_i u_j}(\tau)}{\sqrt{\overline{\left(u'\right)^2(t)}}\cdot\sqrt{\overline{\left(u'\right)^2(t+\tau)}}} \\ R_{u_i u_j}(\tau) &= u_i(t)\cdot u_j(t+\tau) = lim_{T\to\infty}\frac{1}{T}\int_0^T u_i(t)\cdot u_j(t+\tau)\,dt \end{aligned} \tag{2}$$

where the second expression represents the covariance function of the process *u(t)* determined by measuring it in two different points in space at the difference of time τ. According to Taylor’s hypotheses [7], inter-correlation between any of the fluctuating parts discarding wind instantaneous speed measured in two points and separated by the distance Δx in the direction of the flow is equal with the auto-covariance determined for the period $\tau = \Delta x \big/ \bar{U}_z$, that is in the plane situated at the same altitude from the ground level, the following relationship defining this:

$$\overline{u_i(x)\cdot u_j(x+\Delta x)} = u_i(t)\cdot u_i(t+\tau)\text{ i.e. } \bar{U}_z << u' \tag{3}$$

If the hypotheses of homogeneity and isotropy of the flow are taken into account, then the inter correlation functions as described above are independent in space and in the orientation of axes (directions). The inter-correlation functions give information concerning the dimensions of the wind gust in the direction of wind action.

The existence of mean values of the wind speed inside the turbulent flow has the following explanations: in a certain point, *i*, the turbulence has a certain periodicity in time and after a certain period the phenomenon repeats itself in space.

These two conclusions are those on which we rely on for the determination of the turbulence scales in time and space. The turbulence scales define more or less a frequency of the gusts of wind dynamic action.

The integral length scales correspond to the spatial nature of the wind action, longitudinal, lateral and vertical scales

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\begin{aligned}
&L_x = \int_0^\infty \rho_{u_i' u_i'}(\Delta x,0,0)\,d(\Delta x), \\
(4)\qquad & \\
&L_y = \int_0^\infty \rho_{u_i' u_i'}(0,\Delta y,0)\,d(\Delta y);\; L_z = \int_0^\infty \rho_{u_i' u_i'}(0,0,\Delta z)\,d(\Delta z).
\end{aligned}
$$

The most important of these three is the longitudinal scale, the other two being practically its derivatives and as the integral time scale of the turbulence may be analytically defined with the following formulae:

$$\Lambda_T = \int_0^\infty \rho_{u_i' u_i'}(\tau)d\tau. \tag{5}$$

According to Taylor's hypothesis previously announced the longitudinal scale of turbulence may be expressed with the help of the integral time scale and the mean wind speed value in the stream wise direction, namely:

$$L_x = \bar{U} \cdot \Lambda_T \tag{6}$$

Studies developed for the determination of the turbulence scale both at natural scale (these ones not so numerous) and in laboratory by modeling the wind flow in the atmospheric layer, produced some so called empirical relationships, one of the best acknowledged being Davenport's one:

$$\Lambda_T = 0.084 \cdot \frac{L}{\bar{V}_{10}},\ [\mathrm{s}], \tag{7}$$

where: L is the longitudinal scale of the in-wind speed, according to Davenport equal with 120 m and to Harris equal with 180 m; $\bar{U}_{10}$ is the mean wind speed. The integral longitudinal length scale is determined with the relationship:

$$L_x = 151\frac{\bar{U}(z)}{\bar{U}_{10}},\ [\mathrm{m}], \tag{8}$$

Between this scale and the lateral and vertical scales of the in-wind component of the speed, respectively there the following approximate relationships were set:

$$L_u^y \approx 0.3L_u^x; L_u^z \approx 0.5L_u^x \tag{9}$$

Until now the influence of the terrain roughness on the length scales is proved only for the longitudinal scale, the other two seem to increase with the height inside the boundary layer.

This paper focuses on the scale of turbulence or the length scales, because more than other data, they may provide indirect information concerning the real scale of the flow in the tunnel, regardless of the simulated depth of the boundary layer.

2.3.Data Acquisition

The instantaneous speeds in two points simultaneously was made both longitudinally and transversally in order to use the data for the analysis (sampling rate of the wind speed data is 0,02 sec). Computer aided programs have been developed under MATLAB and graphs have been plotted for mean speed profile and turbulence intensity. A constant power law coefficient of α = 0.3…0.4 and a maximum turbulence intensity 20…22 % were obtained, matching the model of typical urban exposure.

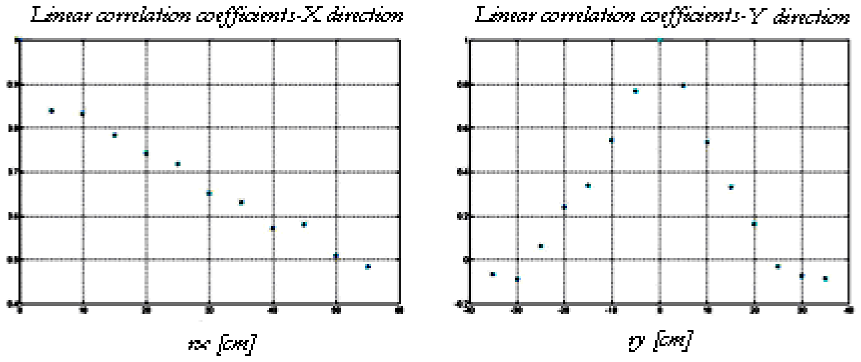
The data obtained from the measurements with two probes were processed for the determination of the real scale of the flow in the tunnel, regardless of the simulated depth of the boundary layer. Inter-correlations and auto-correlations were determined in a horizontal plane placed at 15 cm above the floor of the tunnel. One set of graphs was plotted for the longitudinal direction starting from the test area and finishing at 55 cm along the tunnel. The other set was plotted for the transversal direction, both sides the center of the test area covering a 70 cm span.

3. Results and Discussions

After the determination of Λ_T from autocorrelations at 15 cm height above the floor level, a very constant value of 28…29x10^{-3} s was obtained from both longitudinal and transversal measurements. In conclusion:

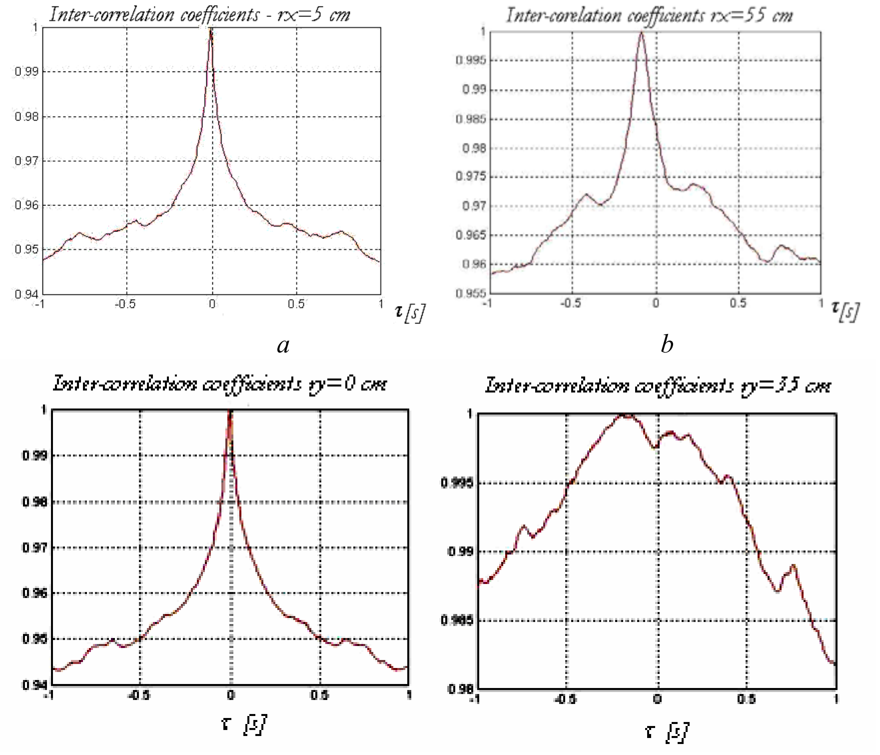
a) comparing the length scale in nature (rel. (5),…,(7)) with the scale obtained in tunnel a 1:200 modeling scale was considered to match;

b) from the data extracted at 15 cm the length scale of the vortices was determined to be 5 cm, confirmed by the perfect correlation in the graphs from Figs. 3. (a), (b);



a *b*

Fig. 2. – Inter-correlation of instantaneous wind speed values in laboratory at 15 cm above the level: *a* – longitudinally; *b* – transversally.



a *b*

c *d*

Fig. 3. – Inter-correlation functions described by the relevant interval of time: *a, b* – in the longitudinal direction; *c, d* – in the transversal direction.

c) inter-correlations coefficients stream-wise show a delay of time of about 0,15 s sequentially observed from 5 cm to 55 cm, which would produce an integral length scale of 0,33 m; this result compared with the length scales observed at 25 m height, for the urban terrain exposure presented in literature, matches again with a modeling scale of 1:200.

d) transversally it was observed that the time of delay is about 0.05 s producing a lateral length scale of 0,11 m which is in accordance with the relationship (8).

4. Conclusions

Controlling the flow characteristics of atmospheric boundary layer during the simulations in wind tunnels is essential for the quality of the acquisition of data and hence, for the reliability of the results. The experiments presented in this paper along with the refinement of the measurements technique through experimental research show coherent results towards insuring and controlling the accuracy of the model of wind speeds inside the tunnel. A scale of about 1:200 of time and dimensions is found to be rather well defined in the test area suggesting that a scale under this value for larger models of buildings is not advisable.

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VALIDAREA MASURATORILOR DE VITEZE OBTINUTE PRIN MODELAREA ACTIUNII VANTULUI IN TUNEL AERODINAMIC CU STRAT LIMITA ATMOSFERIC

(Rezumat)

Lucrarea prezintă aspecte ale unui studiu în tunel aerodinamic cu strat limită atmosferic destinate obţinerii datelor cât mai complete privind câmpul de viteze instantanee al curgerii aerului peste o expunere de tip urban.

In paralel cu analiza mai amănunţită a simetriei curgerii în tunel SECO 2 din cadrul Laboratorului de Aerodinamică a Construcţiilor de la Facultatea de Construcţii şi Instalaţii Iaşi, studiul s-a concentrat pe determinarea scărilor de lungime şi temporale ale mişcării turbionare spaţiale a vântului. Analizele şi sinteza rezultatelor sunt trepte ce condiţionează determinarea unor scări corecte de modelare a interacţiunii vânt-anturaj construit cât şi a unor valori realiste ale coeficienţilor aerodinamici de presiune pe suprafaţa machetelor unor diverse construcţii.