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Modeling of the mean wind loads on structures

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Abstract. Correct determination and consideration of wind loads are primary importance in the design of unique architectural objects such as high-rise buildings, sport arenas, airports, large-span bridges. One of the most accurate ways to determine wind loads is to carry out model tests in specialized wind tunnels. Nowadays, during wind tests much attention is paid to the correct modeling of natural wind properties. In present work comparison of the most popular approaches for turbulence length scale determination is presented. One of the purposes of this study is to compare the main aerodynamic characteristics of the simple cube model obtained in uniform flow and during ABL modeling. This paper provides a brief overview of the method for ABL modelling in test section of the Landscape wind tunnel and contains experimental data on mean flow velocity distribution, turbulence intensity, dimensionless spectral density and integral scale of turbulence. The comparison of experimental data obtained for cube model in various wind tunnels revealed the influence of ABL on geometry and intensity of separation zones at the cube sides, and, as consequence, the influence of the same on integral and local aerodynamic characteristics of the object. On the basis of the obtained experimental data, it was concluded that the intensity of the separation zones has significant influence on the total aerodynamic loads, which is usually not taken into account in the framework of applied calculations. The difference in numerical values of aerodynamic characteristics was up to 30 %.

1. Introduction

According to Russian and foreign regulatory documents on the design of structures [1], wind load is to be determined with allowance for the specifics of atmospheric boundary layer (ABL). This requirement has to do with significant influence of ABL on aerodynamic characteristics of high-rise buildings and structures. Full-scale characteristics of ABL for each type of locality are known and specified in numerous design regulatory documents and meteorological reference guides and handbooks.

In the 50s of the last century, researchers began to pay attention to the study and modeling of ABL in wind tunnels, due to the fact that the designed at that time buildings began to show increased sensitivity to the wind's effects, which required to take into account the wind loads acting on the structures more accurately [2]. For a detailed account of wind loads, it was necessary to change experimental approach of studies of models of structures in a uniform flow and proceed to conducting experimental studies in wind tunnels that allow the characteristics of the atmospheric boundary layer to be reproduced. Despite this, research in wind tunnels, creating a uniform air flow, is still very popular in modern practice due to both the high prevalence of such experimental stands, and their great development. That's why it is important to understand how the experimental data obtained in laboratories differs from the information about real objects.

The task to determine the simulation criteria in wind tunnel tests of buildings and structures is not easy question. For example, it is impossible to perform tests with Reynolds number equals to the nature one. Besides, during wind tunnel tests it is important not only to simulate air-structure interactions but also atmospheric boundary layer properties. One of the main criteria for modeling ABL properties in this case is the

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Jensen number [3], which allows to estimate the necessary length of the test section for the natural growth of the boundary layer with the necessary characteristics. In accordance with this criterion, the minimum length of the test section can be estimated as 15–20 meters. In special-purpose wind tunnels with shorter test section, ABL modeling is based not only on natural boundary layer build-up along the length of test section wherein the additional large-scale obstacles and discrete roughness elements. The correctness of modeled ABL characteristics (mean wind velocity profile, vertical variation in turbulence intensity, energy characteristics of the flow, integral scale of turbulence) is to be ensured by proper selection of test section geometry, the geometry and number of obstacles. A seemingly simple method of ABL representation offers significant diversity in practical implementation [4, 5].

Determination of wind effects on modern buildings during wind tunnel tests can be difficult due to the complex geometry of the structure or not trivial properties of surrounding territory, for example in high-density cities. In case of low-rise buildings there are some challenges that are less evident with large buildings [8]. These challenges are connected with fundamental questions of simulation of ABL properties and can be formulated in simplify form as: what part of the turbulent spectrum should be simulated? High-frequency part corresponds to turbulence intensity changing with height, while low-frequency part corresponds to integral length scale changing with height. It should be noted that it is much harder to simulate changing of turbulence length scale than turbulence intensity. For the other hand changing of turbulence length scale with height in test section should correlate with well-known dependencies. Simplification of models geometry can be effective method for investigation of fundamental air-structure interaction. Besides information about pressure distribution on sides of the cube for example is commonly used in a lot of practical applications.

Modeling of interaction between air flow and bluff body is one of the basic tasks of wind tunnel tests. The main sources of information about properties of model of cube are [6–12]. In [9] comparison of pressure distributions on the sides of cube for uniform flow and ABL flow is presented. This data set is commonly used for validation of computational model and verification of experimental data obtained in wind tunnels. However information about full aerodynamic loads in this work is absent. In [10] the major attempt of results comparison of different laboratories is described. It should be noted that conditions of wind tests were not be the same but still data about pressure distribution in characteristic points on the surfaces of the model is in a good agreement. Works [8, 11] must be mentioned in this list due to performed experiments with natural-sized model – Silsoe cube. Nowadays data about pressure distribution on the surfaces of Silsoe cube is very popular due to the fact that wind tests using full-scale model provide possibilities of more accurate comparison. On the other hand, the number of papers where data about pressure distribution in high range of cube orientation is presented is limited. Such data were published in [12] but the height of test section in wind tunnel was not large enough to perform correct modeling.

The primary objectives of this study are as follows:

1. To compare the main aerodynamic characteristics (coefficients C_x, C_y, C_p) of cube model obtained in uniform flow and during ABL modeling,

2. To verify the main ABL parameters modeled in Landscape wind tunnel of the Krylov State Research Centre (Figure 1).

2. Methods

Experimental studies were carried out in two wind tunnels of the Krylov State Research Centre: large wind tunnel generating uniform stationary velocity profile (case *I* in Figure 2a), and Landscape wind tunnel (LWT) making it possible to simulate vertical distribution of the main ABL parameters (case *II* in Figure 2a)

Large wind tunnel of the Krylov Centre is a subsonic closed-circuit tunnel with open test section (length 5 m, width 4 m, height 2.5 m). Maximum flow velocity in test section is up to 100 m/s.

Landscape wind tunnel of the Krylov Centre is a two-level subsonic wind tunnel wherein the return flow channel is fitted with 7 impellers generating air flow at speeds up to 15 m/s. Test section (length 18 m, width 11 m, height 2.3 m) constitutes the first level in its entirety. Large-scale obstacles and different-scale discrete roughness elements are used to model ABL characteristics (as described in [5]).

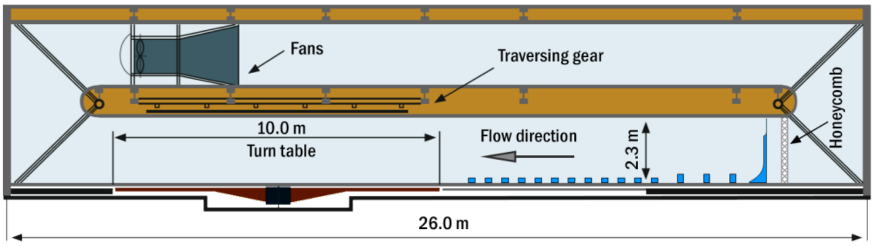


Figure 1. Scheme of the Landscape wind tunnel.

The main ABL parameters were determined in LWT using single-wire anemometer, velocity values were registered at sampling rate of 5 kHz, and measurement time at each point was equal to 900 seconds. This set of parameters made it possible not only to describe average processes, but also to obtain data on velocity fluctuations at measurement points with high level of accuracy.

In order to compare aerodynamic parameters of the cube obtained for different types of wind flow, a 400 mm cube model (Silsoe cube model [8]) was manufactured. Total aerodynamic loads on the cube were determined using load cell mounted at the base of the cube. Cell's axes system is shown in Figure 2b. For the purpose of pressure measurement, 87 perforations were bored in the cube as shown in Figure 2c (corresponds to [11]). The perforations were connected to pressure scanner by means of tube transfer system. In the course of experiment, pressure was measured during 30 seconds at 100 Hz within the range of angles from 0° to 180° where zero angle corresponds to normal flow incident on the face side of the cube. Thirty perforations were placed on one of the quadrant of the top side that made it possible to obtain data on pressure field at different angles of incident flow. The length of the tubes was chosen according to criteria of influence minimization on experimental data. Considering the dimensions of test sections of wind tunnels and cube size under study, flow chocking did not exceed 1 %. Reynolds number, calculated using side height and flow velocity at cube height, for both cases was equal to $Re = 2.1\times10^5$.

3. Results and Discussion

3.1. Mean flow characteristics

The analysis of experimental data obtained for the purpose of modeling of ABL characteristics in LWT test section was performed using the following approach. Mean velocity was determined by the following ratio

$$\overline{U}=\frac{1}{n}\sum_i u_i, \tag{1}$$

where n is number of measured points;

u_i is instantaneous velocity at i-th point of time. Mean square deviation and turbulence level were calculated using the formulae respectively.

$$\sigma_u=\sqrt{\overline{\left(u_i-\overline{U}\right)^2}}, \tag{2}$$

$$It=\frac{\sigma_U}{\overline{U}}\cdot 100. \tag{3}$$

Measurement algorithm is described in detail in the following study [14]. Vertical variation in dimensionless mean velocity profile is shown in Figure 3,a.

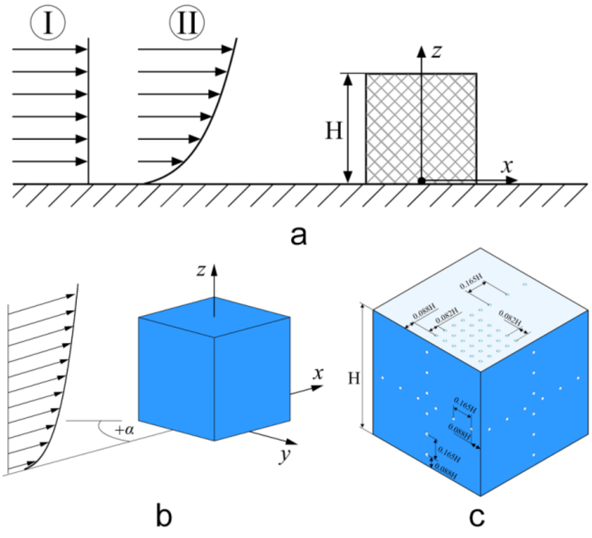


Figure 2. Cube model a) flow boundary conditions; b) model-linked coordinate system; c) pressure measurement points at cube surface.

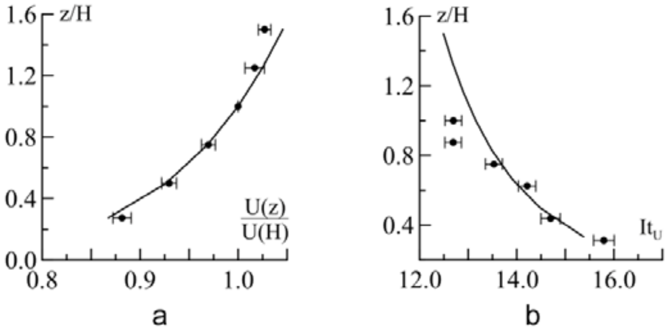


Figure 3. Changing of the main properties of the flow with test section height a) mean velocity; b) turbulence intensity.

The cube height was chosen as a reference height $z_{ref} = H$ = 0.4 m, and the velocity at that height was chosen as a reference velocity U_{ref}. Exponential law for vertical variation in mean velocity specific for "0" type of locality pursuant to [1] is also plotted in the figure. Vertical variation in turbulence intensity as well as respective ratio from [1] are shown in Figure 3, b. It can be concluded that selected configuration of large-scale obstacles and discrete roughness makes it possible to reproduce main characteristics of full-scale wind for specified type of locality with sufficient accuracy.

3.2. Turbulence length scales in LWT

The questions of scale open up the whole area of physical simulation [3]. The basis of theories often includes considerations about dimensionless criteria: Strouhal, Reynolds, Froude, Jensen etc. In ABL wind tunnels not only dimensionless criteria is important but also mean and actual properties of the modeled flow, such as turbulence length scale.

The description of algorithms to determine turbulence scales is available in numerous well-known studies, e.g. [13, 14]. In present study, the scales were determined using autocorrelation coefficient (4) and Karman spectrum (5). In this case, it was assumed that Taylor hypothesis is true for the entire height of wind tunnel test section.

$$L_x^U = \bar{U} \cdot \int_0^{\infty} \frac{\overline{u_i'(t)u_i'(t+\tau)}}{\overline{u_i'^2}} d\tau, \tag{4}$$

$$\bar{S} = \frac{4 \cdot \bar{f}}{\left[1 + 70.7 \cdot \bar{f}^{\,2}\right]^{5/6}}, \tag{5}$$

where $\bar{S} = \dfrac{f \cdot S}{\sigma^2}$ is dimensionless spectral density,

$\bar{f} = \dfrac{f \cdot L_x^U}{\bar{U}}$ is dimensionless frequency. Formula (5) can only be used on the assumption that all spectral densities of signals at different heights coincide in dimensionless form. Dimensionless spectral densities at different heights within the LWT test section are shown in Figure 4. In can be seen that they match well both in high-frequency band ("-5/3" law) and low-frequency band (position of maximum).

Turbulence scales determined using the abovementioned methods are given in Figure 5. As it is shown in the figure, these methods give similar results, so both of them can be used to obtain reliable data on flow parameters.

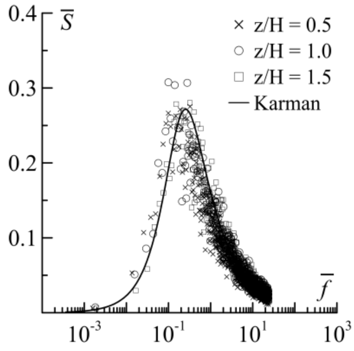


Figure 4. Dimensionless spectral density at different heights.

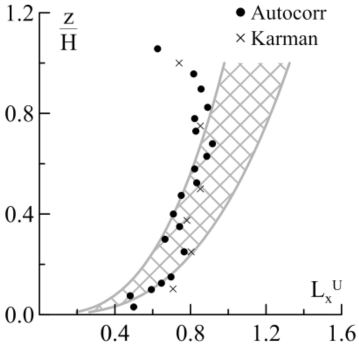


Figure 5. Changing of L_x^U and its acceptable 15 % variation range.

Vertical variation in longitudinal integral turbulence scale in full-scale conditions can be described using the formula proposed in [15]

$$L_x^U = 25 \cdot (z-d)^{0.35} z_0^{-0.063}, \tag{6}$$

where d is zero place displacement in law-of-the-wall velocity,

z_0 is roughness length parameter in law-of-the-wall. Full description of all parameters can be easily found in [14].

The procedure for scale determination using formula (6) is suggested in [13]. Vertical variation in longitudinal integral turbulence scale in LWT test section as well as the range to cover the determined scales in accordance with formula (6) and requirements set forth in [15], are indicated in Figure 5. The results given therein imply the possibility to model longitudinal integral turbulence scale in LWT test section.

As outlined above and previously discussed in numerous well-known studies, e.g. [11], in order to determine mean wind loads on buildings and structures, it is sufficient to model mean velocity profile, turbulence intensity and high-frequency part of energy spectrum since these are parameters which are the most influential on obtained results. In case of study of aeroelastic oscillations simulations of turbulence length scales and Reynolds stresses have to be included in addition to parameters noted above.

3.3. Aerodynamic forces

High frequency load cells were used to record the values of aerodynamic forces and moments. The values measured in model-fixed coordinate system were non-dimensionalized using ratio (7). If it is necessary to change from object-fixed coordinate system to flow-fixed coordinate system ($C^{\text{flow}}{}_x$; $C^{\text{flow}}{}_y$), simple rotation matrix can be used.

$$C_{x,\,y} = \frac{F_{x,\,y}}{\rho \frac{V^2}{2} S}, \qquad (7)$$

where $F_{x,\,y}$ is aerodynamic force, acting in respective direction, N;

ρ is air density, in experimental conditions it was equal to 1.225 kg/m^3;

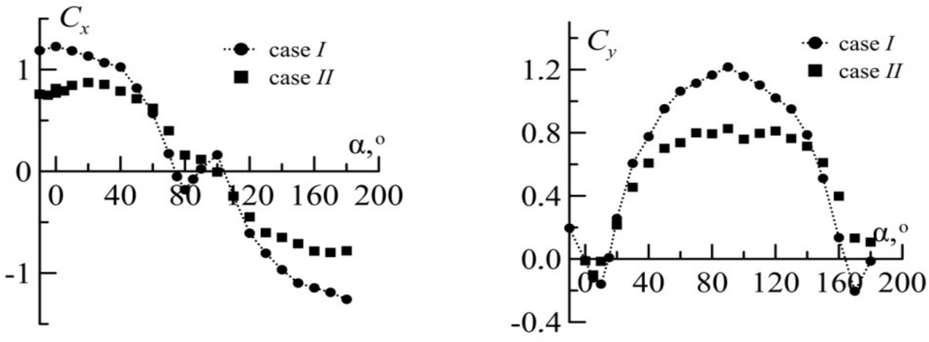
S is cube side area, m^2;

V is incident flow velocity, m/s.

The experiment was performed for those incident flow velocities wherein the aerodynamic characteristics do not vary with Re number. Aerodynamic coefficients C_x and C_y at two different flow velocities within the angular range from 0° to 180° are shown in Figure 6. It can be seen that C_y distribution is symmetrical about the angle of 90°, maximum values of coefficients coincide and occur at angles spaced 90° apart, that fully corresponds to the airflow physics. There was also discovered a non-monotonic variation in C_x coefficient in the vicinity of angle of 80° as well as similar non monotonic variation in C_y distribution at 10° and 170°, associated with separation zones occurring at the cube sides [16]. It is well known that for square prism flow patterns can be classified into two types, perfect separation type where angles of attack is less than ~14° and reattachment type where angle of attack is larger than ~14°. Aerodynamic coefficients change drastically at this point, i.e. mean drag coefficient becomes minimum and magnitude of the lift coefficient reaches maximum [17, 18].

Dependencies for aerodynamic coefficients, obtained in both cases are qualitatively similar while quantitative difference between them can be up to 30 % as it has already been shown in other studies [19]. In some cases, such wind load overstating is acceptable; however, in a number of designs, this kind of “margin” may result in unjustified strength/mass/material consumption overrating.

It should be noted that transition from aerodynamic coefficients to dimensional aerodynamic force is to be made using dependency (7) in strict compliance with selected area S and height wherein the velocity V is determined, both in full-scale and experimental conditions.



a b

Figure 6. Distribution of aerodynamic coefficients
a) coefficient C_x; b) coefficient C_y.

3.4. Mean wind loads

The main outcome of aerodynamic tests at the design stage is determination of mean, fluctuating and peak aerodynamic wind loads (following by [1]), acting on the facades of building and structures. In accordance with regulatory documents (e.g. [1]), wind loads can be determined using aerodynamic coefficients represented by dimensionless pressure coefficients.

For this purpose, during the experimental studies in LWT, instantaneous pressure values are measured at the points on the surface of object model. Values of sampling rate and measurement time are selected for each object individually depending on density of surrounding buildings (if any), the geometry of the object itself and other factors. Typical values of sampling rate exceed 100 Hz, minimum measurement time is 30 seconds.

Measurement data on instantaneous pressure at the points on the surface of object model at different angles of incident airflow make it possible to use mathematical tools of statistics theory in order to determine the required parameters. However, this paper deals only with mean pressure distribution on the surface of the cube under study.

In general engineering problems pressure coefficient is understood as a sum of coefficients for external and internal pressure acting on the surface element. In case of experimental studies in wind tunnel, internal pressure is usually not determined due to the difficulties associated therewith, so from this point on C_p will be used as external pressure coefficient determined as follows

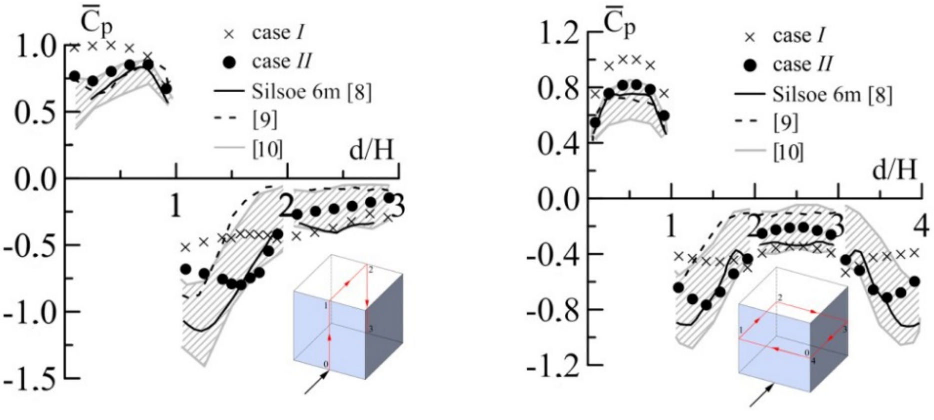
$$\overline{C}_p = \frac{\frac{1}{N}\sum_j p_j}{q}, \qquad (8)$$

where N is amount of data, obtained within measurement time$

p_j is pressure measured at each point of time, Pa;

q is mean dynamic pressure at the cube height measured at 3H distance from its lateral side, Pa. All results are presented against dimensionless coordinate d/H, where d is distance from the point with “0” index as shown in explanatory figures and in Figure 2c.

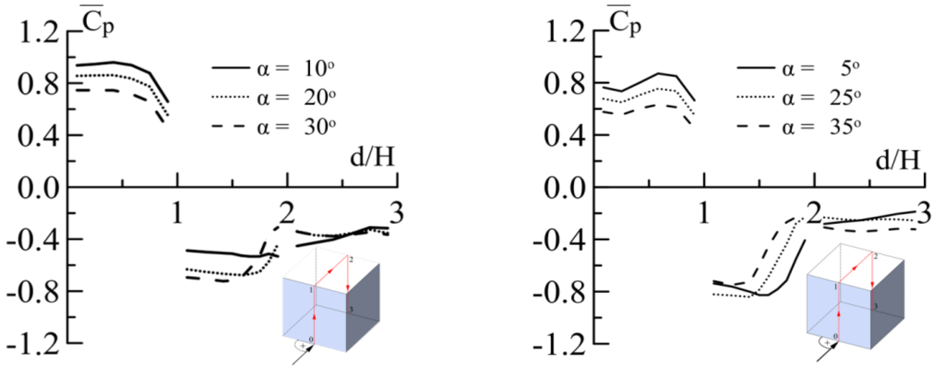
Mean pressure coefficient distribution along symmetry lines at zero angle α obtained in both cases is shown in Figure 7. Figure also contains data presented in well-known studies [8–10]. As it can be seen, pressure coefficient along the front side for uniform flow remains almost constant. Pressure coefficient C_p = –0.4 at the top side for this case remains almost constant as well. Influence of the top side of the cube on pressure distribution in both cases starts at distance 0.75·H from floor – pressure coefficient become smaller than 1 in uniform flow (Figure 7,a). In case of nonuniform incident flow profile, pressure coefficient distribution along the face side is not constant and correlates well with experimental data obtained in other studies and with full-scale measurement results, including local minimum on the face side at distance 0.25·H from floor. In addition it should be noted that there is significant difference in pressure distribution between two cases along the top, left and right sides, associated with influence of gradient flow on geometry and intensity of separation zone. According to Figure 7.b there is a symmetry in pressure coefficient distribution along intervals 1→2 and 3→4 and even for back side of the cube in both cases.



a b

Figure 7. Pressure coefficient distribution along symmetry lines a) vertical; b) horizontal.

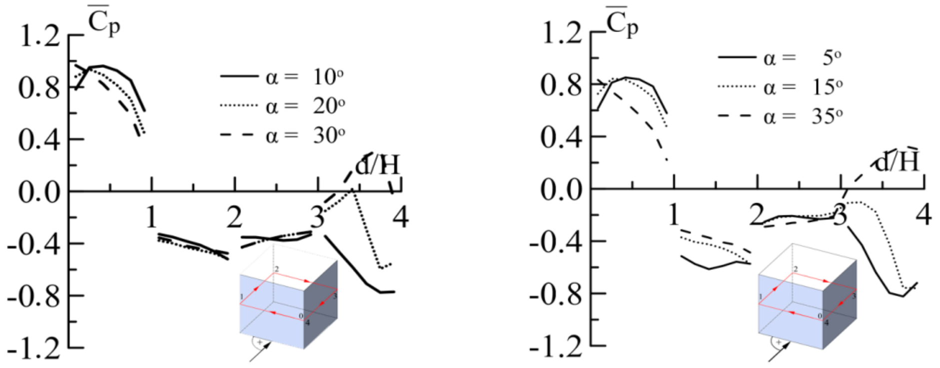
Mean pressure coefficient distribution along symmetry lines at different angles α, obtained in both cases, is shown at Figures 8 and 9. There is no big difference in pressure distribution between all presented angles on the back side in uniform flow (Figure 8,a). Size of the separation zone on the top side in case *I* is much smaller than in case *II*. It should be taken into account, for example during snow drift simulation where sizes of separation zones play significant role.



a

b

Figure 8. Pressure coefficient distribution along vertical symmetry line for different angles a) case *I*; b) case *II*.



a

b

Figure 9. Pressure coefficient distribution along horizontal symmetry line for different angles a) case *I*; b) case *II*.

4. Conclusion

Nowadays, correct determination and consideration of wind loads are of primary importance in the design of unique architectural objects such as high-rise buildings, sport arenas, airports, large-span bridges. Moreover, correct modelling of ABL parameters in test section of wind tunnel is quite challenging, since it requires simultaneous representation of mean velocity profile of full-scale wind, vertical variation in its turbulence intensity, energy characteristics and turbulence integral scale.

This paper contains the results for resolving the following tasks:

1. To compare the main aerodynamic characteristics (coefficients C_x, C_y, C_p) of cube model obtained in uniform flow and during ABL modeling,

2. To verify the main ABL parameters modelled in Landscape wind tunnel of the Krylov State Research Centre.

Large-scale obstacles and discrete roughness were used to create ABL in LWT test section; this made it possible to reproduce mean velocity profile, varying in accordance with exponential law, and turbulence intensity of longitudinal velocity. Spectral densities obtained using Welch spectrogram demonstrate that high-frequency portion of energy spectra, which has an utmost importance in determining flow influence on the modeled objects, are predicted correctly. The data about integral turbulence scale presented herein [20] and obtained using two of the most frequently implemented approaches demonstrate the possibility for this parameter to be modeled in wide test section of wind tunnel.

In order to estimate the influence of ABL on main aerodynamic parameters, the model of cube was tested in two wind tunnels with and without ABL being considered. Experimental data obtained in the course of present investigation regarding air flow influence on cube model in ABL, correlate well with the results obtained by other researches in earlier studies. Comparison of experimental data revealed significant influence of ABL on geometry and intensity of separation zones at cube sides and, as consequence, the influence of the same on integral (C_x, C_y) and local C_p aerodynamic characteristics of the object. The difference in numerical values of aerodynamic characteristics was up to 30 %.

Based on experimental results discussed herein the following may be concluded:

1. experimental data on mean flow velocity distribution, turbulence intensity, dimensionless spectral density and integral scale of turbulence are in good agreement with existing dependencies and previous studies;

2. pressure distribution on the surfaces of cube model, obtained during the experiment in LWT, correlate well with existing full-scale measurement data and the results of experimental studies performed using similar test facilities;

3. the main ABL characteristics can be modeled correctly in LWT test section using the method for flow non uniformity generation described in this paper;

4. correct ABL modelling used to determine aerodynamic parameters of structures makes it possible to eliminate unreasonable wind load margins.

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Моделирование средних ветровых нагрузок на сооружения

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Ключевые слова: аэродинамическая сила на здания, атмосферный пограничный слой, ветровая нагрузка, физическое моделирование, куб Силсо, аэродинамическая труба, коэффициент давления, фасады

Аннотация. Правильное определение и учет ветровых нагрузок имеют первостепенное значение при проектировании уникальных архитектурных объектов, таких как высотные здания, спортивные арены, аэропорты, большепролетные мосты. Одним из наиболее точных способов определения ветровых нагрузок считается проведение модельных испытаний в специализированных аэродинамических трубах. В последние десятилетия подход к моделированию воздействия воздушного потока на статические сооружения претерпел значительные изменения – в настоящее время все большое внимание уделяется корректному моделированию особенностей натурного ветра. При этом важно понимать, какое именно значение на результат эксперимента оказывает учет или не учет параметров ветра. В работе представлено сравнение наиболее популярных методов определения масштабов турбулентности – с использованием корреляционной функции и соотношения Кармана. Также целью данного исследования является сравнение основных аэродинамических характеристик (коэффициенты Cx, Cy, Cp) модели простого куба, полученных в однородном потоке и во время моделирования атмосферного пограничного слоя (АПС). В статье представлен краткий обзор метода моделирования АПС в рабочей части Ландшафтной аэродинамической трубы, а также экспериментальные данные о распределении средней скорости потока, интенсивности турбулентности, безразмерной спектральной плотности. Сравнение экспериментальных данных, полученных для модели куба в различных аэродинамических трубах, выявило влияние АПС на характеристики зон отрыва на сторонах куба и, как следствие, влияние на интегральные (Cx, Cy) и локальные (Cp) аэродинамические характеристики объекта. На основе полученных экспериментальных данных сделан вывод о существенном влиянии интенсивности отрывных зон на суммарные аэродинамические нагрузки, что обычно не учитывается в рамках практического расчета. В частности, показано, что учет особенностей градиентного потока приводит к снижению определяемых коэффициентов на 30 %.

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