Advantages of modeling ABL properties to determine wind loads on structures

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Abstract. In present paper we introduce the main advantages of modeling atmospheric boundary layer (ABL) properties for determination of mean and peak wind loads on structures. Experimental tests were carried out using wind tunnel with uniform velocity profile and new Landscape Wind tunnel (LWT) of Krylov State Research Centre. General characteristics of simulated boundary layer (such as mean velocity profile and turbulence intensity profile) are presented. For wind loads measurements model of Silsoe cube in a scale of 1:15 was used. Comparison of the data obtained at both test rigs with data published in early studies is performed. New data about aerodynamic forces acting on the model in range of angles of oncoming flow are presented. Algorithm for determination of peak wind loads is discussed.

1 Introduction

In the age of computer algorithms correct physical tests still is one of the main sources of data almost in all aerodynamic tasks. Indeed quality of the numerical simulations can be proven only by comparison with experimental data. For modern applied build engineering tasks the most interest question is determination of full and local wind loads on the surface of the designed object, for example stadium, exhibition hall, dwelling house etc. For a long time wind tunnels with uniform velocity profile were used to perform necessary simulations. Even in building regulations documents (such as [1]) all formulas for determinations of wind loads are based on such type experimental investigations. However the growing level of difficulty and responsibility of design of the structures became the reason to develop new type of test rigs – atmospheric boundary layer wind tunnels [2, 3].

The main aims of creation of such experimental stands are desire to correctly simulate of wind properties for different conditions, i.e. suburban conditions, open areas and seas, for different year seasons etc. The use of such stands allows obtaining more accurate data for objects with complex geometry, or buildings located in a densely built-up area.

Landscape Wind tunnel of Krylov State Research Centre is subsonic wind tunnel with closed-type large-size test section. Dimensions of this section provide possibilities to

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perform large-scale measurements of testing object with necessary number of surrounding development. The goal of present study is to compare results obtained in wind tunnel with uniform velocity profile with data obtained in LWT, i.e. summary and local wind loads. For this purpose model of the Silsoe cube [4 – 6] was created in scale 1:15.

2 Methods

The scheme of the LWT is shown at the fig. 1. There are a lot of known approaches to create boundary layer in wind tunnel [7 – 9], but the most verified one is use large-size spires for creation of main form of wind profile [10] and small-size blocks for creation of correct form of turbulent intensity profile [11]. Properties of modeling ABL was corresponded to “0” type profile in [12]. Photo of the model of the cube in LWT test section is shown at the fig. 2a. For determination of summary wind loads single dynamometer (with coordinate system which is shown at the fig. 2b) was used.

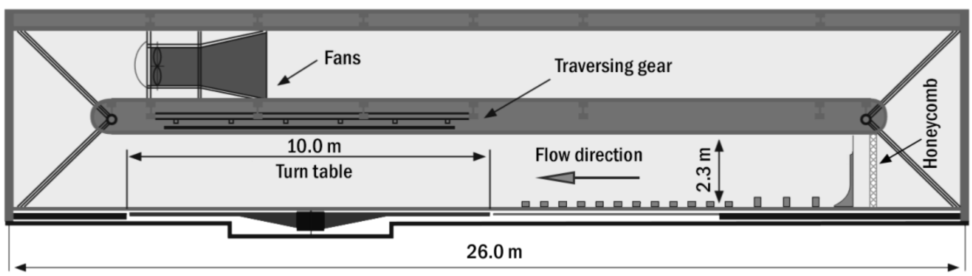
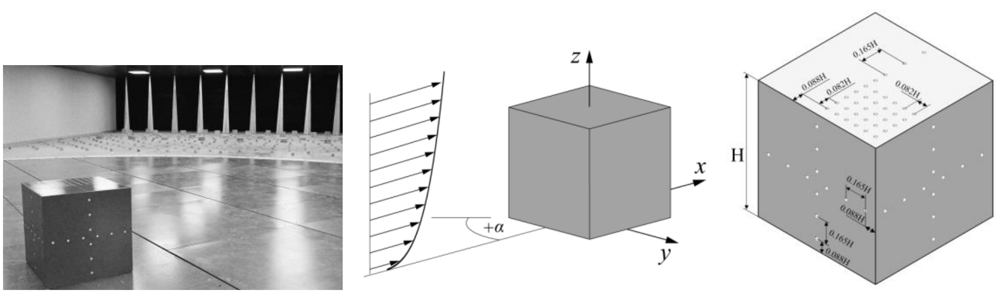


Fig. 1. Scheme of the LWT



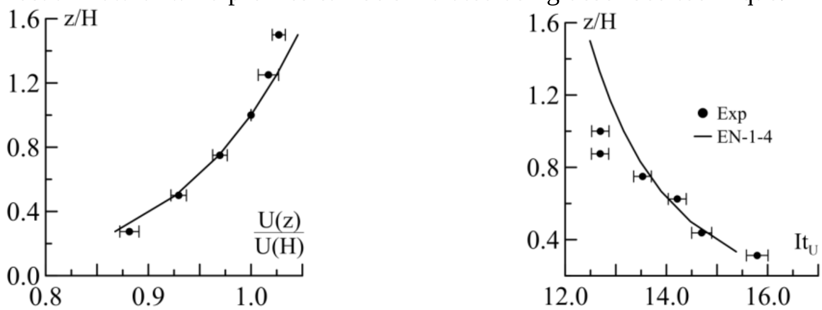
a b c

Fig. 2. Model of the cube
a – in test section of the LWT; b – coordinate system associated with model and direction of positive changing of the angle of oncoming flow; c – scheme of the pressure taps on the surfaces of the model

To perform measuring of the local loads 87 taps were made on the surfaces of the cube (12 on each side and 39 on the top side) like it is shown at the fig. 2c. Each tap was connected to the record system using tubes with length 200 mm and diameter 1 mm. Complete time of measurement for one angle α was 30 s and data sampling frequency was set as 100 Hz. According to the configuration of the used wind tunnels and sizes of the model blockage ratio in both experiments was less than 1 %. Reynolds numbers calculated using height of the model (H) and velocity at the height of the model (V_H) were in range Re = [2…5] $\times 10^5$ for case I and 2.9×10^5 in case II. Strictly speaking Reynolds number almost in all natural-size objects is higher than 5×10^5, but in experimental investigation it is impossible to make Reynolds number comparable with natural. That’s why independence of some observed data from Reynolds number will be shown further.

3 Results and Discussion

Denote experimental investigation in wind tunnel with uniform velocity profile as “case *I”* and experimental investigation in LWT as “case *II”*. All linear sizes are reduced to dimensionless form using cube height, all velocities – using velocity of the flow at the cube height. Mean velocity $\overline{U}$ and turbulence intensity It (determined as $It = \sigma_U / \overline{U} \cdot 100$ where σ_U is RMS of the velocity signal) in LWT are shown at the fig. 3. It should be noted that almost all natural wind profiles can be simulated using described technique.



a b

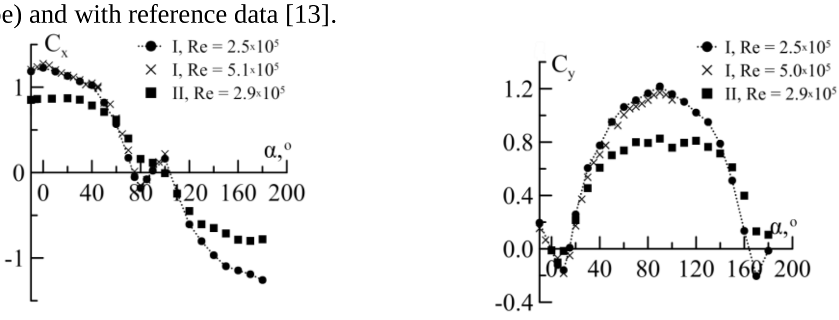
Fig. 3. Characteristics of the modeled ABL in LWT
a – mean velocity profile; b – turbulence intensity profile

For demonstration of the aerodynamic force acting on the cube dimensionless coefficients are used

$$C_{x,\,y} = \frac{F_{x,\,y}}{\rho \dfrac{V^2}{2} S}, \tag{1}$$

where $F_{x,\,y}$ – aerodynamic force in N; ρ – air density in kg/m^3; S – area of the cube side in m^2; V – velocity of the oncoming flow at the cube height in m/s. It is very important to use correct values of area and velocity to transform experimental results to full scale data.

The dimensionless coefficients of aerodynamic force are shown at the fig. 4. Data in case *I* are independent from Reynolds number (as it was mentioned before). The coefficients at the angles 0°, 90°, 180°, are in good agreement with each other (symmetry of the cube) and with reference data [13].

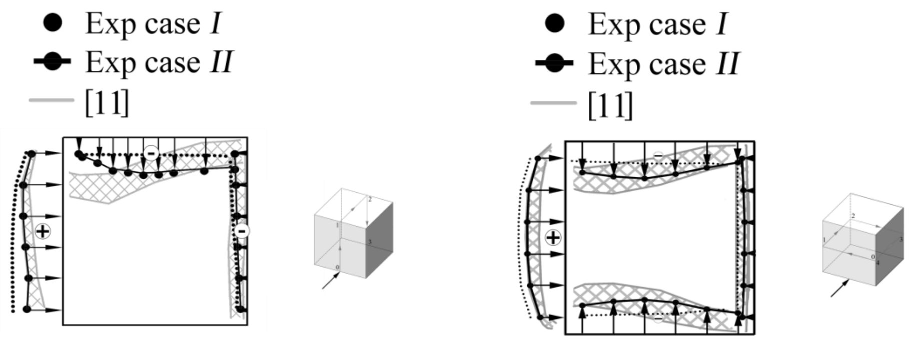


a b

Fig. 4. Dimensionless coefficients of aerodynamic force
a – in *x* direction; b – in *y* direction

Data obtained in LWT (case *II*) are less than data in case *I* on average by 20 %. This effect was presented before in [14]. So not taking into account inhomogeneities of real velocity profile can cause significant and unjustified rise in prices of the project in real engineering tasks. In both cases changing of the coefficients is not monotone (angles ~ 0-10^{o}, 80-90^{o}; 170-180^{o}). That can be explained by formation of detached air "bubbles" at the corner of the model.

The main results of the tests in wind tunnel that can be used to compute wind loads are pressure coefficients – mean and peak. Information about distribution of mean coefficients on the surface of the cube in ABL conditions is highly common in world literature [4 – 6, 15 – 18]. The pressure diagrams for both cases are presented at the fig. 5. The main difference between all data observed on the top surface of the cube. It should be noted that correct measure of roof pressure is still the big problem for engineers [19]. In present work reason of such difference can be difference in model Reynolds numbers or turbulence intensities.



a b

Fig. 5. Distributions of pressure coefficients along symmetry line
a – vertical symmetry line; b – horizontal symmetry line

The most important and most interesting part of tests is determination of peak pressure, because algorithm of this procedure does not described in regulations documents. More than ten different techniques can be found in papers of different authors (for example [20, 21]). Almost all of them recommend to use approaches of probability theory and try to find best fitted curve for experimental data. In present work we show how this algorithm can work applied to experimental data. Algorithm which will be described further is just an example appropriate for simple geometry. For real tasks we highly recommend to use more accurate algorithms, though the accuracy of algorithms are the separate topic for full research work.

Suggesting approach contains four steps:

1. separate input signal to small intervals;
2. find global maximums (or minimums for negative peak values) on each interval. Form a new "signal" using these maximums (or minimums);
3. calculate probability distribution function (or cumulative distribution function) for this new "signal";
4. use this PDF (or CDF) to find limits of the data. In such case upper limit corresponds to positive peak value and lower limit corresponds to negative peak value (if lower limit is negative).

Step 3 can be seriously simplified using known PDF, for example, Gumbel function, which was specially developed for these purposes [22]. Demonstration of determination of the negative peak values at vertical symmetry line for angle 0^{o} is presented at fig. 6, where letter "*d*" denotes distance from bottom edge (as shown on a scheme near to the graph). It should be noted, that for windward side at the angle 0^{o} determination of negative peak values is impossible. Positive peak values (C_p^{peak+}~1.15) are in a good agreement with technical data (such as [1] where C_p^{peak+}~1.20).

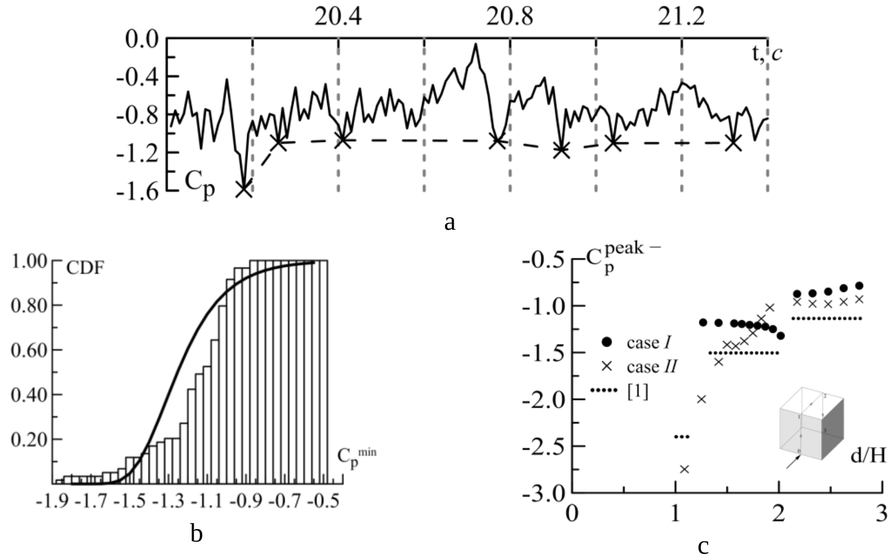


Fig. 6. Demonstration of determination of the peak values at angle 0°
a – input signal with marked minimums for the top surface central point in case *II*; b – Gumbel PDF for new "signal" in case *II*; c – positive peak values for vertical symmetry line compared with [SP] (dotted line)

4 Conclusions

In this paper, we present the main results that must be obtained in experimental study of aerodynamic loads on architectural objects.

Two methods for conducting an experimental study are considered: an experiment performed in a uniform velocity profile and an experiment performed taking into account the unevenness of the velocity profile (the velocity profile of the Atmospheric Boundary Layer). Both studies were performed on the basis of the Krylov State Research Center, in particular using a new Landscape Wind Tunnel [23-27].

As a result of the tests, data about the total and local aerodynamic loads on the model of Silsoe cube at a scale of 1:15 were obtained. The total aerodynamic loads are represented using aerodynamic coefficients C_x, C_y. It is established that qualitatively the dependences of the coefficients on the angle of the flow are similar in both sets, but quantitatively the data can differ by 20–30%.

Local aerodynamic loads – the main result of the experimental tests – are represented by distributions of mean and peak pressure coefficients. The average coefficients are in good agreement with the data presented in known works [4–6, 16–19]. Research performed in the Landscape Wind Tunnel makes it possible to more accurately determine the average loads and reduce the influence of extra functions in determination of the loads (the algorithm described in [1]).

The paper presents a simple and intuitive way to determine peak loads, which is applicable for simple geometry or during methodological experiments. However, the data obtained using this approach are in good agreement with the data recommended by [1].

References

1. *SP 20.13330.2016 – Loads and actions*
2. J. Counihan, Atmos. Environ., **3**, 197–214 (1967)

3. N.J. Cook, J. of Ind. Aerod., **1**, 3–12 (1975)
4. P.J. Richards et al., J. Wind Eng. Ind. Aerodym., **89**, 1553–1564 (2001)
5. P.J. Richards et al., J. Wind Eng. Ind. Aerodym., **95**, 1384–1399 (2007)
6. S.E. Norris, P.J. Richards, *19th Australian Fluid Mechanics Conference*, 4 (Melbourne, Australia, 2014)
7. J. Armitt, J. Counihan, Environ., **2**, 49–71 (1968)
8. Khalid Aldin Bin Za'aba et al., IOP Conf. Ser.: Mater. Sci. Eng., **184**, 12 (2017)
9. V.I. Kornilov, A.V. Boiko, Thermophys. Aeromech., **19**, 247–258 (2012)
10. H.P.A.H. Irwin, J. Wind Eng. Ind. Aerodym., **7**, 361–366 (1981).
11. T. Balendra et al., J Wind Eng. Ind. Aerod., **90**, 675–688 (2001)
12. Eurocode 1: Actions on structures – 1–4: General actions – Wind actions
13. M. Berezin, V.V. Katyushin, Atlas of aerodynamic characteristics of building structures (Olden-Poligraphiya, Novosibirsk, 2003)
14. A. Pustoshny, S. Solovev, Marine Intellectual Technologies, **3** (41), 69–75 (2018)
15. N. Hölscher, H.-J. Niemann, J. Wind Eng. Ind. Aerodym., **74**, 599–608 (1998).
16. I. P. Castro, A.G. Robins, J. Fluid Mech., **79** (pt. 2), 307–335 (1977).
17. H. Sakamoto, J. Wind Eng. Ind. Aerodym., **9**, 275–293 (1982)
18. O. Hubová et al., Roczniki Inżynernii Budowlanej – ZESZYT 143, (2014)
19. P. Sarkar et al., Full-scale study of conical vortices and roof corner pressures. Wind Struct., **4** (2), 131–146 (2001)
20. J.D. Holmes, L.S. Cochran, J. Wind Eng. Ind. Aerodyn., **91** (7), 893–901 (2003).
21. P. Ramu et al., Struct. Saf., **32** (2), 124–137 (2010)
22. E.J. Gumbel, *Statistical Theory of Extreme Values and Some Practical Applications. A Series of Lectures. Technical Report* (1954)
23. S. Solovev. E. Khrapunov, Vestnik of Saint Petersburg University. "Mathematics. Mechanics. Astronomy", **4**, (2018)
24. V.V. Titkov, A.B. Bekbayev, T.M. Munsyzbai, K.B. Shakenov, Mag. Civ. Eng., (4), 171–180 (2018)
25. V.N. Derkach, Wind, Mag. Civ. Eng., **60** (8), 38-43 (2015)
26. S.V. Petinov, Solid Mech. Appl., **251**, 35–42 (2018)
27. V.V. Bakaev, A.E Bolotin, V.S. Vasil'eva, Teoriya i Praktika Fizicheskoy Kultury (2015)