Journal of Engineering Physics and Thermophysics, Vol. 87, No. 1, January, 2014

HYDROGASDYNAMICS IN TECHNOLOGICAL PROCESSES

SIMULATION OF THE WIND EFFECT ON AN ENSEMBLE OF HIGH-RISE BUILDINGS BY MEANS OF MULTIBLOCK COMPUTATIONAL TECHNOLOGIES

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UDC 532.517:4

The numerical simulation of the wind effect on an ensemble of high-rise buildings is based on the solution of Reynolds-averaged Navier–Stokes equations closed with the help of a shear stress transfer model modified with account for the influence of the curvature of streamlines with the use of multiblock computational technologies in the VP2/3 package. It has been shown that the nonstationary aerodynamics of construction ensembles of closely spaced high-rise buildings has the characteristic features inherent in tandems of blunt bodies, and the pulsating loads in the lee buildings are largely determined by the self-organization of the jet-vortex structures in the space between buildings.

Keywords: *ensemble of high-rise buildings, wind effect, nonstationary flow, force loads, pulsations, numerical simulation, multiblock meshes, turbulence models.*

Introduction. In modern town planning, high-rise buildings play an important role, responsible for the appearance of towns and being erected on already developed areas to increase the density of buildings on them. The past half century has seen a change not only in the number of stories of skyscrapers, but also in their appearance aspect. For instance, in the 1960s high-rise buildings in the form of uncomplicated plain glass prism were widely erected. The gradual erection of skyscrapers-prisms in large cities, as well as progress in material science, stimulated a search for more complex and extraordinary designs. At present, the appearance of designed buildings is characterized by intricate geometrical shapes, for which the values of the aerodynamic coefficients needed for determining wind loads on the bearing structures are not known, as a rule. The wind load determines not only the strength of structures, but also their shape (in buildings of the so-called "dynamic architecture"). The concept of "dynamic architecture" was proposed by David Fisher. This architect became famous owing to the design of rotating towers-skyscrapers — apartment houses supplied with energy generated by horizontal wind turbines located between rotating horizontal floors and by photoelements covering their surface (15% of the surface is open to sunbeams at all times). It is interesting to note that, from the viewpoint of the "dynamic architecture" concept, it is expedient to use limited-rigidity skeleton and skeleton-framed systems in buildings of height of up to 40 stories, core systems in buildings of up to 50–60 stories, and core-frame systems and frame systems in buildings of up to 80–90 stories; higher buildings should be erected according to the "tube-in-truss" scheme. Thus, the reduction of free areas in large cities leads to the necessity of erecting high-rise buildings (according to the current building code, buildings higher than 75 m are considered to be high-rise ones).

Along with the complication of the architectural aspect, the density of buildings increases. In this connection, more stringent requirements are imposed on inhabitants′ and pedestrians′ comfort. At the same time, wind effects on high-rise buildings determine the dominating loads on them, and studies of the building aerodynamics form a considerable part of the volume of design works [1, 2]. However, the corresponding standard base is lacking, which retards, to a certain extent, the development of high-rise buildings.

According to the estimates of Japanese specialists [3], for buildings higher than 200 m a wind corresponding to the wind region VI of the Russian Federation is more dangerous to the total strength of the building than a magnitude 9

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0062-0125/14/8701-0112 ©2014 Springer Science+Business Media New York

earthquake, and in the Moscow region wind loads on buildings higher than 75 m can exceed the design effect of an earthquake of magnitude 5.

The development in the USSR and in the Russian Federation of the normative base for calculations of wind loads is associated with the works of É. I. Retter [6], A. G. Sokolov [7], G. A. Savitskii [8], I. M. Besprozvannaya [7], F. L. Serebrovskii [9], M. F. Barshtein [10], B. G. Korenev [11], M. I. Kazakevich [12], N. A. Popov [13], S. V. Nikolaev [4, 5], A. V. Perel′muter [14], and others. The currently used methods for calculating wind loads were developed in the early 1970s at the Kucherenko Central Research Institute for Building Structures with the use of A. G. Davenport′s works (1962–1967) [15, 16] and realized in Building Code and Rules (SNiP) II-6-74 [17]. In formulating SNiP 2.01.07-85 "Loads and Effects" [18], the expressions describing the dynamic reaction of structures under the action of a wind were greatly simplified. In 2000, N. A. Popov worked out "Recommendations on more exact dynamic calculations of buildings and structures with account for the pulsating component of the wind load" [13]. In the revised version of SNiP 2.01.07-85* "Loads and Effects" [20], the methods for calculating wind loads remained almost unchanged.

Besides the approximate character of the used dynamic approaches, it should be noted that neither the SNiP of [20] nor the Methodological documents in construction (MDS) "Temporary norms in specifying loads and effects on multifunctional high-rise buildings and complexes in Moscow" [21] consider variants of locating a high-rise building in a developed area and take into account the interference of vortex waves from neighboring buildings and the terrain. Forecasts of aerodynamic loads made according to the SNiP sometimes have significant errors and require corrections. The static pressure distribution according to Davenport describes well wind loads only on the windward side of the building. The variations of turbulence with the height of the building observed in natural tests are ignored. The specific features of the forces acting on the roofs and coverings with parapets and shields are not taken into consideration. The positions of high-pressure zones also need to be reconsidered. The existing methods for estimating wind loads are suitable, in general, for low- and medium-rise buildings, as well as in areas with a low density of buildings. For high-rise buildings (the more so for their relatively compact ensembles in an area with a relatively high density of buildings) more exact methods are needed. It is also necessary to take into account the fact that in the surface layer at altitudes above 200 m mesojet flows (atmospheric layers of thickness 100–300 m) with a high dynamic pressure [7] have been discovered, and in designing and erecting high-rise buildings in Moscow only the incident flow velocity of 10 m/s is taken into account and the change in the wind velocity in the vertical direction is completely ignored.

Wind loads are one of the main kinds of effects produced on enclosure structures of buildings. Of particular importance is the estimation of the maximum and minimum pressures on aerodynamic surfaces with account for their statistical straggling. SNiP 2.01.07-85* gives no (or gives partly) methods for normalizing the peak (intensity-maximum) values of wind loads that should be taken into account in designing enclosure structures of high-rise buildings and elements of their mounting. As mentioned above, the main guidance document on wind effects produced on high-rise buildings for Moscow is MDS 20-1.2006. According to this document, at different stages of designing a high-rise building, it is necessary to determine:

1) the mean and pulsating components of the calculated wind load on the bearing structures of the building;
2) the peak (minimum and maximum) values of the static pressure for calculating the strength of building enclosures;
3) the wind effects violating the comfort conditions of pedestrian zones;
4) the wind effect on the building connected with the excitation of aerodynamic oscillations (buffeting, galloping, wind resonance);
5) the maximum vibrations of the floors of upper stories under the action of the pulsating component of the wind load.

To solve the above-listed complex problems of nonstationary aerodynamics arising under the action of a wind on an ensemble of high-rise buildings, methods of computational modeling with the use of applied program packages have been developed in the last few decades. This development was largely stimulated by the rapid progress in computer engineering, and the creation of multiprocessor and multikernel systems with paralleling of computing operations. In 2007, a team of leading European specialists worked out, within the framework of the project COST732 on order of the European standardization committee, recommendations on numerical simulation of wind effects. The Architecture Institute of Japan [23] prepared a number of test problems. However, these materials are intended for problems of ecology and pedestrian comfort rather than for simulating the wind effect on high-rise buildings.

Brief Survey of Calculation Approaches in Building Aerodynamics. It seems useful to characterize briefly the acquired experience in using methods of numerical simulation for solving problems of building aerodynamics on the basis of investigations carried out mainly in the Russian Federation and classify the corresponding approaches, models, and methodological tools [24–32]. First of all, it should be noted that the approaches based on two-dimensional approximations, including those with the use of ideal liquid models, are still acceptable. For instance, the discrete feature methods were used in [19, 24, 25]. Although the developed meshless methods have many advantages primarily due to the low dissipation of perturbations in their transfer for long distances, their application is limited because of the impossibility of representing correctly turbulent processes from the viewpoint of the ideal liquid model.

Apparently, the problem of numerical simuation of the turbulent transfer is the main problem in computational building aerodynamics. The current engineering approach to its solution is associated with the use of semi-empirical turbulence models with closing of Reynolds-averaged Navier–Stokes equations. A more correct and promising method, although requiring computing resources an order of magnitude larger, is the use of large eddy simulation (LES) and detached eddy simulation (DES) models [33, 34]. The above models enter into the catalogues of universal commercial packages (e.g., ANSYS Fluent, Star CD), which stimulates their wide use [26–28]. However, the specificity of the solution of problems of predicting the characteristics of the wind effect on high-rise buildings connected with high Reynolds numbers (of the order of 10^6–10^8) require thorough discretization of computational domains in the boundary and shear layers, as well as in the zones where vortex streets and a jet-vortex flow develop. The latter is not always taken into account in using universal packages (sometimes calculations are carried out at a value of the near-wall parameter y^+ of the order of hundreds and thousands). Sometimes the investigation of the nonstationary process of development, e.g., of a wake and interference of vortex streets behind an ensemble of bodies, is replaced by the solution of the quasi-stationary problem described by stationary Reynolds equations [28].

The main problem in using universal commercial packages is the fact that they represent a "gray" box. Problems arise when numerical forecasts obtained with the use of a package disagree with the available experimental data. As a rule, commercial packages have a kernel "closed" to users in order to guarantee the obtaining of a solution of the problem stated. Therefore, it is not always possible to determine the reasons for the appearance of errors in numerical forecasts. It may seem that the free packages (of the type of OpenFOAM) readily accessible in the internet are better than their commercial analogs since they have open codes. But this is not so. The problem is the level of the programmer's mastery of the package. Ideally, he must not only understand the logic of writing the program, but also explain each operator used, i.e., actually be the author of the program. Thus, a certain advantage of the so-called "author′s" (in-house) packages is determined. What is more, problems of structural aerodynamics are closely connected with problems of structural mechanics and thermal physics and with ventilation and air conditioning problems, i.e., a complex of conjugate and related problems of mechanics and aerothermodynamics arises, and it is expedient to solve them within the framework of a single specialized package.

In the last fifteen years, multiblock computational technologies (MCT) and a specialized package VP2/3 (velocity–pressure, 2D/3D versions) have been developed [35]. An undoubted advantage of MCTs is the resolution of detached flow elements of different scales on a set of simple-topology meshes of the corresponding scale superimposed on one other. As a result, not only a substantial saving in mesh resources, but also an increase in the accuracy of solution, is attained due to the placement of separate fine meshes in desirable places (determined interactively) with their set-up for the reproduced flow pattern. For example, the good resolution of the near-wall region of the flow due to the introduction of a separate fine mesh made it possible to switch over, without major problems, to modern low-Reynolds turbulence models such as the Menter shear stress transfer (MSST) model and the Spalart–Allmaras model. The number of introduced meshes is unlimited, and in the VP2/3 package their automatic connection and establishment of relations between them are realized by object-oriented software. Of course, the introduction of an additional mesh connected with a particular hydrodynamical (or physical) specific feature of the flow (the field of characteristics) and their set-up for the corresponding scale are carried out in the course of obtaining a preliminary solution. An important role is played thereby by the data interpolation from mesh to mesh both at the stage of preparation for solving the problem and in the process of solving the problem. This approach is equivalent to the use of adaptive nonstructured meshes but differs from it by much smaller computational resources, i.e., it is more economic. It also provides proper accuracy without refinement of meshes, since it resolves automatically the scales of detected hydrodynamical features. We tested the MCTs on problems of structural aerodynamics of single buildings in [29–32]. The present paper illustrates their application for ensembles of high-rise buildings.

Computational Methodology and Object of Investigation. The mathematical model represents a system of Reynolds-averaged Navier–Stokes equations for a viscous incompressible fluid complemented with transfer equations of turbulent characteristics. To close them, the differential equations of the semi-empirical model of shear stress transfer proposed by Menter [36, 37] are used. As was shown in [37], the MSST model is preferable in calculating vortex and detached flows.

The used computational algorithm is based on the generalized procedure of global iterations [38] intended for solving nonstationary Navier–Stokes equations by the finite-volume method on multiblock intersecting meshes. The system of input equations is written in divergent form for increments of dependent variables, namely in Cartesian velocity and pressure components in curvilinear nonorthogonal coordinates. In approximating the source term incorporating, in the case of a nonstationary problem, a time derivative of a dependent variable, convective flows are calculated by means of one-dimensional upstream schemes of second-order (in particular, with the use of the Leonard quadratic upstream scheme [39]).

The computational procedure at each time step is based on the concept of splitting into physical processes realized in the SIMPLEC procedure of pressure correction [40]. A characteristic feature of the considered iteration algorithm is the determination at the "predictor" step of preliminary velocity components for "frozen" pressure fields followed by pressure correction on the basis of the solution of the continuity equation with velocity field corrections. The computational process is constructed so that one "predictor" step falls at several local iteration steps in the pressure correction block.

The computational procedure includes also an interpolation block of determining dependent variables in the subregion overlap zones. The concept of multiblock meshes appears to be the most rational for correct interpretation of flow elements of different scales having a complex structure. A combination of meshes permits also representing flows in multiply connected regions. It is important to emphasize that in this case simple-topology meshes are superimposed on one another, which considerably simplifies the problem of constructing computational meshes and permits avoiding the generation of a complex curvilinear mesh. We tested the package for solving problems of structural aerodynamics in modeling cyclic processes of vortex formation behind a cube placed on the wall [41].

In the present paper, we solve the three-dimensional problem of interaction of the wind flow with an ensemble of high-rise buildings composed of four buildings of different height in terms of the solution of Reynolds-averaged nonstationary Navier–Stokes equations. All variables were reduced to dimensionless form. For the characteristic linear size, we assumed the cross-section of the building $L = 50$ m. The pressure is referred to the doubled dynamic pressure. For the characteristic area for determining integral loads, we chose the area $L \times L$. Thus, the Reynolds number calculated by the given velocity U and the characteristic linear size L is $\mathrm{Re} = 3.5 \cdot 10^7$. At such Reynolds numbers the flow around the ensemble of buildings is assumed to be self-similar, i.e., the flow characteristics are independent of the velocity (the Reynolds number). Calculations were carried out up to a value of the dimensionless time equal to 50, which equals in dimensional form 250 s (or 2500 m of the wake behind the complex of buildings at a velocity $U = 10$ m/s). The time step was equal to 0.05 s, and the boundary layer thickness at the input to the domain was given equal to L.

The sizes of the computational domain were chosen as follows: the distance from the ensemble of buildings to the inflow boundary of the computational domain was 500 m, the distance to the outflow boundary was 1200 m, the distance to the lateral and upper boundaries was 500 m, and the total number of computational cells in the meshes was of the order of 1.25 million (Fig. 1). It should be noted that the profiles of buildings with small-scale superstructures depicted in Fig. 1a and b are replaced by parallelepipeds with plain walls and rounded-off edges (the rounding-off radius is of the order of 1.5 m). The computational domain is broken down by large cells of the external rectangular mesh (Fig. 1c), inside of which a Cartesian mesh with small steps is built-in for correct representation of the nonstationary vortex wake behind the ensemble of buildings (Fig. 1d). Near each building, an O-type curvilinear mesh close to an orthogonal one is constructed (Fig. 1e and f). The width of the layer of cells around the buildings is chosen so that the meshes near the buildings do not intersect. However, the density of high-rise buildings in the ensemble under consideration is rather high, i.e., the buildings are located close to one another. The architecture of the ensemble is such that three buildings of about the same height are located so that their walls are parallel, and the fourth building is much (almost twice) lower and is placed at an angle to the others. Numbering of the buildings proceeds clockwise, the number of the fourth building being lower than the numbers of the other buildings. Several directions of the wind effect are considered. In each case, the Cartesian coordinate system and the Cartesian velocity components are wind-oriented, i.e., the directions of the longitudinal axis x and of the wind velocity vector coincide.

Analysis of the Results of Calculations of the Flow around an Ensemble of High-Rise Buildings. In accordance with the data of the Research Institute "Atmograf" on the most probable directions of winds at the site of the complex, we consider in the present paper three variants of flows around an ensemble of high-rise buildings for various directions of the wind: from north to south, from southwest to northeast, and from west to east.

In each case of flow around the buildings, we obtained the fields of the longitudinal velocity component in the horizontal sections parallel to the earth plane for three values of the dimensionless height $h = 0.01$, 0.8, and 1.6 (Fig. 2), the static pressure fields in the horizontal sections for three values of the dimensionless height $h = 0.01$, 0.8, and 1.6 (Fig. 3), the distributions, over the aerodynamic surfaces of the buildings, of the average value of the difference between the maximum

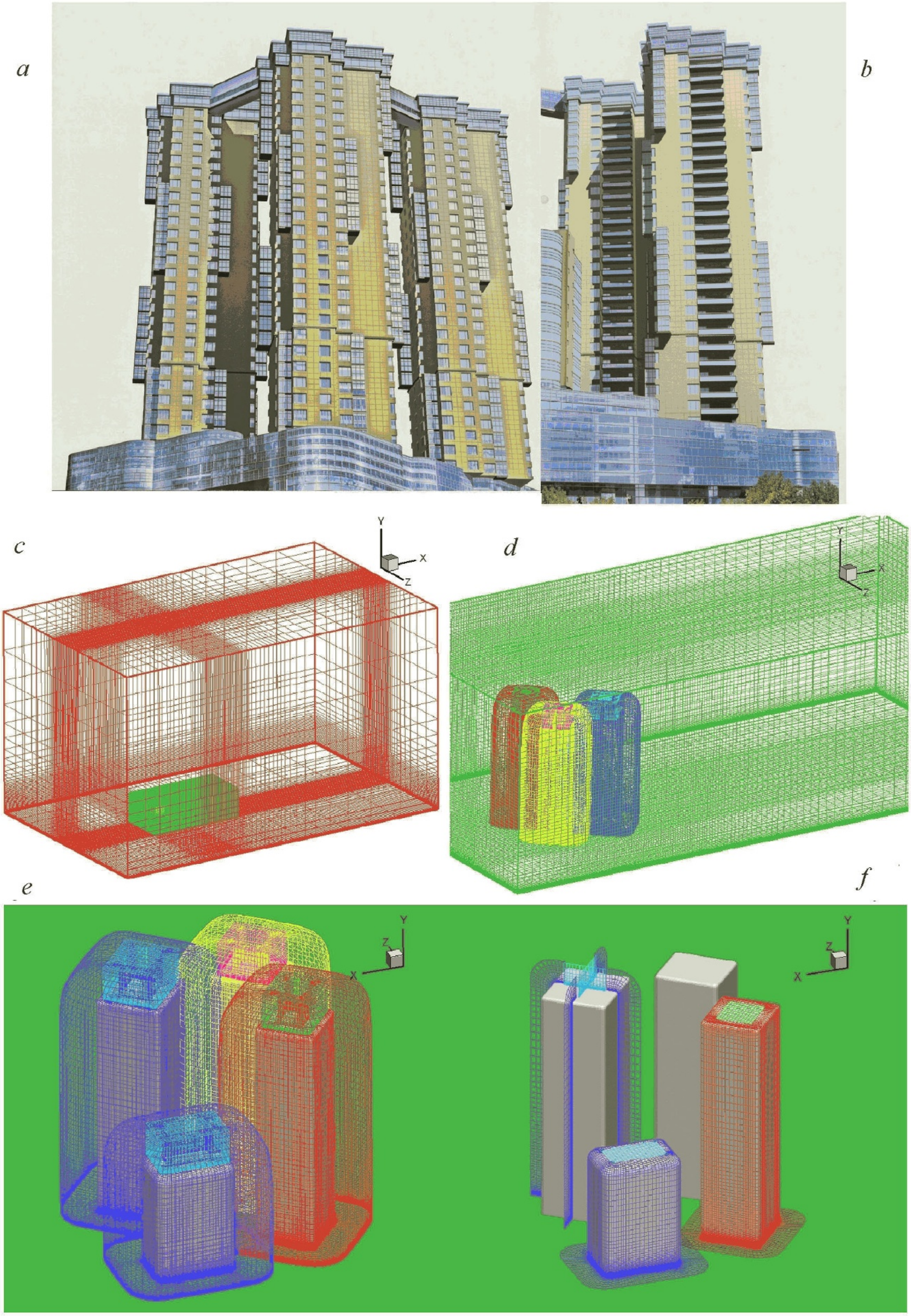

Fig. 1. Front view (a) and side view (b) of the ensemble of high-rise buildings, scheme of the computational domain with a multiblock mesh (c) including an internal rectangular mesh (d) and sections of the curvilinear meshes surrounding the buildings (e and f).

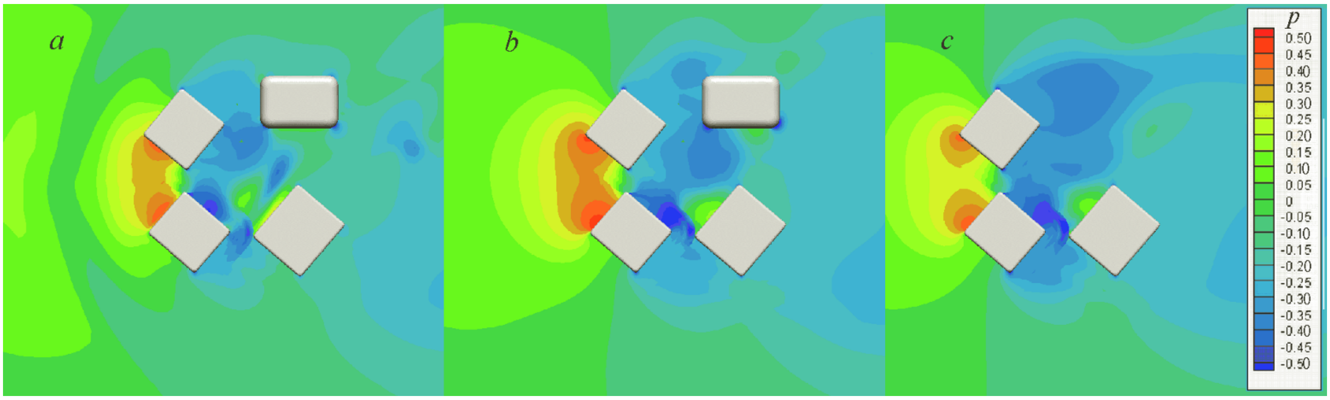

Fig. 2. Comparison of the isofields of the longitudinal velocity component of the air flow in horizontal sections $y = 0.01$ (a), 0.8 (b), and 1.6 (c) in the north wind.

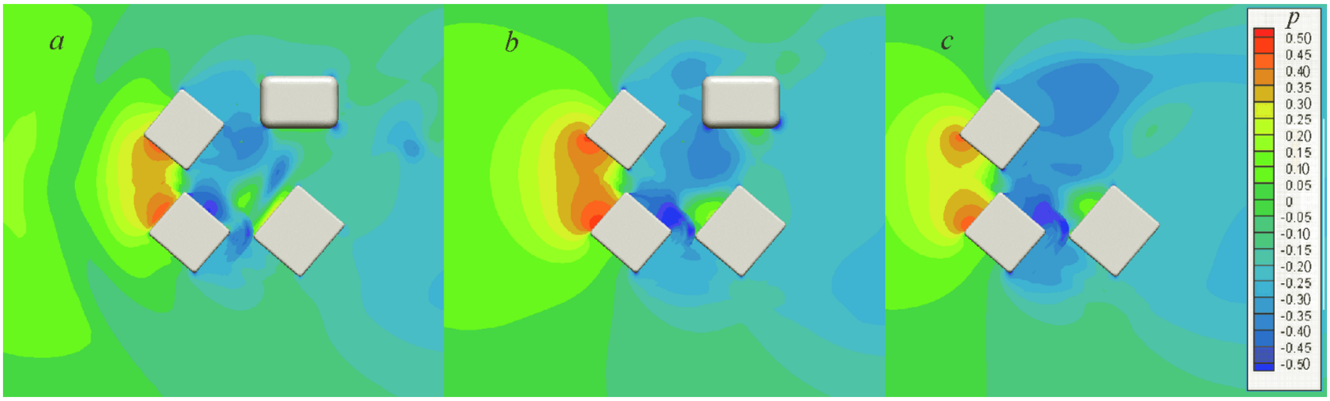

Fig. 3. Comparison of the isofields of the averaged static pressure in horizontal sections $y = 0.01$ (a), 0.8 (b), and 1.6 (c) in the north wind.

and minimum values of the averaged pressure $p' = (p_{\max} - p_{\min})/2$ in the dimensionless time interval $\Delta T = 10$ (Fig. 4), three-dimensional pictures of computer visualization of labeled particle trajectories in the averaged flow (Fig. 5), and graphs of the change with time in the dimensionless coefficients of the drag forces, the lifting forces, and the lateral forces acting on the buildings (Figs. 6–8).

Comparison of the distributions of the longitudinal velocity component with the height of horizontal sections (Fig. 2) points, in the first place, to the presence near the earth (at the level of the human height) ahead of the ensemble of buildings of a large-scale detached zone with a reverse flow propagating with the maximum velocity (of the order of 60% of the wind velocity). Detached zones arise also inside the microdistrict, mainly in front of building No. 1, as well as in the wake behind it. Upon receding from the earth surface spatial detached zones between pairs of buildings 1, 2, and 3, 4 develop. In the space between buildings 2 and 3, on the windward side of the ensemble, a powerful slit jet, whose maximum velocity reaches 1.2 and whose scale increases with height, develops. The pictures of isobars in Fig. 3 complement the fields of the longitudinal velocity component. Ahead of the ensemble, before buildings 2 and 3, high-pressure zones arise, and their sizes first increase with height and then decrease. The low-pressure (comparable in value to the maximum level of high pressure) appear in the wake behind the front buildings. The described picture of the wind effect on the ensemble of buildings and its related pressure distribution are analogous to the vortex structures and aerodynamic effects arising in a uniform flow around a tandem of closely spaced bodies [31, 40].

However, unlike trapped steady vortices [40] arising in spaces between bodies, the specificity of the wind effect on ensembles of buildings is connected with the nonstationary character of the flow around objects. As a result of averaging over a fairly large time interval, averaged and pulsating local loads on the buildings can be distinguished. As is seem from Fig. 4, the maximum of pressure pulsations (of the order of 0.2) falls at the edge of building 1 situated in the wake behind building

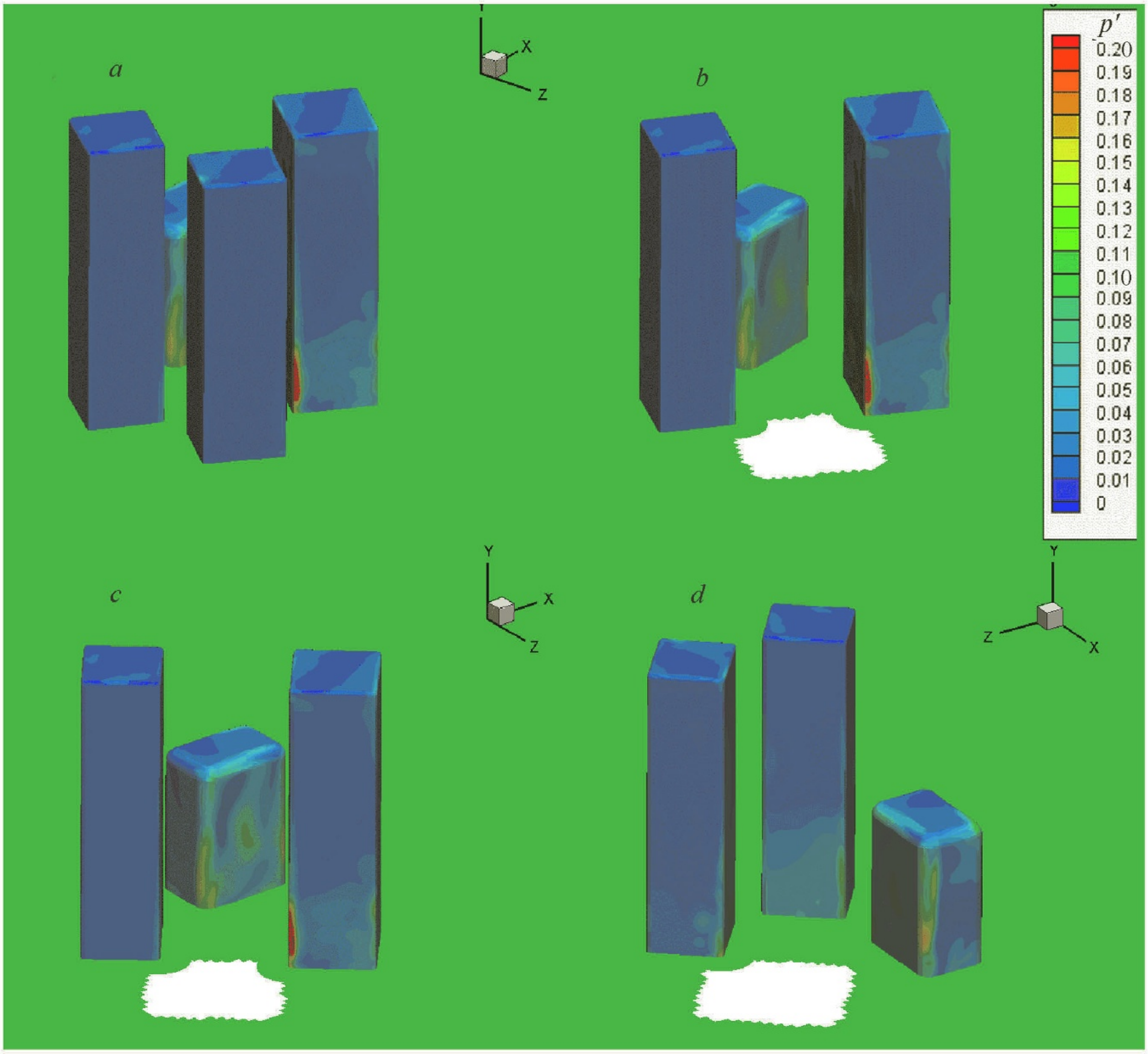

Fig. 4. Comparison of the isofields of the pulsating pressure p' on the surfaces of high-rise buildings in the north wind for various angles of aspect, including those with removed elements.

2. However, less intense, but distributed practically over the entire aerodynamic surface, pressure pulsations are observed on building 4. This is largely due to the fact that it is situated in the aerodynamic shadow of building 3 and is subjected to the strong nonstationary action of the wake behind this building. Strictly speaking, this becomes clear in analyzing the jet-vortex pattern of the action of a north wind on the ensemble of high-rise buildings in Fig. 5. Like the flow around a blunt body on a plain wall of the type of a cube [30, 31, 41], before the ensemble of buildings at a short distance from the earth an intense horseshoe-shaped vortex is formed (Fig. 5a). It is interesting to note that in the space between the buildings there arises an ascending swirling tornado-like flow turned to building 4 whose height is smaller compared to the other structures. It is precisely the fluctuations of the above flow that form the field of pressure pulsations on building 4.

Let us consider the changes with time in the integral force loads on the buildings according to the wind direction (Figs. 6–8). When the wind blows from the north, the front buildings 2 and 3 of the ensemble suffer the greatest pressure, whereas the similar structure situated behind building 2 suffers a load six times lower, and building 4 is completely under the action of a negative (actually, very low) force. The lateral loads on the front buildings 2 and 3 are almost equal; they are six times smaller than the ram loads and are opposite in sign (they tend to move the buildings of the ensemble apart). Building 1 is subjected to the action of a lateral force of approximately the same magnitude as that of the force acting on building 2 situated down the stream. The lateral force acting on building 4 is smaller in magnitude but opposite in sign to the lateral

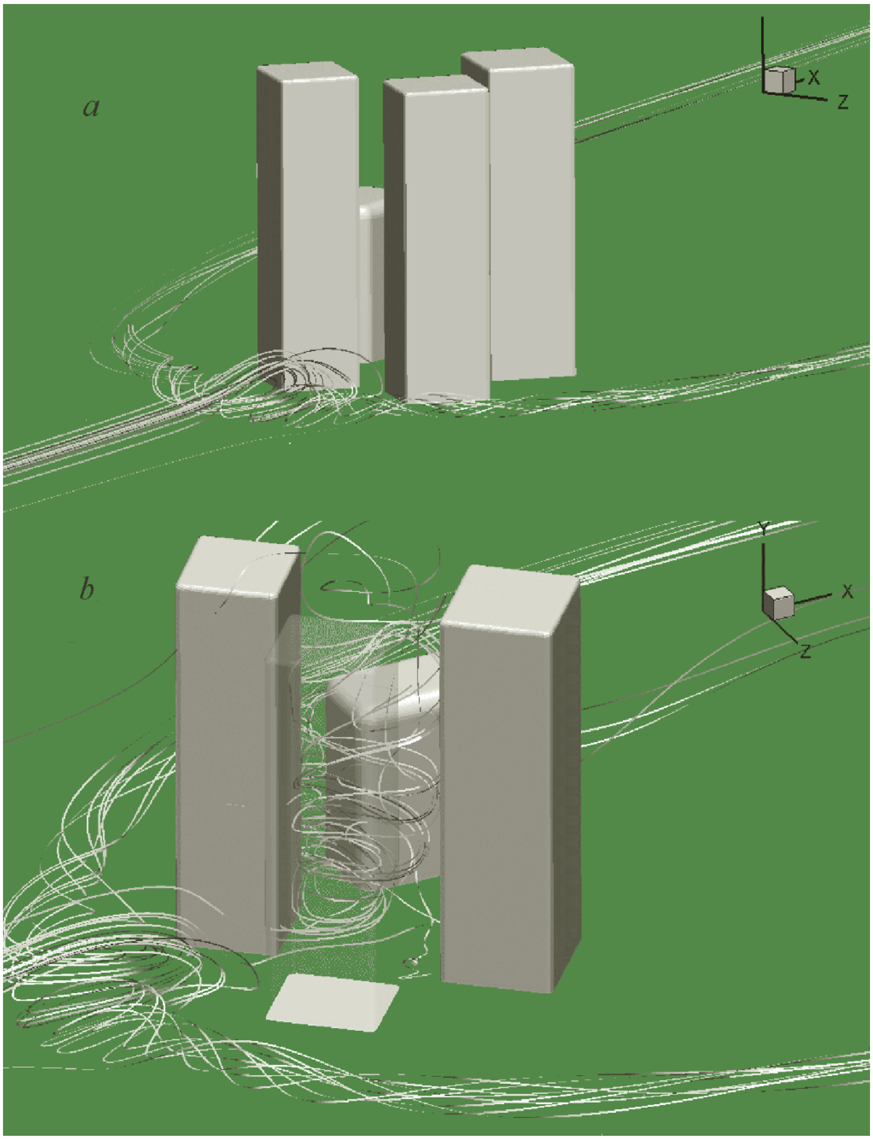

Fig. 5. Patterns of vortex structures under the action of the north wind on the ensemble of high-rise buildings (a) and on the same ensemble in the absence of the front building (b).

force acting on the front building 3. The small change with time (after $T = 30$) in the integral force loads in the north wind is also worth noticing (Fig. 6).

In the west wind, the self-oscillatory flow around the ensemble is more clearly defined (Fig. 7), i.e., the time dependences of the ram and lateral forces have a periodic character. In this case, the windward buildings of the ensemble are almost the same as in the north wind, and building 4 is turned by an angle of $90^{\rm o}$ and its short side is wind-oriented, i.e., the frontal part of the building is transverse to the flow, which most likely predetermines high pulsations of loads. The front buildings 1 and 2 experience approximately the same loads as buildings 3 and 4 do in the north wind. The load on building 3, as opposed to the load on the corresponding building 1 (in the north wind), is much lower (is almost absent). The negative force on building 4 is about twice higher than the load in the north wind. The lateral force on building 1 turns out to be the same as in the north wind, although the building is situated windward, and not leeward. The lateral force on building 2 is greater in magnitude by 30% than in the north wind. Buildings 3 and 4 are under the action of a rocking lateral load pulsating with a peak amplitude of about 5% of the largest ram load on the ensemble elements.

In the southeast wind (Fig. 8), building 4 turned at an angle of $45^{\rm o}$ to the incident flow turns out to be in the front, and the fronts of the other three high-rise buildings are oriented normally with respect to the wind direction. As a result, the ram

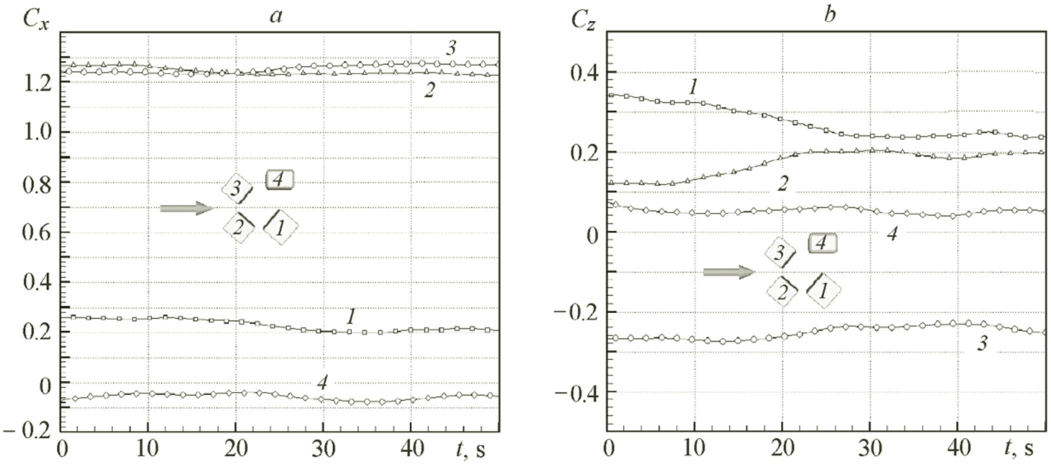

Fig. 6. Time dependence of the averaged longitudinal (a) and lateral (b) integral loads on the buildings in the north wind.

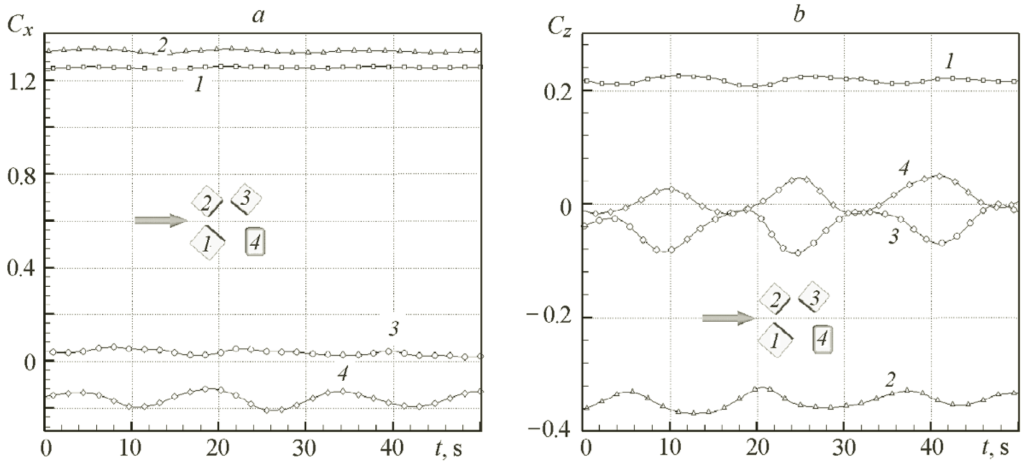

Fig. 7. Time dependence of the averaged longitudinal (a) and lateral (b) integral loads on the buildings in the west wind.

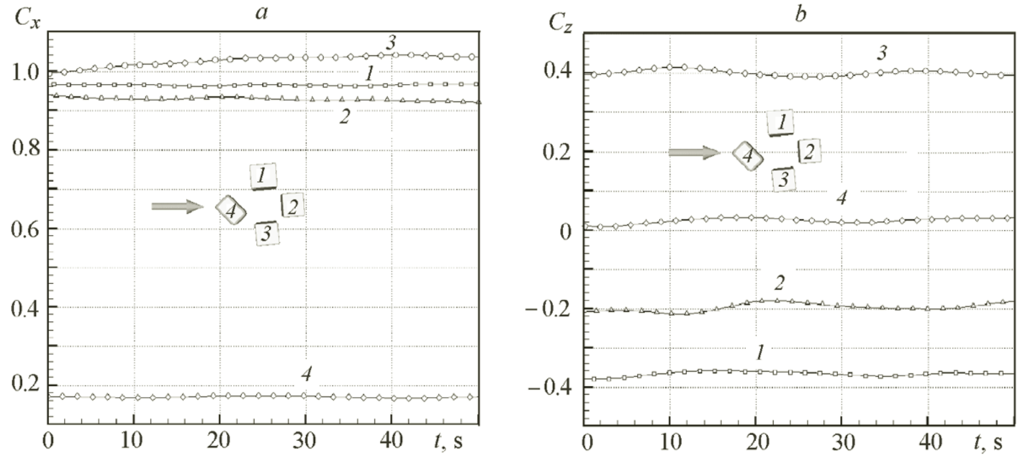

Fig. 8. Time dependence of the averaged longitudinal (a) and lateral (b) integral loads on the buildings in the south-east wind.

load on building 4 is small but positive, unlike that in the previous cases. The ram load on buildings 1–3 situated in the wake behind the fourth building is much lower than in the north and west winds, which corresponds to the tandem arrangement of bodies [40]. The lateral loads on the high-rise buildings 1 and 2 turn out to be much higher than in the above cases, which is most likely due to the fact that the density of buildings in the ensemble in the southeast wind, when there is a strong mutual influence of elements of the ensemble of bodies on one another, is low. The lateral load on the front building 4 is low because the building is in the aerodynamic shadow of the other buildings of the ensemble. The lateral force acting on building 2 is rather significant — it is only twice lower than the force acting on building 1.

CONCLUSIONS

1. The current SNiP and temporary norms are not completely applicable to the analysis of the wind effect on high-rise buildings. To evaluate these unique structures, it is necessary to use a combination of methods of physical and numerical experiments. It is important to note that the use of wind tunnels (even special meterorological ones) for taking into account the terrain, as well of the simulation of gusts and vibrations of structures, is limited as to Reynolds numbers. At the same time the applicability of applied program packages should rely on the verification of models and a high qualification of calculators specialized in aerodynamics.
2. Brief analysis of the application of universal and specialized program packages for solving problems of structural aerodynamics shows that it is preferable to develop construction-oriented programs aimed at solving conjugate problems of aerothermomechanics. In this connection, it seems expedient to use the proposed multiblock computational technologies realized in the VP2/3 package. The MCTs are aimed at correct resolution of the processes proceeding in a space with constructional elements of different scales, around which three-dimensional jet-vortex flows are streaming.
3. We present the results of calculations of the wind effect on the ensemble of high-rise buildings under construction in the "ÉKO" complex in Moscow obtained on the basis of the finite-volume solution of Reynolds-averaged Navier–Stokes equations closed by the equations of the Menter shear stress transfer model on multiblock structured simple-topology meshes of various scales with partial superposition.
4. It has been shown that the nonstationary aerodynamics of construction ensembles consisting of closely situated high-rise buildings has the characteristic features inherent in tandems of blunt bodies. At the same time an important role is played by the spaces between the buildings in the ensemble leading to the formation of slit jet flows. The nonstationary loads on the buildings situated on the leeward side are largely determined by the self-organization of jet-vortex structures in the space between them.

This work was supported by the Russian Foundation for Basic Research (projects Nos. 11-01-00039, 12-08-90001, and 3-08-90468) and the Belarusian Republic Foundation for Basic Research (project T12R-217).

NOTATION

C_x and C_z, longitudinal and lateral loads with respect to the direction of the wind flow, fractions of $\rho U^2 L^2$; h, height of vertical sections above the earth surface, fractions of L; L, characteristic size of the building, m; p and p', pressure and pressure pulsations, fractions of ρU^2; Re = fractions of $\rho UD/m$, Reynolds number; t, time, s; U, air flow velocity at the input to the computational domain, m/s; u, longitudinal (codirectional with the wind) velocity component of the air flow, fractions of U; μ, air viscosity, Pa·s; ρ, density of air, kg/m^3.

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