Advanced numerical simulation of wind effects on high-rise buildings, structures and complexes

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Abstract. The article is devoted to the Russian design codes theoretical updating foundation ensuring the numerical modelling “legitimization” of wind effects (computational aerodynamics) on high-rise buildings, structures and complexes. Basic governing equations, requirements for computational model (boundary conditions, initial conditions, geometric model, spatial model discretization (computational grid), several numerical analysis parameters, research scheme, the peak pressure values design assessment for facade (enclosing) structures, pedestrian comfort analysis and the numerical method software implementation for wind loads computing are under consideration.

1. General remarks
As it is known, it is necessary to be guided by the section 11 of SP 20.13330.2016 “SNiP 2.01.07-85” “Loads and Impacts” [1] for the wind loadings determination on high-rise buildings, structures and complexes in Russia. For construction objects of high level of responsibility with unique architectural form and constructive solutions, as well as in cases not covered by clause D.1 of Appendix “D” from [1], wind loads computing must be performed using more accurate techniques such as numerical modeling and experimental modeling based on the wind tunnel simulation with allowance for necessity of reproducing the atmospheric boundary layer. Corresponding modifications are presented in [2]. In determining the wind load, structural engineer must consider the following aspects: space-planning, architectural and structural solutions of designed high-rise buildings, structures and complexes; the local terrain nature; the nearby buildings (surrounding buildings) impact; meteorological information about the construction area.

It is necessary to determine the following loads and impacts when designing the high-rise buildings, structures and complexes.

1. Wind loads on load-bearing structures. It is necessary to compute the following loads:
   - average and dynamic (amplitude or half-size) components of total design wind loads on the load-bearing structures in the building axes or in the wind axes (for instance, FX is the drag force, FY is the force across the wind flow, FR is the load vector sum; MZ is the torque moment relative to the building
central axis) for several wind directions (the recommended number of wind directions is equal to 24, angular step is equal to 15°);

- average \( f \), dynamic (amplitude or half-size, \( \text{fdyn} \)) components of force per unit length and dynamic magnification factor \( (\text{kdyn} = \text{fdyn}/f) \) for the corresponding component (aerodynamic load collection surface in the floor level) of each floor in the building / structure;

2. Wind loads on facade/enclosing structures. It is necessary to compute the following loads:

- envelopes of the maximum and minimum pressure values on the facade/enclosing structures for all wind directions;

- envelopes of the maximum and minimum wind pressure values calculated on the facade structures on the floor; the wind pressure maximum values upper envelope isofield, the wind pressure minimum values lower envelope and the corresponding wind attack angles at which these envelopes are realized;

- the average and pulsating components of the computed wind pressure on the facade/enclosing structures for the most dangerous wind directions.

3. Wind impacts in pedestrian areas (pedestrian comfort analysis). It is necessary to consider the computed fields of wind speed magnification factors wind velocity gain factors (relative wind velocities in gusts) in the pedestrian zone (at a height of 1.5 meters) and computed pedestrian comfort levels (the wind velocity repeatability in gusts) according to three regulatory criteria.

4. Analysis of aero elastic instability emergence possibility of buildings and structures. Aero elastic instability of buildings, structures (which dimensions correspond to the condition \( h/d > 7 \), where \( h \) is the height, \( d \) is the transverse minimum size) and structural members includes the following effects:

- resonant vortex excitation; galloping in a wipe; divergence (for buildings with an asymmetrical cross-sectional shape of typical floors, as well as in cases where the typical floors mass center does not coincide with their rigidity center); flutter (for billboards installed on high-rise buildings and structures, as well as for hinged facade structures).

When designing the high-rise buildings, structures and complexes, special constructive solutions should be used in order to exclude the aerodynamically unstable vibrations excitation and satisfy the dynamic comfort conditions for the people being in them (MGSN 4.19-05, Appendix P.6.1 [3]).

5. The comfort level analysis of being on the upper floors for visitors, co-workers and service personnel under the wind load action. This comfort level can be estimated in accordance with the buildings overlap computed acceleration from the wind load.

2. The wind effects numerical modeling on high-rise buildings, structures and complexes

2.1. Theoretical foundations.

Wind flows computing and impacts are reduced to the numerical solution [4] of three-dimensional (3D) nonstationary nonlinear hydrodynamic equations in the Navier-Stokes formulation [5]:

\[
\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right); \tag{1}
\]

\[
\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right); \tag{2}
\]

\[
\rho \frac{\partial w}{\partial t} + \rho u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right), \tag{3}
\]

where \( u, v, w \) are the unknown components of the velocity vector (along \( x, y, z \) axes); \( p \) is the pressure; \( t \) is the time; \( \mu \) is the viscosity for air dynamic coefficient; \( \rho \) is the density.

The equations of continuity (conservation of mass) and state must be satisfied

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0; \rho = \text{const.} \tag{4}
\]
In order to simplify modeling, wind flows are assumed to be incompressible and isothermal, mass forces are not taken into account.

Direct solution of equations (1) - (4) with allowance for vortices of all scales (DNS, Direct Numerical Simulation) with modern computer capabilities is practically feasible only for very low flow rates and purely research problems. Let us consider the basic approaches to modeling turbulence.

1. Large Eddy Simulation (LES). This method is the second most labor intensive of the existing approaches after the DNS. The idea of this method is to “filter” the parameters (characteristics) of turbulent flow from short-wave inhomogeneities. Spatial averaging over domains with dimensions of the order of the filter is used. Therefore, the vortex structures with sizes larger than the filter sizes are solved “exactly”, and the smaller vortex structures are modeled by the “subgrid” turbulence models.

2. Reynolds Averaged Navier-Stokes Equations (RANS). This method is based on a semi-empirical approach based on decomposing velocity into time-averaged and pulsating components. As a result of the corresponding transformations of the Navier-Stokes equations, additional unknowns appear (the so-called shear “Reynolds” stresses). The system turns out to be open loop and requires additional agreements (“models of turbulence”).

3. Detached Eddy Simulation (DES). This approach resides in the fact that “disconnected” energy-carrying vortices that inhabit the separation zones are computed “exactly” by the LES method, and RANS models describe the areas of the attached boundary layers.

Semi-empirical approach to solution of practical science-intensive engineering problems dominates in modern computational practice. This approach is based on the velocity decomposition into the time-averaged and pulsation components and transition to solution of so-called “Reynolds-averaged Navier-Stokes equations (RANS):

\[
\frac{\partial}{\partial t}(\rho \overline{u_i}) + \frac{\partial}{\partial x_i}(\rho \overline{u_i} \cdot \overline{u_j}) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \rho \overline{u_i} \overline{u_j}\right]; \frac{\partial u_i}{\partial x_i} = 0, \ldots, \frac{\partial u_i}{\partial x_i} = 0,
\]

(5)

where \( p \) is the average pressure, indices \( i = 1,2,3 \) and \( j = 1,2,3 \) correspond to the coordinates \( x, y, z \). The shear (Reynolds) stresses \( \rho \overline{u_i} \overline{u_j} \) are the additional six unknowns to the averaged motion parameters (\( \overline{u_i}, \overline{p} \)). They are approximated, as a rule, by the Boussinesq hypothesis:

\[
\rho \overline{u_i} \overline{u_j} = -\mu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) + \frac{2}{3} \rho k \delta_{ij},
\]

(6)

where \( \mu_t \) is the additional viscosity caused by pulsations; \( k \) is the averaged energy of turbulent pulsations (TKE). The system is open loop and requires additional agreements (“turbulence models”).

Solution of (5) can be obtained within stationary and nonstationary formulations. Stationary problem is reduced to iterative solution of sparse system of linear algebraic equations with nodal pressures, velocity components, and local turbulence measures (particularly TKE) as unknowns.

2.2. Requirements for computational model.

2.2.1. Dimensions of computational domain.

The lateral border for a parallelepipeded-shaped computational domain must be located at least at \( 5H \) distance from the building center (where \( H \) is the size of the tallest building/structure), the back border of the domain (“outlet” is located downstream of the simulated building) is located at distance greater than or equal \( 10H \), the front border of the domain (“inlet” is located downstream before the considering building) is located at distance greater than or equal \( 5H \), the upper boundary of the domain (height of the computational domain) is located at distance greater than or equal \( 5H \). For a cylinder-shaped computational domain, the radius is equal to 1-3 kilometers or at least \( 10H \).

2.2.2. Boundary conditions.
As the flow characteristics (boundary conditions at the “inlet”), wind velocity profiles and turbulence parameters (kinetic energy of turbulence and dissipation energy, intensity of turbulence and vortex scale) are set, corresponding to the computed values of loads taking into account the safety factor for load 1.4 and corresponding to specified wind regions and terrain types according to [1]. The turbulence scale is assumed to be 300 meters.

At the “outlet” “soft” Neyman boundary conditions (zero derivatives) are assigned with zero additional pressures and the same turbulence parameters as at the “input”.

Flow symmetry condition is set at the domain upper boundary. At the domain lower boundary and for all buildings/structures, special so-called condition of “No-Slip Wall” is set ($U = V = W = 0$), which excludes the substance penetration through the surface.

Equivalent roughness can be set for the walls. However, it is recommended to use “natural” modeling whenever possible (with allowance for model of the terrain, balconies and window openings, etc.) in order to take into account, the walls roughness instead of selecting the wall functions or the corresponding standard parameters correction.

2.2.3. Initial conditions

Zero velocities $U = V = W = 0$ are set as initial conditions in the entire domain. Zero additional pressures and turbulence parameters corresponding to the flow at the “inlet” are set in the entire domain as well. Besides, results of the converged preliminary analysis within stationary formulation can be used as initial conditions.

2.2.4. Geometric model.

The 3D geometric model of object (building, structure) or complex is constructed in accordance with initial (source) data (architectural and structural drawings). It should be noted that detalization of the object 3D geometric model is selected in accordance with the problem formulation. The highest level of the object geometry detalization (reproducing the actual facades shape (balconies, window openings, fire shutters, canopies, etc.) is necessary for the aerodynamic pressures adequate assessment, their local extremes and distribution over the object surface. Reasonable simplification of the object geometric shapes is allowed in case of computing only the integral aerodynamic loads on load-bearing structures.

When modeling real buildings, a nearby territory with a radius of 1-3 kilometers is considered. The surrounding building is modeled in a simplified manner according to the initial data (the situational plan drawings). Actual buildings/structures locations relative to the target object, their height and cross-section in the plan, as well as local terrain (height differences near the target object) are taken into account within the construction geometric model creation.

The computational air domain is formed as follows: after creation of 3D geometric models of the considering object and surrounding buildings geometric volumes of the target building/structure and buildings are “subtracted” from the airspace model (in the form of a parallelepiped or cylinder). Either the geometric volume of the target building/structure is “subtracted” from the airspace model (in the form of a parallelepiped or cylinder) (if the surrounding building is modeled by the “immersed boundary method”).

2.2.5. Spatial discretization of the model (computational grid (mesh)).

Finite volume method (FVM) is the most effective method in high-precision modelling of considered problems. It does not require such detailed modeling of the boundary layer as the finite element method (FEM), and it is more convenient when describing complex computational domains of real buildings than the finite difference method (FDM).

Before basic aerodynamic analysis of building/structure with allowance for surrounding buildings it is necessary to provide the verification and validation studies (checking grid convergence) for the model of the building/structure “in the open field”. The main objective is to select the optimal parameters of the computational grid directly on the surface and near the considering object. The recommended surface mesh initial value on the target object should not exceed the characteristic dimensions of the facade structures (near 1 meter). The number of computational cases (the number of mesh thickenings) must be greater or equal to 3.
Unstructured tetrahedral grid is created and nodal components are assigned (for the convenience of further assignment of boundary conditions) for computational geometrically complex real-world models of tall buildings and urban buildings.

The recommended parameters for computational grids for basic aerodynamic computational analysis are as follows. The grid (mesh) elements dimensions on the target object surface are equal to 0.5 meters; in the target object near zone (within a radius of ~ 0.5 km) the elements dimensions on the neighboring buildings/structures surfaces reach 4 meters, at a sufficient distance from the building the sizes on the surrounding building surfaces of buildings/structures reach 10 meters. On the surface of the ground and the surface air layer (~ 4 meters in height from the ground), the characteristic elements size is equal to 1.5 meters; in the case of pedestrian comfort, the surface air layer is chosen to be equal ~ 2 meters in height from the ground with a characteristic element size of 0.3 meters. The maximum element size in the computational domain reaches 16 meters (within a radius of 500-1000 meters, above 150 meters).

2.2.6. Parameters in numerical analysis.

The physical time of computing for nonstationary analysis is chosen so that the flow passes the entire computational domain at least 3 times.

The time step is chosen so that at least 10-20 points describe the period of oscillation of aerodynamic loads. Thus, we have Courant number

\[ C_0 = U_{max} \Delta t / \Delta x_{min} < 3, \]  

where \( \Delta x_{min} \) is the minimum size of the cell stream; \( U_{max} \) is the maximum flow rate.

High-resolution advection scheme and an implicit time integration scheme of the second order are used.

The convergence and termination criterion for stationary formulation is the maximum residuals \( 10^{-3} – 10^{-5} \) given level achievement and reaching asymptote dependence of the aerodynamic forces on the step number (conditional time).

The criterion of convergence and termination for nonstationary formulation is the transition to stable flow regime. It is monitored by the aerodynamic forces periodic nature time dependences, and by the achievement of a given level of maximum residuals \( 10^{-3} – 10^{-5} \). In this case, the maximum iterations number at a step is taken to be 5 – 10.

2.3. Research scheme.

Research scheme includes the following stages.

1. Analysis of the wind regimes of the construction area, the local terrain of the construction site, existing buildings, structural and architectural features of the considering object. Construction of boundary and initial conditions for flow in the computational domain (subsections 2.2.2-2.2.3).

2. The wind aerodynamics 3D models development of the considering object without taking into account the surrounding buildings (“in the open field”).

3. Validation of a numerical model with the use of various computational grids with different degrees of discretization (verification of grid convergence; subsection 2.2.5). The grid main parameters choice on the surface of the considering object, on the borders and inside the computational domain for further basic multivariate computational studies.

4. The wind aerodynamics 3D models development of the considering object with allowance for surrounding buildings.

5. Aerodynamic analysis of building/structure models “in the open field” with allowance for surrounding buildings within stationary formulation for several wind directions (the recommended number of wind directions is equal to 24, angular step is equal to 15º).

6. According to the multivariate aerodynamic analysis, within stationary formulation results the following aspects are determined:

wind loads on load-bearing structures; wind loads on facade/enclosing structures; wind impacts in pedestrian zones (pedestrian comfort analysis); possibility analysis of the aero elastic instability of
buildings, structures, structural members (such as galloping, wraparound galloping and divergence); analysis of comfort level for visitors, employees and service personnel to stay on the upper floors of building under the wind load action.

The average design wind pressures are computed as a result of stationary analysis, the dynamic component, the maximum and minimum pressures are computed with the use of the method presented in section 2.1.

1. After considering results of multivariate aerodynamic analysis, within stationary formulation the most dangerous wind directions are determined from the point of view of the realization of maximum loads on the load bearing and facade structures. Wind velocities growth in pedestrian areas that do not meet the criteria for pedestrian comfort is considered. Accelerations of the building/structure overlap, which are greater than 0.08 m/s², and possibility of aero elastic vibrations due to wind exposure are under consideration as well.

2. Analysis within nonstationary formulation is performed for the selected wind directions. In case of significant difference in average values, it may be necessary to perform the nonstationary analysis for numerous wind directions or “all” wind directions.

3. According to the aerodynamic analysis within nonstationary formulation results, the following parameters are determined:
   – pulsation component refined values of criterial parameters (computed values of pressure and wind velocity, total loads on the load-bearing structures), kinetic energy of turbulence;
   – safety (use) factor (section 2.1);
   – frequency parameters (characteristics) of wind exposure, pressure pulsation spectra in characteristic points of the surface;
   – updated wind impacts in pedestrian areas (pedestrian comfort analysis);
   – possibility of aero elastic instability of buildings, structures and their structural members such as vortex resonance and flutter;
   – comfort level for visitors, employees and service personnel to stay on the upper floors of the building when the wind load is applied.

2.4. Design assessment of peak pressure values for facade/enclosing structures.

The so-called safety factors are the extreme pressures variation range main characteristics on facade structures. Their values are determined by the nonstationary analysis results based on the ratios:

$$\theta_{\text{max}} = \frac{(P_{\text{max}} - P)\sigma_p}{\theta_{\text{max}}} = \frac{(P - P_{\text{min}})}{\sigma_p},$$

where $P_{\text{max}}$, $P_{\text{min}}$ and $P$ are the computed values of minima, maxima and average pressure at a point on the surface; $\sigma_p$ is standard deviation of pressure.

Due to extreme labor-intensiveness of variant nonstationary analysis, special practical method for estimating of peak design loads on facade structures, $(P_{\text{max}}$ and $P_{\text{min}}$) based on the turbulent pulsations TKE energy stationary analysis results with allowance for averaged safety factors $\theta_{\text{max}}$ and $\theta_{\text{min}}$ is applied to minimize the computation amount.

In this case, first it is necessary to compare the corresponding values obtained after stationary analysis and after nonstationary analysis. In accordance with the structural analysis practical problems solution experience, the average pressures are computed with practical accuracy (up to 5%). The kinetic energy of pulsations within stationary analysis is often underestimated, which can be “compensated” by a corresponding increase in safety factors.

We have the following main formulas:

$$P = \rho V^2/2; \quad \text{TKE} = 3/2 \cdot (I \cdot V)^2 = 3 \cdot P / \rho \cdot I^2; \quad I = (\rho \cdot \text{TKE} / \text{abs}(P) / 3)^{1/2}; \quad \sigma_p = (I^2 + 2 \cdot I) \cdot \text{abs}(P); \quad P_{\text{max}} = P + \sigma_p \cdot \theta_{\text{max}}; \quad P_{\text{min}} = P - \sigma_p \cdot \theta_{\text{min}}; \quad P_{\text{pulse}} = (P_{\text{max}} - P_{\text{min}})^{\nu/2},$$

$$\theta_{\text{max}} \in [0, 1], \quad \theta_{\text{min}} \in [-1, 0], \quad \nu \in [1, 2].$$
where $\sigma_p$ is the standard pressure deviation (standard) $P$; $I$ is the turbulence intensity (standard of velocity pulsations); $V$ is local wind velocity; $\nu$ is pressure correlation coefficient on surfaces (for preliminary estimates it is defined in accordance with [1]; further it will be computed as a nonstationary analysis result).

The wind loads computing results on the facade structures and the velocity distribution around considering object can serve as baseline data for more detailed and sophisticated analysis of flows distribution near the facade structures with allowance for temperature difference and leakage into the air space between the wall and the curtain wall. This may lead to increase or decrease in the design wind loads on the facades.

2.5. Pedestrian comfort analysis.
After computational analysis for “all” wind directions (16 or 24 rhumbs are normally used), the results are processed using a special computer module. The growth values in the characteristic building points are summed with the weight coefficients corresponding to the frequency of a given direction wind impact occurrence and a given velocity range. It should be noted that 1.5 meters are taken as the estimated height.

After numerical modeling for “all” wind directions (as a rule, $j = 1,2,...,24$) “time of discomfort of the $l$-th level” $K_{ctl}$, $l = 1,2,3$ for a representative pedestrian zones points set is determined by the relations:

$$K_{ctl} = \sum S_{ij}T_{ij} \quad V_{ij} = V_i/V_{10} (V_j + \theta \cdot I),$$

where $V_i$, $i = 1,2,3$ are the velocities in the table of weather data (wind rose); $T_{ij}$ is the duration (in accordance with meteorological data, hours per year) of wind direction $j$ influence; and average velocity $V_i$; $V_j$ is the average wind velocity at this point according to the corresponding analysis for the direction $j$ at the velocity $V_{10}$ at height of 10 meters; $V_{ij}$ is the maximum velocity at a point in gusts at wind velocity $V_i$; $\theta$ is the safety factor for the analysis task (usually in the range from 1 to 3); $S_{ij}$ is an indicator (with values 0 or 1) that the local wind velocity $V_{ij}$ exceeds the critical value $V_{ctl}$ for a given level of comfort $l$; $I = (\rho \cdot \text{TKE}/\text{abs}(P)/3)^{1/2}$ is intensity of turbulence (standard of velocity pulsations); $P = \rho V^2/2$ is the average pressure; $\text{TKE} = 3/2 \cdot (I \cdot V)^2$ is the turbulent pulsations energy.

The wind rose is defined according to the weather data. Weibull distribution is used normally (in practice) in order to estimate the distribution of wind over velocity inside the rhumb,

$$f(u) = (k/c) \cdot (u/c)^{k-1} \exp[-(u/c)^k].$$

The parameters $c$ and $k$ values are determined at the specific meteorological data approximation stage. The shape parameter $k$ can be determined using the wind velocity integral repeatability graph, built in logarithmic coordinates. The integral repeatability of wind velocity in % of the total number of cases of observations is plotted on the abscissa axis, and the wind velocity value in m/s is plotted along the ordinate axis. The experimental data application on such a graph gives, as a rule, a linear relationship. The inclination angle cotangent of a straight line to the $x$-axis gives the value of the parameter $k$.

The best fit to the experimental data is obtained with the values of the parameter $k = 1.8 - 2.3$ and the parameter $c$ close to the value of the average wind velocity.

The standard deviation (standard) of the pulsation velocity component is estimated from the turbulent pulsations TKE energy stationary analysis results taking into account the safety factor $\theta = 2$.

$$\sigma = \sqrt{2/1.5 \cdot \text{TKE}}.$$  

Wind velocity with gusts ($V_{ij}$ in corresponding formula) is determined using the average velocity $V_m$ with the following formula use
\[ V_{\text{max}} = V_m + \sigma \theta. \]  \hspace{1cm} (15)

Pedestrian comfort analysis within nonstationary formulation is advisable only after field measurements of wind velocities and pulsations directly on the construction site.

2.6. Software implementation of the numerical method for computing of wind loads.

Mathematical and numerical modeling approaches of fluid dynamics problems, considering in the distinctive paper as a rule are programmed in research (including open source) and commercial software products, such as ANSYS CFD (CFX, Fluent), SIMULIA Abaqus, LS-DYNA, Star-CCM, Flow Vision, OpenFOAM.

Summary

Functionally, corresponding software product consists of three relatively independent modules including preprocessor, solver, and postprocessor. The preprocessor objective is to import the computational grid, specify the type of the problem to be solved, select the simulation environment and define the initial and boundary conditions. The solver has a number of features that allow flexible and efficient organization of the computational process. Besides, some software products have the ability to perform parallel computing. The postprocessor supports the necessary functions for analyzing, processing and visualizing of information, it is possible to create graphs and animations.

Carrying out a large amount of multivariate computations (in particular, with different wind directions), an important advantage of some software products is the presence of a built-in programming language that supports the parameters, arrays, request information from databases, input/output to text files, cycles, conditional branching, built-in math functions, macros, encryption, etc., the ability to create user-defined typical models - “primitives”, to include user-defined algorithms.

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