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СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ



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Modern Approaches to Studying the Aerodynamic Stability of Complex Curvilinear Buildings



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Abstract

Introduction. Modern architecture is characterized by the extensive use of buildings with complex curvilinear forms that are high expressive yet require tackling new engineering challenges associated with ensuring their aerodynamic stability. Normative methods for calculating wind loads are largely focused on buildings with a simple geometric shape and fail to account for the flow characteristics of free-form shells. This highlights the need to systematize modern approaches to analyzing wind effects on such structures. The aim of the study is to summarize and compare normative, experimental, and numerical methods for assessing the aerodynamic stability of complex-shaped buildings.

Materials and Methods. The object of the study is a building with a biomorphic three-beam structure characterized by smooth contours and a complex spatial topology. In order to analyze its aerodynamic characteristics, numerical simulation of wind flow was performed using the RWIND Simulation software. The study was conducted in order to identify the flow characteristics and distribution of aerodynamic loads on the surface of a complex-shaped building.

Research Results. As a result of the calculations, distributions of the pressure, velocity, and pressure coefficients over a building surface were obtained. Zones of a local pressure increase and dilution were identified in the areas of volume junctions and roof recesses. It was found that the curvilinear form of a building contributes to a reduction in the overall aerodynamic drag; however, it also induces the formation of local vortex structures, which is to be considered in designing façade and roofing systems.

Discussion and Conclusion. The results confirm the effectiveness of applying Computational Fluid Dynamics (CFD) methods for analyzing the aerodynamic properties of complex-shaped buildings. The integrated use of normative, experimental, and numerical approaches ensures a more accurate assessment of wind effects and contributes to developing a cutting-edge methodology for designing aerodynamically stable architectural structures.

Keywords: aerodynamic stability of buildings, wind effects, complex-shaped buildings, curvilinear shells, computational fluid dynamics, numerical simulation, aerodynamic pressure, vortex flow structures, wind loads on structures

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Современные подходы к исследованию аэродинамической устойчивости зданий сложной криволинейной формы

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Аннотация

Введение. Современная архитектура характеризуется активным использованием зданий сложной криволинейной формы, обладающих высокой выразительностью, но требующих решения новых инженерных задач, связанных с обеспечением их аэродинамической устойчивости. Нормативные методы расчёта ветровых нагрузок ориентированы преимущественно на здания простой геометрической формы и не учитывают особенностей обтекания свободных оболочек. Это обуславливает необходимость систематизации современных подходов к анализу ветрового воздействия на подобные сооружения. Целью настоящего исследования является обобщение и сравнение нормативных, экспериментальных и численных методов оценки аэродинамической устойчивости зданий сложной формы.

Материалы и методы. Объектом исследования является здание с биоморфной трёхлучевой структурой, характеризующееся плавными очертаниями и сложной пространственной топологией. Для анализа аэродинамических характеристик выполнено численное моделирование ветрового потока с применением программы RWIND Simulation. Исследование выполнено с целью определения особенностей обтекания и распределения аэродинамических нагрузок на поверхность здания сложной формы.

Результаты исследования. В результате выполненных расчетов получены распределения давления, скоростей и коэффициентов давления по поверхности здания. Выявлены зоны локального повышения и разрежения давления в областях сопряжения объёмов и углублений кровли. Установлено, что криволинейная форма здания способствует снижению интегрального аэродинамического сопротивления, однако вызывает образование локальных вихревых структур, которые необходимо учитывать при проектировании фасадных и кровельных систем.

Обсуждение и заключение. Полученные результаты подтверждают эффективность применения методов вычислительной гидродинамики (CFD — Computational Fluid Dynamics) для анализа аэродинамических свойств зданий сложной формы. Комплексное использование нормативных, экспериментальных и численных подходов обеспечивает более точную оценку ветровых воздействий и способствует формированию современной методологии проектирования аэродинамически устойчивых архитектурных сооружений.

Ключевые слова: аэродинамическая устойчивость зданий, ветровое воздействие, здания сложной геометрии, криволинейные оболочки, вычислительная гидродинамика, численное моделирование, аэродинамическое давление, вихревые структуры обтекания, ветровые нагрузки на сооружения

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Introduction. The architecture of the 21st century is characterized by a surge in the number of buildings and structures of complex curvilinear shapes. In conjunction with use of new composite materials and systems of enclosing structures, modern technologies of design, modeling and construction enable implementation of architectural ideas that used to be considered utopian. Renewed interest in curvilinear architectural structures is a testimony to the reemergence of the trends that date back to the late 20th century, when plastic and biomorphic forms started being considered as a tool of combining aesthetics, functionality and engineering rationality [1]. Concert halls with shell coverings, museums with asymmetric volumes, sports arenas with domed and combined roofs, as well as high-rise complexes with facades containing bends, twisted and torsion elements are emerging in the largest global megacities. Such structures are a cornerstone of the modern architectural image of cities becoming visual representations and symbols of a regional cultural identity.

The growing proportion of buildings with a non-standard geometry is posing new engineering challenges. One of the major factors critical to safety, operational reliability and durability of such structures is their aerodynamic stability under the influence of wind loads [2]. Unlike the traditional rectilinear or cylindrical shapes, curvilinear structures create a complex structure of airflow flow accompanied by intense eddy formation, local separation zones and pressure concentration [3]. These cause loads to distribute unevenly over the surface, enhance oscillatory processes and in some cases

might generate resonant effects. On top of that, local high-pressure areas might damage facade systems, translucent structures, and roofing elements. In the context of dense urban development, the interaction between adjacent buildings exacerbates the aerodynamic pattern increasing local vortex zones as well as pressure on enclosing structures [4].

The issue of an adequate assessment of a wind impact on buildings of complex shape is a daunting one. In engineering practice, regulatory methods fixed in national and international standards are still dominant. In Russia, the main documents are SP 20.13330.2016 "Loads and Impacts" and SP 267.1325800.2016 "Buildings and Structures. Design Rules for Wind Impacts", regulating methods for identifying calculated wind pressure, aerodynamic drag coefficients and dynamic characteristics. Overseas similar provisions are contained in Eurocode EN 1991-1-4, ASCE 7-22, AIJ Recommendations for Loads on Buildings (Japan) and GB 50009-2012 (China). These documents define the core principles of calculating wind loads, but their application to objects with complex geometries is restricted as the calculated dependencies have been developed for bodies of simple shapes — prismatic, cylindrical and domed ones.

At the same time, experimental and numerical methods for investigating wind impacts are actively developing. Wind tunnel aerodynamic tests provide a high degree of accuracy and allow identification of local pressure concentration zones, flow separation and formation of turbulent structures. Field measurements on actual structures provide an insight into the actual behavior of buildings in conditions of natural wind, however, they call for considerable financial and time resources.

Numerical methods based on solving Navier-Stokes equations have been developed within the CFD approach that involves discretization of a calculation domain and numerical solution of equations of motion and conservation of mass for a flow being studied. Use of CFD makes it possible to analyze nonstationary three-dimensional aerodynamic processes around objects of almost any configuration as well as to obtain detailed fields of velocities, pressures, and vortex structures. The accuracy of such calculations is largely due to a choice of the turbulent model (RANS — Reynolds-Averaged Navier-Stokes, LES — Large Eddy Simulation and hybrid DES — Detached Eddy Simulation) [5, 6], correctness of the boundary conditions and a degree of detail of a calculation grid.

The state of the art in the field of aerodynamic stability of buildings of complex geometry is thus characterized by a broad range of approaches, but the shortage of a unified methodology to ensure both the accuracy of calculations and their practical applicability. This serves to highlight the need for a comprehensive analysis of architectural and construction aerodynamics considering the relationship between shape, structure and air flows [7]. There is an imperative to systematize the existing methods, compare their capacities and limitations as well as to develop a strategy for further development of this scientific and technical field.

The aim of the study is a comprehensive analysis of the modern approaches to studying wind effects on buildings of a complex curvilinear shape. The paper discusses the provisions of the regulatory framework, experimental methods of aerodynamic testing and modern CFD modeling technologies. Special attention is paid to a comparative assessment of accuracy, computational efficiency and integration of these methods within a single methodological system.

Materials and Methods. The study of the aerodynamic stability of buildings with complex curvilinear shapes relies on the analysis of the three major groups of methods: normative, experimental and numerical (CFD) ones. This division reflects the state of the art in engineering practice and allows comparisons of their accuracy, scope and limitations.

Normative methods for calculating wind effects are based on generalizing statistical data from long-term meteorological observations and results of aerodynamic experiments for typical building geometries. In domestic practice, calculations are regulated by the document SP 20.13330.2016 "Loads and Impacts" where the estimated wind speed and pressure are identified taking the wind area, terrain category and height of the structure into consideration. According to modern research, the existing regulatory dependencies developed mostly for buildings of a simple shape demonstrate a limited scope of applicability in analyzing objects with a complex or curvilinear geometry leading to a decrease in the accuracy of calculations of aerodynamic loads [8].

Experimental methods include aerodynamic tests in wind tunnels and field measurements making it possible to obtain pressure and velocity distributions along the surface of building models [2, 9]. Modern research makes use of highly sensitive pressure sensors, as well as flow visualization techniques such as PIV (Particle Image Velocimetry) and digital anemometry. Use of scale models of fragments of urban development enhances the realism of the resulting data, which is of particular importance for buildings located in a dense urban environment [10]. In spite of their high degree of accuracy, such tests call for considerable material and time costs with their results frequently limited to specific flow scenarios. Experimental methods are thus largely employed in order to verify numerical models and refine turbulence parameters.

Numerical methods (CFD) are a universal tool for analyzing wind impacts on buildings of complex shapes. They make it possible to investigate three-dimensional unsteady flows and evaluate the influence of a shape, angle of attack, and surface roughness on the aerodynamic characteristics [11]. As part of this study, a computational model of the building was designed in the Rhinoceros 3D environment and exported to the RWIND Simulation software package that implements a method for finite-volume solution of Navier-Stokes equations in a stationary formulation using the turbulent

$k-\omega$ SST model [12, 13]. The program automatically generates an adaptive finite-volume grid thickened in areas of an increased curvature and expected flow separation. Depending on a tasks at hand, various turbulent models can be employed - RANS, LES, and hybrid DES [5, 6, 14]. CFD analysis provides detailed pressure fields, velocities, and turbulent energy, visualization of vortex structures, and identification of aerodynamic coefficients. Special attention is paid to the quality of a calculation grid and correctness of the boundary conditions the reliability of the results depends on [15].

The integrated application of normative, experimental and numerical approaches provides a comprehensive assessment of the aerodynamic stability of buildings. Normative methods set the initial design guidelines, experimental tests refine the pressure distribution, and CFD modeling indicates the spatial structure of the flow and zones of local aerodynamic effects. This integrated approach lays the foundation for the modern methodology for analyzing and designing buildings of a complex shape ensuring their stability, safety and durability.

Research Results. The object of the numerical analysis is a building with a smooth curved architectural form with no clearly defined faces and a three-ray structure typical of modern biomorphic forms (Fig. 1). According to the plan, the building is a three-ray structure formed by three interconnected oval volumes united in the central part. This geometry makes it possible to investigate the features of the interaction of flows in the areas of volume coupling and those with variable surface curvature. The streamlined contour of the building contributes to the uniform redistribution of the incoming airflow and reduces the intensity of local vortex formations.



Fig. 1. Architectural rendering of the object

The roof surface has a continuous smoothed geometry with three large oval depressions with glazed dome structures inside it. These depressions form closed contours that smoothly interface with the main body of the building, which avoids sudden changes in the curvature and minimizes the likelihood of areas of a local increase in the aerodynamic drag. Visually, the shape of the building resembles a biomorphic shell seamlessly integrated into the surrounding space and adapted to the wind flow direction.

A digital geometric model was designed in the Rhinoceros 3D environment using the NURBS representation of geometry (Fig. 2) making it possible to accurately reproduce the curved shape of the shell with controlled radii of curvature and ensure a high degree of correspondence between the architectural concept and the calculated model [11, 15]. Based on the designed model, the surface was prepared for CFD analysis in the RWIND Simulation software environment [3, 14, 15] where algorithms for generating an adaptive finite-volume grid and modeling wind flows around complex spatial shapes are implemented.

Numerical analysis of aerodynamic stability was performed in RWIND Simulation using the finite volume method for solving Navier-Stokes equations in a stationary formulation [3, 11]. $K-\omega$ SST was employed as a turbulent model [12] that provides an accurate description of the flow in the boundary layers and correct modeling of flow separation zones on curved surfaces [3, 14]. A three-dimensional computational domain was defined for the calculation that ensures the free development of the flow with no boundary effects. A uniform velocity profile with a maximum value of 41.2 m/s was set at the input. The outlet boundary was identified by the condition of zero pressure gradient, upper and side surfaces by the condition of free sliding. The surface of the building was assumed to be rough making it possible to take the influence of the microrelief of the roof and facade elements into consideration.

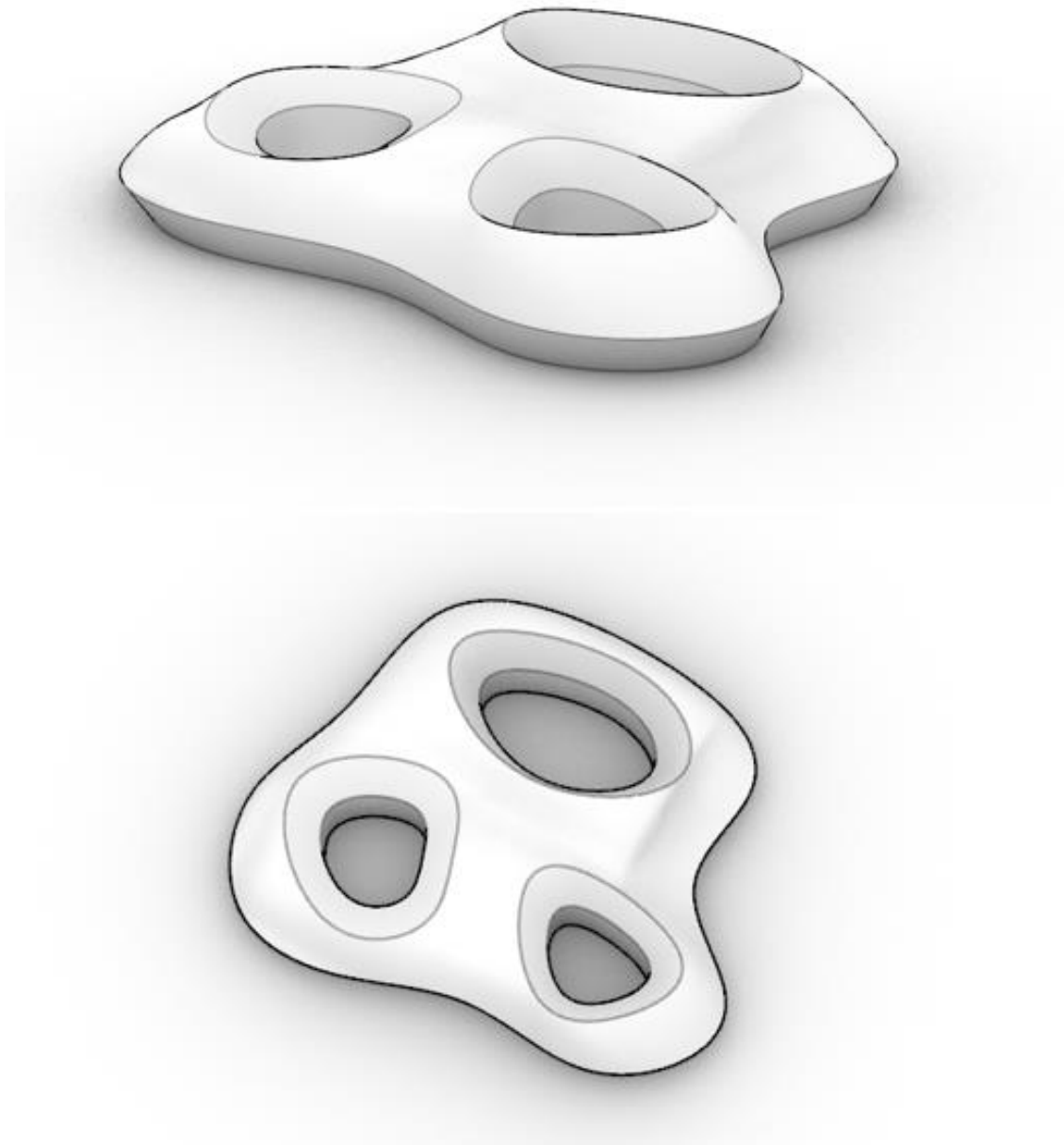


Fig. 2. Digital NURBS-shell model

The results of the numerical simulation include three-dimensional fields of static pressure, aerodynamic coefficient (c), velocities and trajectories of an air flow. Fig. 3 shows the distribution of static pressure over the building surface. The maximum positive values of +574 Pa are observed in the windward sections of the shell, mostly in the front convex zones and in the central part perpendicular to the wind direction. In the areas between the oval depressions and in the rear part of the structure, negative pressure values up to –864 Pa are recorded, which is indicative of the formation of rarefaction zones and local vortex structures.

Fig. 4 shows the distribution of the aerodynamic coefficient C . The highest values ($C = 1.02$) occur in the frontal sections of the roof where the air flow is inhibited. The minimum values ($C = -1.54$) are observed in the depressions and behind the rear edges of the volumes where recirculation zones are formed, i.e., areas of reverse flow movement accompanied by reduced pressure and eddy formation. Data analysis confirms that there are stable vortex structures in the inter-petal regions causing pressure pulsations and an increase in the dynamic component of the wind load [13].

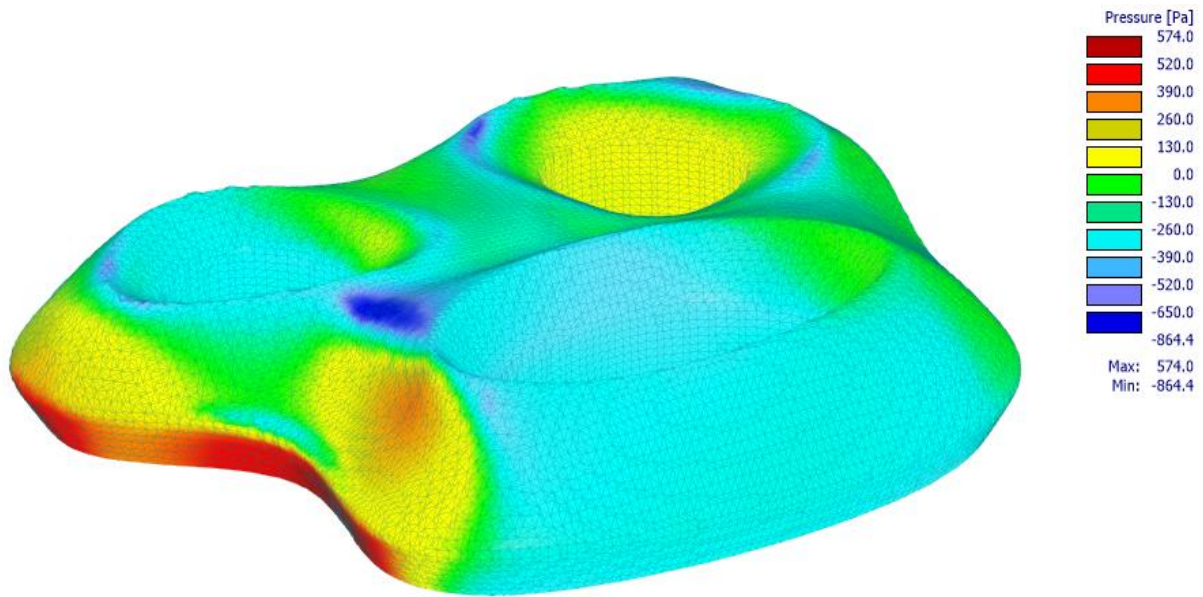


Fig. 3. Static pressure on the building surface

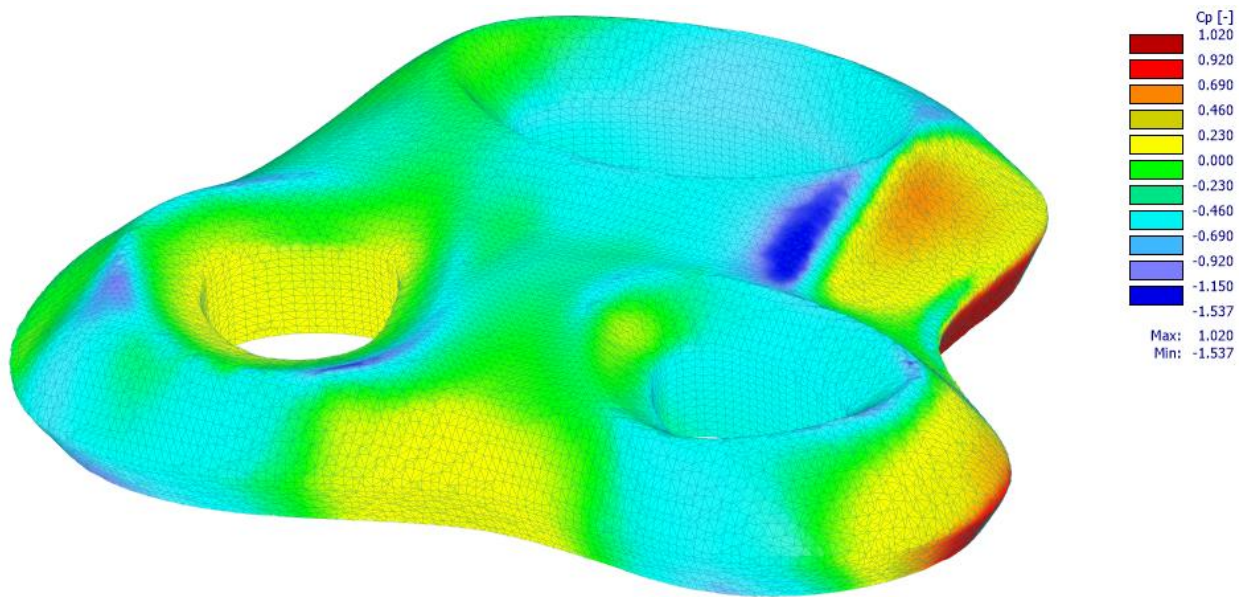


Fig. 4. Pressure coefficient distribution C_p

Fig. 5 shows the velocity distribution in the flow section. Along the surface of the building, the flow velocity decreases to 3–5 m/s in the boundary areas and vortex formation zones, whereas the acceleration to 30–35 m/s is observed between the main volumes. A large-scale vortex wake forms above the central part gradually fading as it recedes. This flow structure is typical for aerodynamically streamlined but geometrically complex shapes combining smooth transitions and the mutual influence of conjugated shell elements.

Numerical modeling has thus confirmed the high aerodynamic efficiency of curvilinear architectural forms in the presence of smooth interface surfaces. The results make it possible to quantify the distribution of wind loads and visualize the flow structure, which is a critical step in optimizing the architectural shell and increasing the reliability of complex-shaped building structures.

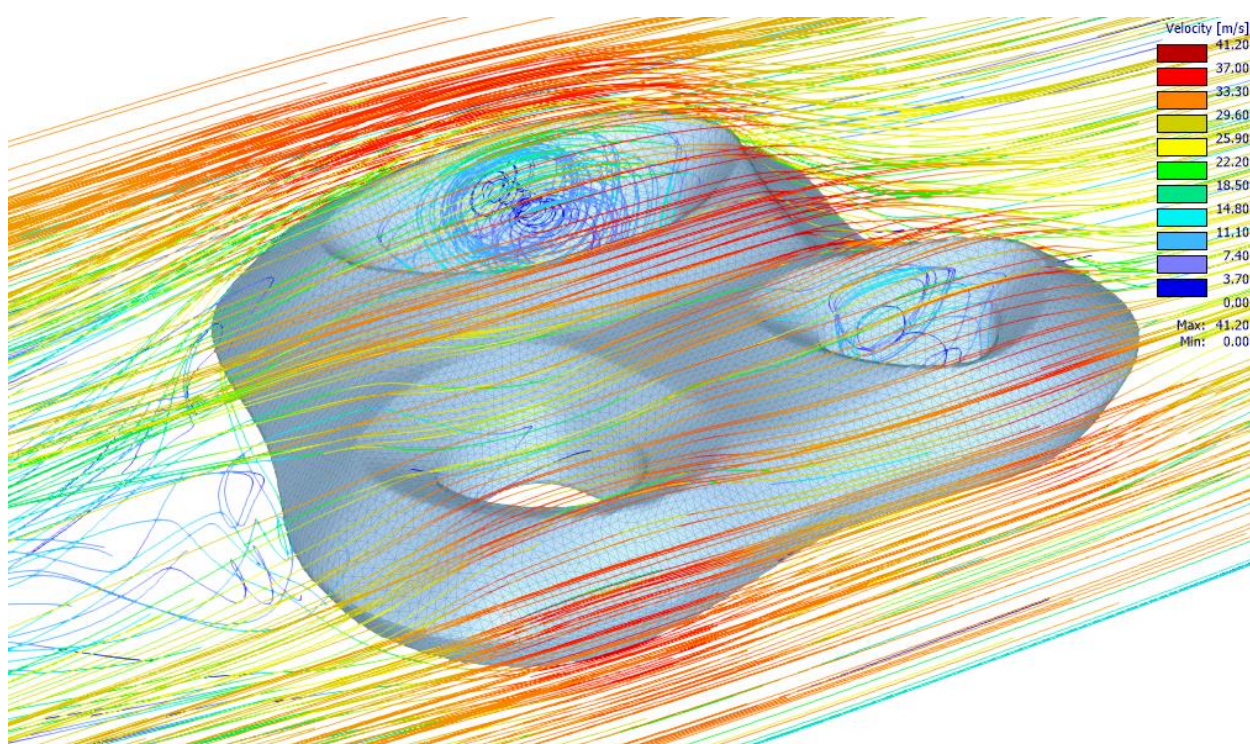


Fig. 5. Velocity distribution in the flow section

Discussion and Conclusion. The research has shown that architectural objects with a distinct curvilinear geometry have not only a high aesthetic and functional value [1], but also place increased demands on the aerodynamic stability and accuracy in calculating wind impacts. The analysis of normative, experimental, and numerical approaches has confirmed that the traditional methods based on the simplified models and averaged coefficients are not sufficiently accurate while calculating complex-shaped buildings. At the same time, use of modern computational aerodynamics tools can serve to considerably increase the reliability of projections and detail a flow pattern.

Using the example of a building with a three-beam shell, it is shown that the combination of Rhinoceros 3D and RWIND Simulation software environments provides a possibility of a comprehensive analysis of the aerodynamic characteristics. Use of the turbulent $k-\omega$ SST model [12] made it possible to correctly reproduce vortex structures and identify the pressure distribution over the surface as well as the areas of local loads and potential instability. The results are consistent with data from overseas studies [11, 13] and confirm the efficiency of the CFD approach in analyzing buildings with a free architectural plastics.

Integration of the numerical analysis methods is at the core of the modern methodology for designing buildings of complex geometry ensuring the relationship between an architectural concept and engineering reliability. Use of CFD modeling in the early stages of design makes it possible to identify unfavorable aerodynamic zones, optimize the geometry of the shell and prevent resonant vibrations. This approach contributes to enhancing safety, durability and energy efficiency of structures and is in compliance with the principles of sustainable architectural development.

The prospects for further research are integrating the numerical and experimental methods, designing unified databases of aerodynamic coefficients for typical geometries as well as introducing digital building doubles for monitoring wind impacts in the operating conditions [16]. On top of that, the urgent task is yet to improve the national regulatory framework including SP 20.13330.2016 and SP 267.1325800.2016 bringing their provisions in compliance with the international standards Eurocode EN 1991-1-4, ASCE 7 and AIJ Recommendations.

The implementation of these directions will enable a single comprehensive methodology for analysis and design ensuring improved calculation accuracy, operational reliability and stability of buildings of a complex curvilinear architecture.

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Claimed contributorship:

MI Telemakov: formation of the basic concept, aims of the study, development of building geometry, calculations, preparation of the manuscript, analysis of the research results, visualization of data, systematization of modern approaches to the analysis of wind impacts, comparative analysis of normative and numerical methods, formation of the conclusions;

NA Buzalo: scientific supervision, analysis of the research results, revision of the manuscript, correction of the conclusions.

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