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Numerical simulation of the transverse flow over spans of girder bridges *

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Численное моделирование поперечного обтекания пролетных строений балочных мостов***

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Introduction. The technique of numerical modeling of the transverse flow over span structures of bridges on the basis of the two-dimensional URANS (Unsteady Reynolds-averaged Navier-Stokes) approach used in the modern methods and software packages for computational fluid dynamics is verified. The work objective was debugging and experimental substantiation of this technique with the use of the database on the aerodynamic characteristics of the cross-sections of span structures of girder bridges of standard shapes pre-developed by the authors.
Materials and Methods. A numerical simulation of the transverse flow of low-turbulent (smooth) and turbulent air flows around the bridge structures in a range of practically interesting attack angles is carried out. SST $k-\omega$ turbulence model was used as the closing one. The technique was preliminarily tested on the check problem for the flow of the rectangular cross-section beams. Calculations were carried out using the licensed ANSYS software.
Research Results. The calculated dependences on the attack angle of the aerodynamic coefficients of forces (drag and lift) and the moment of the cross sections of the girder bridges of standard shapes are obtained. These data refer to the span structures at the construction phase (without deck and parapets, without parapets) and operation phase, under the conditions of model smooth and turbulent incoming flow. The latter allows us to outline the boundaries for more weighted estimates of the aerodynamic characteristics of the girder bridges in a real wind current. The best agreement with the experimental data was obtained from the drag of the cross-section. The magnitude of the lifting force is more sensitive to the presence and extent of the separation regions, so its numerical determination is less accurate. The reproduction of the angle-of-attack effect on the aerodynamic moment of the cross-section is the most challeng-

Введение. Верифицирована методика численного моделирования поперечного обтекания пролетных строений мостов на основе нестационарного решения Рейнольдса для уравнений Навье — Стокса (URANS, Unsteady Reynolds-averaged Navier — Stokes). Данный двумерный подход используется в современных методах и пакетах прикладных программ вычислительной гидроаэродинамики. Цели работы — отладка и экспериментальное обоснование указанной методики. Для реализации поставленной цели использована ранее разработанная авторами база данных по аэродинамическим характеристикам поперечных сечений пролетных строений балочных мостов типовых форм.
Материалы и методы. Проведено численное моделирование поперечного обтекания мостовых строений низкотурбулентными (гладкими) и турбулентными воздушными потоками в диапазоне практически интересных углов атаки. В итоге использовалась модель турбулентности SST $k-\omega$. Методика предварительно отработана на тестовой задаче обтекания балок прямоугольного поперечного сечения. Расчеты проводились с помощью лицензионного программного комплекса ANSYS.
Результаты исследования. Показано, каким образом угол атаки определяет силы (подъемную и лобового сопротивления) и момент поперечных сечений балочных мостов типовых форм. Полученные расчетные зависимости относятся к пролетным строениям на стадиях монтажа (без плиты перекрытия и ограждений, без ограждений) и эксплуатации в условиях модельных набегающих потоков — гладкого и турбулентного. Это позволяет очертить границы для более взвешенных оценок аэродинамических характеристик балочных мостов в реальном ветровом потоке.
Лобовое сопротивление сечению демонстрирует наилучшее согласование с опытными данными. Величина подъемной силы более чувствительна к наличию и протяженности отрывных зон, поэтому ее расчетное определение менее точно. Наиболее проблемным для большинства конфигураций является воспроизведение

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ing for the majority of configurations.
Discussion and Conclusions. Comparison of the calculated and experimental data indicates the applicability of the URANS approach to the operational prediction of the aerodynamic characteristics of the single-beam span structures. In the case of multi-beam span structures, where the aerodynamic interference between separate girders plays an important role, the URANS approach must apparently give way to more accurate eddy-resolving methods. The results obtained can be used in the aerodynamic analysis of structures and in practice of the relevant design organizations in the field of transport construction.

влияния угла атаки на аэродинамический момент сечения.
Обсуждение и заключения. Сравнение расчетных и опытных данных свидетельствует о применимости URANS-подхода к оперативному предсказанию аэродинамических характеристик однобалочных пролетных строений. Если же речь идет о многобалочных пролетных строениях, существенную роль играет аэродинамическая интерференция между отдельными балками. В этом случае вместо URANS-подхода следует применять более точные вихреразрешающие методы. Полученные результаты могут быть использованы в исследованиях аэродинамики сооружений и в практике проектных организаций в сфере транспортного строительства.

Keywords: mechanics of fluid, gas and plasma; mathematical simulation; computational aerohydrodynamics, URANS approach, bridge spans, aerodynamic characteristics.

Ключевые слова: механика жидкости, газа и плазмы; математическое моделирование; вычислительная гидроаэродинамика; URANS-подход; пролетные строения мостов; аэродинамические характеристики.

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Introduction. It is known that wind flow around engineering structures is, as a rule, instable turbulent in nature; different-scale eddy structures are observed in the flow [1, 2]. Nearby bluff bodies (to which, in particular, bridge spans belong), unsteady detached flow regions occur [3]. Accordingly, adequate modeling of the turbulence effects is now an important requirement for the simulation experiment techniques.

Large Eddy Simulation, LES, and Detached Eddy Simulation, DES, are used to evaluate the aerodynamics of structures. However, the use of these methods is complicated by their high resource intensity, the reasons for which are as follows:

— tridimensionality of the task;
— strict requirements to the computational grid density in the near-wall region and in the “focus” region [4];
— restrictions on the time integration step;
— relatively large time window length for gathering nonstationary statistics in steady state.

At the same time, it is known [5] that for cylindrical prisms that are close in shape to beam bridge spans, the two-dimensional approach reproduces the basic flow properties (primary unstable mode in the body wake is essentially two-dimensional). Thus, a POD analysis (Proper Orthogonal Decomposition) of the flow near the prism with $B / H = 5$ (H is depth of section) relative section depth was performed in [6]. As a result, it was established that the 1st and 2nd disturbance modes are two-dimensional (constant over the span) and correspond to the vorticity transfer along the surface. Three-dimensional modes change along the span at a reference length that is no less than B section depth.

For the operational prediction of aerodynamic characteristics (ADC) of bridge structures and wind-tunnel test tracking, the authors used nonstationary 2D modeling based on URANS approach, Unsteady Reynolds-averaged Navier-Stokes. Its applicability to the definition of ADC of the bluff bodies (stationary and oscillating) was studied in a number of works by foreign authors (see, for example, [7]).

Materials and Methods. When setting up computer-based experiments, the recommendations given in [8–10] were considered. The calculations were carried out in the ANSYS Fluent program.

The technique was preliminary tested on the check problem of flow around beams with rectangular cross-section. As a result, $k — \omega$ shear stress transport (SST) model was chosen to describe the flow turbulence, and the grid parameters and the numerical algorithm were selected.

The extension of the rectangular computational domain is (30 ... 40) *H* lengthwise, and (14 ... 20) *H* – transversely. The front face of the streamlined body was spaced apart from the input boundary at (8 ... 12) *H*.

We used low-Reynolds-number grids ($y^+ \leq 4$ ... 5 dimensionless distance of the first node to the wall) that enabled to calculate the boundary layer separation and reattachment. Considering the complexity of the streamlined body contours, multiblock grids were constructed. The internal female block consisted of quadrilateral elements whose density increased closer to the body surface. A layer with a structured orthogonal quadrilateral grid was generated immediately at the wall. The wake region was covered with a grid of square cells sizing of no more than *H*/15 ... H/10. The cell size increased to *H*/4 ... *H*/3 to the outer boundaries. The cross-sectional perimeter contained about 10^2 ... 10^3 cells depending on its shape. The total number of cells ranged from 40–50 thousand (for sections of simple shapes) to 250–300 thousand (for complex ones). An example of the computational grid near a beam of trapezoidal section with overlapping and fencing is shown in Fig. 1.

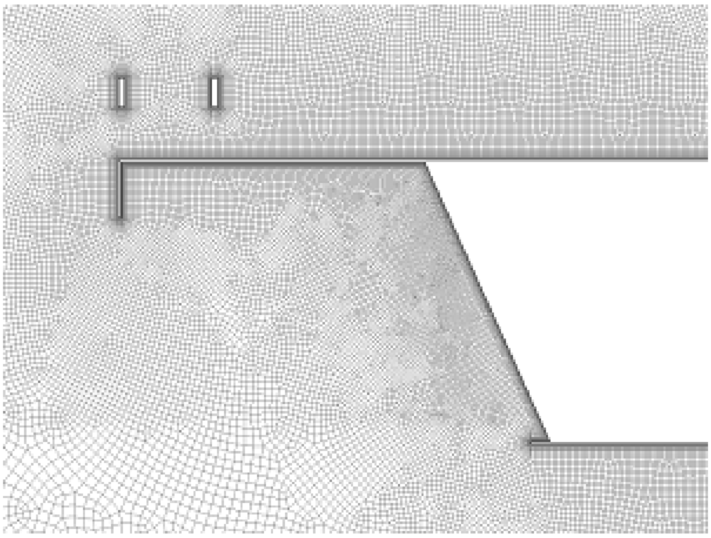
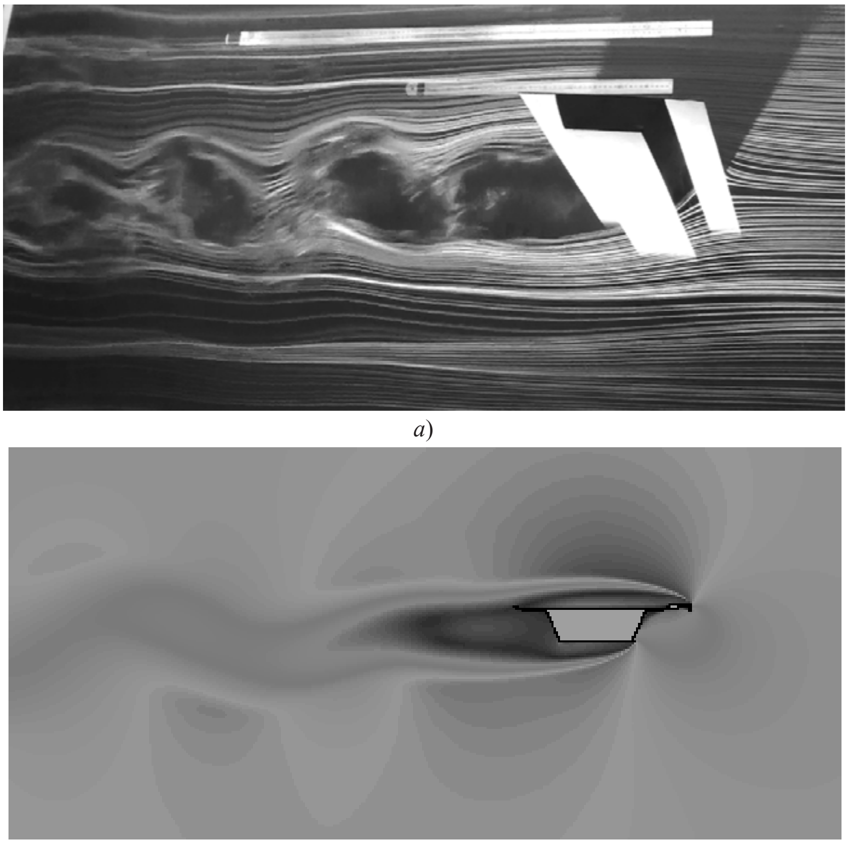


Fig. 1. Example of computational grid (fragment)

When solving the Navier – Stokes equations, the velocity – pressure relationship was implemented using the SIMPLE algorithm. The convection and viscous terms of the equations of flow and the transport of turbulent parameters were approximated by schemes of second-order accuracy.

The numerical integration was carried out by an implicit time scheme of the second-order accuracy. Δt integration step was (0.02… 0.04) *H/V* (*V* is incident flow velocity), i.e., under the vortex shedding with dimensionless frequency *f H/V* = 0.1, it was approximately 250–300 times less than 1/f period, and this provided an acceptable resolution of the non-stationary flow parameters. The established vortex trail was usually formed by *H*/*V* moment (60 ... 120). Thus, the total number of integration steps averaged 6000 ÷ 10,000. To collect nonstationary statistics, a time interval of at least 5 periods was used.

An example of a qualitative comparison of the computational and experimental flow patterns near the span is shown in Fig. 2.



a)

b)

Fig. 2. Example of flow pattern over bridge span: experiment (*a*), calculation (*b*)

Research Results. Detailed information on ADC typical cross sections can be found in [11]. Figures 3–14 present a comparison of the computational and experimental data on the coefficients of averaged aerodynamic forces (drag, lift) and the moment for some specific sections.

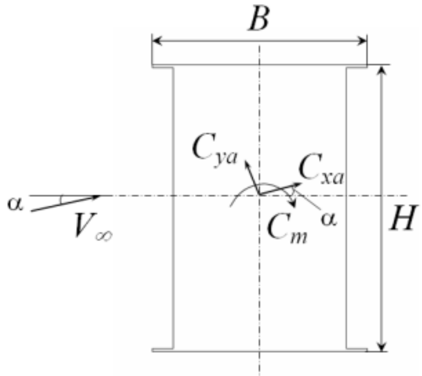
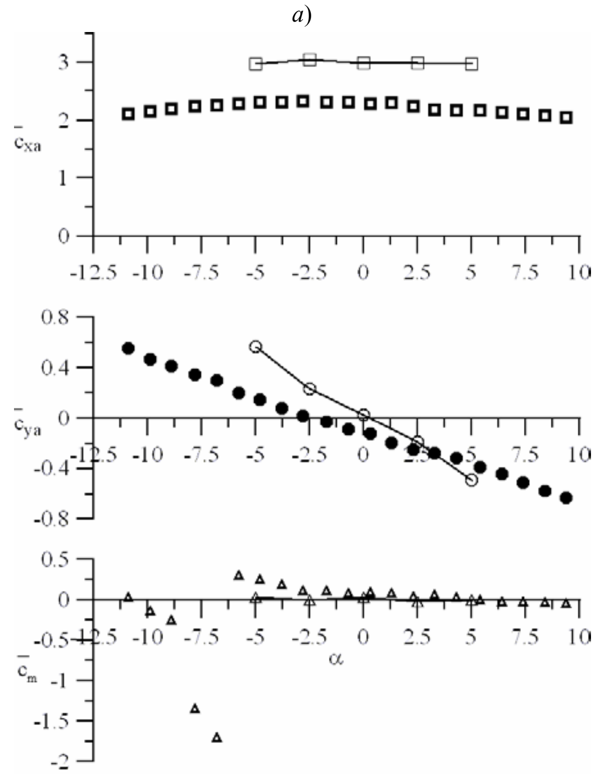


Fig. 3. Coefficients of averaged aerodynamic forces. Here: $\bar{C}_{xa}$ is drag; $\bar{C}_{ya}$ is lifting force; $\bar{C}_m$ is moment; *B* and *H* are longitudinal and transverse section dimensions (excluding fencing); α is angle of attack

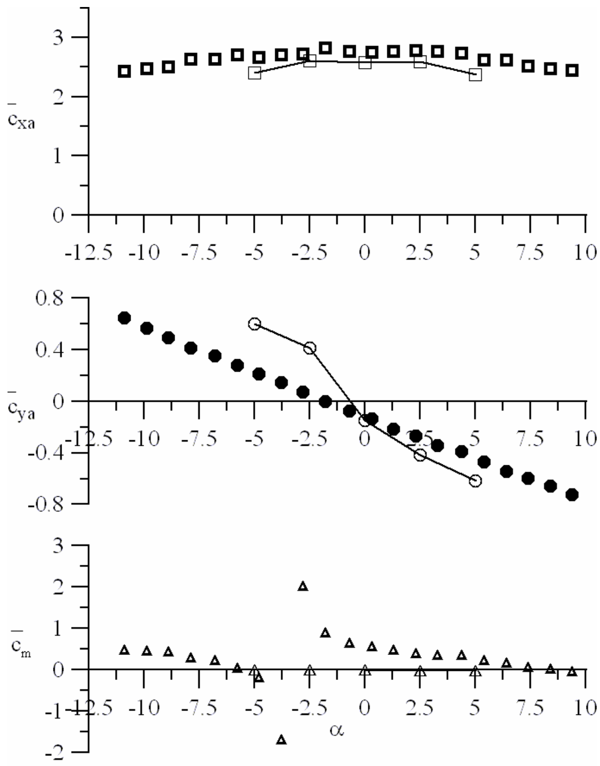
The incident smooth flow is characterized by the intensity of 0.5%, the turbulent one – of 8%. The computation data is represented by solid lines.

$B/H = 0{,}75$

a)



b)



c)

Fig. 4. Narrow single square girder (B/H 0.75 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

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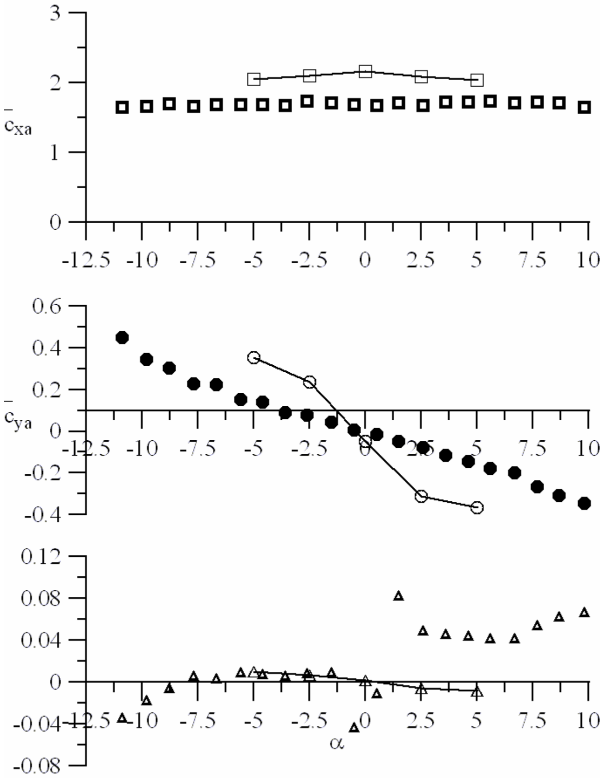
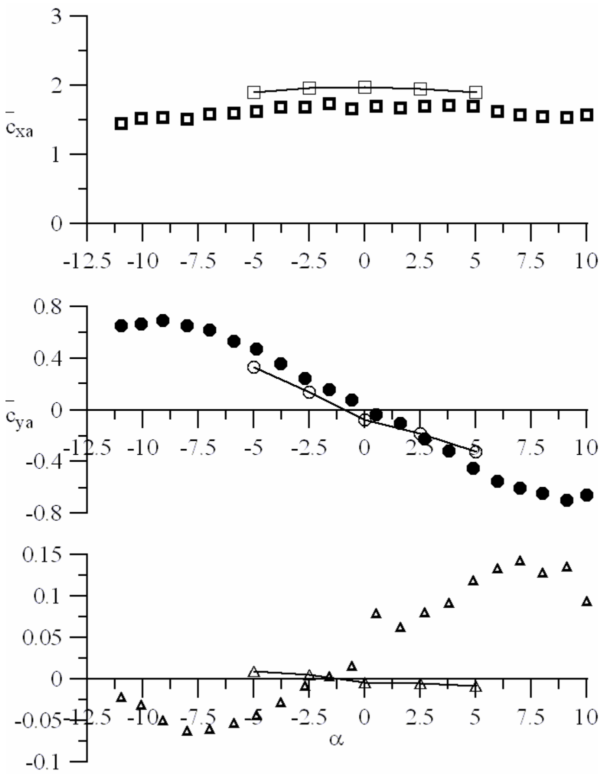
B/H =1,24

a)



b)

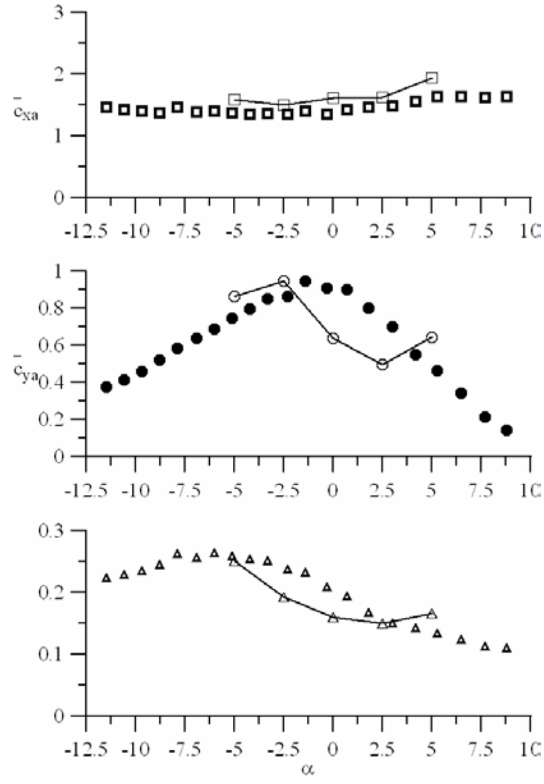


c)

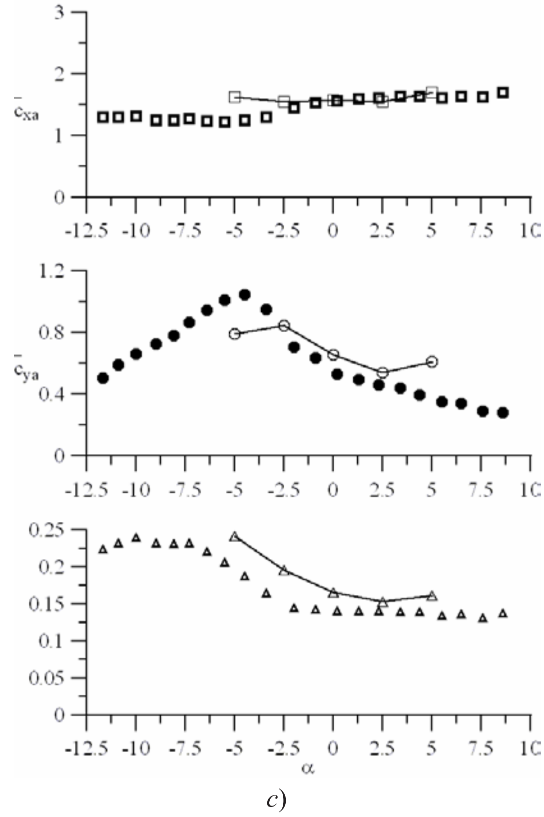
Fig. 5. Narrow single square girder (B/H 1.24 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

$B/H = 2{,}3$

a)



b)



c)

Fig. 6. Narrow single girder with overlapping (B/H 2.3 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

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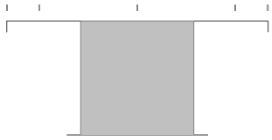
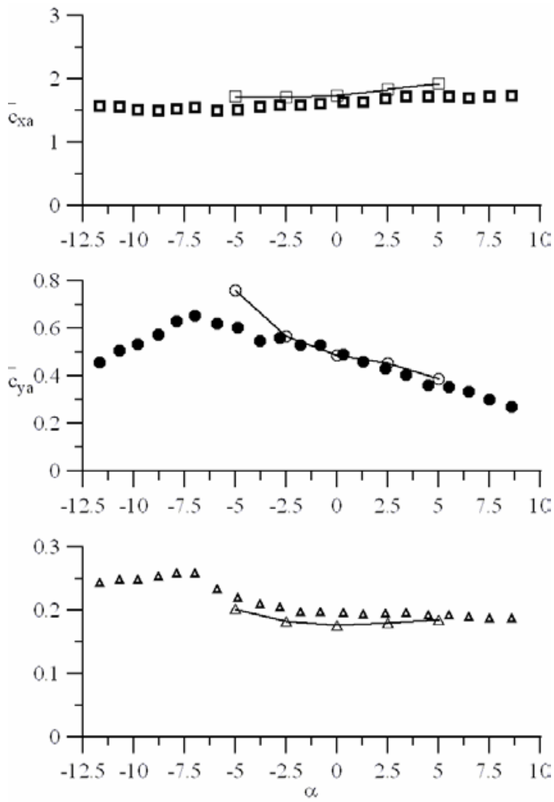
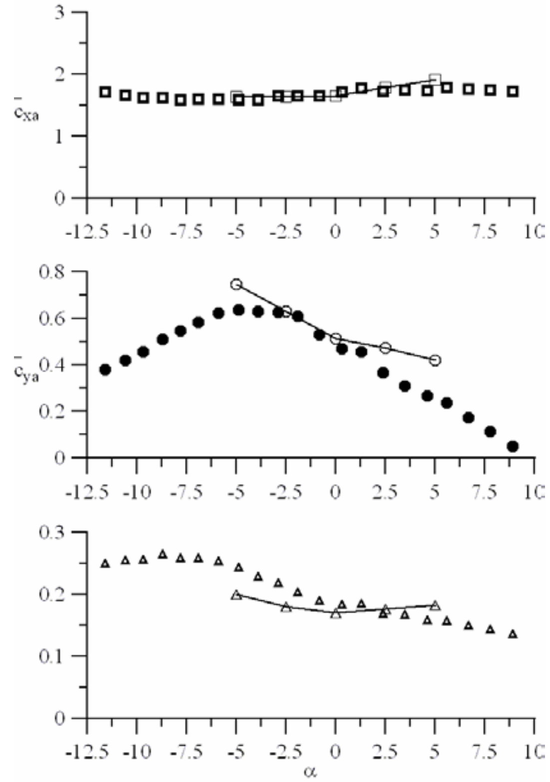


$B/H = 2{,}3$

a)



b)



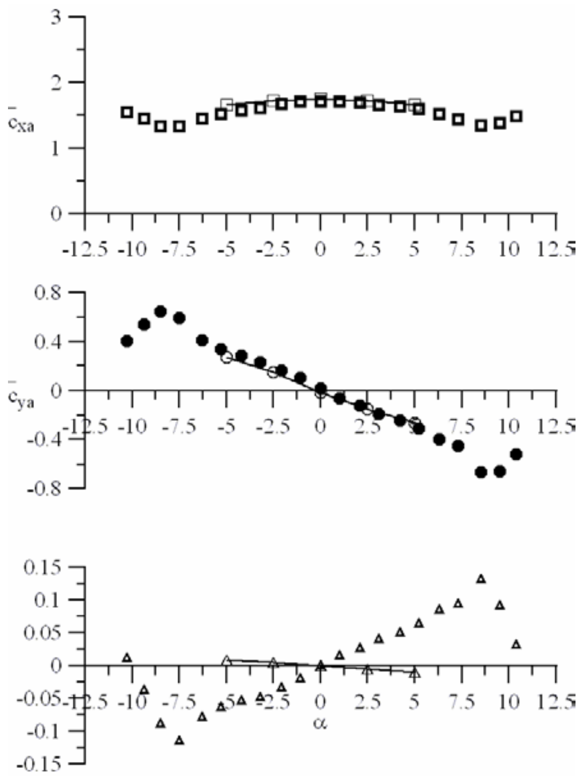
c)

Fig. 7. Narrow single girder with overlapping and fencing (B/H 2.3 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

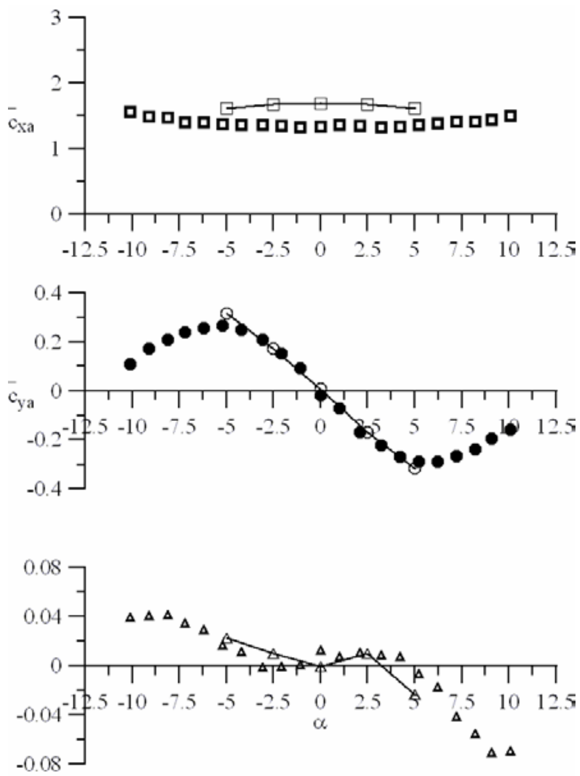
Mechanics

$B/H = 1{,}85$

a)



b)



c)

Fig. 8. Wide single square girder (B/H 1.85 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

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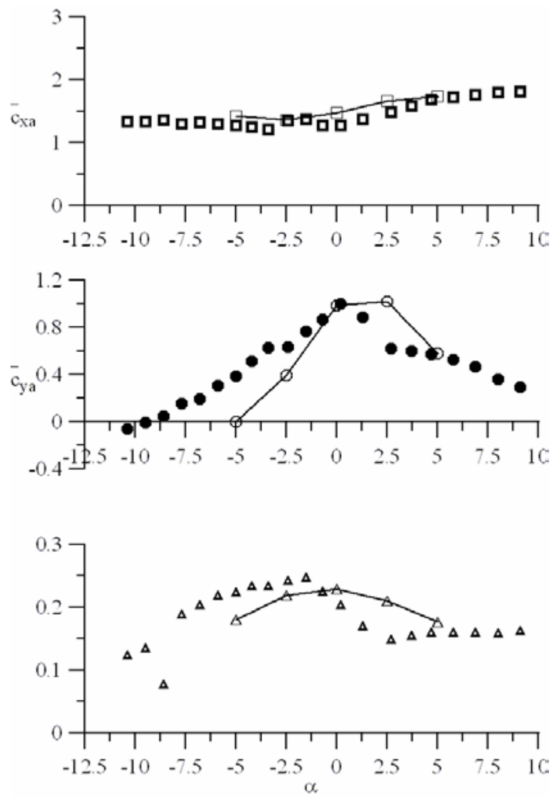
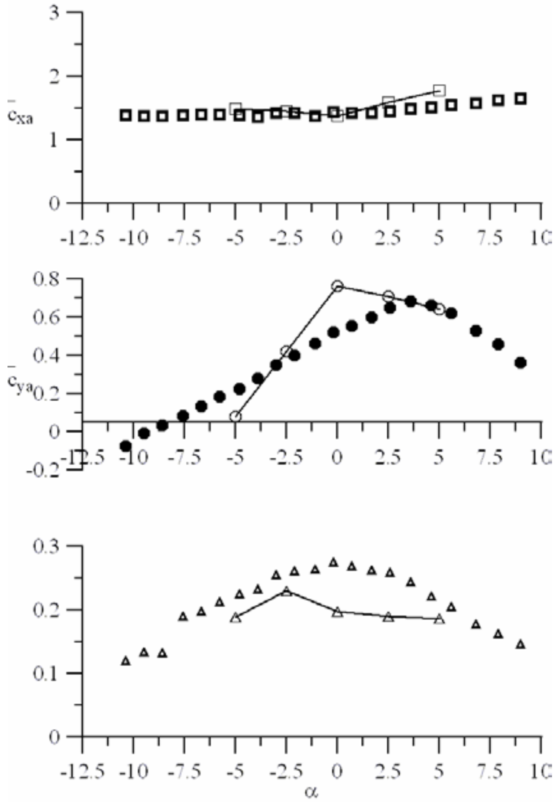
$B/H = 3{,}9$

a)



b)

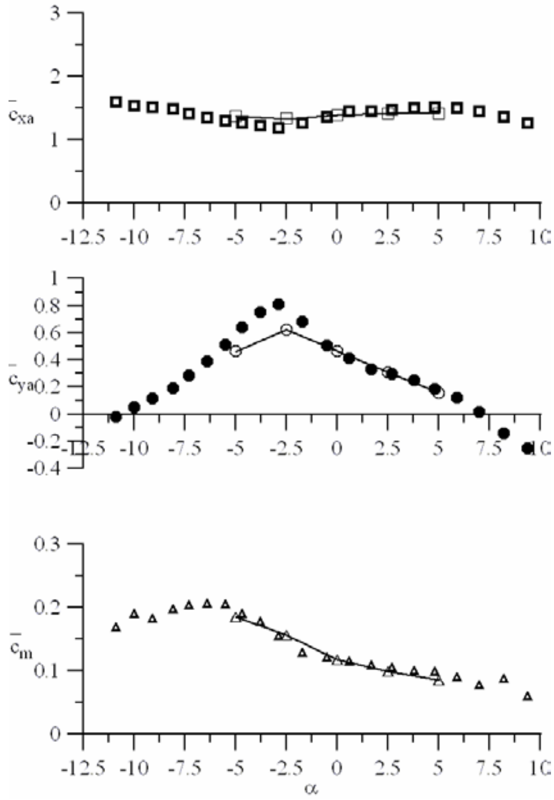


c)

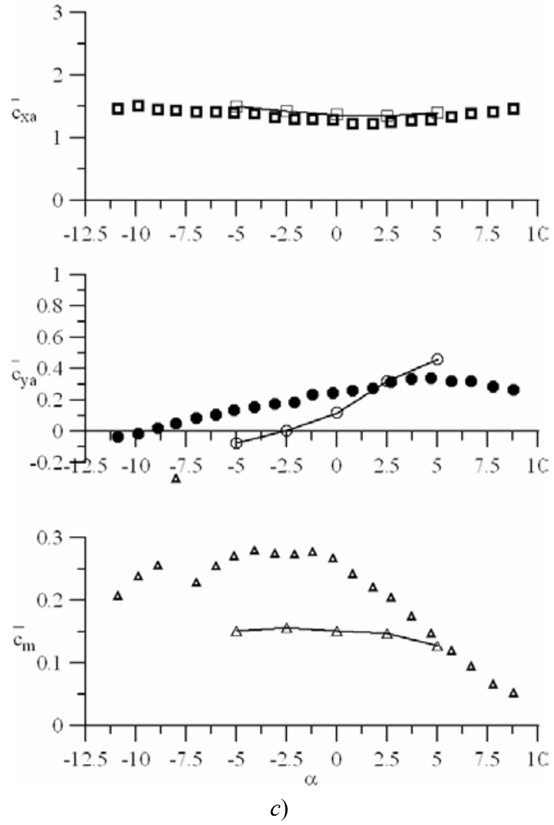
Fig. 9. Wide single girder with overlapping (B/H 3.9 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

$B/H = 3{,}09$

a)



b)



c)

Fig. 10. Trapezoidal girder (B/H 3.09 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

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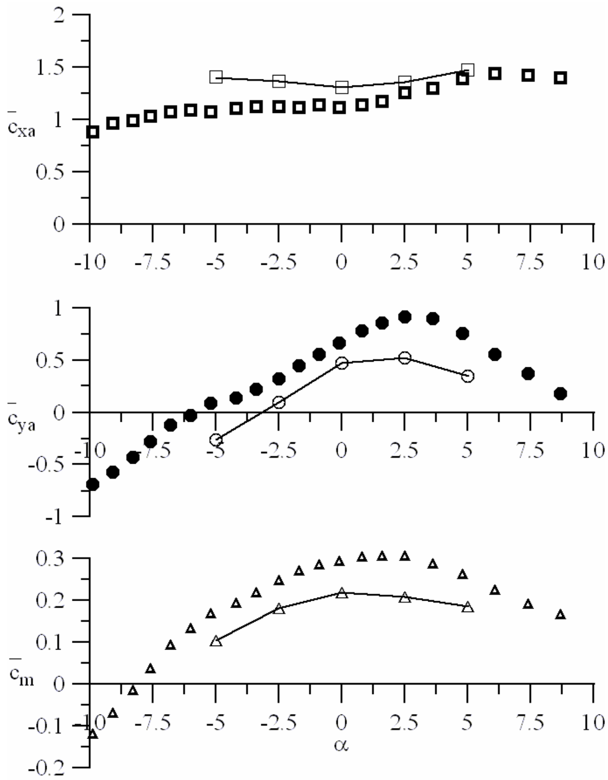
$B/H = 5{,}1$

a)



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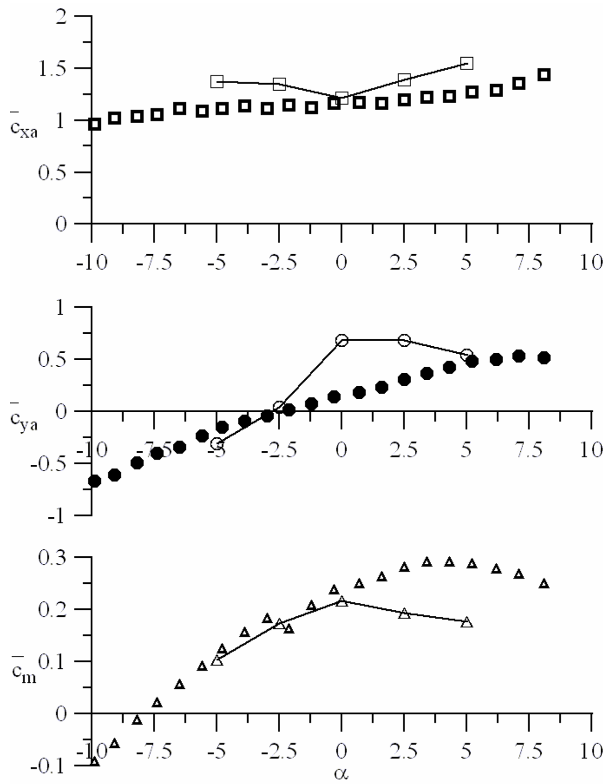
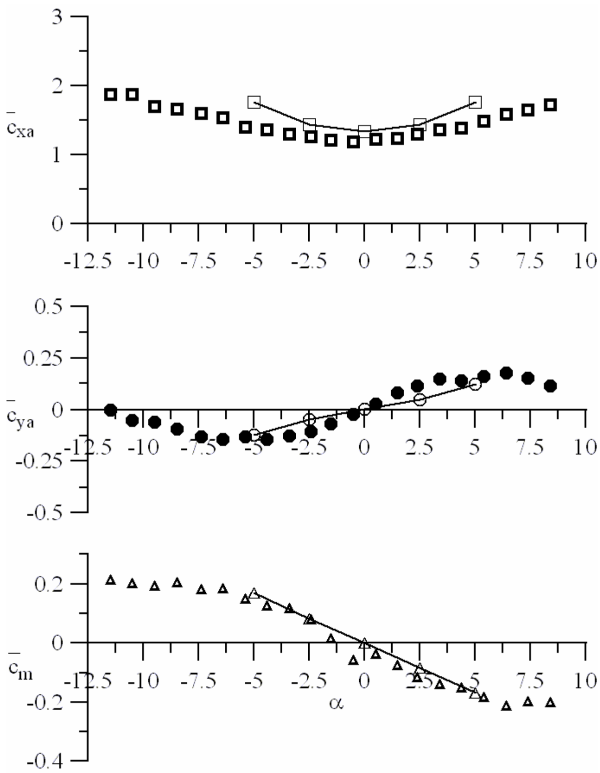


c)

Fig. 11. Trapezoidal girder with overlapping (B/H 5.1 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

$B/H = 2{,}75$

a)



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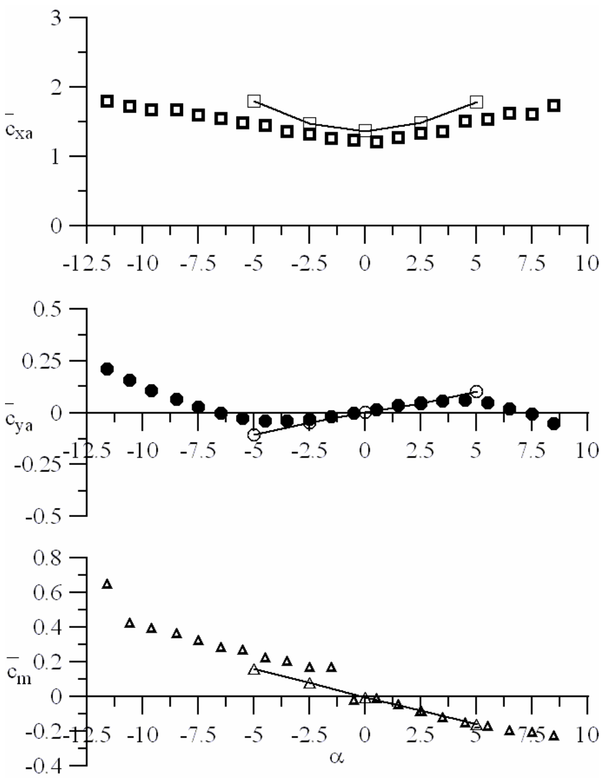

c)

Fig. 12. Double-girder structure (B/H 2.75 ratio): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

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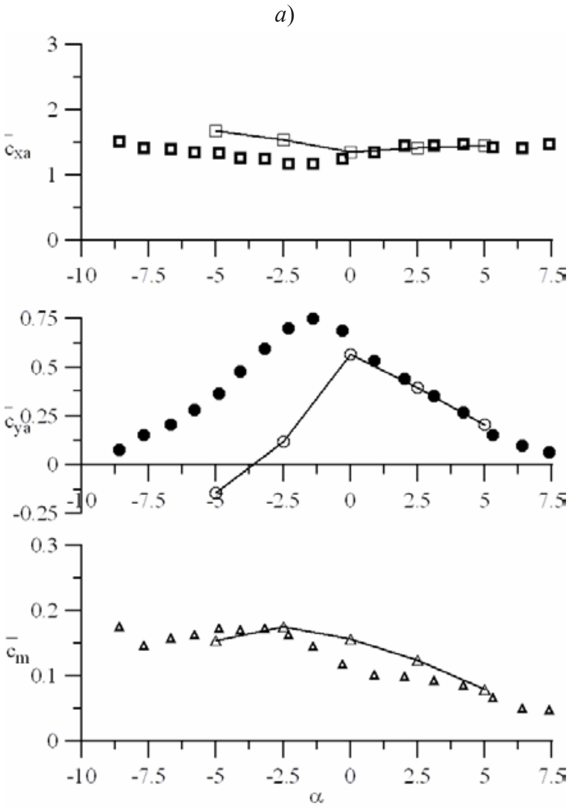
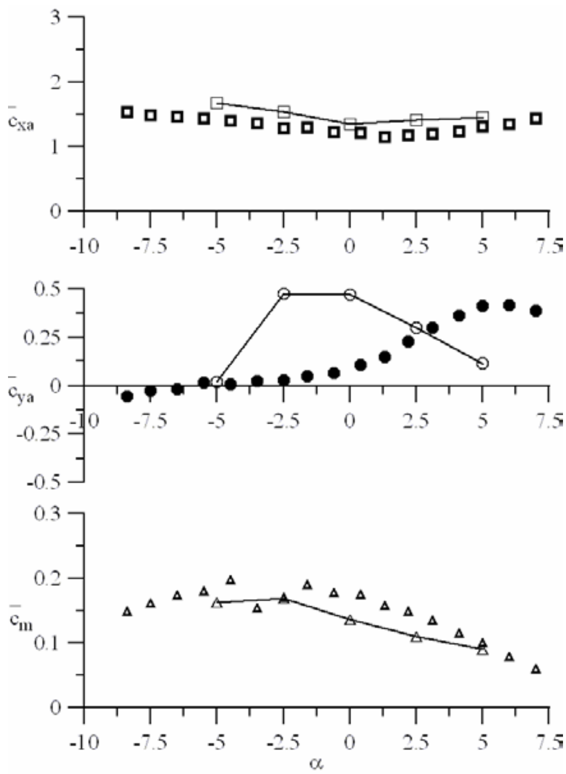
$B/H = 3{,}85$

a)

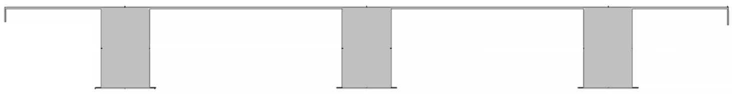


b)



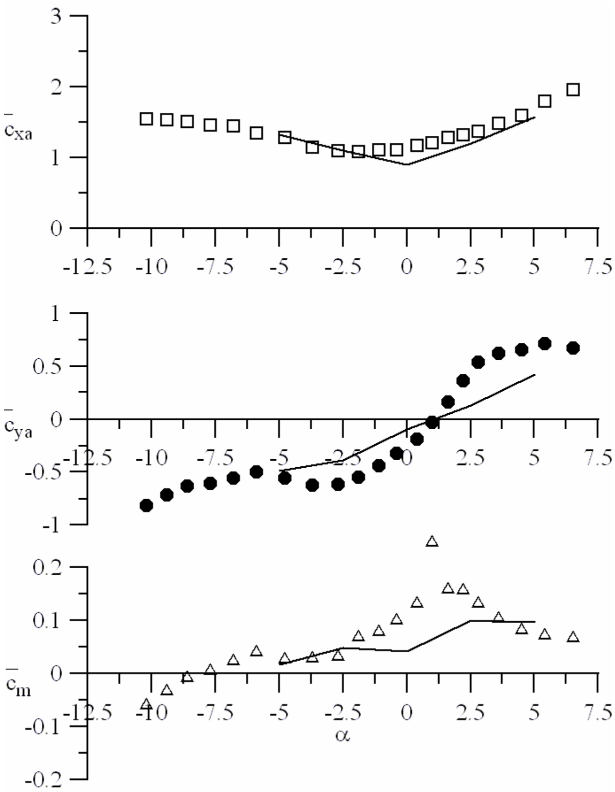
c)

Fig. 13. Double-girder overlapping structure (B/H 3.85): cross-section shape (*a*); smooth flow (*b*); turbulent flow (*c*)

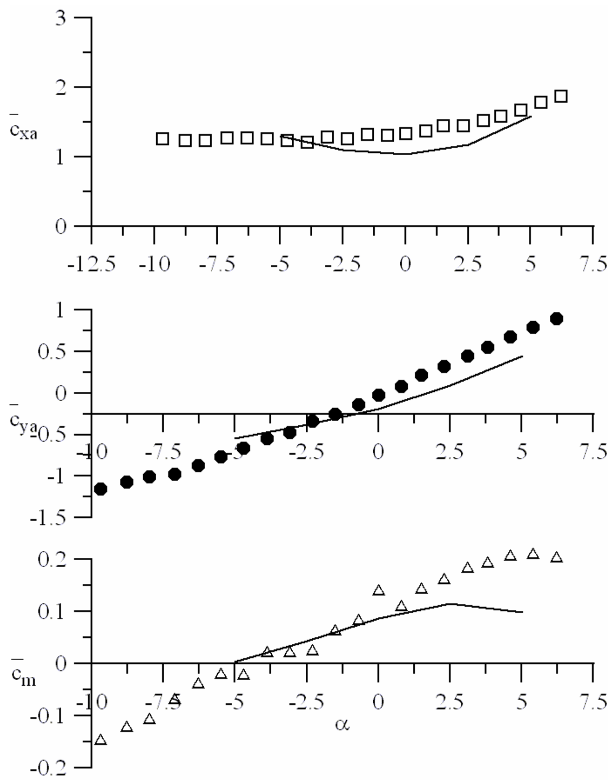


$B/H = 9$

a)



b)



c)

Fig. 14. Multi-girder structure with overlapping (B/H 9): cross-sectional shape (*a*); smooth flow (*б*); turbulent flow (*в*)

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Discussion and Conclusions. The analytical results show that, with some exceptions, with an increase in the relative width of the B / H cross section of a single-beam structure, the accuracy of the calculated prediction of its ADC rises. As a rule, the best agreement is indicated for the frontal resistance of the section. For most configurations, the computation data is slightly higher than the drag coefficient obtained experimentally. It should be clarified that for the considered bluff bodies, the major contribution to the cross-section drag is made by the form (pressure) drag, which is mainly determined by the difference in pressure forces on the upstream and leeward sides of the cross section. The accepted theoretical approach coarsens the dynamics of the vortex structures in the zone behind the body, which leads to an underestimated pressure recovery in this area.

The lift magnitude is more sensitive to the presence, extent and type (open/closed) of the detached flow regions. This applies especially to the span structure equipped with a slab; in this case, it is possible to re-attach the flow to the upper side of the slab with the formation of a closed separation zone (approximately at $B/H \geq 5$). Therefore, in comparison with frontal resistance, the calculated determination of lift force is less accurate, especially for superstructures with a floor slab.

The reproduction of the angle-of-attack effect on the aerodynamic moment of the cross section is a challenge for most configurations.

If the aerodynamic interference [12] occurs under the cross-flow around multi-girder spans between beams, the accuracy of the ADC prediction falls with an increase in the number of beams (relative overall section width). In this case, it is advisable to use more accurate DES and LES eddy-resolving methods instead of the URANS approach.

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