DOI: 10.23968/2500-0055-2022-7-3-65-75

STABILITY AND RELIABILITY OF LONG-SPAN BRIDGE STRUCTURES

Olga Poddaeva[1], Pavel Churin[1]*, Alexey Loktev[2], Chafic-Touma Salame[3]

[1]University Research and Production Laboratory for Aerodynamic and Aero-Acoustic Testing of Building Structures, National Research Moscow State University of Civil Engineering
Yaroslavskoye Shosse, 26, Moscow, Russia
[2]Russian University of Transport
Chasovaya str. 22/2, Moscow, Russia
[3]European Academy for Sustainable Development
11 Rempart Saint Theibault, Metz, France

*Corresponding author: pashok_@inbox.ru

Abstract

Introduction: Despite the fact that, in recent years, the construction of long-span bridges has been extensively developed, cases of bridge structures buckling in wind still occur, but the issue of their interaction with wind has not been sufficiently studied. **Purpose of the study:** We aimed to improve the structural integrity and operational safety of long-span bridge structures by conducting a computational and experimental study on the effect of various designs of aerodynamic dampers on the aerodynamic stability of such structures. **Methods:** The study was performed in two stages. At the first stage, preliminary two-dimensional numerical modeling was conducted to study the effect of various designs of aerodynamic dampers on the wind flow over selected bridge spans. Based on the results of the preliminary two-dimensional numerical modeling, we chose the most effective designs of aerodynamic dampers and made their models to conduct experimental studies on aerodynamic stability on a special test bench**. Results:** Based on the obtained computational and experimental results, we analyzed the effectiveness of various designs of aerodynamic deflectors and fairings used to improve the aerodynamic stability of the standard bridge structure under consideration. **Discussion:** For a span with one main girder, we determined the deflector design that reduces the vibration amplitude at high wind velocities.

Keywords

Bridge structures, aerodynamics, aerodynamic stability, experimental studies, numerical modeling, damping, deflector, fairing.

Introduction

The stability of elastic structures in wind is one of the most knowledge-intensive and insufficiently studied aspects of structural aerodynamics. Aeroelasticity — a branch of structural aerodynamics covering this aspect — deals with solving nonlinear problems of the dynamics of building structures in wind, and, as a consequence, assessing the likelihood of aeroelastic instability phenomena. In general, the tasks, goals, research methods, and even the terms pertaining to the aeroelasticity of building structures are very similar to those pertaining to the classic aerodynamics of aircraft. The aerodynamics of aircraft brought us terms that determine aerodynamic instability phenomena: vortex excitation, galloping, flutter, etc. Their occurrence during the construction and operation of buildings and structures gave rise to the development of aerodynamics as a separate branch of construction science.

Below we list some well-known cases of elastic structures buckling in wind. However, it should be noted that aerodynamic instability phenomena are becoming more common in metal girder spans (Tozaki Viaduct, Trans-Tokyo Bay Highway Bridge, the bridge crossing to Kansai Airport, the spans and approaches to Oshima Bridge, the spans and approaches to Great Belt Bridge (East Bridge), etc.), although it was historically believed that cable-stayed and suspension structures with longer spans were the most sensitive to dynamic wind action (Ovchinnikov et al., 2015).

Ensuring the stability and safety of bridge structures around the world is regulated by relevant regulatory documents. In the Russian Federation, such regulatory documents include Regulations SP 35.13330.2011 “Bridges and culverts” and State Standard GOST 33390-2015 “Automobile roads of the general use. Bridges. Load models and actions”, in Europe — Eurocode 1: Basis of design and actions on structures - Part 2-4: Actions on structures - Wind actions (with national applications), in the USA — ANSI/ASCE 7-95, etc. The experimental studies of elastic structures in wind tunnels are an integral part of design. In international regulatory documents, the corresponding experimental techniques are represented more widely and in more detail.

The scientific and technical literature distinguishes three basic ways to improve the aerodynamic stability of bridge structures (Kazakevich, 2015; Kazakevich and Zakora, 1983; Kazakevitch, 2020):

- aerodynamic damping (installation of fairings and deflectors);
- installation of man-made mechanisms for vibration energy dissipation (various dampers, shock absorbers, shock transmitters, etc.);
- changes in the design model of a structure.

In terms of ensuring the stability of a structure in wind, it is rational to use aerodynamic damping. Most studies assessing the effectiveness of various aerodynamic dampers addressed particular bridge structures at the stage of design. Besides, most of the structures studied are suspension and cable-stayed long-span bridges. As for girder bridge structures, they have been studied less. Meanwhile, in recent years, the construction of long-span girder bridges has been extensively developed.

Methods

To conduct studies, we chose a typical span of a long-span girder bridge with one main stiffening girder, commonly used in modern construction (Figure 1).

To study the designs of aerodynamic dampers, we chose fairings of the most common shapes: a fairing of a beak shape (Figure 2a), a fairing with a smooth contour (Figure 2b), a fairing with a sharp edge (Figure 2c), which have proved their effectiveness in the assessment of the aerodynamic stability of suspension and cable-stayed bridge spans, as well as two types of deflectors (Figures 2d, 2e) ensuring favorable flow over a span.

To pre-select the optimal aerodynamic damping model, it is advisable to use numerical modeling in special flow dynamics software. This method makes it possible to choose the most effective shape of a deflector, based on the analysis of a qualitative pattern of wind flow over the bridge cross-section.

These studies are sufficiently reliable for choosing the shape and design of a fairing. Moreover, experimental studies in wind tunnels are a necessary condition to ensure the aerodynamic stability of a bridge structure.

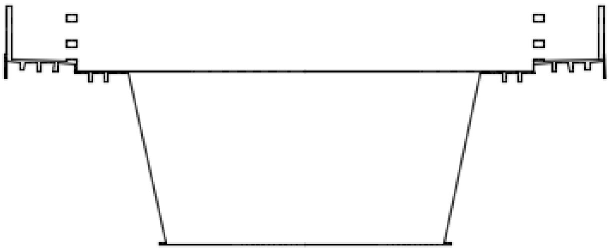


Figure 1. A span with one main stiffening girder

To conduct preliminary numerical modeling, we used recommendations based on the experience of using computational fluid dynamics (CFD) packages in the aerodynamics of buildings and structures, accumulated expertise, and ANSYS user manual.

The inlet of the computational domain was represented by surfaces through which the flow entered the computational domain. On the bridge surfaces, the so-called no-slip wall condition was set, and the flow velocity was zero. At the outlet, an average relative static pressure of 0 Pa was set. In the case of zero angle of attack at the upper and lower boundaries of the computational domain, the boundary conditions of impermeability were set. Hybrid initialization was used. Pressure-Velocity coupling was specified according to the SIMPLE algorithm.

At the first stage, we analyzed the flow over the selected types of spans with no account for the design of fairings. The modeling was conducted for the following three angles of attack of the incoming flow: –3° (downward flow), 0°, and +3° (upward flow). It was established that the upward flow (angle of attack: +3°) is the most unfavorable in terms of aerodynamic stability. Below we present the results of preliminary modeling with various designs of deflectors and fairings for this angle of attack (Figures 3–8).

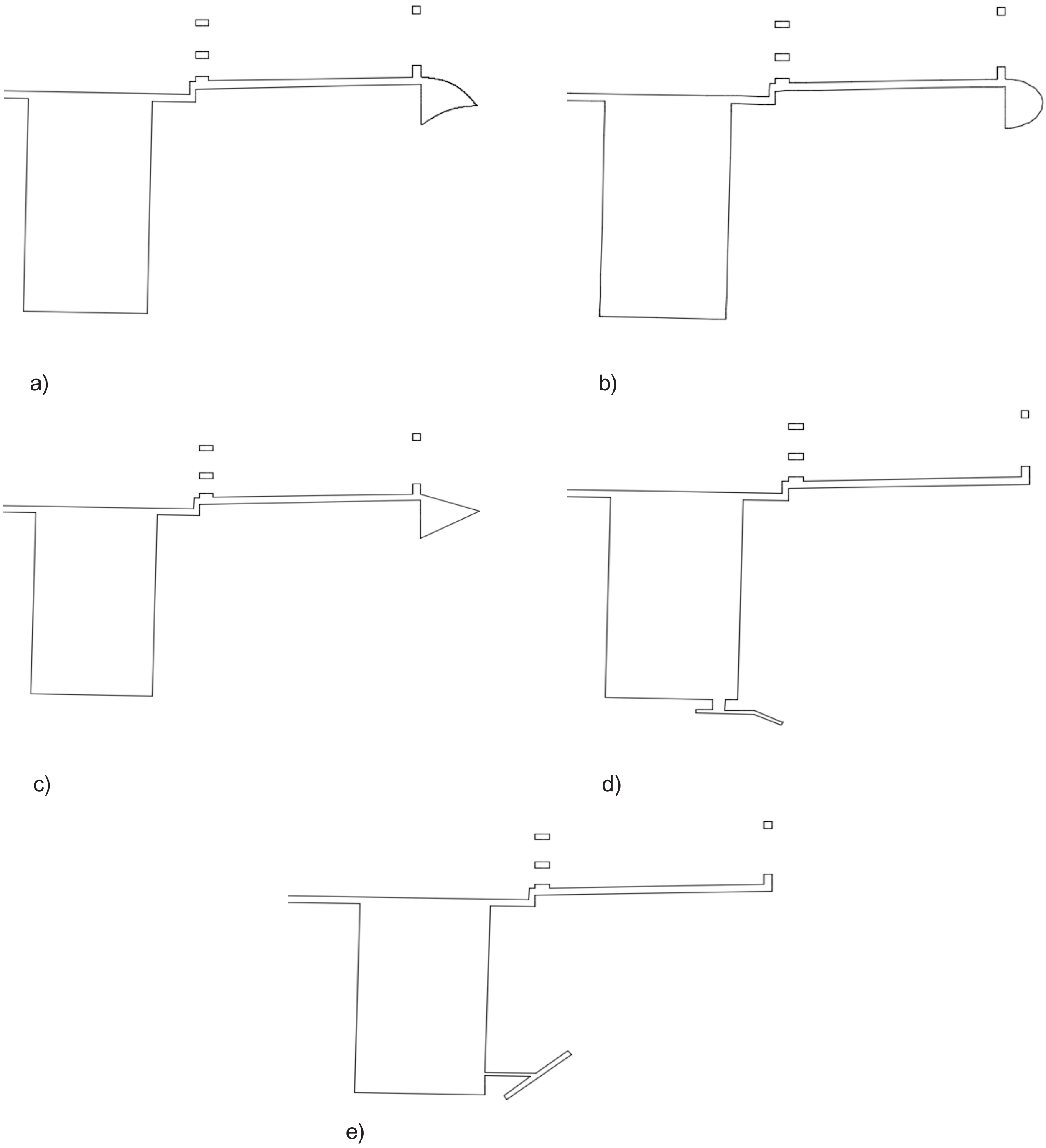
Based on the analysis of the results obtained (flow pattern), the following preliminary conclusions can be drawn: as for the selected span with one girder, it is deflector of type 2 that has the most favorable effect. It deflects the wind flow from the lower edge of the main girder, thus changing the flow pattern for the better. The studied designs of fairings did not have any significant impact on the flow pattern, which is most likely due to their small dimensions.

It should be noted that in all cases under consideration, vortices still periodically separate from the span, which indicates the need for experimental studies to obtain complete information on the aerodynamic stability of a structure in wind.

At the second stage, we conducted experimental studies on the aerodynamic stability of a span with the selected deflector design, by using a special test bench as part of a unique research setup — the Large Gradient Wind Tunnel, — and analyzed the results obtained.

Considering the scale of the available sectional models, we determined the scale and basic characteristics of the deflector for their manufacturing. The deflector model was made of 1.5 mm thick sheet aluminum (Figure 9).

The method of conducting experimental studies with the use of sectional models (Figure 10) of spans on special test benches for static and dynamic tests is described in detail in the scientific and technical



a) b) c) d) e)

Figure 2. Diagrams of aerodynamic fairings and deflectors

literature (Highways Agency, 2001; Kazakevich and Zakora, 1983; National Research Council of Italy. Advisory Committee on Technical Recommendations for Construction, 2010; Poddaeva et al., 2018; Salenko, 2005).

In the course of dynamic testing of a span, the following parameters of the forced vibrations of a model induced by wind are determined: vibration amplitudes, vibration frequencies, vibration modes, and vibration spectrum.

The experimental studies were performed at a yaw angle of 0° — the flow was perpendicular to the axis of the span, which is the most unfavorable direction in terms of aerodynamics.

During dynamic testing, the model was fixed with spring suspensions on the special test bench. The characteristics of the spring suspensions and the corresponding flow velocity scale were determined at the stage of model design. The damping level of the model was as follows: $\delta = 0.02$, which meets the requirements of the regulatory documents. The low damping level is ensured by the rigid metal structure of the model and its low dissipative properties.

Results

The results of the experimental studies are presented as a graph that shows the span vibration

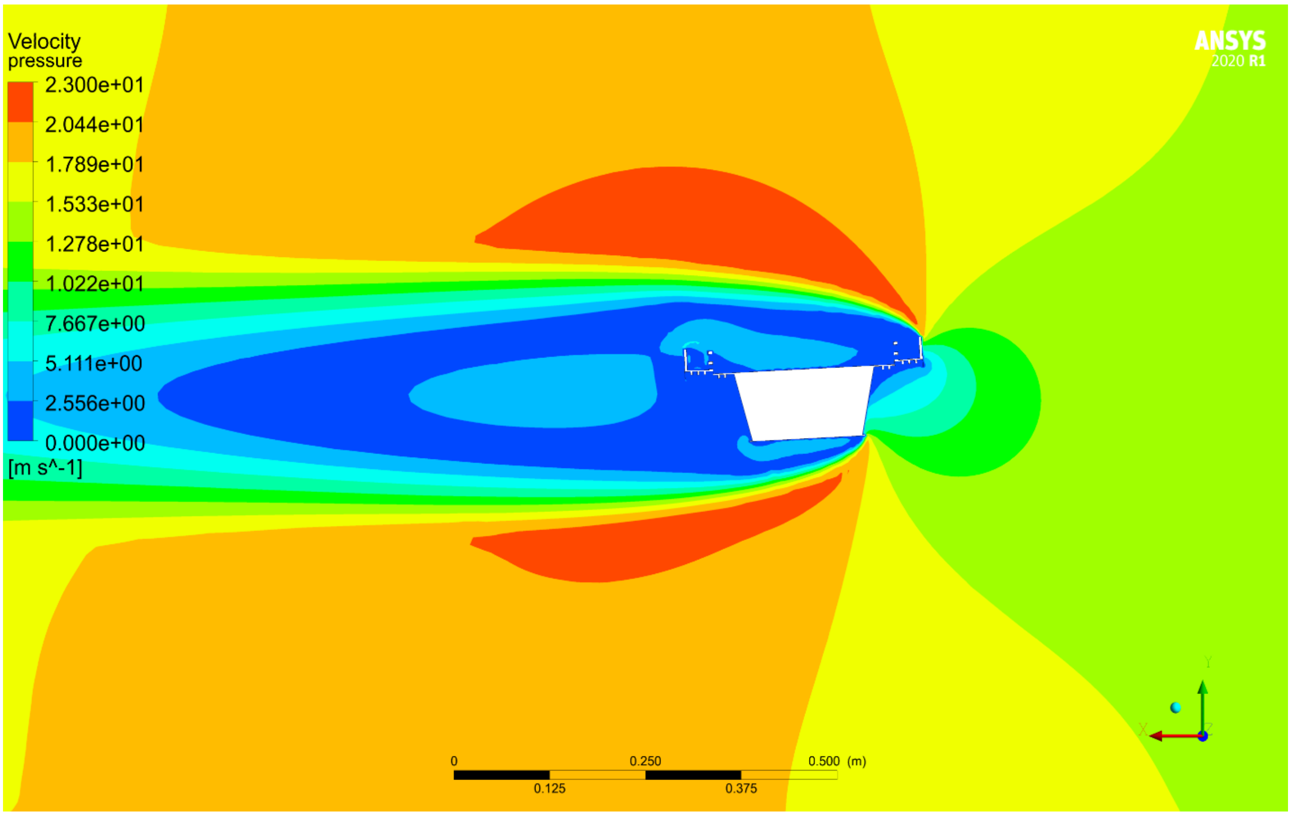


Figure 3. Flow velocity distribution at α = +3° (without fairings)

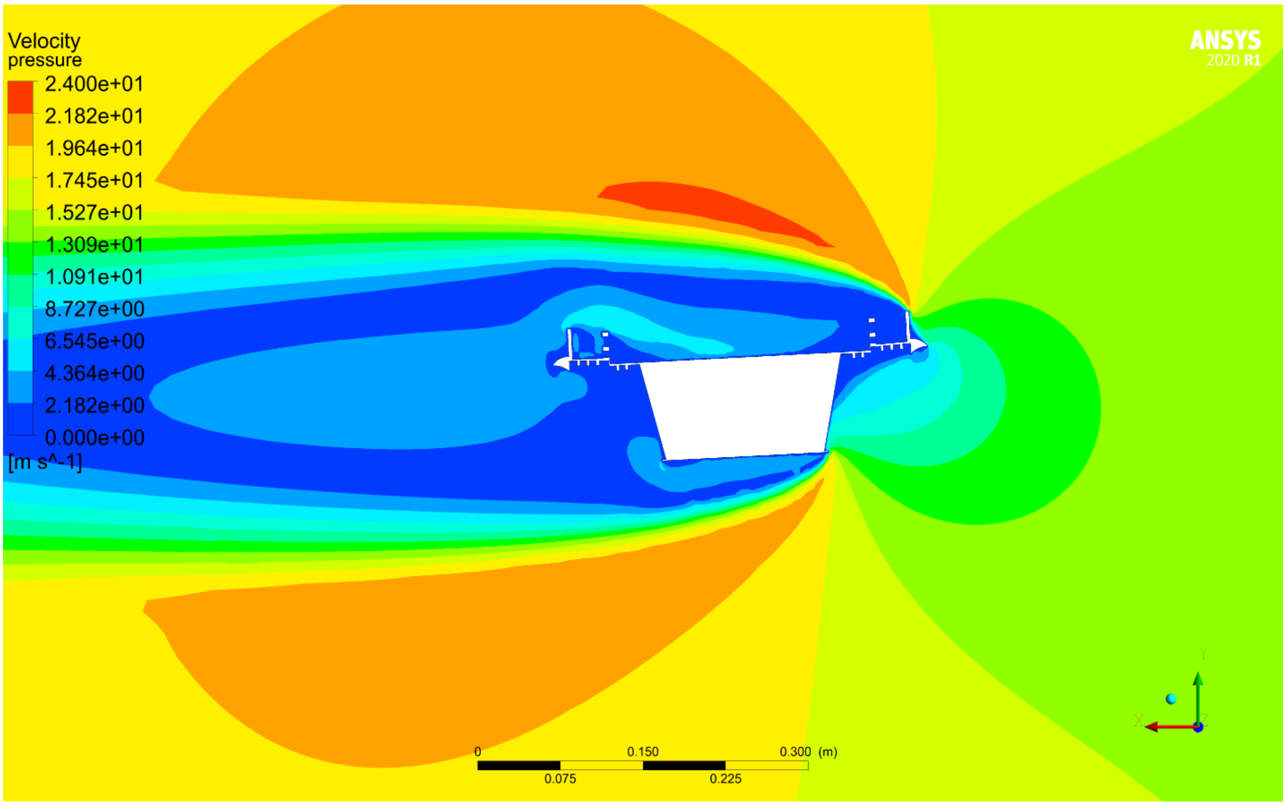


Figure 4. Flow velocity distribution at α = +3° (fairing of a beak shape)

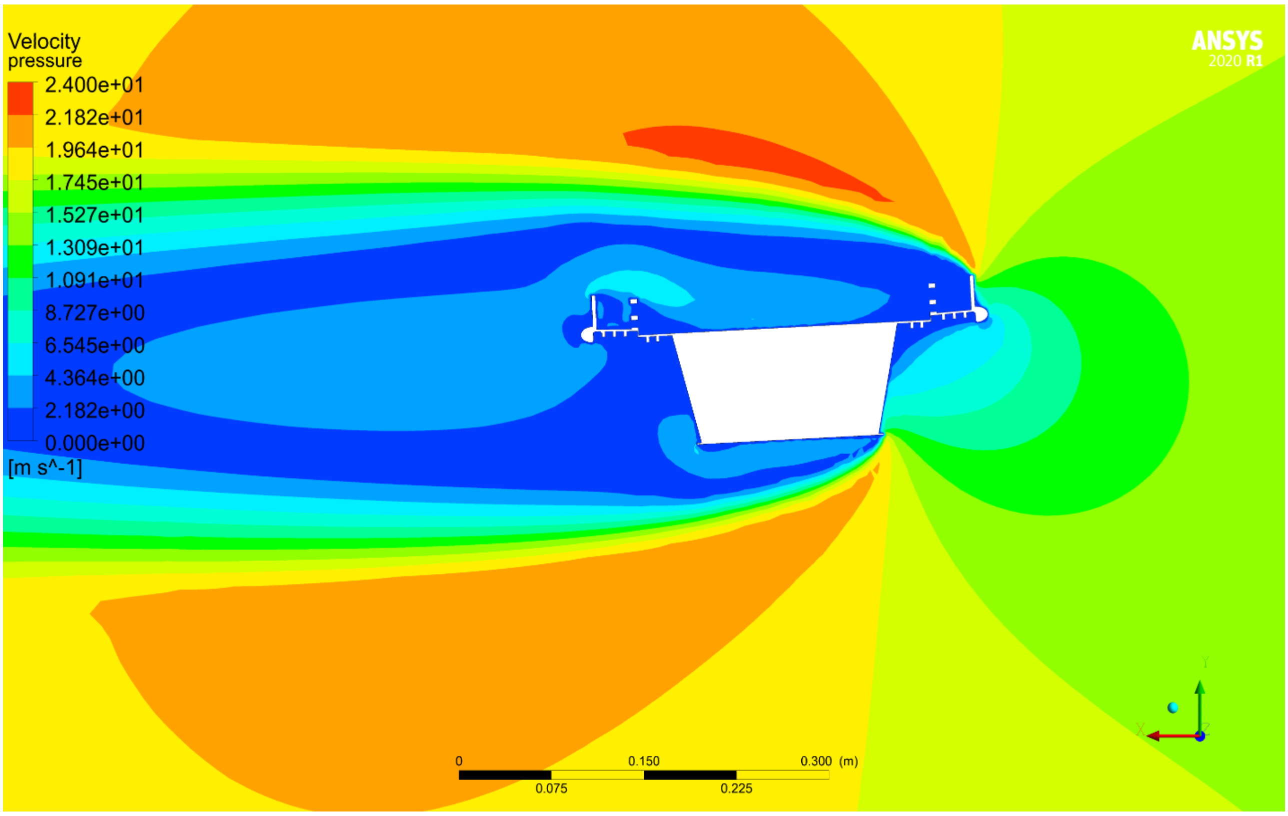


Figure 5. Flow velocity distribution at $\alpha = +3°$ (fairing with a smooth contour)

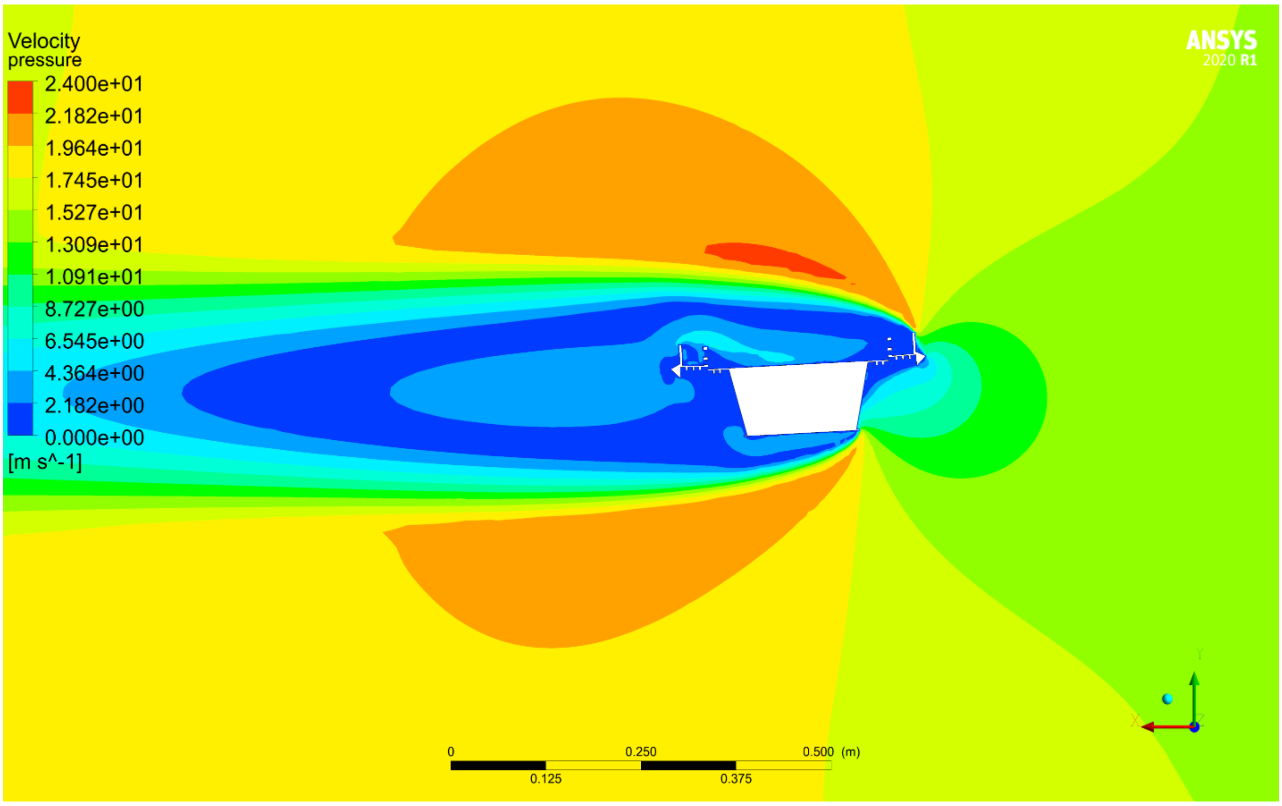


Figure 6. Flow velocity distribution at $\alpha = +3°$ (fairing with a sharp edge)

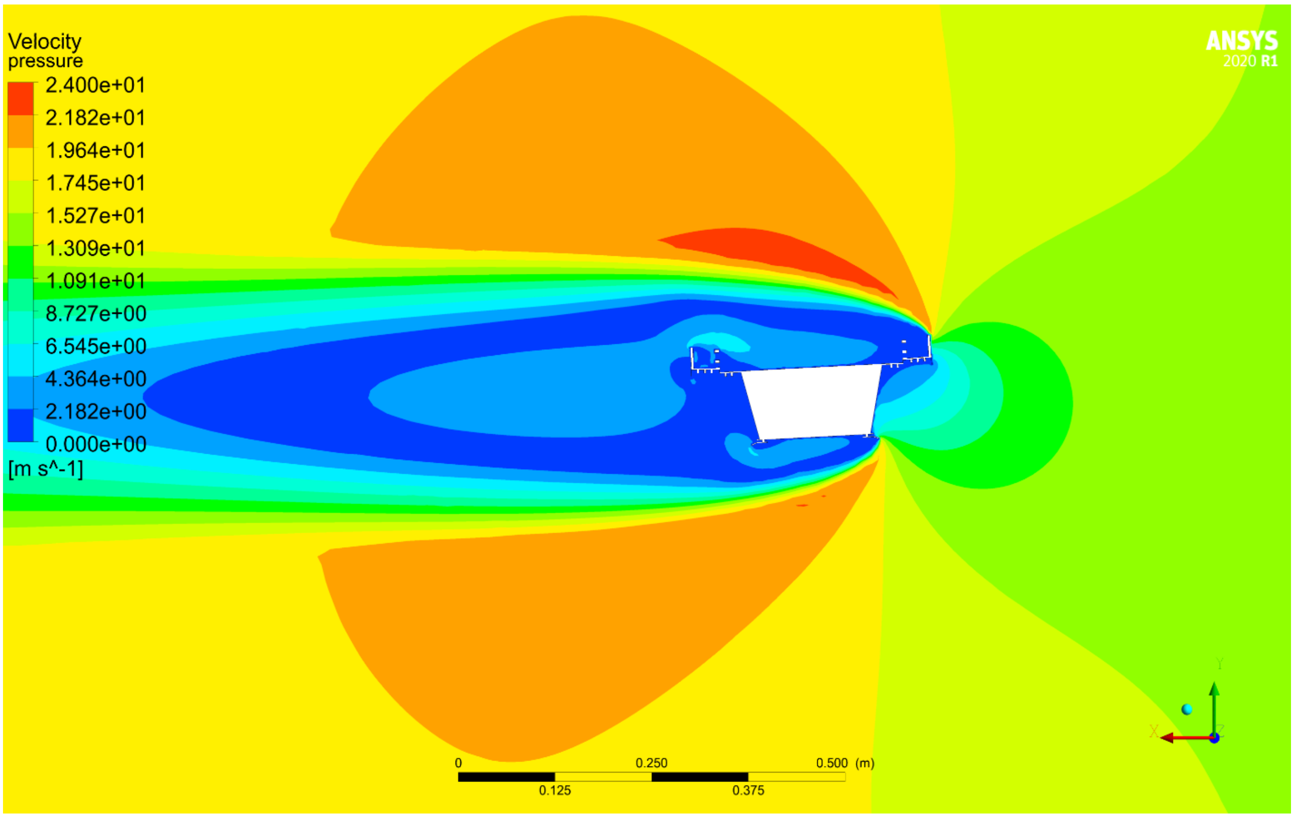


Figure 7. Flow velocity distribution at *α* = +3° (deflector of type 1)

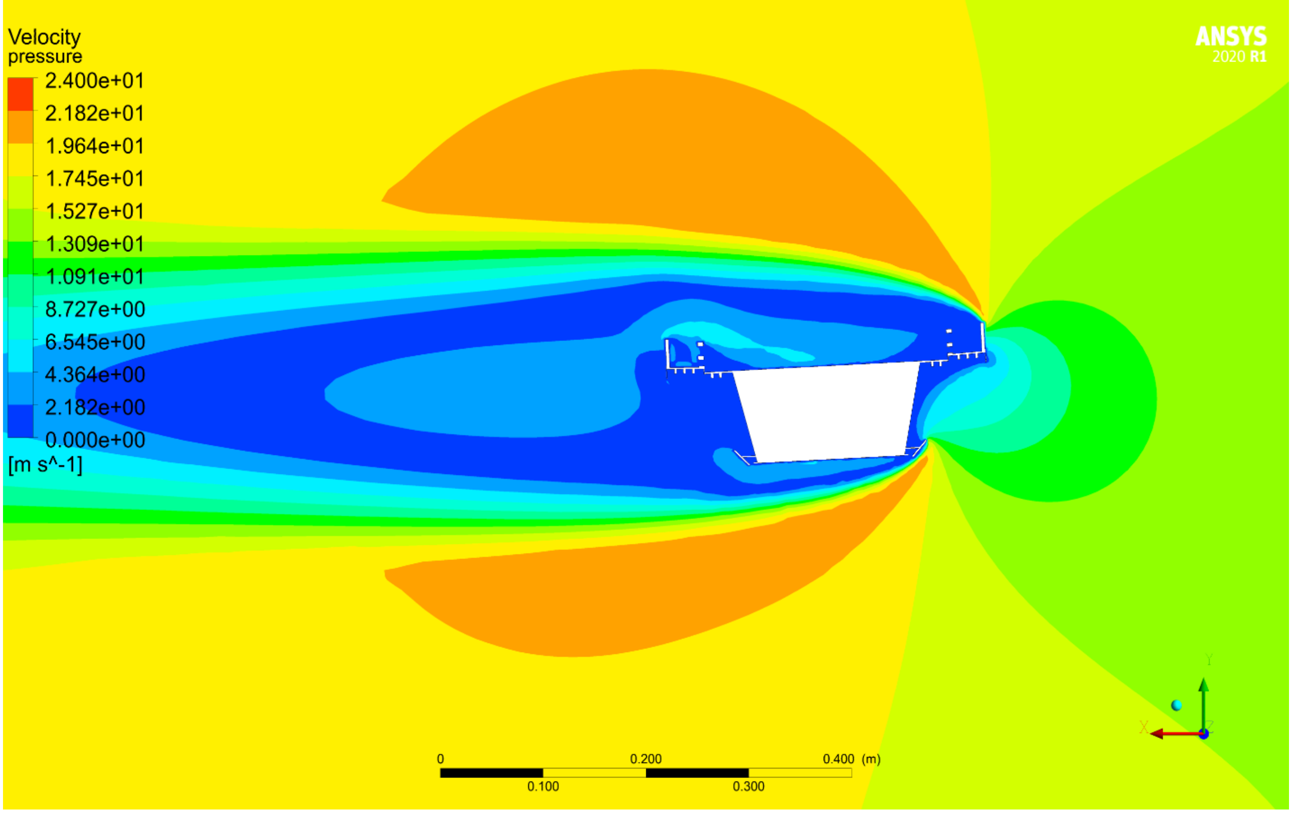


Figure 8. Flow velocity distribution at *α* = +3° (deflector of type 2)

Figure 9. Aerodynamic deflector, type 2 (model)

Figure 10. Sectional model of a span

amplitude dependence on the wind velocity.

Based on the results of the experimental studies, it was established that the deflector design (type 2) under consideration reduces the vibration amplitude at high wind velocities, and there is no unlimited increase in the amplitude of torsional vibrations characteristic of divergence. Meanwhile, the amplitude of vibrations under vortex excitation increases significantly. Thus, before assessing the applicability of this model, we need to evaluate the maximum allowable amplitude of span vibrations.

In general, based on the analysis of the preliminary numerical modeling and conducted experimental studies, it is fair to say that all the studied designs of fairings and deflectors do not have a significant positive effect on the stability of a single-girder span with geometric characteristics close to those studied. First of all, this is due to the dimensions of the fairings and deflectors under consideration. They do not introduce significant changes in the flow pattern. The phenomenon of vortex resonance excitation in the range of wind velocities between 20 and 30 m/s persists, even when the most effective model with the deflector of type 2 is used, while the amplitude of vibrations changes, and the critical wind velocity, at which the peak of the vibration amplitude is observed, increases slightly. It is important to note the local effect from the deflector of type 2, which eliminates the possibility of divergence.

Conclusions and Discussion

The regulatory documents applicable in the Russian Federation contain only instructions for the performance of studies on the aerodynamic stability of bridge structures. The method of conducting such studies is partially described in the industrial standards as well as the scientific and technical literature. The international documents provide recommendations on the performance of experimental studies with the use of wind tunnels. However, the regulatory documents contain no recommendations for the improvement of the stability of bridge structures in wind.

Most studies assessing the effectiveness of various aerodynamic dampers addressed particular bridge structures at the stage of design. Besides, most of the structures studied are suspension and cable-stayed long-span bridges. As for girder bridge structures, they have been studied less. Meanwhile, in recent years, the construction of long-span girder bridges has been extensively developed.

To assess the effectiveness of the design of aerodynamic dampers, an integrated computational and experimental approach was chosen. At the first stage, we conducted preliminary numerical modeling, and, as a result, obtained a qualitative pattern of wind flow over the span under consideration. At that stage, various designs of aerodynamic dampers were considered. Based on the flow pattern analysis, the most effective option was selected. At the second stage, experimental modeling in a special wind tunnel was conducted for the selected fairing/deflector design. Such an approach makes it possible to significantly optimize the time and cost of studies by reducing the number of physical tests performed.

For a span with one main girder, it was established that the deflector design (type 2) under consideration reduces the vibration amplitude at high

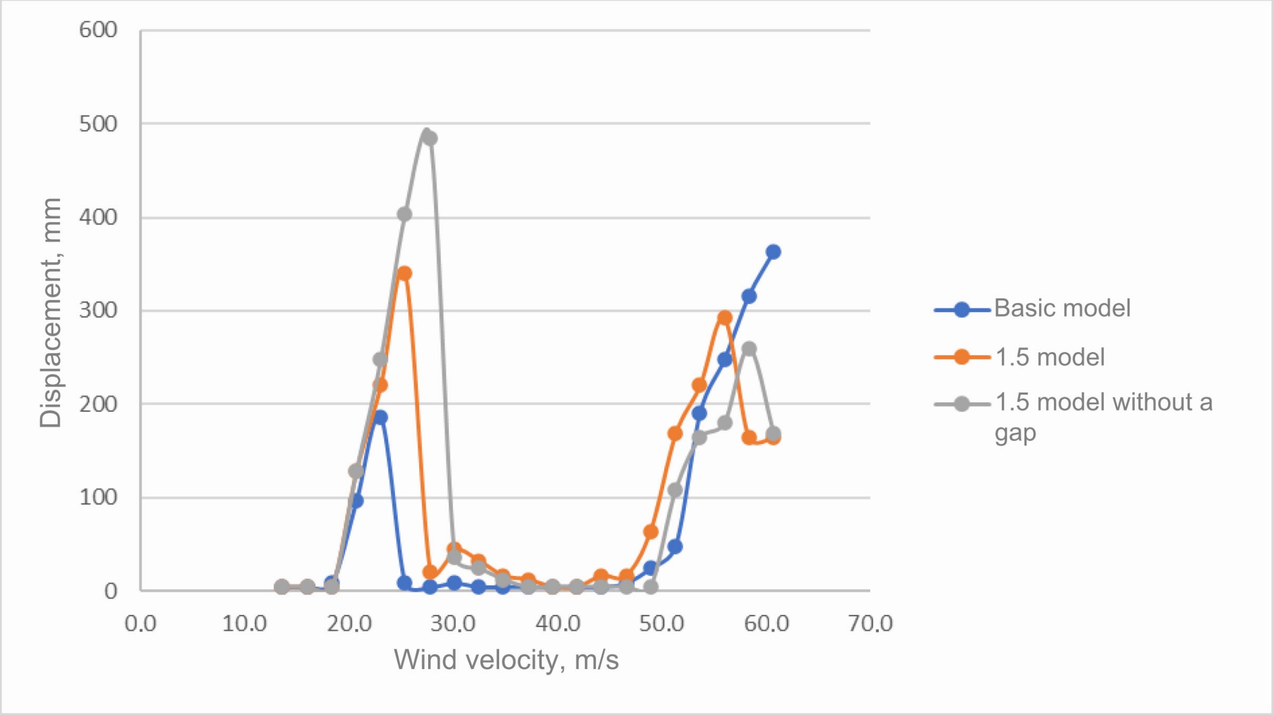


Figure 11. Vibration amplitude dependence on the wind velocity. Angle of attack: 0°

wind velocities, and there is no unlimited increase in the amplitude of torsional vibrations characteristic of divergence. Meanwhile, the amplitude of vibrations under vortex excitation increases significantly. Thus, before assessing the applicability of this model, we need to evaluate the maximum allowable amplitude of span vibrations.

Funding

This study was funded by the Ministry of Science and Higher Education of the Russian Federation (project: theoretical and experimental design of new composite materials to ensure safety during the operation of buildings and structures under conditions of technogenic and biogenic threats #FSWG-2020-0007).

All tests were carried out with the use of equipment of the Head Regional Shared Research Facilities and the Large Gradient Wind Tunnel, courtesy of the National Research Moscow State University of Civil Engineering.

References

American Society of Civil Engineers (2005). *ANSI/ASCE 7-95. Minimum design loads for buildings and other structures.* American Society of Civil Engineers, 419 p.

Arena, A., Lacarbonara, W., Valentine, D. T., and Marzocca, P. (2014). Aeroelastic behavior of long-span suspension bridges under arbitrary wind profiles. *Journal of Fluids and Structures*, Vol. 50, pp. 105–119. DOI: 10.1016/j.jfluidstructs.2014.06.018.

Churin, P. and Poddaeva, O. I. (2014). Aerodynamic testing of bridge structures. *Applied Mechanics and Materials*, Vols. 477–478, pp. 817–821. DOI: 10.4028/www.scientific.net/AMM.477-478.817.

Highways Agency (2001). *DMRB. Vol. 1. Highway structures, approval procedures and general design. Section 3. General design. Part 3. BD 49/01. Design rules for aerodynamic effects on bridges.* London: Highways Agency.

Kazakevich, M. I. (2015). *Wind safety of the structures. Theory and practice*. Moscow: Institut Giprostroymost, 287 p.

Kazakevich, M. I. and Zakora, A. L. (1983). *Oscillation damping in bridge structures*. Moscow: Transport, 134 p.

Kazakevitch, M. I. (2020). *The fundamentals of the structure calculations on the wind effects*. 2nd edition. Moscow: MISI – MGSU Publishing House, 190 p.

Larsen, A. (2000). Aerodynamics of the Tacoma Narrows Bridge - 60 years later. *Structural Engineering International*, Vol. 10, Issue 4, pp. 243–248. DOI: 10.2749/101686600780481356.

Malomo, D., Scattarreggia, N., Orgnoni, A., Pinho, R., Moratti, M., and Calvi, G. M. (2020). Numerical study on the collapse of the Morandi bridge. *Journal of Performance of Constructed Facilities*, Vol. 34, Issue 4, 04020044. DOI: 10.1061/(ASCE)CF.1943-5509.0001428.

National Research Council of Italy. Advisory Committee on Technical Recommendations for Construction (2010). *CNR-DT 207/2008 Guide for the assessment of wind actions and effects on structures.* Roma: CNR, 331 p.

Ovchinnikov, I. I., Ovchinnikov I. G., and Filippova, V. O. (2015). How unique oscillations the Volgograd Bridge? *Technical Regulation in Transport Construction*, No. 6 (14), pp. 81–91.

Poddaeva, O. and Churin, P. (2021). Aerodynamic stability of bridges with various levels of structural damping. *Architecture and Engineering*, Vol. 6, No. 4, pp. 54–62. DOI: 10.23968/2500-0055-2021-6-4-54-62.

Poddaeva, O., Churin, P., Fedosova, A., and Truhanov, S. (2018). Investigation of the stability of a two-span bridge with the use of a high-precision laser displacement sensors. *IOP Conference Series: Materials Science and Engineering*, Vol. 317, 012020. DOI: 10.1088/1757-899X/317/1/012020.

Poddaeva, O. and Fedosova, A. (2021). Damping capacity of materials and its effect on the dynamic behavior of structures. Review. *Energy Reports*, Vol. 7, Suppl. 5, pp. 299–307. DOI: 10.1016/j.egyr.2021.07.119.

Poddaeva, O. I., Fedosova, A. N., and Churin, P. S. (2020). The influence of the structural vibrations' logarithmic decrement on its stability in the event of vortex excitation. *IOP Conference Series: Materials Science and Engineering*, Vol. 913, 042069. DOI: 10.1088/1757-899X/913/4/042069.

Poddaeva, O., Fedosova, A., and Gribach, J. (2019). The study of wind effects on the bridge constructions. *E3S Web of Conferences*, Vol. 97, 03030. DOI: 10.1051/e3sconf/20199703030.

Salenko, S. D. (2005). *Unsteady aerodynamics of high-drag multi-beam structures. DSc Thesis in Engineering.* Novosibirsk: Novosibirsk State Technical University.

Shu, C. S. (2013). Wind tunnel experimental research on flutter stability of Liujiaxia Bridge. *Applied Mechanics and Materials*, Vols. 361–363, pp. 1105–1109. DOI: 10.4028/www.scientific.net/AMM.361-363.1105.

Zhang, X., Xiang, H., and Sun, B. (2002). Nonlinear aerostatic and aerodynamic analysis of long-span suspension bridges considering wind-structure interactions. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 90, Issue 9, pp. 1065–1080. DOI: 10.1016/S0167-6105(02)00251-9.

УСТОЙЧИВОСТЬ И НАДЕЖНОСТЬ БОЛЬШЕПРОЛЕТНЫХ МОСТОВЫХ КОНСТРУКЦИЙ

Ольга Игоревна Поддаева[1], Павел Сергеевич Чурин[1]*, Алексей Алексеевич Локтев[2], Chafic-Touma Salame[3]

[1]Учебно-научно-производственная лаборатория по аэродинамическим и аэроакустическим испытаниям строительных конструкций, НИУ Московский Государственный Строительный Университет
Ярославское шоссе, 26, Москва, Россия
[2]Российская открытая академия транспорта
ул. Часовая, 22/2, Москва, Россия
[3]Европейская академия устойчивого развития
11 Ремпарт Сен-Тейбо, Мец, Франция

*E-mail: pashok_@inbox.ru

Аннотация

Несмотря на то, что строительство большепролетных мостов в последнее время получило широкое распространение и развитие, до сих пор наблюдаются случаи потери устойчивости мостовых конструкций в ветровом потоке, а сама тема взаимодействия мостовых конструкций с ветром освещена в научно-технической литературе в недостаточной степени. **Цель работы:** Повышение конструктивной прочности и безопасности эксплуатации большепролетных мостовых конструкций путем проведения расчетно-экспериментального исследования влияния различных вариантов аэродинамических демпферов на их аэродинамическую устойчивость. **Методы:** Работа состоит из двух этапов: на первом этапе проводится предварительное двумерное численное моделирование влияния различных вариантов аэродинамических демпферов на обтекание пролетных строений мостовых конструкций выбранного типа ветровым потоком. На основании результатов предварительного двумерного численного моделирования выбраны наиболее эффективные конструкций аэродинамических демпферов и изготовлены их модели для проведения экспериментальных исследований аэродинамической устойчивости в специализированном стенде**. Результаты:** На основании полученных расчетных и экспериментальных результатов исследования проведен анализ эффективности различных вариантов аэродинамических дефлекторов и обтекателей, применяемых для повышения аэродинамической устойчивости рассматриваемых типовой конструкции моста. **Обсуждение:** Для пролетного строения с одной главной балкой установлена конструкция дефлектора, снижающая амплитуду колебаний на высоких скоростях ветрового потока.

Ключевые слова
Мостовые конструкции, аэродинамика, аэродинамическая устойчивость, экспериментальные исследования, численное моделирование, демпфирование, дефлектор, обтекатель.