

ASSESSMENT OF BUFFETING IN THE WAKE EFFECT ON BRIDGE AERODYNAMIC STABILITY BASED ON EXPERIMENTAL MODELLING

Olga Igorevna Poddaeva

Research and Production Laboratory of Aerodynamic and Aeroacoustic Testing of Building Structures,
Moscow State University of Civil Engineering, Moscow, Russia

*Corresponding author's email: poddaevaoi@gmail.ru

Abstract

Introduction. This paper addresses the problem of aerodynamic stability of bridge structures, specifically the phenomenon of buffeting. The relevance of the study is driven by regular accidents and failures of bridges, among the causes of which are insufficient consideration of wind effects and aerodynamic instability of structures. The aim of this work is to experimentally assess the aerodynamic stability of a two-span road bridge (with a central span length of 130 m) considering the possible occurrence of buffeting. **Methods.** The research methodology includes manufacturing a physical model of the superstructures with geometric and dynamic similarity, conducting static tests to determine aerodynamic coefficients, and dynamic tests of the aerodynamic stability of the model. **Key results.** Experimental studies on section models have shown that buffeting can occur in a superstructure located in the aerodynamic wake behind another — with the inclination of the structure relative to the oncoming flow and the difference in the overall dimensions of the fairings playing a critical role. Experimental modelling in wind tunnels remains the key method for assessing the possibility of aerodynamic instability phenomena in long-span bridges. Refinement of computational models will reduce the risks of bridge structure failures caused by wind effects.

Keywords: buffeting, experimental modelling, wind tunnels, wind effects, aerodynamic instability, bridges.

Introduction

The analysis of recent disasters is consistent with the findings of studies (Maistrenko et al., 2017; Maistrenko et al., 2018; Ovchinnikov et al., 2017; Ovchinnikov et al., 2018): accidents and failures of transport structures represent a persistent global problem, independent of the level of economic development of countries. Poddaeva (2022) notes that such incidents have been recorded in the past, continue to occur today, and are likely to persist in the future, with their frequency potentially correlating with the total number of transport facilities. Among the key risk factors confirmed by both Russian and foreign experts, insufficient consideration of wind effects stands out. In particular, the series of works (Maistrenko et al., 2017; Maistrenko et al., 2018; Ovchinnikov et al., 2017; Ovchinnikov et al., 2018), representing one of the most comprehensive analyses of bridge structure failures, classifies the underestimation of wind loads and aerodynamic instability as an independent group of causes of disasters.

The increase in spans and flexibility of modern bridges (especially cable-stayed and suspension bridges) enhances susceptibility to buffeting. Even structures that are stable under static wind loads may

experience critical dynamic effects in the wake. The resulting losses of stability of bridge structures, up to and including failure, demonstrate that for bridge structures, verification of aerodynamic stability is one of the key stages in their design.

The design of bridge structures necessarily includes a stage of ensuring their aeroelastic stability. The regulatory framework of the Russian Federation defines the procedure for investigating wind effects, which is established in GOST R 59625–2022 “Public Roads. Bridge Structures. Rules for Calculation and Confirmation of Aeroelastic Stability”. In accordance with clause 5.1 of the standard, the consideration of wind effects should cover the following aspects:

- static wind effect on the structure and its elements;
- dynamic effect, including wind gusts, squalls, and the influence of thunderstorm fronts;
- aeroelastic interaction of the flow with the superstructure.

Calculations for static and dynamic loads are performed according to GOST 33390; SP 20.13330.2016; SP 35.13330.2011.

Special attention should be paid to the phenomenon of buffeting — one of the least studied forms of aeroelastic instability (Kazakevich,

2020) — which occurs under turbulent conditions or in the wake behind structural elements due to the superposition of heterogeneous aerodynamic forces. A characteristic feature of buffeting is an increase in oscillation amplitude (“build-up”) due to wake impacts. The high danger of this phenomenon is due to its insufficient theoretical development (Kazakevich, 2020).

The requirements for ensuring aerodynamic stability are specified in clause 12 of GOST R 59625–2022:

$$\frac{S_0}{H} > 50. \quad (1)$$

where S_0 is the clear distance between structures or individual structural elements, and H is the characteristic dimension of the structure across the flow, in the wake of which the structure under consideration is located, m.

Clause 12.2 of GOST R 59625–2022 prescribes that if condition (1) is not satisfied, the results of model tests in wind tunnels should be followed.

Soloviev (2016) states that the influence of buffeting can be neglected if the distance between bridge structures exceeds 10 times the width of the central span of the bridge. However, if two practically identical superstructures are located in the same plane and separated only in the longitudinal direction by a gap of less than 1 m, the wind force on the windward side can be calculated in the same way as for a composite structure. In other cases, it is necessary to investigate the mutual influence of bridges.

Bridge aeroelasticity plays a key role in long-span bridge buffeting response, and therefore correct modelling of self-excited forces in turbulent flow is crucial (Barni et al., 2022). Several studies (Diana et al., 1993; Diana and Omarini, 2020; Chen and Kareem, 2001) have also demonstrated that the aeroelastic behaviour of most bridge cross-sections is significantly affected by a variation of the mean angle of attack. Barni et al. (2022) propose a time-domain framework based on the 2D self-excited force model, yielding a time-variant state-space formulation of the buffeting problem. In the research by Gao et al. (2024), the phenomenon of buffeting in the wake is investigated using numerical modelling. The results indicate that

the wake-induced vibration of the suspender exhibits a lock-in phenomenon with large cross-wind amplitudes at specific incoming wind velocities. Morais da Costa et al. (2022) propose an improved bridge buffeting theory with an emphasis on skew wind directions, for both turbulence- and motion-dependent forces. Traditional models often consider wind acting strictly along or across the bridge. The new theory accounts for skew angles of attack and simultaneously models the influence of turbulence and “feedback”: when the motion of the bridge itself changes the aerodynamic forces acting upon it.

Thus, the primary method for assessing the aerodynamic stability of bridge structures remains experimental modelling in wind tunnels. Further development of the theory and practice of investigating superstructures for buffeting phenomena will improve the accuracy of computational models, enhance regulatory design requirements, and reduce the risks of bridge failures due to insufficient consideration of wind effects.

Methods

As the object of study for the possible occurrence of buffeting, a two-span road bridge with a central span length of 130 m was selected. The cross-sectional layout of the bridge is shown in Fig. 1. The distance between the two spans is 1.1 m. According to Fig. 1, the criterion for ensuring aerodynamic stability is not satisfied; therefore, the verification of aerodynamic stability must be carried out based on the results of model tests in wind tunnels.

In accordance with clause 5.48 of SP 35.13330.2011 “Bridges and Pipes”, the assessment of the aerodynamic stability of a bridge requires modelling of the longest span section — as the most susceptible to dynamic wind effects. The methodology of aerodynamic experimental studies is described in detail in reference (Poddaeva, 2022). The experiments are performed at the Unique Scientific Facility “Large Research Gradient Wind Tunnel” of NRU MGSU. The physical model of the superstructures is manufactured at a scale of 1:64.2 from sheet aluminium. The choice of material ensures high geometric similarity accuracy, lightness, and rigidity of the structure. The resulting model meets the requirements of clause 15.4.2 of

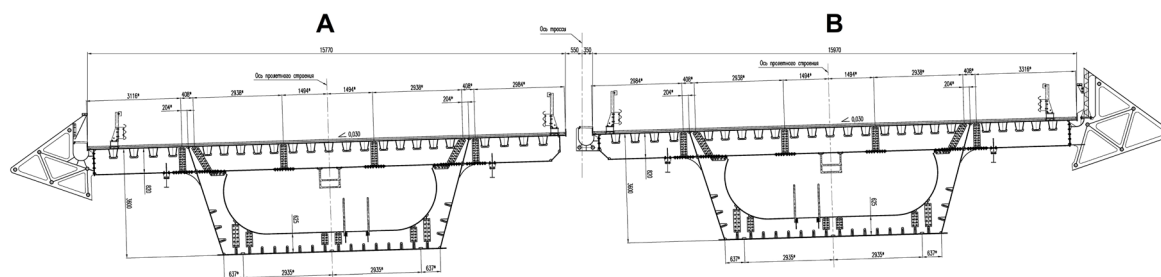


Fig. 1. Typical cross-sectional layout of the bridge superstructure

GOST R 59625–2022 regarding geometric similarity and mass distribution relative to the full-scale object. Similarity in Newton and Scruton numbers is maintained. The manufactured model (Fig. 2) corresponds to the full-scale object in the following parameters: geometric similarity; correspondence of mass distribution; correspondence of geometric centres of mass; which fully satisfies the requirements of GOST R 59625–2022. The calculated similarity criteria values are presented in Table 1.

The designed model corresponds to the full-scale object in the following parameters:

- geometric similarity;
 - correspondence of mass distribution;
 - correspondence of geometric centres of mass;
- which fully satisfies the requirements of GOST R 59625–2022.

The correspondence of the section model to the similarity laws ensures the representativeness of the aerodynamic test results. In this case, the actual behaviour of the superstructure is adequately reflected by the behaviour of its model

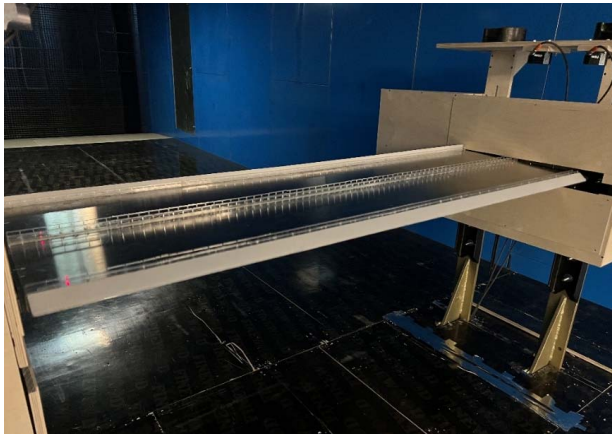


Fig. 2. Model of the investigated object

in the wind tunnel, which allows direct extrapolation of experimental data to the full-scale object. Dynamic similarity of the model and its frequency characteristics are modelled by specialised springs of the measuring stand.

When investigating the dynamic behaviour of the downstream superstructure, the recommended standard values of oscillation frequencies were adopted as reference points for verification of experimental data:

- the frequency of the first (bending) mode of oscillation was set at $f_{bend} = 0.68$ Hz, which corresponds to typical parameters of similar structures;

- the frequency of the fifth (torsional) mode of oscillation was adopted as $f_{tors} = 3.38$ Hz, reflecting the expected response of the system to torsional effects.

An important parameter characterising the dissipative properties of the structure is the logarithmic decrement of damping. At small oscillation amplitudes, its value was $\delta = 0.02$, which is typical for rigid metal structures with low internal damping.

For a comprehensive assessment of damping properties across the entire range of investigated regimes, data on the logarithmic decrement of damping are presented in Table 2. These values allow for: assessing the change in damping depending on the oscillation amplitude; comparing experimental results with computational models; confirming the correctness of the selected reference frequencies.

The scales of wind velocity, geometric dimensions, and frequencies are determined based on the ratio of the model and full-scale bridge dimensions — the corresponding data are presented in Table 3. The results of oscillation frequency measurements of the superstructure model, performed on the measuring stand, are shown in Figs. 3–5.

Table 1. Calculated similarity criteria values

	Model	Full Scale	Model / Full Scale
Newton similarity	$Nw_{mod} = 942$	$Nw_{full} = 974$	$\frac{Nw_{mod}}{Nw_{full}} = 0.97$
Scruton similarity	$Sc_{mod} = 37.68$	$Sc_{full} = 38.96$	$\frac{Sc_{mod}}{Sc_{full}} = 0.97$

Table 2. Logarithmic decrement of damping values at different oscillation amplitudes

Oscillation Amplitude	Model Damping Decrement Value
Amplitudes around 50 mm in full-scale equivalent	0.02
Near-zero amplitudes at the end of the decay process	0.018
Amplitudes around 150 mm in full-scale equivalent	0.027
Amplitudes around 300 mm in full-scale equivalent	0.04
Amplitudes around 400–500 mm in full-scale equivalent	0.06

Table 3. Ratios for the model and full-scale object

	Oscillation Mode	Full-Scale Object	Model	Velocity Scale U^*
Full-scale object and model frequencies	Bending (1st mode)	0.68 Hz	9.15 Hz	4.77
	Torsion	3.38 Hz	16.7 Hz	12.9

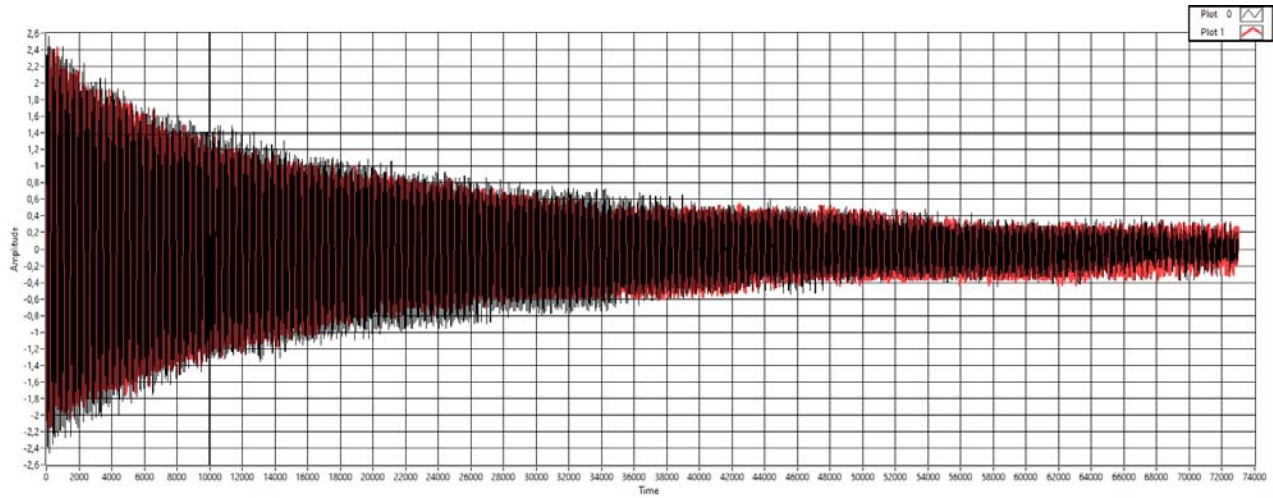


Fig. 3. Damped oscillatory process

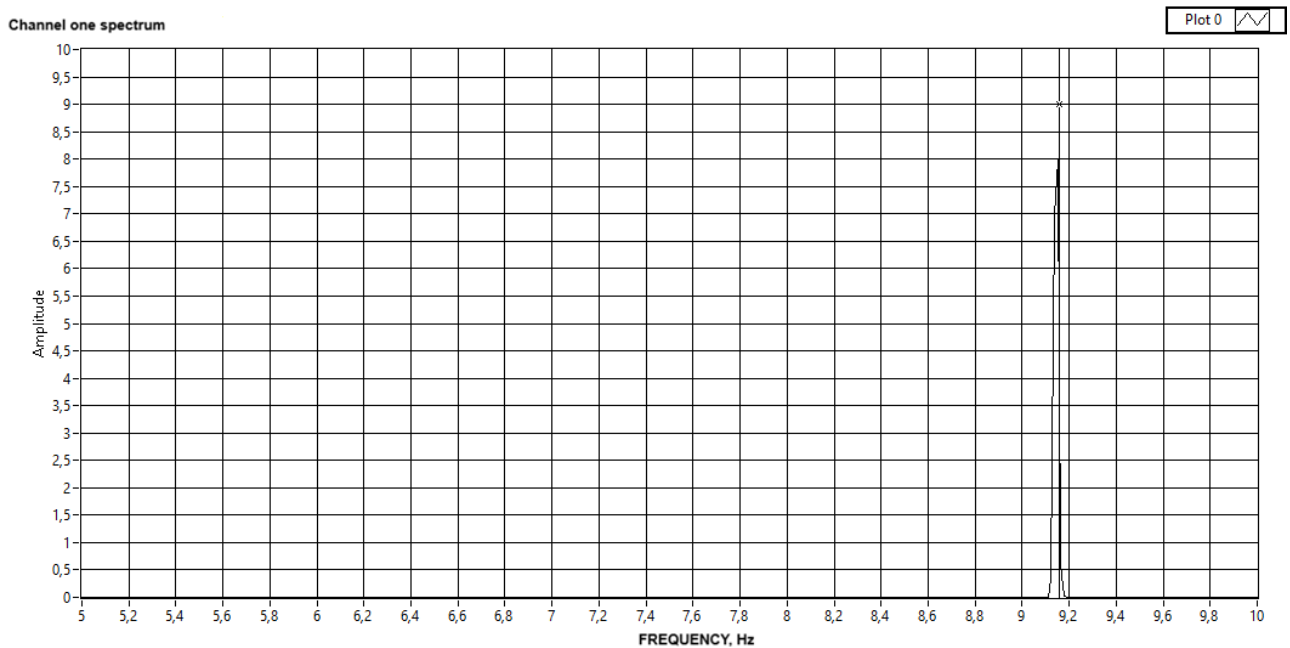


Fig. 4. Power spectral density for bending oscillations

The calculation of the wind velocity scale for bending oscillations was performed using the classical Strouhal formula:

$$U^* = L^* \cdot f^* = 64,2 \cdot \frac{0,68}{9,15} = 4,77 \quad (2)$$

Preliminary aerodynamic tests of the bridge model confirmed that the experimental Strouhal number (calculated based on the flow velocity and oscillation frequency) corresponds to analytical

estimates for similar structures. The layout of the force-moment sensors is shown in Fig. 6, and the range of considered angles of attack of the oncoming wind flow is shown in Fig. 7. Preliminary tests of the bridge model in the flow showed that the obtained Strouhal number (calculated from the flow velocity and oscillation frequency) corresponds to the analytical estimate for similar structures.

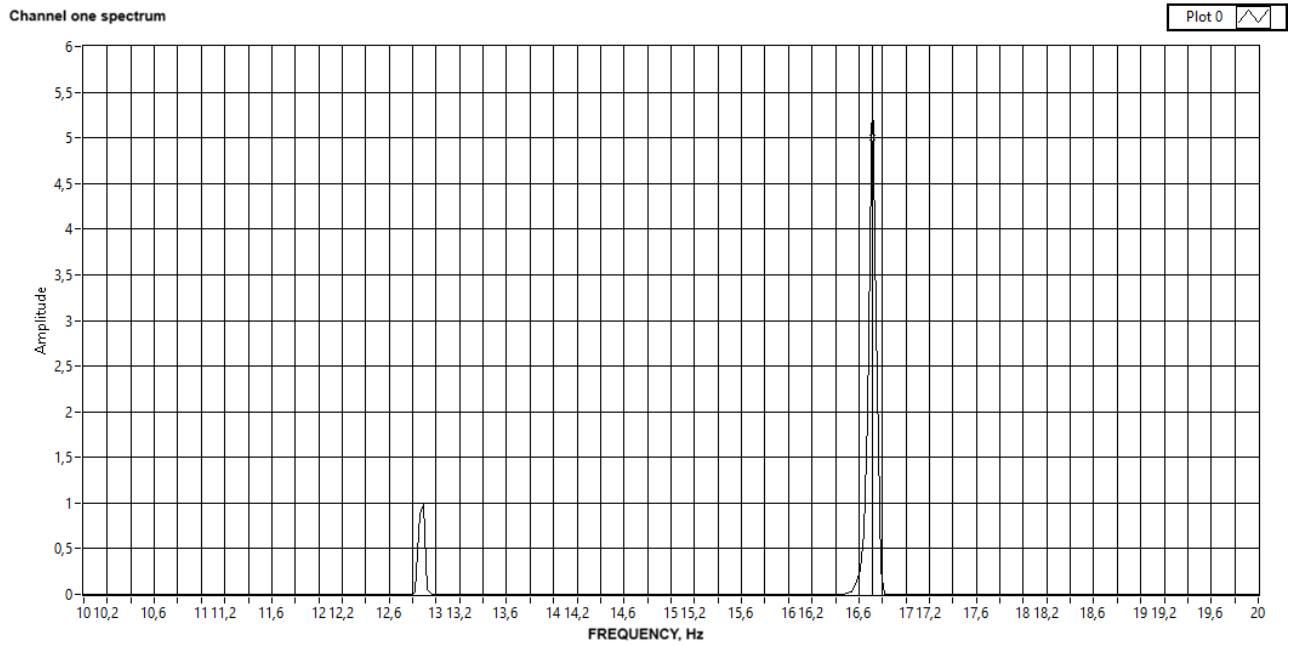


Fig. 5. Power spectral density for torsional oscillations

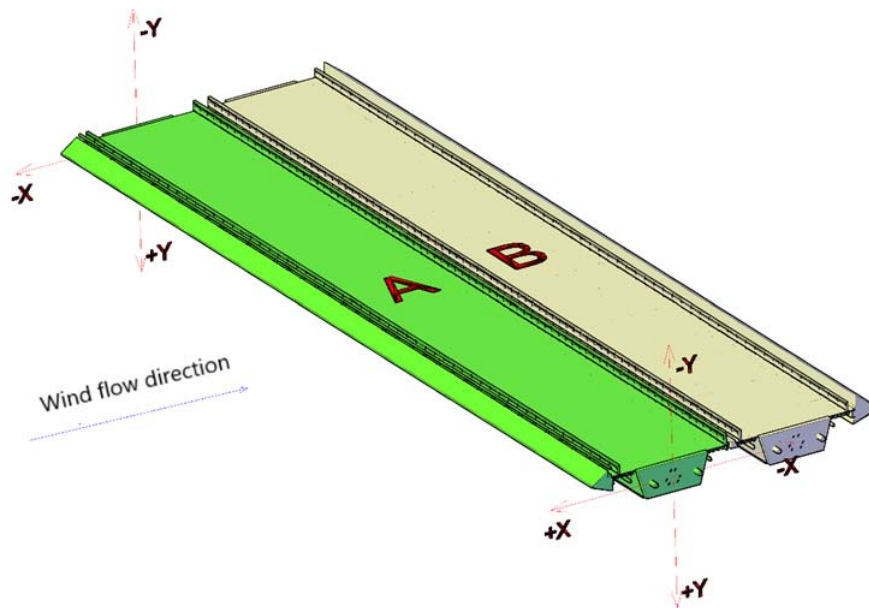


Fig. 6. Placement of force-moment sensors during static tests

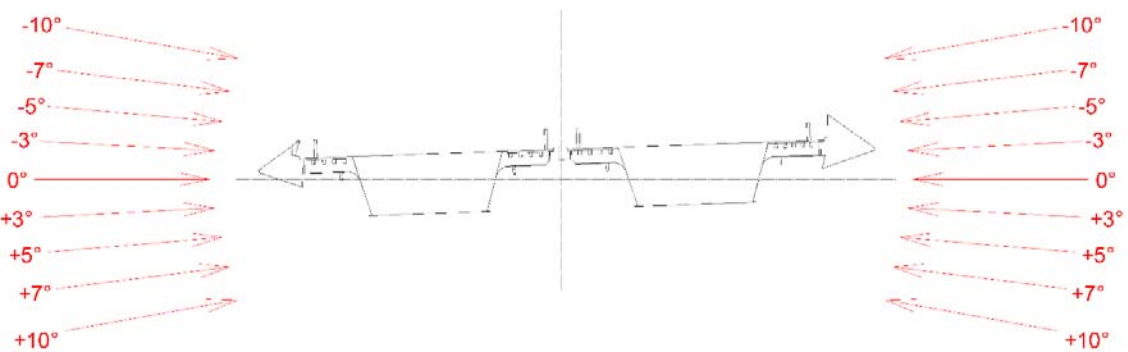


Fig. 7. Angles of attack of the oncoming wind flow considered during experimental studies

In accordance with the adopted methodology (Poddaeva, 2022), at the first stage of the study, static tests are conducted to determine the aerodynamic coefficients. The obtained graphs of the dependence of lift force (C_y), drag force (C_x), and pitching moment (Cm_z) on the angle of attack of the flow at angles of attack (-10° to $+10^\circ$) for spans located in the wake are presented in Fig. 8.

In accordance with the methodology (Poddaeva, 2022), at the second stage of the study, dynamic tests of the aerodynamic stability of the superstructure model were conducted. The experimental studies

were performed at yaw angles of 0° and 180° , which correspond to the flow direction perpendicular to the axis of the superstructure — the most unfavourable from an aerodynamic point of view. During the dynamic tests, the model was mounted on spring suspensions in a specialised stand. The characteristics of the suspensions and their corresponding flow velocity scale were determined at the model design stage. The damping level of the model was measured and amounted to $\delta = 0.02$, which meets the requirements of GOST R 59625–2022. The low damping value is due to the rigid metal structure of the model and its

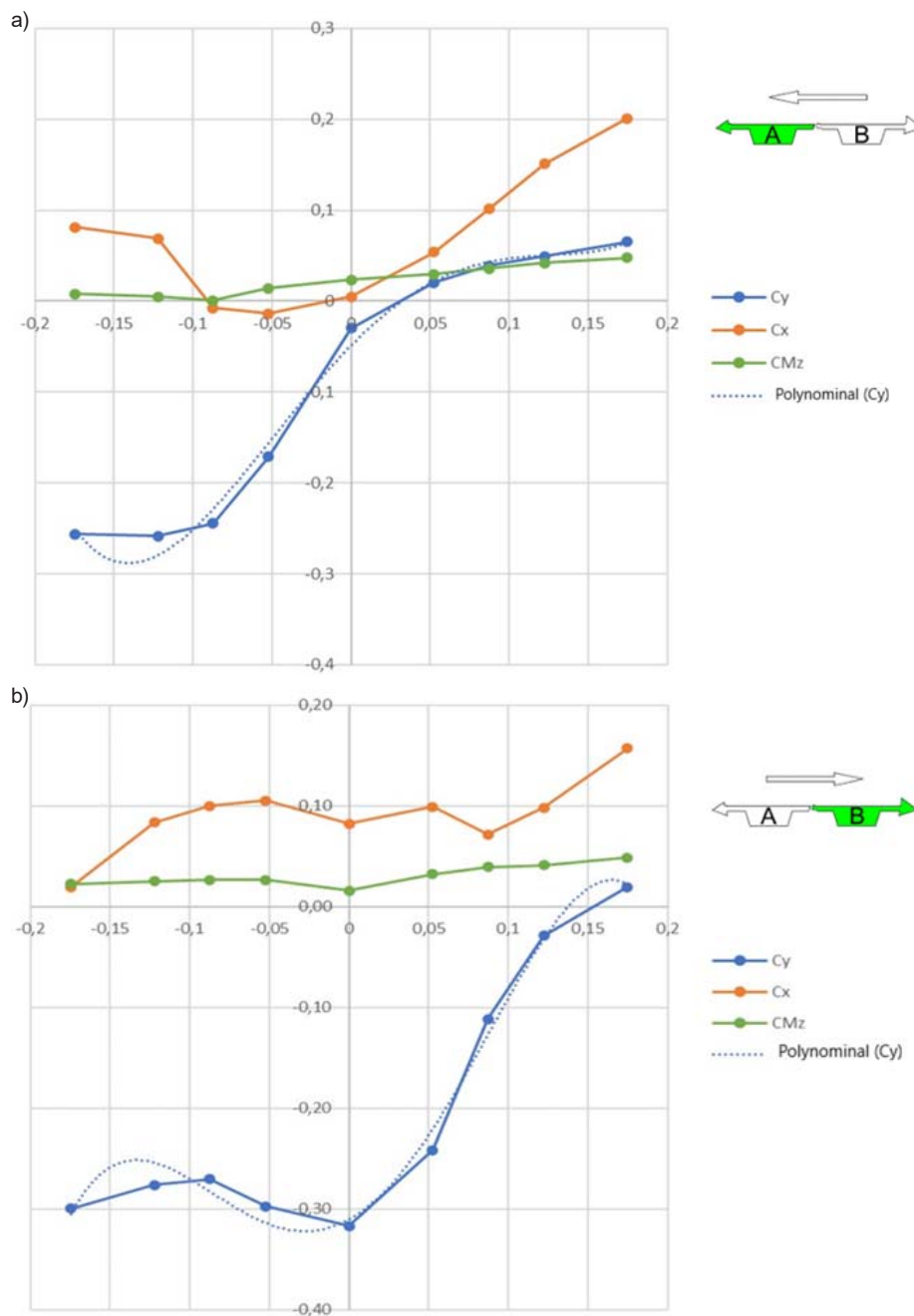


Fig. 8. Graphs of the dependence of lift force (C_y), drag force (C_x), and torsional moment (Cm_z) on the angle of attack of the flow at angles of attack (-10° to $+10^\circ$): (a) Model A in the wake of B; (b) Model B in the wake of A

low dissipative properties. To measure the model displacements, four optical sensors operating on the principle of laser triangulation were used. This method does not affect the free motion of the suspended model. The wind velocity was recorded using a Pitot tube connected to a high-sensitivity pressure sensor. The signals from the displacement sensors first passed through a low-pass filter and then were digitised by a 16-bit analogue-to-digital converter at a rate of 1,000 samples per second. Displacement measurements were taken relative to the zero level at a wind velocity of 0 m/s.

The stability assessment results are presented in the form of a graph of the full-scale superstructure displacement versus the mean wind velocity (Fig. 9). Vertical lines on the graph indicate threshold flow velocity values:

- design velocity — yellow line;
- critical flutter velocity — red line.

The critical flutter velocity value was calculated in accordance with the requirements of GOST R 59625–2022. The test programme provided for studies at yaw angles of 0° and 180° for angles of attack $\alpha = -5^\circ, -3^\circ, 0^\circ, +3^\circ, +5^\circ$.

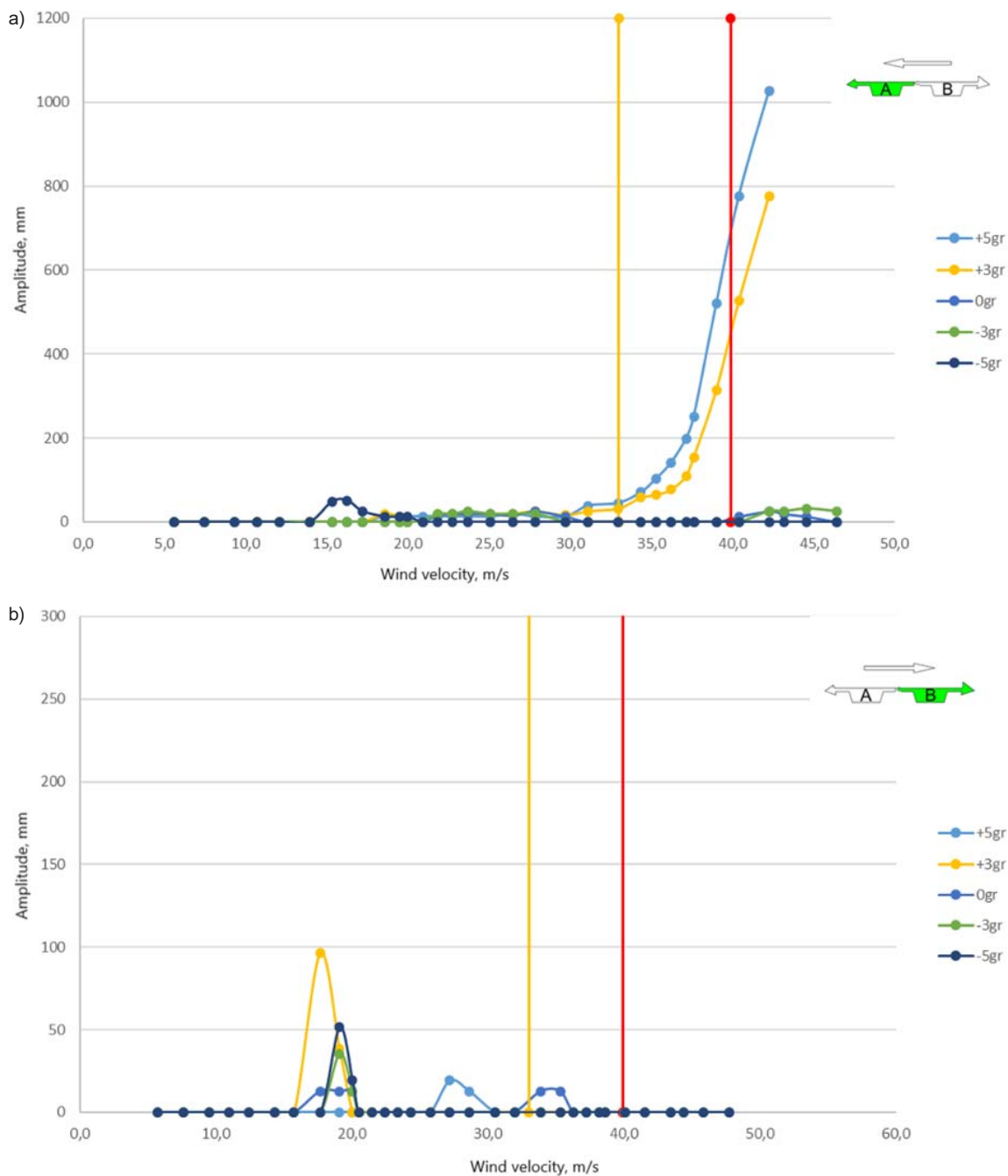


Fig. 9. Dependence of the oscillation amplitude A of the superstructure on the mean wind flow velocity at various angles of attack (bending oscillations in the first mode, yaw angle 180°): (a) Model A in the wake of B; (b) Model B in the wake of A

Table 4. Yaw angle 0° (Bridge B in the wake of A)

Angle of Attack	Phenomenon	Velocity Range (m/s)	Max. Amplitude (mm)
-5°	Vortex-induced excitation	19.1–20.0	51
-3°	Vortex-induced excitation	19.1–20.0	35
+3°	Vortex-induced excitation	17.7–19.1	96
+5°	Vortex-induced excitation	27.2–28.6	19

Table 5. Yaw angle 180° (Bridge A in the wake of B)

Angle of Attack	Phenomenon	Velocity Range (m/s)	Max. Amplitude (mm)	Special Conditions
-5°	Vortex-induced excitation	15.3–20.0	51 (at 16.3 m/s)	—
-3°	Vortex-induced excitation	22.0–28.0	26 (at 23.7 m/s)	—
0°	Vortex-induced excitation	22.0–30.0	26 (at 27.9 m/s)	—
+3°	Bending oscillations with amplitude growth	33.0–42.3	777 (at 42.3 m/s)	Beyond the calculated range for galloping; stopped for safety reasons
+5°	Bending oscillations with amplitude growth	33.0–42.3	1027 (at 42.3 m/s)	Beyond the calculated range for galloping; stopped for safety reasons

Results

During the experimental studies, various regimes of aeroelastic oscillations of bridge structures were identified (Tables 4, 5).

Conclusion and Discussion

As already mentioned, buffeting is one of the least studied phenomena of aerodynamic instability in building structures. Unlike other phenomena, such as galloping, divergence, and the similar-in-nature vortex-induced resonance excitation, there are currently no assessment methods for the analytical evaluation of buffeting occurrence. The only reliable way to assess the possibility of its occurrence is to conduct experimental studies. The conducted studies on section models have shown the occurrence of oscillations for one of the superstructures when it is located in the aerodynamic wake behind the other (Model B, leeward). Despite the fact that the shapes of the superstructures are almost identical,

their inclination relative to the oncoming flow, as well as the difference in the overall dimensions of the fairings, plays a significant role in the possibility of buffeting occurrence. This is precisely why, with the opposite orthogonal flow direction (Model A, leeward), buffeting is not observed. Thus, conducting experimental studies of the aerodynamic stability of twin parallel superstructures is of paramount importance in ensuring their reliability and mechanical safety, as it is currently the only way to identify the possibility of occurrence of such a dangerous phenomenon of aerodynamic instability as buffeting.

Funding

All tests were carried out using research equipment of The Head Regional Shared Research Facilities and Unique Scientific Installation “Large Research Gradient Wind Tunnel” of the Moscow State University of Civil Engineering.

References

- Chen, X. and Kareem, A. (2001). Nonlinear response analysis of long-span bridges under turbulent winds. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 89, Issues 14–15, pp. 1335–1350. [online] Available at: [https://doi.org/10.1016/S0167-6105\(01\)00147-7](https://doi.org/10.1016/S0167-6105(01)00147-7) [accessed on: 04/08/2024].
- Diana, G., Bruni, S., Cigada, A., and Collina, A. (1993). Turbulence effect on flutter velocity in long span suspended bridges. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 48, Issues 2–3, pp. 329–342. [online] Available at: [https://doi.org/10.1016/0167-6105\(93\)90144-D](https://doi.org/10.1016/0167-6105(93)90144-D) [accessed on: 05/09/2023].
- Diana, G. and Omarini, S. (2020). A non-linear method to compute the buffeting response of a bridge validation of the model through wind tunnel tests. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 201, p. 104163. [online] Available at: <https://doi.org/10.1016/j.jweia.2020.104163> [accessed on: 10/03/2023].
- Gao, W., Tao, T., and Wang, H. (2024). Wake-induced vibration of ultra-long suspenders adjacent to bridge tower. *Physics of Fluids*, Vol. 36, Issue 10, p. 105135. [online] Available at: <https://doi.org/10.1063/5.0229591> [accessed on: 09/10/2025].
- Kazakevich, M. I. (2020). *Fundamentals of calculations of structures for wind effects*. 2nd ed., rev. and suppl. Moscow: MISI-MGSU Publishing House.
- Maistrenko, I. Yu., Ovchinnikov, I. I., Ovchinnikov, I. G., and Kokodeev, A. V. (2017). Failures and collapses of bridge constructions, analysis of their causes. Part 1. *Russian Journal of Transport Engineering*, Vol. 4, Issue. 4. DOI: 10.15862/13TS417. [online] Available at: <https://t-s.today/PDF/13TS417.pdf> [accessed on: 05/06/2025].
- Maistrenko, I. Yu., Ovchinnikov, I. I., Ovchinnikov, I. G., and Uspanov, A. M. (2018). Failures and collapses of bridge constructions, analysis of their causes. Part 3. (2018) *Russian Journal of Transport Engineering*, Vol. 1. DOI: 10.15862/08SATS118. [online] Available at: <https://t-s.today/PDF/08SATS118.pdf> [accessed on: 05/06/2025].
- Morais da Costa, B., Wang, J., Bogunović Jakobsen, J., Øiseth, O., þór Snæbjörnsson, J. (2022). Bridge buffeting by skew winds: A revised theory. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 220, p. 104806. [online] Available at: <https://doi.org/10.1016/j.jweia.2021.104806> [accessed on: 10/05/2025].
- Ovchinnikov, I. I., Maistrenko, I. Yu., Ovchinnikov, I. G., and Kokodeev, A. V. (2017). Failures and collapses of bridge constructions, analysis of their causes. Part 2. *Russian Journal of Transport Engineering*, Vol. 4, Issue 4, pp. 1–42.
- Ovchinnikov, I. I., Maistrenko, I. Yu., Ovchinnikov, I. G., and Uspanov, A. M. (2018). Failures and collapses of bridge constructions, analysis of their causes. Part 4. *Russian Journal of Transport Engineering*, Vol. 5, Issue 1.
- Poddaeva, O. I. (2022). *Fundamentals of ensuring technosphere safety of critically important transport infrastructure facilities within the life cycle*. Doctoral dissertation (2.9.10), Dissertation Committee (40.2.002.08). Moscow: Russian University of Transport.
- Soloviev, S. Yu. (2016). Aerodynamic stability of long-span bridges. Transport of the Russian Federation. *Journal of Science, Practice, Economics*, Vol. 5, Issue 66. [online] Available at: <https://cyberleninka.ru/article/n/aerodinamicheskaya-ustoychivost-bolsheproletnyh-mostov> [accessed on: 04/03/2026].

ОЦЕНКА ВЛИЯНИЯ БАФТИНГА В СПУТНОМ СЛЕДЕ НА АЭРОДИНАМИЧЕСКУЮ УСТОЙЧИВОСТЬ МОСТОВ НА ОСНОВЕ ЭКСПЕРИМЕНТАЛЬНОГО МОДЕЛИРОВАНИЯ

Ольга Игоревна Поддаева

Учебно-научно-производственная лаборатория аэродинамических и аэроакустических испытаний строительных конструкций (УНПЛ ААИСК), Национальный исследовательский Московский государственный строительный университет, Москва, Россия

*E-mail: poddaevaoi@gmail.ru

Аннотация

Введение. В статье рассматривается проблема аэродинамической устойчивости мостовых сооружений, в частности — явление бафтинга. Актуальность исследования обусловлена регулярными авариями и разрушениями мостов, среди причин которых — недоучёт ветровых воздействий и аэродинамическая неустойчивость конструкций. Целью работы является экспериментальная оценка аэродинамической устойчивости двухпролётного автодорожного моста (длина центрального пролёта — 130 м) с учётом возможного возникновения бафтинга. **Методика исследования включает:** изготовление физической модели пролётных строений с соблюдением геометрического и динамического подобия, проведение статических испытаний для определения аэродинамических коэффициентов, динамические испытания аэродинамической устойчивости модели. **Основные результаты:** Экспериментальные исследования на отсечных моделях показали, что бафтинг может возникать у пролётного строения, расположенного в аэродинамическом следе за другим, — при этом критическую роль играют наклон конструкции относительно набегающего потока и разница в габаритных размерах обтекателей. Экспериментальное моделирование в аэродинамических трубах остаётся ключевым методом оценки возможности/ невозможности возникновения явлений аэродинамической неустойчивости большепролетных мостов. Совершенствование расчётных моделей позволят снизить риски возникновения аварий мостовых конструкций, обусловленных ветровыми воздействиями.

Ключевые слова: бафтинг, экспериментальное моделирование, аэродинамические трубы, ветровые воздействия, аэродинамическая неустойчивость, мосты.