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The Impact of Traffic on the Aerodynamic Stability of Long-Span Bridges




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ABSTRACT

Under certain conditions, wind effects on long-span bridges can cause aeroelastic instability phenomena. Currently, the main method for studying such structures for occurrence of aeroelastic instability phenomena is experimental modelling in wind tunnels.

Experimental modelling is usually based on the assumption that the cross-sectional shape of the bridge remains unchanged over time. Obviously, such a proposal cannot be true, since the presence of vehicles on the bridge structure changes the cross-sectional profile of the bridge. In this regard, it is extremely important to find out whether it is justified to ignore the change in the cross-sectional profile of bridges due to the presence of traffic. The present study is aimed at obtaining, using experimental modelling in wind tunnels, a notion of the effect of changes in the cross-section of the bridge due to the presence of traffic on its aerodynamic stability.

Keywords: *transport infrastructure, long-span bridges, bridge stability, traffic, wind effects, wind tunnels.*

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INTRODUCTION

In the classical analysis of bridge structures for aeroelastic instability phenomena using both experimental and numerical modelling, car traffic is usually ignored [1–5]. Traffic means the location of motor (or railway) vehicles on the span structure. Obviously, such an approach significantly simplifies the study of the aerodynamics of long-span bridges. If we consider the traffic on the bridges, the cross-sectional profile of the bridge will constantly change due to the moving traffic flow. As a result, the changed cross-sectional profiles of the bridge along the span structure will differ significantly even at the same time; besides, the profiles will also change due to the road and wind conditions at different times. Because of this, the question of whether it is justified to ignore the change in the cross-sectional profile of bridges due to the presence of traffic flow seems significant.

Compared to studies of the influence of traffic as of external dynamic loads on the bridge, studies of the effect of changes in the cross-sectional profiles of the bridge on the aerodynamic behaviour of structures are quite rare.

The authors of [6] conducted a series of experiments in a wind tunnel to study the effect of stochastic traffic on flutter derivatives. Several scenarios were tested to obtain an idea of the changes in flutter derivatives at different sections of the bridge and at different points in time. In the work [7], devoted to the effect of changes in the bridge profile due to the presence of traffic flow on the aerodynamic characteristics of the structure, the authors, having conducted experimental modelling, showed that a change in the cross-section of the bridge due to the presence of traffic can significantly affect the aeroelastic properties of long-span bridges. The work [8] examined a change in the aerodynamic and aeroelastic characteristics of the bridge caused by stationary vehicles with different locations of vehicles on the bridge deck. It was found that for a system with two degrees of freedom, stationary vehicles have a rather beneficial effect on stability of the bridge. The work [9] has studied the wind load on a railway bridge, which makes part of a high-speed line. The authors have come to a qualitative conclusion about the constant fluctuations of the aerodynamic resistance coefficients of the «span structure» – «vehicles» system for various combinations of the positions of the vehicles on the bridge crossing, including for high-speed lines.

One of the *tasks* solved in this work is the study of the influence of traffic flow density and the location of individual vehicles on the span structure on the aerodynamic behaviour of long-span bridges.

For this purpose, a series of *experiments* was conducted in a wind tunnel for two different models of long-span bridge crossings in several settings: the absence of vehicles on the structure (classical setting) and the presence of car traffic, leading to a change in the cross-section of the bridge.

RESULTS

Research Object № 1

Statement of the problem

A span structure with a length of 265,41 m was selected as the object of study (Pic. 1).

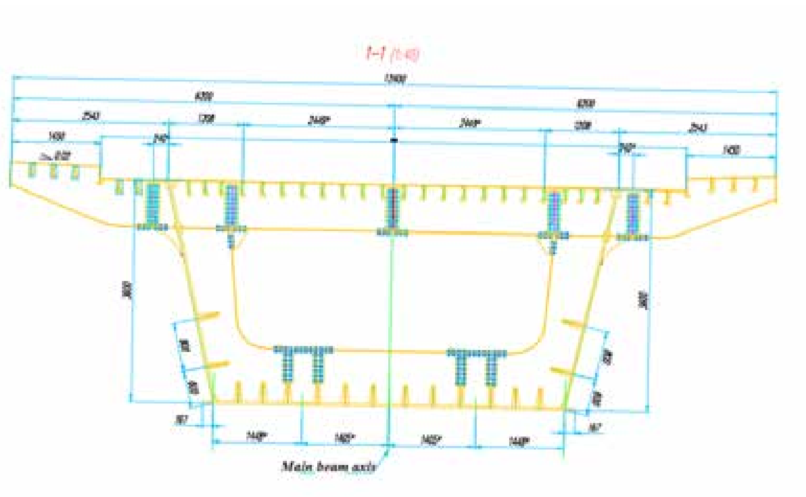
Methodology for conducting aerodynamic experimental studies

According to domestic regulatory documents[1], the aerodynamic stability of such a structure should be tested using experimental modelling in wind tunnels. Currently, depending on the size and main objectives of the tests, the world community of wind energy and industrial aerodynamics (International Associations for Wind Engineering) has officially adopted two methods for studying the wind effect on bridge structures:

1. Testing sectional (cut-off) models of span structures.
2. Testing full-scale models [10].

Conducting full-scale experiments in wind tunnels is associated with several direct and indirect constraints, which include the use of full-sized models, which is associated with the geometric, financial and time aspects of this type of work. Although creation of full-scale models of the object can provide complete reliable information on the actual state and behaviour of the structure under aerodynamic effects, since this is associated with the need for accurate reproduction of the mass-inertial and frequency parameters of the bridge structure, the study of aeroelastic instability phenomena is associated with complexity of scaling models and interpreting the results obtained after the

[1] Code of rules SP 35.13330.2011. Bridges and Pipes. Updated version of SNiP [Construction standards and rules] 2.05.03–84*. [Electronic resource]: https://docs.cntd.ru/document/ 1200084849. Last accessed 05.05.2024.



Pic. 1. Cross-section diagram of bridge № 1 [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

experiment[2] [11–16]. In the process of modelling, it is important to be able to vary a wide range of model parameters, since when conducting scientific and technical support for design of a bridge crossing, design and other engineering solutions can change [10]. It is then proposed to test bridge span structures in wind tunnels in the form of rigid sections, geometrically similar to a real structure, with three degrees of freedom and suspended in the working area of the pipe in a six-coordinate system. This model representation allows for fairly accurate reproduction of real aerodynamic effects in laboratory conditions: various types of aerodynamic flows, changes in wind speed by height, variations in wind flow intensity, various angles of attack, vertical and horizontal load pulsations, visualisation of wind flow distribution in the vicinity of the blown structure, etc. [10].

Sectional tests are the most common research method. This method is appropriate for beam bridges in the absence of high-rise pylons and the need to consider the impact of the cable-stayed system on the span structure.

When testing a sectional model, the section of the longest bridge span is modelled as the most susceptible to dynamic wind effects. Practical experience in conducting experiments in wind tunnels, as well as the requirements set in regulatory documents, allows us to assert that for the most accurate modelling, it is necessary to make the sectional model of the span structure as absolutely rigid one, and model the elastic characteristics using spring hangers on a specialised stand-table. Detailed requirements were previously described in ODM [road industry's methodological document] 218.2.040–2014 «Methodological recommendations for assessing the aerodynamic characteristics of sections of bridge spans»[3]. Now valid is GOST R 59635–2022, a national standard of the Russian Federation «Motor roads of public use. Bridges. Rules for calculating and confirming aeroelastic stability»[4]. Features not specified in the document are comprehended and then considered by empirically varying the characteristics at the beginning of blowing on the model.

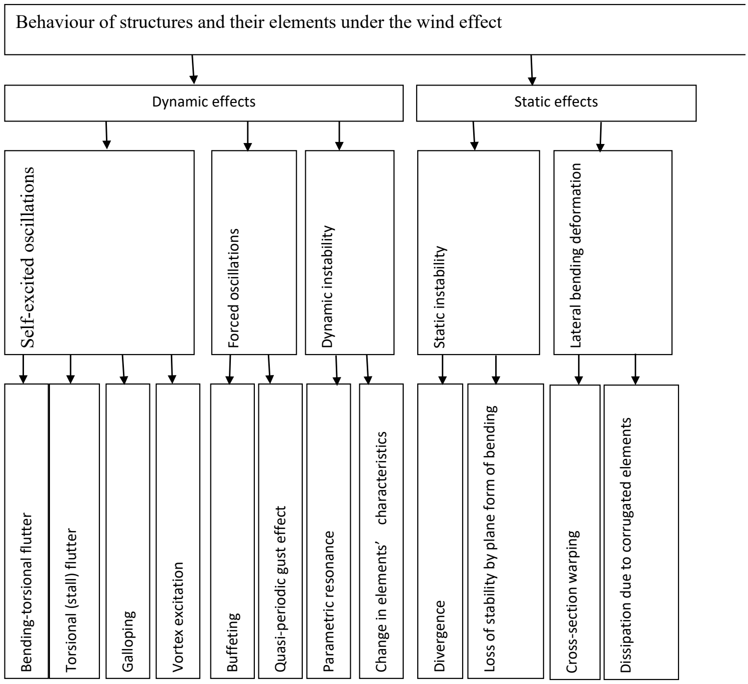
Aerodynamic effects, like any other load, are usually divided into static and dynamic ones; they are based on aerodynamic forces and elastic forces (flutter, buffeting); one of the additional causes of the appearance of dynamic effects are inertial forces.

The classification presented in Pic. 2 covers almost all known forms of motion of elastic bodies in a wind flow [10].

[2] Guide for the assessment of wind actions and effects on structures National Research Council of Italy. CNR-DT 207/2008

[3] ODM 218.2.040-2014 «Methodological recommendations for assessing the aerodynamic characteristics of sections of bridge spans». Confirmed by the order of Federal Road Agency, dated 24.03.2014 № 478-r. [Electronic resource]: https://rosavtodor.gov.ru/docs/prikazy-rasporyazheniya/13183. Cancelled by the order of Federal Road Agency, dated 05.05.2022 № 1414-r. [Electronic resource]: https://rosavtodor.gov.ru/docs/prikazyrasporyazheniya/522301. Last accessed 05.05.2024.

[4] State standard GOST R 59625-2022. «Motor roads of public use. Bridges. Rules for calculating and confirming aeroelastic stability». [Electronic resource]: https://docs.cntd.ru/ document/1200182851. Last accessed 05.05.2024.



Pic. 2. Classification of aeroelastic phenomena by M. I. Kazakevich [10] [performed by A. A. Loktev].

The impacts to which bridge structures are exposed can also be divided into technogenic and natural, depending on the nature of their occurrence, but given the nonlinear nature of most of them, the results of their combined action cannot be obtained by the usual aggregation of single phenomena. Since the contribution of individual types of impacts to the final result can be significant, researchers are forced to sophisticate the applied approaches and models, combining, for example, the effect of vehicles being on the bridge deck and snow (and/or ice) deposits, the location of which can also change depending on the direction and intensity of the wind.

For example, during the physical modelling of the snow load on the model of the artificial structure, a special plastic powder was used, the fractions of which correspond to the parameters of scaling the structure, considering the humidity in the laboratory room, to prevent the effects of adhesion and additional moisture absorption.

The proposed approach to modelling does not allow considering the effects of melting or, conversely, freezing of additional ice on structural elements, that is, it is actually reduced to an additional quasi-static load, the local intensity of which can change due to the transport of particles due to wind. At the same time, the distribution of particles imitating snow makes it possible to predict the appearance of hazardous areas for workers on the structure and in the vicinity of it, associated with increased wind flow speeds and current restrictions as part of ensuring occupational safety.

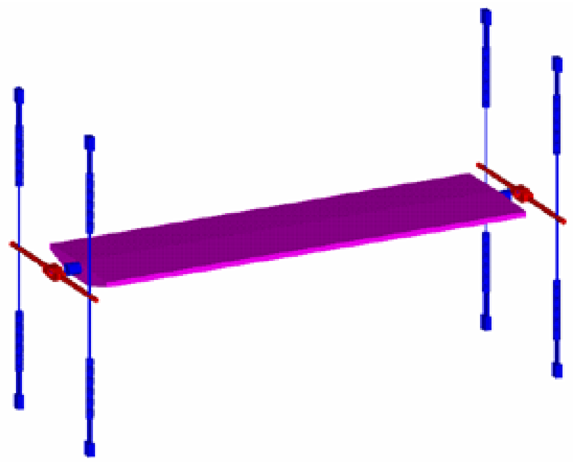
A physical model of a section of the span structure forms the basis of experimental studies for the bridge crossing in a wind tunnel (Pic. 3). The model is suspended on spring fasteners and then subjected to wind action to detect bending and torsional vibrations with aggregation of various vibration modes with their subsequent separation [10].

The physical model is installed in the centre of the cross-section of the wind tunnel on a special stand, the supports of which are rigidly attached to the floor of the chamber and on them, in turn, the span structure is suspended on springs (Pic. 4). This layout of the experiment allows for both static and dynamic testing of the bridge crossing [10; 16].

During dynamic tests of the bridge superstructure, the parameters of forced oscillations of the model under the influence of an aerodynamic load are determined:

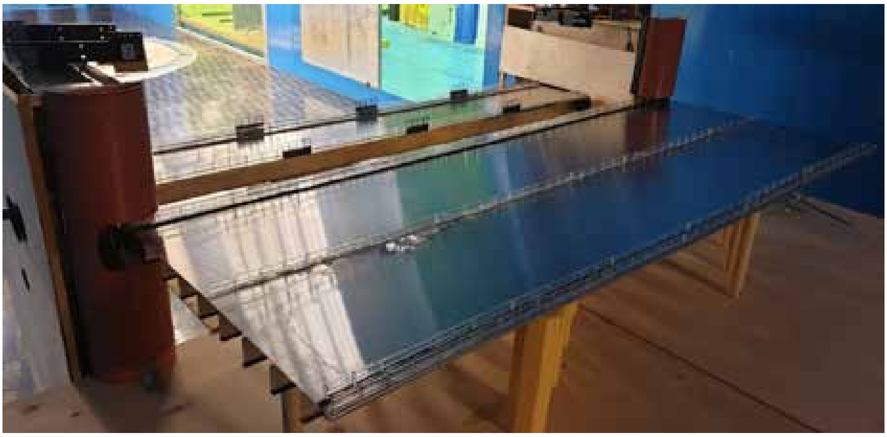
- Amplitudes of oscillatory movements.
- Frequency spectra of oscillations.
- Ordinal forms of oscillations.
- Spectral characteristics of oscillations.

Static tests of the bridge section are necessary to verify the load characteristics and compare

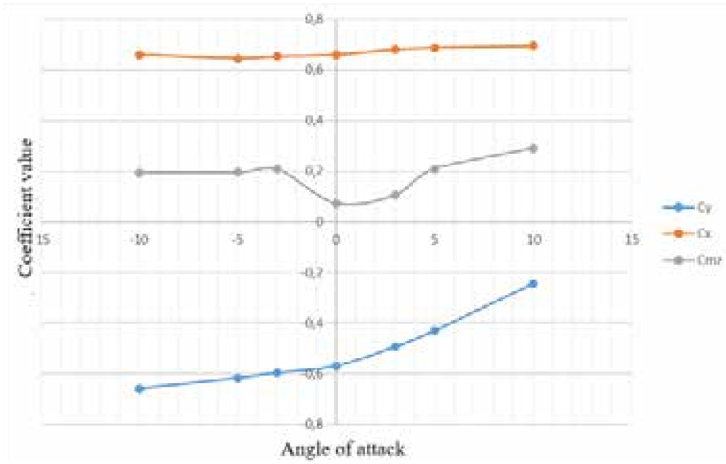


Pic. 3. Scheme of suspension of a section of a span structure on spring braces [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

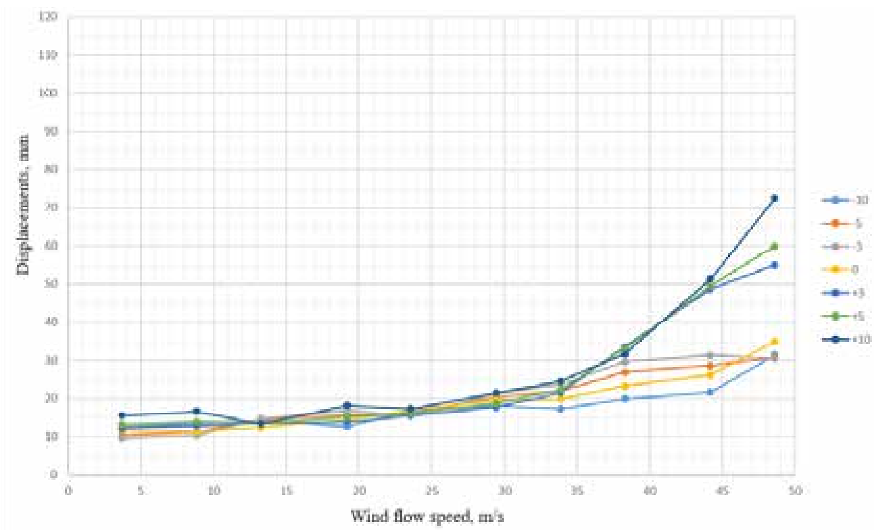
Pic. 4. Installation for testing a model of a bridge crossing in a wind tunnel [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 5. Model № 1 of the bridge span structure [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 6. Graphs of the dependence of the lift force (Cy), drag force (Cx) on the angle of attack of the flow [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 7. Dependence of displacements during oscillatory movements of a model of a span structure on the speed of the wind flow in its various directions [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

them with the parameters of the load acting on the actual structure of the transport infrastructure:

• Drag of a characteristic longitudinal or transverse section.

• Lift force acting both on the span section and on the entire installation.

• Torsional moment around the longitudinal axis of the bridge span section model.

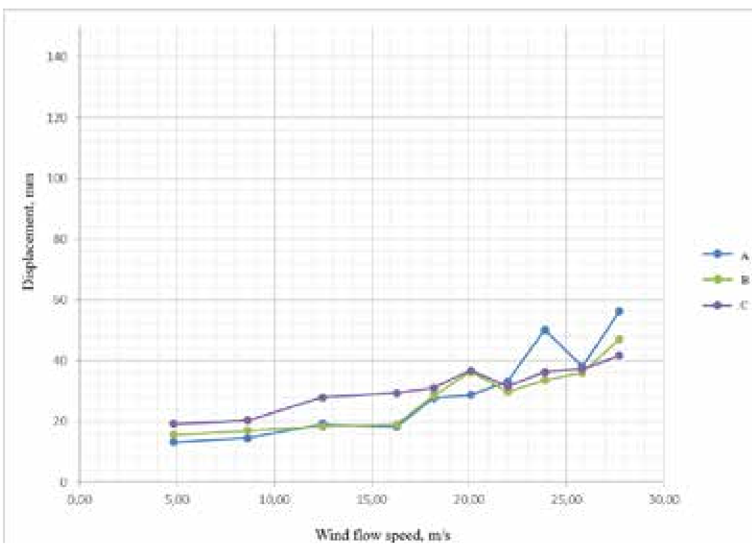
The unique scientific installation «Large Research Gradient Wind Tunnel» (registration number 585332, webportal «Scientific and technological infrastructure of the Russian Federation. Centres for shared use of scientific equipment and unique scientific installations»; registration date: 04.05.2018) is used as an experimental installation for conducting aerodynamic experimental research.

Designing a model

Considering the cross-section of the working area of the wind tunnel (4 x 2,5 m), from the condition of «transparency» and uncluttered air flow, the optimal scale of the model is 1:40 (Pic. 5). To simultaneously ensure geometric similarity, the required ratio of mass and rigidity of the span structure, it is proposed to use flat sheets of aluminium, from which the section of the bridge span is assembled using bolted and riveted joints.

The proposed design solutions for creating the model ensure not only the correct geometric

Pic. 8. Scheme of the experiment to assess the number and location of vehicles on the span structure for its aerodynamic stability [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 9. Dependence of the amplitude of oscillations of the model of the span structure on the wind flow speed for different loading conditions of the structure [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

similarity, but also a reliable distribution of linear masses, in which the centres of mass of the model and the real structure coincide in relative coordinates.

Thus, the designed model corresponds to the full-scale object by the following parameters:

- Geometric similarity.
- Correspondence of mass distribution.
- Correspondence of geometric centres of mass and moments of inertia.

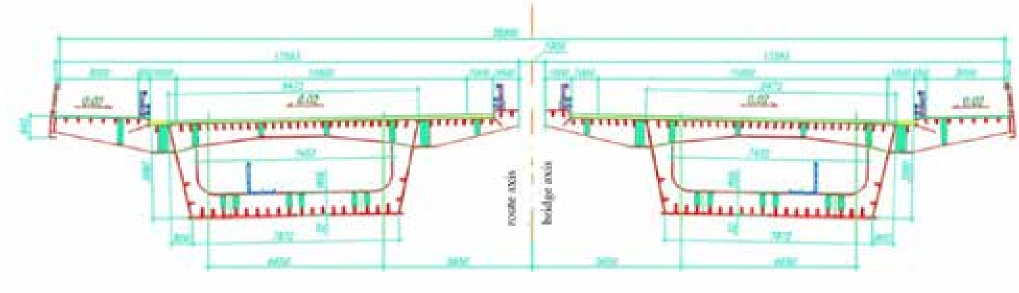
These parameters fully satisfy the requirements for experimental studies.

The correct choice of structural elements allows for similarity in mass and inertial forces, which will allow for the behaviour of the span structure model to be matched to the behaviour of the real transport infrastructure facility under aerodynamic impacts of varying intensity and direction [16].

All frequency characteristics of the span structure are modelled by specialised springs of the measuring stand.

Experimental studies are carried out in two stages:

- Static tests, during which the values of lift force (Cy), drag force (Cx) and aerodynamic moment (Cmz) are determined.
- Dynamic tests aimed at calculating the amplitudes of bending and torsional vibrations at different values of speed and wind flow directions (α).



Pic. 10. Cross-section diagram of the bridge [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

Pic. 11. Model of the span structure [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

Static tests

As a result of static tests, the following graphs were obtained showing the dependence of the lift force (Cy), drag force (Cx) on the angle of attack of the flow (Pic. 6).

Based on the obtained values of the aerodynamic coefficients (Pic. 6) for model № 1, it is possible to check the necessary condition for the occurrence of aeroelastic instability of galloping – the Glauert – Den-Hartog criterion [10]:

$$[C_L(\alpha) + C_D(\alpha)] < 0. \quad (1)$$

As can be seen from Pic. 6, the lift coefficient increases within the interval, and the drag coefficient is positive, accordingly, the Glauert-Den Hartog criterion is not satisfied, and galloping is impossible.

Dynamic tests

The studies on the dynamic impacts of the span section are carried out on the stand described above (Pic. 3, 4), while the parameters of the spring suspension rigidity are linked to the wind flow speeds and are set in the model during its design. The results of the tests are shown in Pic. 7.

The impact of car traffic on aerodynamic stability also was assessed (Pic. 8, 9).

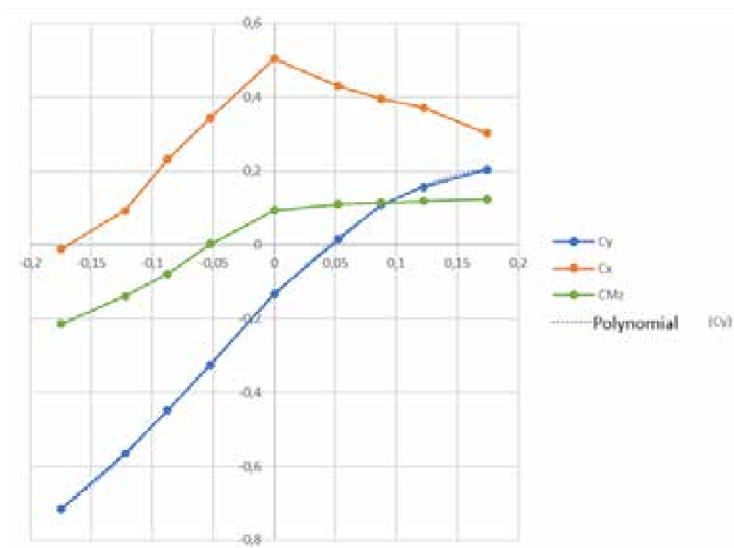
Tests were conducted for the windward and leeward spans of the bridge under study in the following configurations:

A. Free span (Pic. 5).

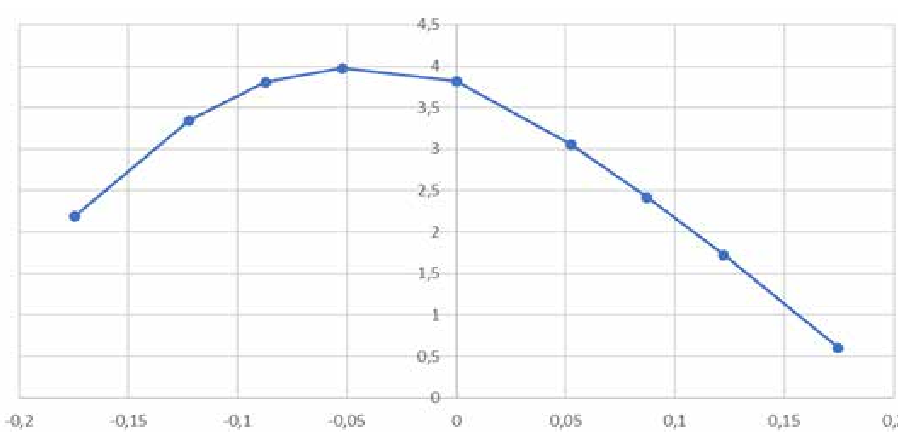
B. Span with car traffic (Pic. 8).

C. Span with car traffic and snow deposits.

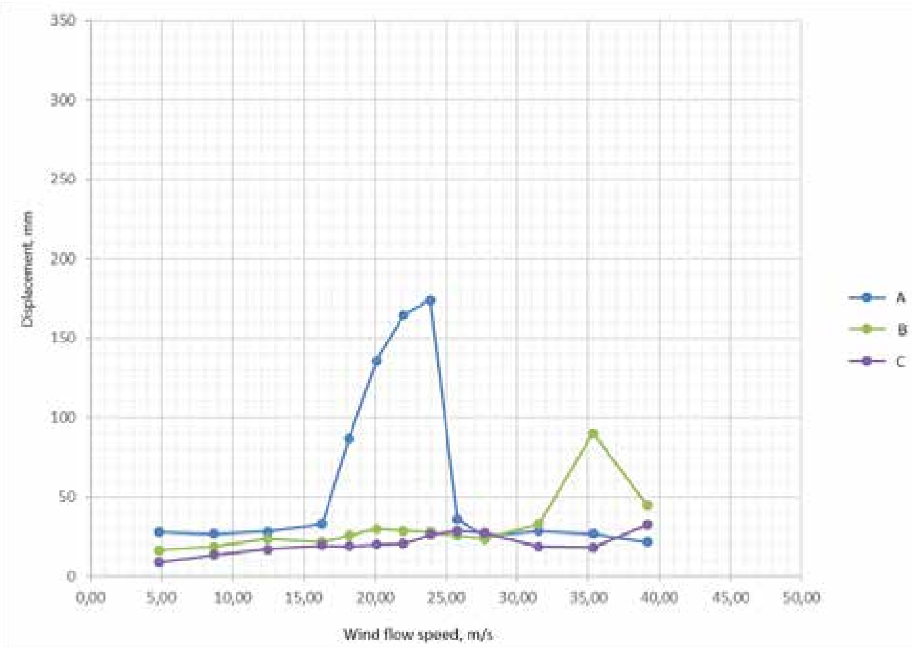
Pic. 12. Model of the bridge span structure (car traffic) [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 13. Graphs of the dependence of the lift force (Cy), drag force (Cx), torque (Cmz) on the angle of attack of the flow at angles of attack (–10° – +10°) [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 14. Graph of the dependence of the Glauert – Den-Hartog criterion value on the flow attack angle at attack angles (–10° – +10°) [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].



Pic. 15. Dependence of maximum displacements of bridge span points during oscillatory movements on wind flow speed with its direction α = 00 °) [performed by O. I. Poddaeva, P. S. Churin, A. N. Fedosova].

Test results

The results of the physical experiments conducted for two directions of wind flow with an attack angle varying in the range from – 10º to + 10º showed that the phenomena of aerodynamic instability, according to the classification (Pic. 2), do not occur.

The results of the experiment also showed that the presence of vehicles and locally cumulated snow bags does not significantly affect the aerodynamic stability of the span structures in the considered quasi-static setting of car traffic. The determining factor is the influence of the existing bridge crossing located in the immediate vicinity. The influence of road traffic in this case is negligible.

Research Object № 2

Statement of the problem

A span structure with a length of 600 meters is being studied (Pic. 10).

Designing a model

The 1:70 scale model is made of sheet aluminium (Pic. 11).

The results of static tests for the bridge span model considering car traffic (Pic. 12) are shown in Pic. 13.

The Glauert – Den-Hartog criterion was tested using formula (1): for some angles of attack, the necessary galloping condition is met (Pic. 14).

For clarity of the results obtained during the experimental dynamic tests, a graphical dependence of the superstructure displacements on the average wind flow speed is shown on a scale corresponding to the real situation at the transport infrastructure facility. In fact, it is possible to observe a change in the stability function of the bridge structure.

The tests were conducted for the windward and leeward spans of the bridge under study in the following configurations:

A. Free span (Pic. 11).

B. Span with snow accumulation and car traffic.

C. Span with car traffic (Pic. 12).

The situation of accumulation of road vehicles in two directions of traffic alternately (traffic jam) was simulated. In accordance with the average statistical dimensions of vehicles, the following dimensions were taken as a basis for the simulation:

– trucks – 4 x 18 x 2,5 m;

– passenger vehicles – 1,5 x 4,2 x 1,7 m.

Pic. 15 shows the graphical dependencies of the maximum displacements of the span structure on the wind flow speed for various cases of loading the span structure section at an attack angle of $+3^0$.

CONCLUSIONS

Physical tests conducted with a physical model of the structure regarding possible loss of aerodynamic stability of sections of bridge spans considering car traffic have shown that the presence of car traffic, when studied at individual angles of attack, has a favourable effect on the aerodynamic stability of the span, which is consistent with the conclusions of work [8]: for a system with two degrees of freedom, stationary vehicles have a rather beneficial effect on stability of the bridge. This is primarily due to additional turbulence of the wind flow over the span, which, considering the different dimensions of car traffic at its individual sections, prevents the formation of a stable von Karman vortex street path and the occurrence of resonant vortex excitation.

The results obtained appear to offer a possibility of creating more accurate models of aerodynamic loads on bridge structures considering the influence of vehicle traffic and additional snow load.

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