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NUMERICAL SIMULATION OF AERODYNAMIC STABILITY OF LONG-SPAN BRIDGES *

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Statement of the problem. The aim of the work is to simulate the resonant vibrations of the continuous beam span of the bridge in the direction perpendicular to the wind flow by the finite element method. The article deals with a non-standard situation that arose on May 20, 2010 on the bridge over the Volga River in the city of Volgograd.

Results. As a result, an effective algorithm for calculating the aerodynamic stability of large-span bridge structures was developed using one of the most widespread software systems in Russia and neighboring countries - "Lira-SAPR". Recommendations for the selection and modeling of dampers are given.

Conclusions. The developed algorithm makes it possible to numerically describe the disturbing force of periodic breakdown of wind flow vortices, which causes resonant oscillations of bridge spans, to apply this force to the design model in Lira-SAPR, and to obtain parameters that make it possible to assess the stress-strain state of the system during oscillations and to select the optimal characteristics of the damping devices.

Keywords: aerodynamic stability of bridges, resonance, damping devices.

Introduction. Research in the field of interaction of wind flow with bridge structures was carried out by both domestic [4–6, 9–11] and foreign scientists [1, 2, 7, 8, 12–18].

In publications in Russian, one of the most complete studies of the operation of beam structures in a wind flow is presented in the textbook [9], the theoretical and practical aspects of the aerodynamics of bridges are presented in the production publication [4]. The issues of the dynamic design of suspension bridges attracted the attention of a number of researchers immediately after the famous accident of the Tacoma Bridge in the USA in 1940.

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Until that time, numerous problems of interaction of an elastic structure with an air flow were studied by specialists in aircraft construction, and the corresponding field of knowledge was called aeroelasticity. The development of the theory of calculating aircrafts was based on fundamental theoretical results dating back to the works of N. E. Zhukovsky, a large number of experiments with models in wind tunnels and the experience of operating aircraft.

Progress in the field of aircraft construction has always been associated with an increase in the speed capabilities of new designs, the shapes of which have been continuously improved by improving streamlining, which made it possible to reduce power losses when moving in the air. Similar problems arose and were solved in the field of hydrodynamics and shipbuilding. Suspension and cable-stayed bridge structures are mainly formed on the basis of other considerations, mainly related to the need to ensure strength and rigidity under static influences. Moreover, the dynamic effects arising from the action of a temporary load are taken into account due to the conditional increase in the calculated static load by introducing dynamic coefficients. This approach is insufficient for solving problems related to the analysis of bridge vibrations under the influence of wind.

The air flow around obstacles is accompanied by the formation of a vortex wake (Fig. 1). Air vortices are formed directly behind the streamlined body, alternately to the right and left in the direction of the flow, losing contact with the obstacle with a certain frequency, and move in the direction of the flow, representing fairly stable formations.

Fig. 1. General scheme of vortex action (Karman track)

The frequency of vortex stripping is determined by the wind speed, the transverse size of the structure, and the Strouhal number:

$$S_t = \frac{v \cdot b}{V_{cr}}, \quad (1)$$

where v (Hz) is the frequency of vortex stripping, (at the critical wind speed it coincides with the natural frequency of flight); b (m) is the span rise; V_{cr} (m/s) is the critical wind speed.

The amplitude of the intensity of the periodic force of vortex stripping is calculated by the formula:

$$P = 0.5\rho V_{cr}^2 C_{lat} b, \quad (2)$$

where $\rho = 1.29 \text{ kg/m}^3$ is the air density; C_{lat} is the aerodynamic coefficient.

Thus, to calculate the critical wind speed and the amplitude of the periodic force, it is necessary to know 3 parameters: the frequency of the first form of natural oscillations of the span ν , the Strouhal number S_t and the aerodynamic coefficient C_{lat} .

So, for the preliminary aerodynamic calculation for wind resonance, the initial data are the same as for the usual static calculation (static scheme, stiffness characteristics, constant loads). Additionally, it is only required to reliably determine 2 aerodynamic characteristics: the Strouhal number S_t and the aerodynamic coefficient C_{lat} . At the stage of pre-design studies, they can be determined theoretically using Eurocode 4 [3].

1. Subject of research. Numerical modeling of the vortex resonance of a girder bridge is carried out on the example of a "dancing" bridge across the river Volga in Volgograd (Fig. 2). Traffic on the bridge was stopped on May 20, 2010 due to dispatchers reporting a strong swaying of the structure (while the structure was commissioned six months earlier). The survey did not reveal any defects and showed that the bridge was ready for use. In the morning of May 25, after a test drive of heavy trucks loaded with rubble, the movement of light vehicles on the bridge resumed.

Fig. 2. View of the roadway of the bridge during oscillations

According to the conclusions of the expert group, the wind resonance was the cause of the oscillations. The magnitude of the amplitude was 0.4 m with the wind direction across the span and a speed of about 15—17 m/s; vibration frequency 0.4 Hz; period 2.5 s.

The span structure of the bridge under consideration is metal, box-section, continuous beam, with lower and upper orthotropic slabs (Fig. 3). The span structure is a continuous beam and is made according to the scheme $2 \times 86.6 + 3 \times 126 + 3 \times 155 + 126 + 69$ m. The dimension of the roadway is G-14.25 m (3 lanes). The width of the orthotropic slab is 17.38 m, the height of the main beam is 3.29 m.

Fig. 3. Cross-section of the superstructure

Oscillations have arisen in the middle part, which has the scheme 3×155 m. The Volga River in the construction area belongs to the first class of waterways, and according to regulatory requirements, navigable spans in the clear should be: downstream — 140 m, upstream — 120 m, this is the reason for such a large length of girder spans, which is not typical for both Russian and foreign bridges. At the same time, the low rise of the superstructure (3.29 m) should also be noted, which together makes the structure very flexible.

In Russian standards, the issue of calculating the aerodynamic stability of girder bridges was practically not considered before the case with the Volgograd bridge. At the time of the design of the bridge across the Volga, the regulatory documents mention the need to check only suspension and cable-stayed bridges for aerodynamic stability. In subsequent editions of these

documents, there is already an addition: "Suspension and cable-stayed bridges, as well as steel beam bridges with spans of more than 100 m, should be checked for aerodynamic stability..." Thus, the oscillations of the Volgograd bridge were an ideal full-scale non-destructive experiment, according to the results of which the corresponding amendments were made to the normative and technical documentation. To identify the aerodynamic parameters of the span one can use Eurocode 4 [3]. The maximum height of the span (taking into account the transverse gradient and the bench) is $b = 3.6$ m; the width along the edges of orthotropic deck is $d = 17.4$ m; ratio $d/b = 4.83$; the Strouhal number $St = 0.115$ (Fig. 4); the aerodynamic coefficient based on the corresponding table [3] is $C_{lat} = 1.1$.

Fig. 4. Defining the Strouhal number based on Eurocode 4 [3]

2. Modeling the disturbing force of vortex stripping in the software package “Lira-SAPR”. The calculations of oscillations of the Volgograd bridge are performed by the finite element method (FEM) in the licensed software package “Lira-SAPR”. The design scheme is made in the form of a continuous beam, composed of rod finite elements with the following stiffness characteristics (which were calculated based on the real structure of the span):

- axial stiffness $EF = 1.622 \cdot 10^8$ kN;
- vertical bending stiffness $EI_y = 3.367 \cdot 10^8$ kN·m²;
- horizontal bending stiffness $EI_z = 2.901 \cdot 10^9$ kN·m²;
- torsional stiffness $GI_k = 1.855 \cdot 10^8$ kN·m²;
- weight per meter (taking into account the bridge floor) $q = 89.07$ kN/m.

The periodic force of vortex stripping acts on the nodes of the design scheme of the span according to the harmonic law [9, p. 172]:

$$P = (0.5\rho V_{cr}^2 C_{lat} b) \cdot l \cdot \sin(\nu t). \quad (3)$$

Here the expression in square brackets is the amplitude of the intensity (distributed along the length of the span); l is the step of splitting the design model (the distance between the nodes

of the span); ν is the vortex stripping resonance frequency (natural frequency of the span oscillations); t is the time.

3. Comparison of oscillations of a superstructure without dampers (resonance) and with mass dampers. On the structure under consideration, after the occurrence of vibrations, the following main measures were taken:

- 1) installation of mass dampers in the middle of the oscillating spans (Fig. 5), which excludes the possibility of resonance, since the frequency of natural oscillations of the dampers is selected in such a way as to most effectively knock down the oscillation frequency of the spans;
- 2) installation of fairings on the ends of the orthotropic plate, significantly weakening the effect of the wind flow on the structure under consideration.

Fig. 5. Mass dampers

Within this work, the simulation of free (without dampers) resonant oscillations of the Volgograd bridge, which occurred on May 20, 2010, was carried out, as well as the simulation of oscillations with installed dampers under a similar wind action (i.e., without taking into account the fairings). The performed calculation proved the effectiveness of the installed dampers and showed the possibility of performing preliminary analytical calculations of the aerodynamic stability of large-span bridges using one of the most widespread software systems in the Russian Federation and neighboring countries, “Lira-SAPR”. A simplified technique has been developed that can predict the possibility of similar situations and justify the need for detailed aerodynamic tests of large bridges.

Fig. 6 visually presents the phenomenon of resonance in the form of a graph of a smooth increase in the kinetic energy of the system (the calculation was performed in the "Dynamics Plus" module of the "Lira-SAPR" software package). Successively performed approximations showed that increasing the amplitude of oscillations up to 0.4 m (the value according to the conclusions of the expert commission) occurs when the duration of exposure to the harmonic force is 70 s. In this case, the kinetic energy of the flight reaches 94 MJ.

Fig. 6. The increase in kinetic energy in the absence of dampers
(Integration time 100 s; integration step 0.01; number of shots 10000)

Fig. 7 presents the distribution of kinetic energy in case of installation in the middle of each three spans of mass dampers, spring-mounted charges 20 tons in weight. The stiffness of the springs was selected in such a way that the vibration energy was minimal. At the same time, the kinetic energy was reduced 40 times, from 94 MJ to 2.4 MJ. With the increase in the time of action of the perturbing force up to 300 s, the kinetic energy does not increase, and resonance does not arise.

Fig. 7. The distribution of kinetic energy after installation of the dampers
(Integration time 300 s; integration step 0.01; number of shots 30000)

Calculation in the software package "Lira-SAPR" also makes it possible to evaluate the increment of efforts during oscillations with the given amplitude. In the most loaded sections of the Volgograd bridge with an amplitude of 0.4 m, the moment increased from 171185 to 221706 kN·m (± 50521 kN·m). Since the limiting moment is 358065 kN m, the limiting state from the oscillations that occurred in 2010 did not arise.

Conclusions. For the preliminary aerodynamic calculation for wind resonance, the same initial data are required as for conventional static calculations (static scheme, stiffness characteristics, constant loads). Additionally, it is only required to reliably determine 2 aerodynamic characteristics: the Strouhal number S_t and the aerodynamic coefficient C_{lat} . At the stage of pre-design studies, they can be determined theoretically using Eurocode 4 [3]. Then, with the positive result of the numerical aerodynamic calculation, one may make the physical model and test it in a wind tunnel. This will significantly reduce the labor intensity of real aerodynamic studies, since at the very design stage, the span structure solutions unstable to wind resonance will be excluded from consideration.

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