Analysis of normative and scientific and technical documents in the field of testing bridge structures for wind loads

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Abstract. In this paper, more than 40 domestic and foreign normative and scientific and technical documents in the field of calculation, testing and research of bridge loads on wind impacts was analyzed. It is established, that in the normative documents acting in the territory of the Russian Federation it is indicated that it is necessary to check the aerodynamic stability of the large-span bridge structures and the method of such testing is partially given in the industry standards. The requirements reflected in the standards do not fully exploit the achievements of modern architectural and construction aerodynamics, they lack methods of conducting the most common tests currently available on dynamically similar models of span structures in specialized stands, there are no methods for testing complete dynamically similar models of bridge structures giving the most complete and reliable information about the behavior of the object under investigation in the wind flow. Only static tests on geometrically similar models of span structures are being considered, allowing to estimate the possibility of occurrence of negative phenomena of aerodynamic instability, without any quantitative characteristics (maximum amplitudes of oscillations). Normative documents acting abroad contain much more complete information than domestic ones. Although there is no such thing as the experimental technique itself, however, the requirements for both the purpose of the tests and the tests themselves including wind tunnels are indicated, and these requirements are much higher and formulated more clearly than in the domestic ones. Despite this, the techniques themselves, both prototyping and testing are lightly or completely absent. It should be noted that at present, despite a large number of theoretical and experimental studies in the field of aerodynamics of bridges, the theme of the interaction of bridge structures with the wind flow is not exhausted. Currently continues to register incidents of aerodynamic instability of already constructed bridge as well as bridge under construction stage. The testing methods have constantly being improved, and the rapid development of computer technology and calculation software packages makes it possible to develop methods for solving the problems of aerodynamic stability of bridge structures and numerical simulation techniques.

1. Introduction

The most famous examples of aerodynamic instability of bridges are follows: the vibrations of the Rio-Niteroi Bridge (Brazil) (1980, 1997, 1998), the Trans-Tokyo Gulf of Japan Bridge (1995), the Tozaki viaduct (Japan) (1982), the bridge Kansai International Airport (Japan) (1990-1991), the East
Bridge "Big Belt" (Denmark) (1993), the Oshima Bridge (Japan) (2000), the bridge International access to the international airport of Japan (Japan) (2001), the Volgograd bridge (Russia) (2010).

The most famous case of complete destruction of bridge structures due to wind impact is the Tacoma-Narrows bridge (Figure 1). Even during the construction of the builders gave him the nickname "Galloping Gertie" due to the fact that in windy weather, his road cloth was swinging (due to the small height of the beam stiffness). On November 7, 1940 at 11:00 local time, at a wind speed of about 65 km / h, an accident occurred, which led to the destruction of the central span of the bridge. The movement at this point was very weak, and the only driver of the car, caught on the bridge, managed to leave it and be saved.

![Figure 1. Tacoma Narrows Bridge](image)

Determination of the aerodynamic parameters of such structures is possible only by performing computational and experimental studies of wind influences on the object under study.

2. Analysis of Russian regulations

At present, the calculation of bridge structures for wind loads on the territory of the Russian Federation is regulated by the following regulatory documents: building code 35.13330.2011 "Bridges and pipes"; building code 20.13330.2016 “Loads and actions”; order of Federal Road Agency ODM 218.2.040-2014 “Methodical recommendations on the estimation of aerodynamic characteristics of cross-sections of span structures of bridges”; Moscow city building standards 5.02-99 “Design of urban bridge structures (with changes and additions)” [1]-[4].

Building code 35.13330.2011 “Bridges and pipes” [1] contains the basic requirements for calculating wind load on bridge structures, including the need to take into account the dynamic component of the wind load, to which bridge structures are most susceptible. Verification of aerodynamic stability consists of the condition of building code 35.13330.2011 "Bridges and pipes": the critical speed corresponding to occurrence of dangerous aerelastic phenomena, found from the results of aerodynamic tests of models or determined by calculation, should be greater than the maximum wind speed possible in the area of the bridge no less than in 1.5 times.

At the same time, information for calculating the wind loads on the span structures of bridges at these normative documents is clearly not enough (in the joint venture Loads and Effects there are no aerodynamic coefficients for typical cross sections of bridges, the data on the Strouhal number are given only for single rectangular cross sections, at Bridges and pipes in Appendix H only the coefficient of drag for the parts and elements of span structures of bridges is given, without taking into account the features of the shape of the elements).
That is why, according to point 5.48 building code "Bridges and pipes" for hanging and cable-stayed bridges as well as steel beam bridges with spans over 100 m it is necessary to perform a wind-tunnel test for aerodynamic stability and spatial rigidity.

The very method of carrying out such studies, the requirements for testing or links to relevant regulatory documents are not available.

In 1999 the Scientific and Technical Association of Scientists and Transport Construction Specialists led by Academician of the Academy of Transport O.A. Popov the Moscow City Building Standards 5.02-99 "Design of urban bridge structures" was developed [4]. This document significantly expands the requirements for the design of bridges contained in building code 35.13330.2011 "Bridges and pipes", including the methods for calculating span structures for vortex excitation (wind resonance) and for torsional flutter.

At March 24, 2014, by the order of the Federal Road Agency the Methodological Recommendations for the Estimation of the Aerodynamic Characteristics of the Cross-section of the Bridge Overpasses (ODM 218.2.040-2014) were put into effect [3]. These recommendations are an industry document and are not mandatory, however, at the moment, they contain the most complete information on the assessment of wind impact on span structures of bridge structures.

Nevertheless, the authors of the document note that: "using the characteristics given in this ODM can give a very approximate estimate of the wind impact on the structure in the case of even a slight difference in its geometric parameters from those shown in the diagrams. To obtain more accurate and detailed information on this problem, it is necessary to carry out experimental studies on models in wind tunnels when modeling wind parameters at the site of the proposed location of the facility in combination with computational modeling with the help of computer hydroaerodynamics software complexes."

Thus, in the normative documents acting at the territory of the Russian Federation, the verification of the aerodynamic stability of large-span bridge structures is indicated, the methodology of such inspections is partially given in industry standards.

The requirements reflected in the standards do not fully exploit the achievements of modern architectural and construction aerodynamics, they lack methods of conducting the most common tests currently available on dynamically similar models of span structures in specialized stands, there are no methods for testing complete dynamically similar models of bridge structures, giving the most complete and reliable information about the behavior of the object under investigation in the wind flow.

Only static tests on geometrically similar models of span structures are considered, allowing to estimate the possibility of occurrence of negative phenomena of aerodynamic instability, without any quantitative characteristics (maximum amplitudes of oscillations).

3. Analysis of foreign regulatory documents
On the territory of the countries of the European Union, the calculation for wind loads is made according to Eurocode 1 "Actions on structures. Part 1-4: General actions - Wind actions" [5]. These standards were adopted on the basis of the European standard.

Eurocode 1 Part 1-4 is applicable to bridges having no span greater than 200 m, provided that they satisfy the criteria for dynamic response. Eurocode 1 Part 1-4 does not give guidance on the following aspects: bridge deck vibrations from transverse wind turbulence, wind actions on cable supported bridges, vibrations where more than the fundamental mode needs to be considered.

Section 8 deals with wind loads for single-span and multi-span bridges with a constant section height, given for determining the aerodynamic coefficients of drag and lift for a set of typical sections of the span structure, the calculation methodology for wind resonance and other phenomena of aerodynamic instability.

At the same time, it is pointed out The National annex may contain information on those parameters which are left open in the Eurocode for national choice and it can used for the design of buildings and civil engineering works to be constructed in the country concerned.
Direct references to the use of experimental data to study wind loads on buildings and structures not included in the field of application are not available, but it is said that "in addition to this technical code, aerodynamic tests, approved and/or certified numerical methods with appropriate modeling of the structure of the natural wind". For additional information on aerodynamic testing and measurements, Eurocode refers to national applications.

In accordance with the UK National annex [6], the aerodynamic coefficients of forces, moments, internal and external pressures, as well as the number of Struhal (in the evaluation of resonance vortex excitation) should be determined on the basis of model tests carried out in specialized wind tunnels.

During carrying out model aerodynamic tests, certain conditions (criteria) of similarity must be met that ensure the obtaining of the most reliable information about the actual wind loads: geometric similarity; observing the vertical gradient of the wind speed, and also taking into account the intensity and scale of turbulence with the surrounding buildings; the scale of the design model can not be different from the scale of the wind flow profile (no more than three times to calculate the average wind loads, no more than two times to calculate peak wind loads); the similarity of the basic dynamic properties of the model and the structure under investigation (in the experimental determination of the dynamic response).

The main requirement for the study of the aerodynamic stability of "flexible" (dynamically sensitive structures) including bridge is the modeling of dynamic characteristics (as a rule, these are only the lowest bending and torsional natural frequencies and modes of oscillations, as well as the logarithmic damping decrement). This is necessary to evaluate the dynamic response of the structure from the effect of wind load, resonance vortex excitation, and the possibility of aerodynamically unstable oscillations.

In Italy, there is the "Guide for the assessment of wind actions and effects on structures" [7] developed by the Italian National Research Council. In the manual for the extended in terms of designs, structures of non-standard forms, including large span bridge structures, it is recommended to carry out aerodynamic tests, the authors also recommend carrying out tests to optimize non-standard designs, because this can be used not only to economically benefit, but also to increase the safety of such structures.

This manual provides the following recommendations for aerodynamic testing: all physical quantities must be properly simulated; scale should be selected individually depending on the specific task; design and manufacturing of mock-ups, testing and interpretation of results should be carried out by specialists in specialized laboratories.

The wind tunnel should be able to reproduce the wind profile in the boundary layer, so for vertical structures the flow velocity and turbulence intensity must be modeled. For layouts of structures, geometric and dynamic similarity must be observed. Such tests can be carried out only in wind tunnels capable of simulating the surface wind speed gradient. Flow characteristics should be constant throughout the test.

In order for the actual characteristics to be determined from the test results, the following conditions must be met: equality of dimensionless parameters (Reynolds number, Strouhal number, intensity of turbulence) of the model and the real object; use of the same scale for quantities with the same dimensionality, for example, parameters having a length in dimension (geometric dimensions, turbulence length scale, atmospheric boundary layer size); the scales of various physical quantities must satisfy the dimensional equations, so, the speed scale (the ratio of the speed in the pipe to the real speed) must correspond to the time scale.

A separate section of this manual is devoted to the research so-called “flexible” structures. Questions of aeroelasticity are considered. For this purpose, deformable or aeroelastic models are used that reproduce the scaled dynamic properties of the object, that is, the frequencies and shapes of the oscillations, as well as structural damping. Aeroelastic models and techniques for carrying out experimental studies can significantly differ depending on the characteristics of the object under study and the purpose of the studies.
The main types of models and experimental studies for such objects are as follows: fully aeroelastic model models; sectional models and taut-strip models.

Standards ANSI ASCE 7-02 “American Standard of American Society of Civil Engineers” [8] prescribes an analytical calculation for wind loads for buildings of simple forms. Tests in wind tunnels should be carried out in the following cases: for buildings of unusual shapes; buildings, for which wind loads can become decisive; there may be vortex formation or instability due to flutter or galloping; The situational plan is such that tunnel effects arise, or the building is in special wind conditions. Bridges, power lines, cranes, flagpoles and TV towers are separately distinguished.

This normative document contains recommendations for conducting aerodynamic tests. Requirements for testing are as follows: the atmospheric boundary layer should be modeled in accordance with the change in wind speed in height; the longitudinal component of atmospheric turbulence should be simulated at approximately the same scale as the building; the model of the building and the surrounding buildings, as well as the terrain, are similar to the real object, taking into account the scale; the blocking coefficient should not be more than 8%: the gradient of the longitudinal pressure in the wind tunnel should be taken into account in the tests; the influence of the Reynolds number on pressure and force should be minimized; frequency characteristics of the wind tunnel should be consistent with the tests; mass-inertial characteristics of models and a real object should be coincided for dynamic test.

4. Analysis of scientific and technical literature

The processes of bridge structures interaction with the wind flow and the problems of ensuring their aerodynamic stability have been actively studied since the middle of the 20th century. In Russia, the theme of the interaction of the wind flow with various bodies was developed in the early 20th century. For the first time, the problems of aerodynamics of masonry structures were considered in the works of N.A. Rynin [9],[10] in which, on the basis of studies of models of buildings and structures, their flow spectra, operating aerodynamic forces, and also the distribution of wind pressure over the surface were cited.

Russian scientists K.A. Bunkin A.M. Cheremukhin [11] made a significant contribution to the study of the physical foundations of interaction between structures and the wind flow. Soviet scientists E.I. Retter developed technical conditions for the construction of a special wind tunnel with devices for creating varying degrees of flow turbulence.

In different years the problem of the interaction of structures with the wind flow was devoted to the work of L.S. Gandina, G.M. Fomina, M.F. Barstein, A.S. Bernstein, A.I. Tseitlin, N.A. Popova, K.K. Fedyaevsky, L.H. Devmina, G.A. Savitsky, A.M. Lugovtseva, V.P. Mugaleva, E.V. Solovieva, S.M. Gorlina, G.E. Khudyakov, V.A. Samsonova, S.Ya. Herzenstein, I.V. Nekrasov, A.E. Ordanovich, V.B. Kurzin, A.I. Ryabinina, M.S. Komarova, V.V. Nazarenko, K.S. Strelkova, M.A. Berezin and other scientists.

The most detailed and fundamental studies of the wind impact on bridge structures are given in the book by M.I. Kazakevich "Aerodynamics of bridges" [12]. In this book, the main concepts of the interaction of bridges with the wind flow, ways to determine the wind load on the structures, taking into account their aerodynamic properties, as well as aerodynamic calculations that take into account the behavior of bridges in general and their individual elements in a uniform and turbulent wind flow are described. Tests and methods for increasing the aerodynamic stability of bridges during installation and operation are described.

It is necessary to note the work of the collective of the department of the Aerohydrodynamics of the Novosibirsk State Technical University under the leadership of S.D. Salenko [13], [14]. The team conducted numerous tests of bridge structures in the wind tunnel T-503. The results of investigations of the mechanism of the appearance of vibrations of single- and multi-beam structures in the wind flow, studies of non-stationary aerodynamic loads acting on bridge structures were published, the basic features of aerodynamic tests of elastic models of span structures of bridges were described, general approaches to extinction of aeroelastic vibrations were formed.
Of the foreign researchers, one of the first experimental works on studying the flow of building models was conducted by Irminger in 1891 and Stanton in 1903. Various aspects of modeling the interaction of wind with various bodies were studied by the American scientist J. Kermak. In 1963 in the United States under his leadership one of the first wind tunnels with a long working part was built.

From modern foreign studies in the field of interaction of structures with wind flow, it should be noted following works: Davenport, S. Skruton, D. Hunt, E. Plait, E. Simiou, R. Blevins, H. Sakamoto, P. Birman, G. Rushevey, O. Flaman, R. Sasso. In the world's largest laboratories, working in the field of architectural and construction aerodynamics, specialized landscape aerodynamic pipes with a working area width of more than 10 meters were created, allowing to carry out research on full-scale models of bridge structures.

At present, the following types of aerodynamic instability are considered in studies of aerodynamics of bridge structures [15]-[22]:

1) the flexural-torsional flutter is the self-exciting self-exciting bending and twisting self-oscillating) elements of the structure, caused by the mismatch of the aerodynamic center of the structure (the point of application of the aerodynamic forces, the center of gravity) with its center of gravity. For the emergence and development of oscillations in the flutter it is necessary to influence the design of periodic excitation forces, the energy necessary to maintain these oscillations is delivered by a counter flow of air. Due to the discrepancy between the lines of centers of gravity and the line of centers of rigidity of the cross sections, purely bending or purely torsional oscillations of the bridge are practically impossible. Regardless of what the initial impulse, bending or twisting, oscillations are always joint - flexural-torsion;

2) buffing is an aeroelastic instability (vibration) that occurs in a structure that is in a turbulent flow or a vortex wake behind another structure. Buffeting arises from periodic impacts on it by the wake of the wake behind the structure and manifests itself in the form of "swinging", i.e., an increase in the amplitude of the oscillation of the structure;

3) vortex excitation is an oscillation that arises from the coincidence of the natural frequency of the structure with the frequency of Karman vortex shedding. As a rule, the value of the critical wind speed for the appearance of vortex excitation at the 1st natural frequency is in the range 10-20 m / s. This is often a repetitive speed during operation. The cyclic load from the vortex excitation and the associated number of loading cycles can become important for the design calculation;

4) galloping is auto-oscillations across the flow caused by negative aerodynamic damping. Most often it is subject to poorly streamlined flexible elements with aerodynamically unstable cross sections (square or rectangular). Under certain conditions in large-span systems oscillations with large amplitudes are possible in a direction perpendicular to the flow (by a factor of 10 or even much more than the dimensions of the cross section in this direction) at frequencies that are much lower than the vortex shedding frequencies. Galloping is more dangerous than resonance, since it increases with an increase in the flow velocity even above the critical one, and resonance occurs only at a critical wind speed;

5) Torsion Divergence is an aperiodic phenomenon of twisting of a span structure up to destruction caused by an increase in the aerodynamic moment (the moment of elastic forces can not balance the moment of aerodynamic forces).

Evaluation of the possibility of occurrence of the above-mentioned phenomena does not always require aerodynamic tests, for example, there are analytical methods for calculating the critical velocities for wind resonance, given in regulatory documents, criteria for galloping (criterion GlaunytDen-Hartog), nevertheless for the most important structures tests on dynamically similar models are always conducted, providing the most accurate and reliable results.

Along with research and the requirements for their conduct in the modern scientific and technical literature, much attention is paid to the means of combating aeroelastic vibrations. Two main methods are considered: installation of aerodynamic deflectors and fairings, changing the shape of the cross-
section of the problem span, and, accordingly, the shape of its flow; installation of mechanical (mass) dampers in the middle of the spans.

The second option, the installation of dampers, is more expensive and less economical. In addition, these facilities reduce the load capacity of the bridge, which leads to the need to strengthen the structure. But, on the other hand, the installation of dampers lends itself to a more accurate calculation, when in the case of using deflectors it will not be possible to dispense with an experiment at wind tunnel.

One of the most effective ways to reduce the frequency and amplitude of oscillations is to install deflectors. There are a number of classical forms of such devices.

The group of authors (Vorsa VG, Zhirukhin VM, Kislyakov VS, Timokhin GM, Grafsky I.Yu., Dankov VS, Kazakevich MI) is patented Devices for vibration damping span structures of bridges in the form of a plate deflector, and the dependence of the drag coefficient $C_x$ on the parameters of the plate deflector installed on it is revealed (Fig. 2).

![Figure 2. Dependence of the drag coefficient on the parameters of the deflector](image)

The work of deflectors “bridges over the perimeter fences” can be observed in Japan at the Tazaki viaduct. This is a construction length of 1010 meters. Bridge structure is made of steel box-shaped beams, which are connected in continuous loops. Some of them are three, and the other four are flying. When designing this bridge structure, aerodynamic resistance to the wind was laid at speed of up to 50 m/s.

In 2010, a large amplitude of Volgograd bridge oscillations was recorded. People got out of cars, trying to leave the structure quickly. After this incident, it was decided to check the aerodynamic stability of the span structures of the road bridge across the Volga river near the town of Kineshma. The experiment was carried out in the Central Aerohydrodynamic Institute T-103 wind tunnel on a bridge overpass model, made at a scale of 1:30 at flow rates up to 40 m/s.

The test results showed that the installation of the upper and lower deflectors and the closing of the central aperture with a lightweight cover allow reducing the swing range from 3.2 meters to 0.5 meters. And, in addition, the greatest scope is observed at different wind speeds: in the initial state at a speed of 20 m/s, and in the case of using the deflectors only at 28 m/s.

5. Conclusions
It should be noted that, despite a large number of theoretical and experimental studies in the field of aerodynamics of bridges, the theme of the interaction of bridge structures with the wind flow is not
exhausted. Currently continues to register incidents of aerodynamic instability of already constructed bridge as well as bridge under construction stage. The testing methods have constantly being improved, and the rapid development of computer technology and calculation software packages makes it possible to develop methods for solving the problems of aerodynamic stability of bridge structures and numerical simulation techniques.

At the same time, information for calculating the wind loads on the span structures of bridges in these normative documents is clearly not enough (in the joint venture Loads and Effects, there are no aerodynamic coefficients for typical cross sections of bridges, the data on the Strouhal number are given only for single rectangular cross sections, Bridges and pipes "in Appendix H, only the coefficient of drag for the parts and elements of span structures of bridges is given, without taking into account the features of the shape of the elements).

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