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RESONANT VORTEX EXCITATION OF HIGH-RISE STRUCTURES

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Abstract. Subject of the research: Today, the design of flexible, extended in length and height structures of transport, industry, communication is one of the important directions of construction development. Such structures include continuous extended metal constructions such as chimneys, poles, billboards, monuments, bridges, pipelines. Besides ensuring the limit states for strength and deformability, there is another important condition for the durable operation of metal structures which is the absence of aerodynamic instability phenomena (mainly wind resonance) during the whole service life. Objectives: Review of the background, analysis of accidents that have occurred, proposals to avoid such situations at the design stage and in the occurrence of emergency conditions at existing facilities. Materials and methods: Review and analysis of existing data and proposals for further improvement of calculation and design methods. Results: The paper analyzes the mechanisms of the main types of aerodynamic instability (wind resonance, flutter, galloping, oscillations in the airfoil) on different types of structures, presents particular cases of the history of famous unique constructions and the authors' calculation practice, describes the ways to avoid this type of phenomena in the design of new buildings or in emergency situations on existing structures. Conclusions: The phenomena described in the article are applicable to an extremely narrow area of construction and are often ignored in calculation and design. This article is intended to draw special attention to these phenomena not only for designers, but also for research engineers in order to create new mechanisms for their analysis.

Keywords: high-rise metal structures, wind resonance, galloping, flutter, wind loads, vortex excitation, aerodynamic wake, towers, masts, ice load, chimneys, unique structures

О РЕЗОНАНСНОМ ВИХРЕВОМ ВОЗБУЖДЕНИИ ВЫСОТНЫХ СООРУЖЕНИЙ

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Аннотация: Предмет исследования: Проектирование гибких, протяженных в длину и высоту сооружений, для нужд транспорта, промышленности, связи является одним из важных направлений развития строительства на сегодняшний день. К таким сооружениям относятся сплошностенчатые протяженные металлические конструкции – дымовые трубы, столбы, рекламные щиты, монументы, мосты, трубопроводы. Помимо обеспечения предельных состояний по прочности и деформативности, для долговечной эксплуатации металлических конструкций существует еще одно важное условие - невозникновение явлений аэродинамической неустойчивости (главным образом, ветрового резонанса) на протяжении всего срока службы. Цели: Обзор истории вопроса, анализ имевших место аварийных ситуаций, предложения по избежанию подобных ситуаций на этапе проектирования и при возникновении аварийных состояний на существующих объектах. Материалы и методы: Обзор и анализ существующих данных и предложения по дальнейшему совершенствованию методик расчета и проектирования. Результаты: В статье проанализированы механизмы возникновения основных видов аэродинамической неустойчивости (ветровой резонанс, флаттер, галопирование, колебания в аэродинамическом следе) на разных видах конструкций, приведены частные случаи из истории строительства известных уникальных сооружений и расчетной практики авторов, описаны способы избежания данного типа явлений при проектировании новых сооружений или при возникновении аварийных ситуаций на существующих конструкциях. Выводы: Явления, описанные в статье, применимы к крайне узкой области строительного производства и часто игнорируются при расчете и проектировании. Данная статья призвана обратить на эти явления особое внимание не только проектировщиков, но и инженеров-исследователей для создания новых механизмов их анализа.

Ключевые слова: высотные металлические сооружения, ветровой резонанс, галопирование, флаттер, ветровые нагрузки, вихревое возбуждение, аэродинамический след, башни, мачты, гололедная нагрузка, дымовые трубы, уникальные сооружения

INTRODUCTION

High-rise structures due to their design features (length in height and small size in the plan) are most susceptible to wind loads, which increase in proportion to the distance from the ground. Bridge structures and pipelines extended in length, which are also flexible structures with low structural damping, should not be neglected. Seismic loads can also have a significant impact if the structure is located in an earthquake-prone area [1], however, in this work we focus mainly on the wind effects. In addition to ensuring the limit states for strength and deformability, there is another important condition for the durable operation of metal structures that is the non-occurrence of aerodynamic instability phenomena (mainly wind resonance) throughout the service life. In the article the mechanisms of the appearance of the main kinds of aerodynamic instability (wind resonance, flutter, galloping, and oscillations in the aerodynamic trace) are analyzed. The special cases of the well-known unique constructions construction history and the authors' calculation practice are adduced and the ways to avoid this type of phenomena at the designing of new structures or occurrence of emergency situations at the existing constructions are described.

LITERATURE REVIEW

High solid-wall steel structures became widespread in the middle of the last century. To analyze their performance and refine the calculation methods, experimental data of blowing down structural models in wind tunnels were used [2, 3]. The main place for testing in those years was the TsAGI wind tunnel. Only in the beginning of this century wind tunnels began to appear in scientific and educational institutes (in particular, in Scientific and Research Institute of Moscow State University of Civil Engineering). Parallel to the development of experimental studies, mathematical modeling has been actively developed: modern program complexes (Ansys, Nastran) allow modeling any building objects in their interaction with the wind flow [4, 5, 6]. Simulation (experimental, numerical) is an integral part of design of unique, technically complex objects. An important role is still given to numerical simulation methods, experiments on existing structures as it allows corrections and clarifications to regulatory documents, according to which typical objects are designed [7-11].

MATERIALS AND METHODS

It is known that the wind load has a static (average) and dynamic (pulsation) component. And, if the average component is fully enough described in the regulatory documents (SP[1]), the dynamic component, although considered in the standards (SP[1]), is still a subject of research and debate. In terms of mechanics, the wind load is represented as a system of forces that cause dynamic oscillations. Classical mechanics gives a strict and clear, widely known solution of this problem [12], as well as the definition of "resonance" as the coincidence of natural frequency of vibrations of the structure and the frequency of oscillations of the driving load (in our case wind load). The materials, of which the structures are made, have different degrees of susceptibility to the phenomenon of resonance, which is described by the logarithmic damping decrement δ [13] (as the logarithm of the ratio of two neighboring amplitudes of vibrations y_i):

$$\delta = \ln \frac{y_n}{y_{n+1}} = nT_1, \qquad (1)$$

where n is the damping coefficient, T_1 is the damped period.

The value of the logarithmic decrement is used in paragraph 11.1.10 (SP[1]) to calculate the dynamic amplification factor for the pulsation component of wind load and is adopted as in the Table 1.

[1] SP 20.13330.2018 Loads and Actions

Table 1. Logarithmic decrement for different materials

Material	decrement of damping
Reinforced concrete and masonry structures, including those with a steel frame	0.3
Glass, steel and reinforced concrete structures	0.22
Steel structures, lined chimneys	0.15

As can be seen from Table 1, the steel structures have the smallest logarithmic decrement. This means that, being taken out of equilibrium state, they can perform long-term oscillations, the decay of which can occur extremely slowly and lead to an emergency situation [14, 15].

Let's consider further the peculiarities of aerodynamic instability in high-rise (extended) flexible structures and ways to combat the phenomena of aerodynamic instability.

Such forms of aerodynamic instability as flutter, galloping, vortex excitation, oscillations in the aerodynamic trace are inherent to flexible structures.

Vortex excitation (wind resonance) is an intensive increase in the amplitudes of aero elastic vibrations of the structure across the wind flow [16].

Self-excited oscillations (self-oscillations) are undamped oscillations, which are maintained by energy sources that do not have oscillatory properties, such as a uniform wind flow. They can be observed when one of the natural frequencies of the structure coincides with the frequency of Karman vortices, which alternately bounce off the surface of the elements [16].

$$\lambda_e = \frac{l}{d} \tag{2}$$

where l is the height of a facility, d is the minimum cross-sectional dimension;

If the ratio of the dimensions of the solid-wall structure having the form (2) is λ_e>20, then one should perform the check for the possibility of resonant vortex excitation according to Section 11.3 (SP[2]). The critical wind velocities $V_{cr.i}$, m/s, at which resonant vortex excitation by the i^{th} eigenform of vibration occurs, are determined by the formula

$$V_{cr.i} = \frac{k_V f_i d}{St} \tag{3}$$

where f_i, Hz, is the eigenfrequency of the i^{th} bending eigenform; d, m, is the cross-sectional dimension of the structure; St is the Struhal number of cross-section, determined experimentally or by reference data; for circular cross-sections St = 0.2; for sections with sharp edges (including rectangular sections) it is St = 0.11. The coefficient k_v takes account of the effect of capturing the natural frequency of oscillations. It is assumed to be 0.9...1.1 from the condition of realization of the worst variant of loading.

Then, comparison of speeds is performed: critical wind speed for the considered structure (3) and maximum wind speed for the given area $V_{max}(z_{eq})$ at the equivalent height z_{eq}.

$$V_{\max} = 1{,}5\sqrt{w_0 k(z_{эк})} \tag{4}$$

where w_0 is the characteristic wind pressure, and $k(z_{эк})$ is the coefficient of wind pressure variation by height (11.1.4 and 11.1.6 SP).

Resonant vortex excitation does not occur if

$$V_{cr.i} > V_{\max} \tag{5}$$

If condition (5) is not satisfied, then various measures are taken, which will be discussed below.

The most typical is vortex excitation for structures with circular cross section. In a certain flow velocity range, the vortex trace behind such profiles takes the form of the so-called Karman track which is a double row of

[2] SP 20.13330.2018 Loads and Actions

point vortices with a staggered arrangement [16], [17] (Fig. 1).

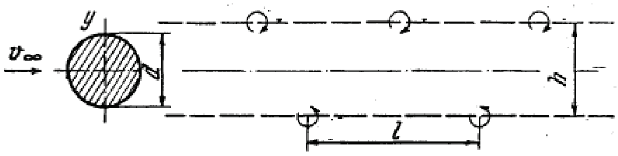


Figure 1. Karman vortex track.
d is the size of the cross section, l, h are the step and width of the track.

The frequency of Karman vortex formation is proportional to the velocity of the incoming flow V and inversely proportional to the cross-sectional size d:

$$\omega_k = \frac{V}{d} St \tag{6}$$

with the coefficient of proportionality (Struhal number St), depending on the shape of the profile.

High-rise solid-wall metal structures most susceptible to wind resonance are chimneys and stacks (Fig. 2).

(a) A chimney in a cage *(b) chimneys connected by platforms* *(c) chimney with interceptors*

Figure 2. Metal chimneys

When designing this type of structures, checking for wind resonance is an obligatory stage of calculation [19, 20]. Contrary to popular belief, the presence of cage (Fig. 2, a) has no effect on wind resonance and comes from technical necessity. Interceptors (Fig. 2, c) help to reduce the value of vortex formation, but cannot prevent resonance. A special difficulty is represented by chimneys arranged in a row (Fig. 2, b) (this case of aerodynamic instability will be considered below). Pillars with height of 20-50 m (Fig. 3) are used for placement of antenna equipment along with towers and masts [14], [15] when there is no necessity of antenna arrangement at high height (for comparison, standard height of lattice towers is 20-100 m). Despite of small height there is also a danger of occurrence of wind resonance for them.

Consider also other types of aerodynamic instability.

Galloping is the self-excited oscillations of flexible structures in the direction across the wind flow. The basis of the galloping process is the following phenomenon: the transverse motion of the body leads to the fact that the resultant relative velocity of the flow on the body is oriented at an angle to the original position of the flow vector, i.e. the effect of changing the angle of attack and there is a negative aerodynamic damping. As soon as it becomes larger than the normal damping (and this circumstance is indicated by Scruton number Sc). The process becomes unstable and galloping oscillations occur [4].

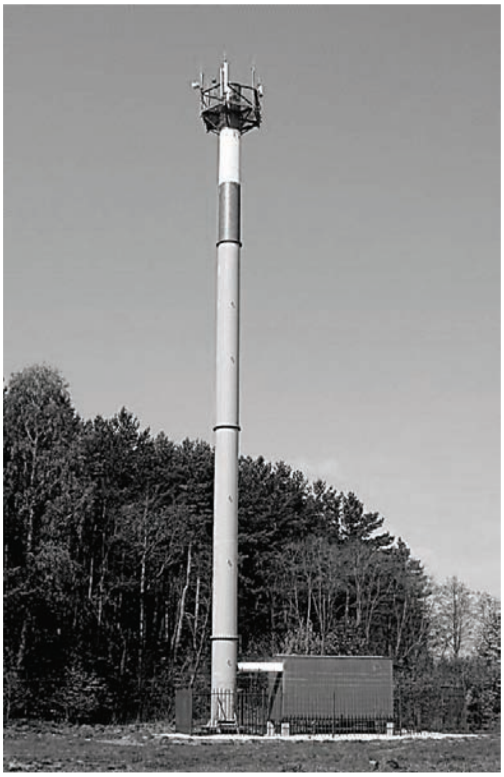


Figure 3. The pole with a height of 35 m

Galloping does not occur in the elements of circular cross section, since the angle of attack does not affect the aerodynamic coefficient, and is inherent in the sections of L-, I-, U-, T-shaped profile. However, this term is very often applied to wires with circular cross-section: galloping or "dancing" of wires. It is explained as follows: during the cold season, icing of wires (Fig.4), ice changes the shape of the cross-section (Fig.5), and at a certain initial wind speed the oscillations of galloping occur. The amplitudes increase rapidly with increasing wind speed and reach tens of cross-sectional body sizes. A similar effect of ice can have on mast structures of great height (Fig.6).

Figure 4. Ice on wires

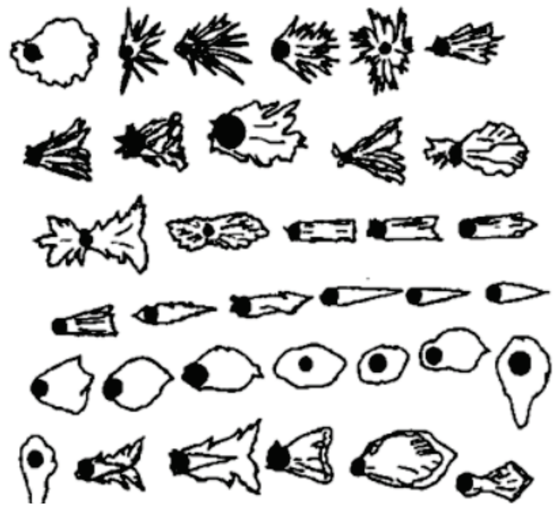


Figure 5. Possible forms of ice deposits on wires

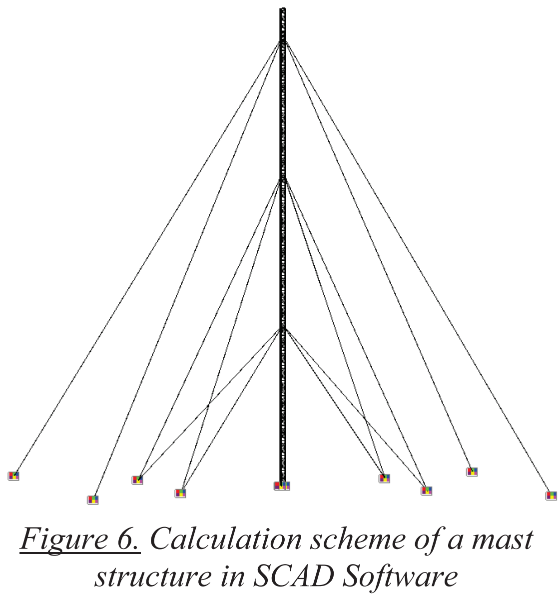


Figure 6. Calculation scheme of a mast structure in SCAD Software

Flutter is an instability that can occur for flexible plate or box structures. A change in the angle of attack in this case causes the profile to twist (disruptive flutter) or to twist together with a displacement across the flow (classical flexural-torsional flutter). A widely known case of flexural-torsional flutter resulted in the collapse of the Tacoma Bridge on November 7, 1940 (Figure 7) [16].
An example of high-rise structures capable of experiencing flutter are billboards and road signs (Fig.6).

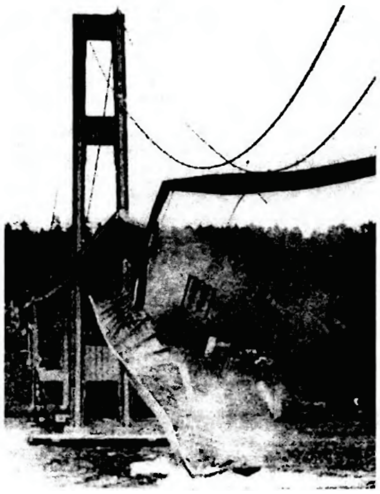


Figure 7. Collapse of the Tacoma Bridge

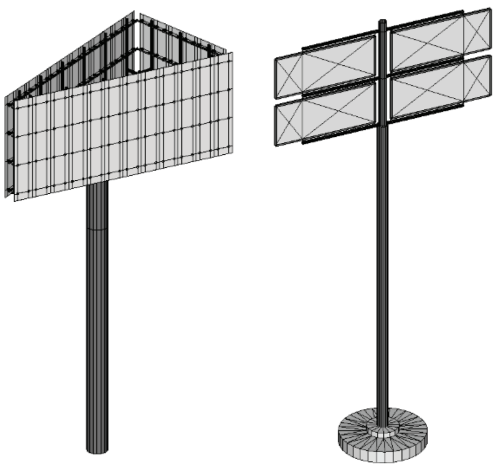
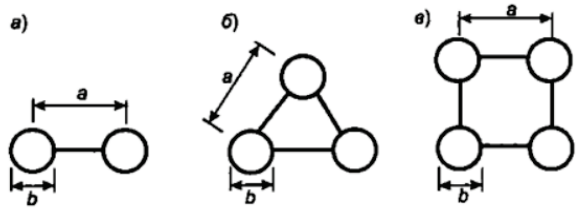


Figure 8. Billboards. Calculation scheme in SCAD Software.

Flexible structures or structural elements, such as trunks or cables, may be arranged in a row or group, may or may not stand in pairs. This leads to the excitation of self-oscillations in the aerodynamic trace. Depending on the a/b ratio (Figure 9), vortex resonance or interferential galloping can occur. Interferential galloping can be excited if two or more cylinders are close to each other without coupling [16].

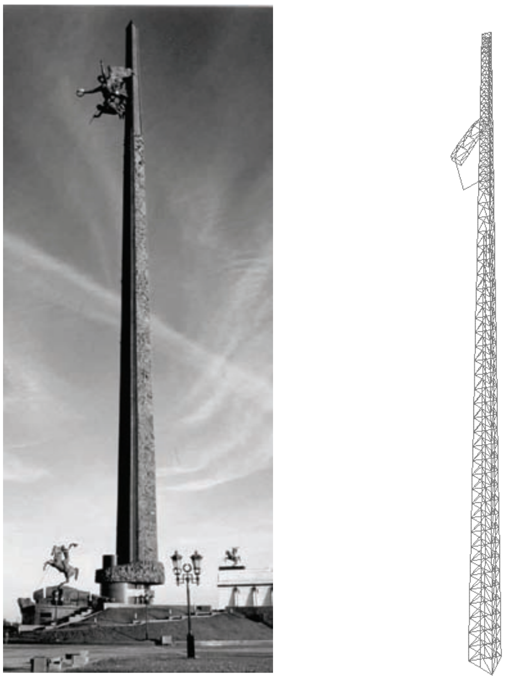


a) b) c)

Figure 9. Arrangement of cylinders in a row or as a group

Flexible structures or structural elements, such as trunks or cables, may be arranged in rows or groups, may or may not stand in pairs
In addition to structures for industrial purposes, special attention in terms of the occurrence of vibrations such as wind resonance should be paid to monuments. Thus, during the construction and operation of several famous domestic monuments accidents occurred because of wind resonance.
The highest and most technically complex in Russia, the Victory Monument is located in the Victory Park in Moscow (Fig. 10). It has a height of 141.8 m and was designed and erected in the shortest possible time for the 50th anniversary of the Victory in the Great Patriotic War [18-21].
Under the direction of the chief engineer of the project, B.V. Ostroumov, the Melnikov Central Research Institute of Construction Materials developed a project of lattice frame in the form of a triangular prismatic tower, on which the half-tower and then decorative bronze panels was mounted. A similar lattice frame is located inside the statue of the goddess Nika.
The frame of the Monument is high and lined with solid panels, which automatically creates an aerodynamically unstable form, unlike the tall lattice-type radio and television towers. Already at the initial stage of the design it

became clear that such a tall, flexible structure clad with decorative bronze panels would not pass the "wind resonance" type of vortex excitation test, and additional measures would be required to protect it from this atmospheric phenomenon.



a) General view of the Monument on Poklonnaya Hill

b) The metal frame of the Monument in SCAD

Figure 10. Victory Monument on Poklonnaya Hill in Moscow

During the design and installation of the structure, several ways had to be used to combat wind resonance. During the installation of the frame, when the bronze panels covered 2/3 of the monument's height, a strong wind rose. The monument was in wind resonance, the vibrations were visible to the naked eye and did not fade. Then the simplest and most urgent way to protect against vortex excitement was used - the installation of stragglers. At the corners of unfinished monument were installed steel cables in the number of three (because the structure in plan is close to the triangle). One end of the cable was fixed to the corners of the frame at a height of 2/3 and the other was fixed to the quickly erected foundations of reinforced concrete blocks within a radius of 10-15 meters from the center of the monument. The scheme of the construction turned from free-console to mast and until the completion of the monument allowed to dampen any dangerous fluctuations in the wind impact.

At the final stage, the dynamic dampers were installed before the removal of cables, which violated the architectural design of the author. Dynamic vibration dampers (DVD) - a device designed to damp the vibrations of the structure. It consists of the inertial mass suspended on the spring and the dampers connected to it. To preserve the architectural appearance of the Monument DVD were placed inside the framework. The main part of the dampers is located inside the sculptural group "Nica", and another is placed along the central axis of the monument at levels above the mark of 90 meters. Dynamic vibration dampers for the Monument were developed simultaneously with the basic design, their characteristics were obtained experimentally by examining the behavior of the structure model in the wind tunnel TsAGI.

Vibration dampers are activated not only at the moments of wind resonance, they also contribute to the reduction of horizontal displacement of the structure under the action of wind load. The efficiency of DVD is provided by their specific location on the structure, in most cases not less than 2/3 of the total height. At a mass of almost 800 tons the total mass of all DVD is equal to 27.5 tons, which is 3.5% of the mass of the structure.

RESULTS

At the end of the article, let's structuring all the mentioned ways to reduce wind resonance of high-rise flexible structures. If condition (5) turned out not to be met at the design stage, use the following ways to increase the damping of the structure:

1. Structural changes in the shape and size of the structure at the design stage allow to change

the components of formulas (2) and (3) and the period of natural vibrations of the structure. Such measures are permissible if allowed by the Technical Design Assignment.

2. Changing the design scheme in principle: use of guy wire as a transition from the cantilever scheme to the scheme with intermediate supports; increasing the throughness of the structure by adding holes. These measures are often used on already constructed structures in case of unforeseen circumstances.

3. Installation of vibration dampers, dynamic or shock dampers. This measure can act as an emergency, but usually dampers are designed at the same time as the construction, when no structural changes can not help to avoid the phenomena of wind resonance. The design must take into account the mass of the dampers, as well as the design of sites for their placement. Vibration dampers require regular inspections and additional adjustments.

CONCLUSIONS

The article analyzes modern studies on the impact of wind flow on extended flexible metal structures such as chimneys, poles, billboards, icy wires, monuments and monuments. Construction of modern unique structures is accompanied by modeling in FE software such as Ansys, Nastran etc., which allows an engineer to get a complete picture of the flow of wind around the structure and to analyze the possible unfavorable factors. However, for typical structures or already built structures, the authors recommend using the methods described in the article.

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