

The distribution of wind gusts in the atmosphere for flexible high-rise structures

Vladimir Mondrus and Anastasia Karakozova*

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. Modern building standards are universal and applicable to the calculation of any structures with one or another measure of stock. However, the calculation of specific groups of structures requires detailed consideration and clarification. The article suggests some refinements in calculating of the high-rise structures made of metal for the pulsating component of the wind load.

1 Introduction

Wind load is a basic load for high-rise steel flexible structures such as towers, masts, steel chimneys. The behavior of such structures under load is described in a special way and strongly depends on the pulsations of the wind speed [1] – [8]. A more accurate determination of the mode of vibration of structures from a wind load as applied to flexible structures with a small vibration decrement can clarify and even reduce the value of the applied load.

2 Wind spectrum

First, consider the wind spectrum. Wind flow velocities, aerodynamic forces, and the reaction of structures to them are random functions of time and are expressed by the energy spectrum $S(\omega)$, which shows how much power of a given process falls on each infinitesimal frequency range $d\omega$. For longitudinal pulsations of the wind speed, the empirical Davenport spectrum [4] (underlying [6]) is used:

$$S_{v'}(n) = \frac{4k_0 u^2 v_{10}^2}{f(1+u^2)^{4/3}} \quad (1)$$

where $u = fL/v_{10}$ - reduced frequency; f - oscillation frequency, Hz; L - length scale; v_{10} - average speed at altitude 10m; k_0 - drag coefficient of the underlying surface.

The spectral characteristics of aerodynamic forces and reactions can be obtained from the speed spectrum using the transfer functions χ (Fig. 1) [9].

* Corresponding author: karioca@mail.ru

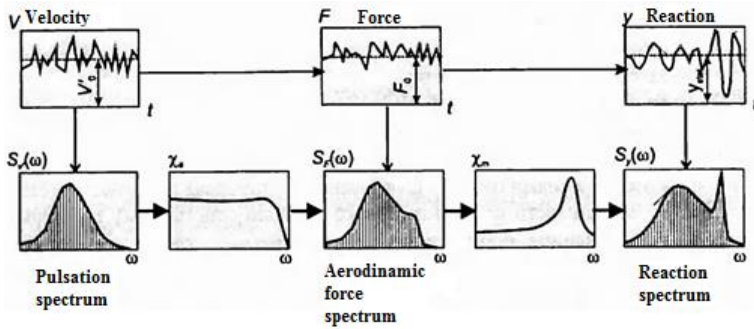


Fig. 1. Scheme for determining the dynamic responses of the system to the action of wind gusts (here $\omega = 2\pi f$ is the circular velocity pulsation frequency, rad / s).

The spectrum of the reaction of the structure to the effect of the random pulsation process is shown in Fig. 2 [4, 9]. It clearly shows the components of the pulsations of the wind velocity: quasistatic (with a maximum of the energy spectrum of the velocity pulsations) and resonant (the maximum is the frequency of natural vibrations).

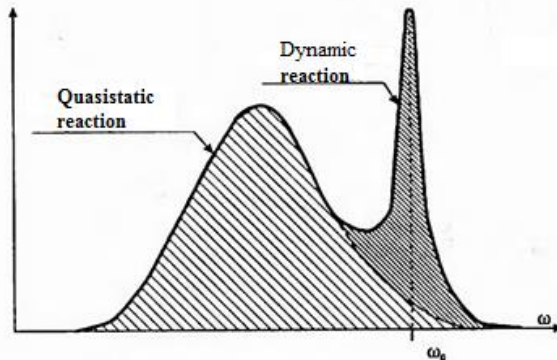


Fig. 2. Reaction spectrum of the structure.

The structures under consideration in the described ranges behave differently. Separation of the reaction into quasistatic and resonant allows avoiding errors in the calculations of fatigue strength and durability; to compensate for the error in pointing the antennas installed on the structures, individually for each component; install dynamic vibration dampers that work only in the resonant frequency region [2], [8], [10]. When determining the pulsation component in the formulas from SP 20.13330.2018 Loads and actions, the coefficient of pulsations of wind pressure at the level of z is used:

$$\zeta(z) = 2\alpha_c \gamma_t \quad (2)$$

where α_c – the security ratio, in SP 20.13330.2018 is taken equal to 2.5; γ_t – turbulence intensity is determined by the expression

$$\gamma_t = \frac{\sigma_{v'}}{v_{10}} \left(\frac{z}{10} \right)^{-\alpha} \quad (3)$$

where α is the exponent in the power law of the change in wind speed with height; z - height; $\sigma_{v'}$ - standard wind speed ripple:

$$\sigma_{v'} = \sqrt{\int_0^{\infty} S_{v'}(f) df} \quad (4)$$

$S_{v'}(f)$ - the energy spectrum of the longitudinal component of the wind velocity pulsations is formula (1).

Thus, when determining the ripple coefficient, the integral is calculated over the entire spectrum. The reaction thus obtained is summarized. There are no recommendations on its division into 2 ranges in SP 20.13330.2018 (various methods are given only in foreign sources such as EN EN 1993-3-1-2006 (E) Eurocode 3: Design of steel structures — Part 3-1: Towers, masts and chimneys — Towers and masts).

The authors of the article propose separation not at the stage of reactions, but at the stage of application of the load [8], presenting the pulsation component as

$$W_p = \sqrt{W_{p.q.st.}^2 + W_{p.res.}^2} \quad (5)$$

The ripple coefficient will be determined separately for quasistatic (p.q.st), separately for resonance (p.res.) by integrating over two ranges - from 0 to f' and from f' to ∞ (the value of the frequency f' will mean a certain boundary of the ranges).

3 Frequency response

Under the influence of a gust of wind, the amplitude of the oscillation of the structure increases gradually (there is a transition process and the unsteady oscillations – A_{non-st}) and soon reaches a maximum - the steady-state amplitude A_{st} (Fig. 3).

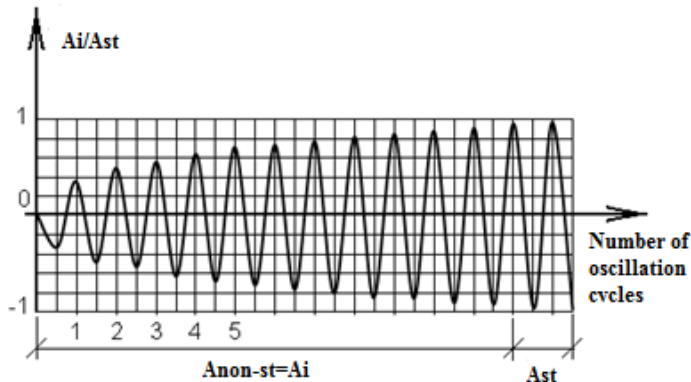


Fig. 3. The increase in the amplitude of oscillations

The duration of the transition process depends on the decrement of oscillations [5]: the number of oscillation cycles until A_{st} is reached, the greater, the smaller δ .

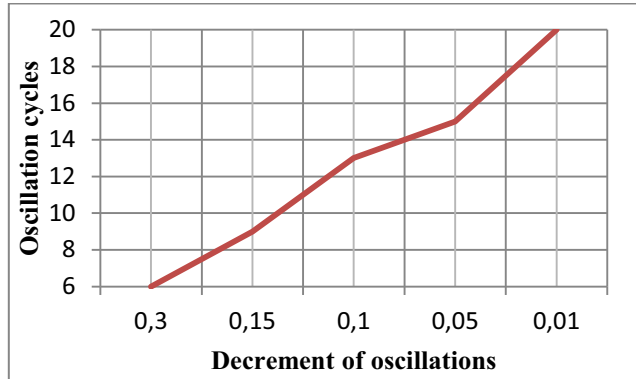


Fig. 4. The dependence of the decrement of oscillations on the number of cycles of oscillation

To achieve A_{st} , tower structures with $\delta = 0,10$ must be subjected to 13 cycles of successive gusts of wind of the same intensity equal to $2,5\sigma_v$, formula (2). However, in reality, only the rush of the first cycle has such intensity, after which the intensity decreases. Thus, the calculated amplitude can be taken as the amplitude corresponding to 1 cycle of oscillation (2 or 3 cycles - to safety margin) - i.e. at the beginning of the transition mode.

The equation of motion of the system will look like:

$$\ddot{x} + 2n\dot{x} + \omega_0^2 x = h \sin \omega t \quad (6)$$

where n - is the attenuation index; h - is the amplitude of the reduced external force; ω - frequency of external force; ω_0 is the frequency of natural vibrations of the structure.

Frequency response (AFC) for a steady process of oscillations (from (6)):

$$C(\omega) = \frac{h}{2\omega} \frac{1}{\sqrt{n^2 + \beta^2}} \quad (7)$$

where β - coefficient equal to

$$\beta = \frac{\omega_0^2 - \omega^2}{2\omega} \quad (8)$$

Frequency response of an unsteady process:

$$C^*(\omega, t) = \frac{h}{2\omega} \sqrt{\frac{(1 - e^{-nt} \cos \beta t)^2 + (e^{-nt} \sin \beta t)^2}{n^2 + \beta^2}} \quad (9)$$

The dynamic coefficient (SP 20.13330.2018) used to determine the pulsation component for the steady state ξ is proportional to (7), for the unsteady one it is proportional to (9). Then

$$K = \frac{\xi}{\xi^*} \approx \frac{C(\omega)}{C^*(\omega, t)} = \frac{1}{\sqrt{1 - e^{-2nt}}} = \frac{1}{\sqrt{1 - e^{-2\delta r}}} \quad (10)$$

where $r = \omega_0 t$ is the number of oscillation cycles, δ is the decrement of oscillations.

Thus, to obtain loads in the transient mode, it is necessary to multiply the values from SP 20.13330.2018 by the coefficient K .

4 Distribution in the atmosphere

Currently, when developing models of the dynamic effects of wind gusts on structures, it is assumed that wind gusts in the atmosphere are distributed according to the normal law. The third and fourth static moments of the distribution, reflecting the asymmetry and excess, are equal to zero. The influence of positive (coinciding with the direction of the average wind flow) and negative (directed towards the average wind flow) gusts is equally probable, which allows us to consider the effect as sinusoidal, described by the Lagrange equation (6) for a system with one degree of freedom. Numerous meteorological studies conducted in recent years on high-rise towers, masts, and wind tunnels [7] have shown that the laws of the distribution of wind gusts are significantly different from normal. So, for example, at the lower levels (0-100m) of the atmospheric boundary layer, there is a positive, and at the upper levels (100-300m) negative asymmetry of the laws of distribution of wind gusts. This makes it possible to replace the model described by equation (6), model:

$$\ddot{x} + 2n\dot{x} + \omega_0^2 x = h|\sin \omega t| \quad (11)$$

for the lower levels of the atmospheric boundary layer, and for the upper levels:

$$\ddot{x} + 2n\dot{x} + \omega_0^2 x = -h|\sin \omega t| \quad (12)$$

5 Conclusions

The calculation of structures for wind gusts according to models (6) and (11-12) shows that in the second case, the calculated amplitudes of movement of the structures are much smaller than in the first case, assuming the law of the distribution of wind gusts in the atmosphere is normal.

It is advisable to use these results when developing new and improving existing regulatory documents.

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