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# Research on the Nature of Tower Crane Metal Structures Loading

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## ABSTRACT

*The analysis of the accident rate of crane structures indicates that the most common cause of accidents with tower cranes is the wind load. The wind load is considered under working and non-working condition. In the working state, the maximum wind load is considered, at which the operation of the crane with the rated load is ensured. In the non-working state, the calculation is carried out using the coefficient accounting for the change in dynamic pressure depending on the height of the location from the ground surface of the given structural element in the non-working and working states of the crane. However, the regulatory documents as a rule do not consider the random nature of the wind load, although the research materials on changes in wind speed (gusts), proposed in the scientific and technical literature, indicate the interval character of their action.*

*The objective of the research was to study the nature of loading of the tower crane structures, which makes it possible to assess the change in the oscillatory process in the element of the crane metal structure exposed to the action of the wind load.*

*The design scheme proposed in the article considers the change in intensity of the wind load along the height of the crane and the random nature of its change, which together lead to the occurrence of longitudinal, torsional, and bending vibrations. Oscillations of the crane metal structure were considered by the authors as oscillations of an oscillator with given parameters of the oscillation amplitude, system masses (boom and tower), and the weight of the load being lifted. The mechanical state of the system (rigidity and elasticity) was considered as well.*

*Theoretical studies of the system under consideration were carried out in two versions:1) as of an elastic-viscous medium; 2) as of a continuous system.*

*The results obtained made it possible to reveal the physical nature of the oscillatory process and to carry out quantitative assessment of the change in the loading of the metal structures of the tower crane.*

*The theoretical studies allowed to obtain expression, which makes it possible to evaluate the change in the oscillatory process in the element of the crane metal structure exposed to the action of the wind load, which has a random nature of loading.*

*Keywords: transport construction, loading of metal elements, tower crane, wind load, loading, oscillatory process.*

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***The text of the article originally written in Russian is published in the first part of the issue.***
***Текст статьи на на русском языке публикуется в первой части данного выпуска.***

## INTRODUCTION

Tower cranes are widely used in civil engineering, e.g. in transport construction for building of infrastructure facilities.

According to the statistics of the Federal Service for Environmental, Technological and Nuclear Supervision of the Russian Federation[1], the largest number of accidents related to lifting equipment occurs with tower cranes. For example, in 2020, during the operation of all types of lifting structures, 53 accidents were recorded, of which the largest number of cases (11) fell on tower cranes. As a result, seven people died. According to the author [1, p. 1] this figure is of 82 %.

The most common cause of tower crane accidents is wind load. According to data of the American National Standards Institute (ANSI) there were 1125 accidents wot tower cranes world-wide during 2000–2010 decade. There were 780 fatal injuries, while 23 % of those accidents were due to high wind load[2]. The necessity to account for wind conditions for safe operation is indicated not only by crane manufacturers but also by crane operators. The significance of that factor is highlighted by the fact that there is a group of companies manufacturing special equipment to warn about dangerous access of values of wind speed[3].

In Russia, the account of the wind load is regulated by GOST [State standard] 1451-77[4] when designing metal structures and mechanisms, brakes, when determining the power of the engines, intrinsic and load stability of the crane. The wind load on the crane in working condition is deemed to be the maximum wind load, at which operation of the crane with the rated load is ensured. In the non-working state, the calculation is carried out using the coefficient considering the change in dynamic pressure depending on the height of the location from the ground surface of the given structural element in the non-working and working states of the crane. There are international and national regulations in other countries, e.g., AS 1418.5 and EN 13000 are used in Australia regarding mobile cranes [2].

The same author [2] underlines the economic effect of the correct choice of the model of the crane based on the admissible wind load. Observations at a location showed that the use of a crane with admissible wind load rate of 20 m/s instead of a crane with admissible wind load rate of 12 m/s allows to increase the number of work hours by 342 % [2].

The existing practices of observing changes in wind speed show that its change has a random nature [3] which will invariably lead to a change in the loading of the elements of the crane's metal structure [4]. In work [5, pp. 44–46], the average statistical frequency of changes in the wind gust was noted, equal to 55–65 s, although other research materials [6, p. 32], carried out in Russia and abroad, show averaged rate of 0,5–5 s, that means that they differ by an order of magnitude.

Consequently, according to the data of later studies [5, pp. 44–46] the frequency of wind impact on a structural element will be equal to 0,0182–0,0154 $s^{-1}$. Such a spread cannot but lead to a change in the longitudinal, transverse, and torsional vibrations of the metal structure of the tower crane. As a result, internal forces in the considered metal structures will bear bending, torsional, and longitudinal vibrations (Pic. 1). Considering the influence on the metal structure of the tower crane, as on the system, from a periodically arising gust of wind, and considering the metal structure of the crane, which is a system consisting of a boom, a tower, and a load, it is evident that the effect of vibrations from the weight of the raised, lowered, or fixed load does not exclude the fact that the structure enters a near-resonance state.

To verify this hypothesis the *goal* was set to study the oscillatory process in the construction of the crane and, using the *methods* of system analysis and differential equations, to reveal the nature of the oscillatory process.

It is worth noting that there are research works dedicated to the description of the models of the impact of wind load on operations performed by cranes, particularly on the cargo, transported by rotary truck crane [7].

## RESULTS

Let's consider the loads acting on the crane in a first approximation (see Pic. 1). Here *q* and

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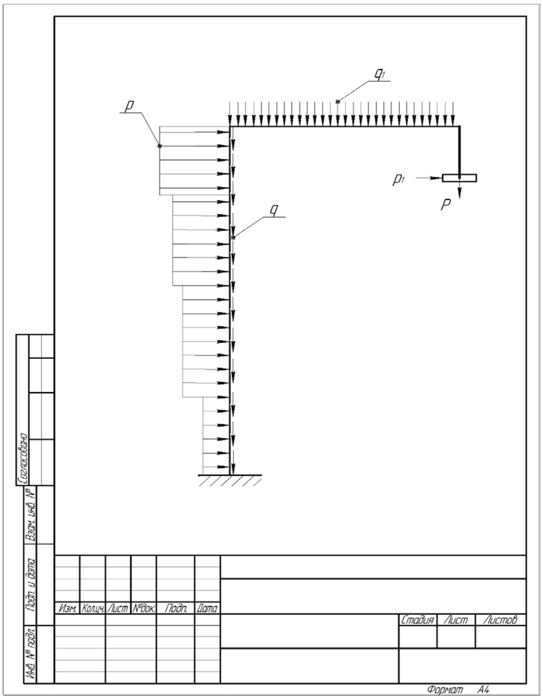
[1] Annual report of the Federal Service for Environmental, Technological and Nuclear Supervision, 2019. Moscow, STC Industrial safety, 2020.

[2] Wind Conditions and Crane Safety. [Electronic resource]: https://www.windcrane.com/anemometer-wind-crane. Last accessed 25.04.2021.

[3] Zajicek, C. Effect of Wind Speed on Cranes. [Electronic resource]: https://www.cranewarningsystemsatlanta.com/post/ effect-of-wind-speed-on-cranes. Last accessed 25.04.2021.

[4] GOST [State standard] 1451-77 Lifting cranes. Wind load. Standard and method of determination. Moscow, Gosstandard USSR, 1977, 19 p.




*Pic. 1. Loads acting on the crane (according to GOST 1451-77).*

$q_1$ are the distributed load from the gravity of the tower and the boom, respectively, N; $p$ and $p_1$ – wind pressure on the tower and the cargo, respectively, N/m²; $P$ – weight of the cargo being lifted, N.

In this case, it is necessary to consider the change in intensity of the wind load along the height of the crane and the random nature of its change. Its action, in combination with cargo characteristics, leads to the occurrence of longitudinal, torsional, and bending vibrations.

Oscillations of any mechanical system can be represented as oscillations of an oscillator [8, p. 125; 5, p. 76].

Using the methodology for calculating oscillatory systems [10, p. 127], we write the boom oscillations in the form of a differential equation. Boom vibrations:

$$m \bullet \frac{d^2 y}{dt^2} + h \bullet \frac{dy}{dt} + k \bullet y = f(t), \quad (1)$$

where $y$ – amplitude of oscillations;

$m$ – mass of the system;

$h$ – viscosity of the structure (coefficient of friction, proportional to speed), which is analogous to elasticity;

$k$ – stiffness factor.

In accordance with Euler's solution [11, p. 282], the general solution of equation (1) will be sought in the form:

$$y = c1 \bullet y1(t) + c2 \bullet y2(t), \quad (2)$$

where c*1* and c*2* – integration constants.

Let's compose the characteristic equation: $m \bullet r^2 + h \bullet r + k = 0$.

Then the equation (2) takes the form:

$$y = c1 \bullet ei\omega t + c2 \bullet e{-}i\omega t = r \bullet \cos(\omega t + \varphi). \quad (3)$$

We will seek the solution using the total energy of the system (kinetic and potential) [6, p. 321]:

$$E = \frac{m \bullet \upsilon^2}{2} + \frac{k \bullet y^2}{2} = \frac{1}{2} \bullet \left[ m \bullet \left( \frac{dy}{dt} \right)^2 + k \bullet y^2 \right]. \quad (4)$$

The oscillation frequency is equal to:

$$\omega = \sqrt{\frac{k}{m}}. \quad (5)$$

Substituting (3) into (4), we obtain that the total energy of the system will be equal to:

$$E = \frac{1}{2} \bullet m \bullet \omega^2 \bullet r^2 \bullet \sin^2(\omega \bullet t + \varphi) +$$

$$+ \frac{1}{2} \bullet k \bullet r^2 \bullet \cos^2(\omega \bullet t + \varphi) = \frac{1}{2} \bullet k \bullet r^2 = const.$$

Considering elasticity of the system and using (1) and (4), we investigate the change in the total energy of the system in time by differentiating equation (4).

$$\frac{dE}{dt} = \frac{1}{2} \bullet \left[ 2 \bullet m \bullet \frac{dy}{dt} \bullet \frac{d^2 y}{dt^2} + 2 \bullet k \bullet y \bullet \frac{dy}{dt} \right] =$$

$$= \frac{dy}{dt} \bullet \left( -h \bullet \frac{dy}{dt} - k \bullet y \right) + k \bullet y \bullet \frac{dy}{dt} = -h \bullet \left( \frac{dy}{dt} \right)^2.$$

The resulting sign «–» indicates damping of the oscillatory process in the system. However, the action of the next gust of wind will inevitably lead to summation of oscillations, which can cause its near-resonance phenomenon.

The solution to the above equation will have the form [11, p. 326]:

$y = c_1 \cdot e^{-at} + c_2 \cdot e^{-bt}$,

where *a* and *b* are the roots of the characteristic equation.

To determine the coefficients $c_1$ and $c_2$, we set the initial conditions:

$$y|_{t=t_0} = y_0; \ \frac{dy}{dt}|_{t=t_0} = \upsilon_0.$$

If the discriminant of the characteristic equation satisfies the condition $D > 0$, then using the initial conditions, we obtain:

$$c_1 = \frac{b \cdot y_0 + \upsilon_0}{b-a} \cdot e^{at_0};$$

$$c_2 = \frac{a \cdot y_0 + \upsilon_0}{a-b} \cdot e^{bt_0}.$$

Let's consider the scheme shown in Pic. 1 as a continuous system. We consider that the total energy of the system is:

$$u = uelas + uext, \tag{6}$$

where $uelas = P \cdot \Delta l$.

The total elongation is the sum of the elongations of the *i*-th sections:

$$\Delta l_i = \frac{(y_{i+1} - y_i)^2}{2 \cdot h}, \tag{6*}$$

where *h* – variation interval.

Then:

$$u_{elas} = \frac{P}{2 \cdot h} \cdot \sum_{i=1}^{n} (y_{i+1} - y_i)^2, \tag{7}$$

$$u_{ext} = -\sum_{i=1}^{n} F_i \cdot y_i. \tag{8}$$

Substituting (7) and (8) in (6), we get:

$$u = \frac{P}{2 \cdot h} \cdot \sum_{i=1}^{n} (y_{i+1} - y_i)^2 - \sum_{i=1}^{n} F_i \cdot y_i. \tag{9}$$

When the system is in balanced state at a fixed time interval (9), we have:

$$\frac{\partial u}{\partial y_i} = 0. \tag{10}$$

And in the absence of balance:

$$\frac{\partial u}{\partial y_i} \to \min, \tag{11}$$

that is, a compensating force is needed to return the system to an equilibrium position. We represent the right side of equation (9) as:

$$\frac{\partial u}{\partial y_i} = \frac{P}{2 \cdot h} \cdot \left[2 \cdot (y_i - y_{i-1}) - 2 \cdot (y_{i+1} - y_i)\right] - F_i =$$

$$= -\frac{P}{h} \cdot (y_{i+1} - 2 \cdot y_i + y_{i-1}) - F_i.$$

Under stationary conditions:

$$\frac{P}{h} \cdot (y_{i+1} - 2 \cdot y_i + y_{i-1}) + F_i = 0. \tag{12}$$

Let's make an equation for two adjacent points ($Fi = F$):

$$y_i = -\frac{(i-1) \cdot i}{2} \cdot \frac{h \cdot F}{P} + i \cdot y_1. \tag{13}$$

When $yn = 0$ we get:

$$y_i = -\frac{(n-1) \cdot i \cdot h \cdot F}{2 \cdot P}, \ i = 1, 2 \ldots (n-1).$$

It is obvious that in the expression (6*) the value:

$$\frac{y_{i+1} - y_i}{h} = y'.$$

Then (6*) can be rewritten as:

$$u_{elas} = \sum_{i=1}^{n} \left[\frac{P}{2} \cdot y'^2 - f_y\right]_i \cdot h = \sum_{i=1}^{n} \left[\frac{P}{2} \cdot y'^2 - f_y\right]_i \cdot \Delta x.$$

If $h \to 0$ we get:

$$P \cdot y'' + f(x) = 0.$$

Or:

$$y'' = -\frac{1}{P} \cdot f(x). \tag{14}$$

Using the initial conditions, with $y(0) = 0$; $y(l) = 0$ function $f(x) = f_0 = const$, then equation (14) will have the form:

$$y' = -\frac{f_0}{P} \cdot x + c_1;$$

$$y = -\frac{f_0}{P} \cdot \frac{x^2}{2} + c_1 \cdot x + c_2.$$

Considering the initial conditions:

$$c_2 = 0;$$

$$c_1 = \frac{f_0}{P} \cdot \frac{l}{2}.$$

Whence the required function will look like:

$$y = \frac{f_0 \cdot x \cdot (l-x)}{2 \cdot P}.$$

In case of the action of an elastic force, work is spent to overcome the elastic forces:

$$\sum \int_0^{y_1} (k \cdot y) dy = \sum \frac{k \cdot y_i^2}{2},$$

where *k* – elasticity coefficient.

Then the expression (6) will have the form:

$$u = \frac{P}{2 \cdot h} \cdot \sum_{i=1}^{n} (y_{i+1} - y_i)^2 + \frac{k}{2} \cdot \sum_{i=1}^{n} y_i^2 - \sum_{i=1}^{n} F_i \cdot y_i. \tag{15}$$

However, considering the design scheme of a tower crane, the state of the latter in case of loading is changed by two parameters *x* and *y*, which change in time by interrelated functions of the form:

$$\begin{cases} x = x(t) \\ y = y(t). \end{cases} \tag{16}$$

These functions change over time at a rate:

$$\begin{cases} \frac{dx}{dt} = P(x, y) \\ \frac{dy}{dt} = Q(x, y). \end{cases} \tag{17}$$

The initial conditions for solving the system of differential equations (17) are determined from the equilibrium condition of the system which is elastic deformation, i.e.:

$$y|_{t=0} = y_0; x|_{t=0} = x_0;$$
$$\dot{y}|_{t=0} = 0; \dot{x}|_{t=0} = 0.$$

that is:

$$\begin{cases} P(x_0, y_0) = 0 \\ Q(x_0, y_0) = 0. \end{cases}$$

Under wind load, displacement of points of the system will be equal to:

$$\begin{cases} x(t_0) = x_0 + \Delta x_0 \\ y(t_0) = y_0 + \Delta y_0. \end{cases} \quad (18)$$

Substituting (18) in (17):

$$\begin{cases} \dfrac{d(\Delta x)}{dt} = P(x_0 + \Delta x, y_0 + \Delta y) = \left(P_x^{'}\right)_0 \bullet \Delta x + \left(P_y^{'}\right)_0 \bullet \Delta y \\ \dfrac{d(\Delta y)}{dt} = Q(x_0 + \Delta x, y_0 + \Delta y) = \left(Q_x^{'}\right)_0 \bullet \Delta x + \left(Q_y^{'}\right)_0 \bullet \Delta y. \end{cases} \quad (19)$$

The characteristic equation of the system has the form:

$$\begin{vmatrix} \left(P_x^{'}\right)_0 - p & \left(P_y^{'}\right)_0 \\ \left(Q_x^{'}\right)_0 & \left(Q_x^{'}\right)_0 - p \end{vmatrix} = 0.$$

For imaginary $p = r + i{\cdot}s$, the solution of the system has the form:

$$ept = ert\cdot (\cos st + i \cdot \sin st). \quad (20)$$

The analysis of equation (20) shows that the growth or damping of oscillations is determined by the sign of the root of the characteristic equation $p$, if $p$ is a real root, and by the sign $r$, if $p$ is imaginary.

Obviously, if at least one root of the equation is equal to 0, then equation (20) will have the form:

$e^{-at} = 1.$

That is, the object is motionless and is in a state of equilibrium, which is impossible in real life.

## CONCLUSIONS

The analysis showed that the existing regulations in Russia governing the calculation of crane structures do not consider the random nature of the wind load.

The carried out theoretical studies made it possible to obtain expression (20), which makes it possible to evaluate the change in the oscillatory process in the element of the crane metal structure exposed to the action of the wind load, which has a random nature of loading.

## REFERENCES


1. Tarasova, T. V. Study of stability of tower cranes under the influence of wind loads [*Issledovanie ustoichivosti bashennykh kranov pri vozdeistvii vetrovykh nagruzok*]. *Modern scientific research and innovations*, 2016, Iss. 6. [Electronic resource]: http://web.snauka.ru/issues/2016/06/68604. Last accessed 25.04.2021.

2. Edwards, S. The effects of wind on crane operation. [Electronic resource]: https://www.cranesandlifting. com.au/the-effects-of-wind-on-crane-operation/. Last accessed 25.04.2021.

3. Jeng, Shyr Long; Yang, Chia Feng; Chieng, Wei Hua. Outrigger force measure for mobile crane safety based on linear programming optimization. *Mechanics Based Design of Structures and Machines*, 2010, Vol. 2 (38), pp. 145–170. DOI: 10.1080/15397730903482702.

4. Korytov, M. S., Sorokin, V., Titenko, V. V., Belyakov, V. E. Study of the crawler crane stability affected by the length of compensating ropes and platform rotation angle in the mode of movement with payload. *Journal of Physics Conference Series,* 2020. DOI: 10.1088/1742-6596/1546/1/012135.

5. Mishin, A. V. Ensuring stability of tower cranes under wind influences. Ph.D. (Eng) thesis [*Obespechenie ustoichivosti bshennykh kranov pri vetrovykh vozdeistviyakh. Dis... kand. tekh. nauk*]. Moscow, MIIT publ., 2014, 169 p.

6. Recommendations for the revised dynamic calculation of buildings and structures regarding action of the pulsating component of the wind load [*Rekomendatsii po utochnennomu dinamicheskomu raschetu zdanii i sooruzhenii na deistvie pulsatsionnoi sostavlyayuschei vetrovoi nagruzki*]. Intr. 1999-15-12.

7. Cekus, D., Kwiaton, P. Impact of Wind on the Movement of the Load Carried by Rotary Crane. *Applied Sciences*, 2019, Vol. 9, pp. 21–22. DOI: https://doi:10.3390/app9183842.

8. Vibrations in technology: Ref.: in 6 volumes. Vol. 3. Oscillations of machines, structures, and their elements [*Vibratsii v tekhnike: Sprav.: v 6 t. T. 3. Kolebaniy mashin, konstruktsii i ikh elementov*]. Ed. by F. M. Dimentberg, K. S. Kolesnikov. Moscow, Mashinostroenie publ., 1980, 544 p.

9. Lazaryan, V. A. Dynamics of vehicles: Selected works [*Dinamika transportnykh sredstv: Izbrannie trudy*]. Kiev, Naukova Dumka publ., 1985, 528 p.

10. Targ, S. M. Short course of theoretical mechanics [*Kratkiy kurs teoreticheskoi mekhaniki*]. Moscow, Mashinostroenie publ., 2010, 416 p.

11. Fikhtengolts, G. M. Course of differential and integral calculus: in 3 volumes. Vol. II [*Kurs differentsialnogo i integralnogo ischisleniya: v 3 t. Tom II*]. Intr. remarks by A. A. Florinsky. 8th ed. Moscow, Fizmatlit publ., 2001, 864 p. ●



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