UDC 621.873

Analysis of studies of stationary tower cranes under wind loads

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Received: 20.09.2023; Accepted: 19.10.2023
https://doi.org/10.32347/gbdmm.2023.102.0201

Abstract. Loading and unloading operations are an integral part of the technological process of construction. Cranes of various types are mostly used to perform these works.

In modern industrial and civil construction, tower cranes of the stationary type are widely used, which are used in the construction of various types of structures and buildings.

Today, it is impossible to imagine a panorama of a city or a fairly large rural village without the upward, light openwork silhouettes of tower cranes. They are clearly visible against the background of new residential buildings, wherever progressive changes are taking place, where construction is underway. More than 200,000 tower cranes are used on construction sites in the country today.

But when using tower cranes, special attention must be paid to their operation in adverse conditions, because they are mechanisms of increased danger.

One of the important factors in the unfavorable conditions during the full-scale Russian invasion of Ukraine was the shock waves that arise as a result of missile strikes. These shock waves, in turn, cause air pressure and oscillations on the Earth's surface and cause certain seismicity.

To ensure trouble-free operation and increase the reliability of tower cranes, it is important to take into account dynamic loads, which are several times greater than static loads, when calculating structures and components of their working equipment.

Ensuring the stability of stationary tower cranes, especially in the conditions of martial law, is one of the important theoretical and practical tasks. The most important aspect of solving this problem is ensuring stability under the conditions of air shock waves, which cause the effect of dynamic loads on the metal structures of the crane.

Keywords: tower crane, air shock wave, stability, dynamic loads.

INTRODUCTION

Tower cranes are the most used among construction cranes that solve the issue of mechanization of loading and unloading work in construction. But their accidents account for 40% of the total number of accidents of boom lifting cranes.

The fall of tower cranes occurs both in our country and abroad, even if all operating rules and safety requirements are observed. The development and subsequent improvement of domestic tower cranes, especially in wartime, is impossible without researching the loads that act on the crane during air shock waves.

PURPOSE OF THE RESEARCH

Analyze studies of stationary tower cranes under wind loads in operating and non-operating conditions of the crane.

PROBLEM ANALYSIS

In recent years, research and publications on this topic are not so much in Ukraine. A significant contribution to the study of this problem was made by the works of Gaidamaki V. F. [1], Erofeeva M. I. [2], Ivanenko O. I. [3], Grigorova O. V. [4]. In these works, individual issues of movement and braking of lifting cranes under the influence of wind are considered. All these works complement each other, but unfortunately, do not give a holistic approach to accounting and the impact of wind loads on the operation of lifting cranes, and especially the effect of air shock waves.

Analysis of recent scientific works in recent years has shown that the stability of tower cranes is influenced by: imperfection of calculation methods, the state of influence of dynamic loads, the impact of loads on supporting elements, the effect of wind loads.

The work of Haidamaki V. F. [1] does not take into account the dynamic impact of wind load on tower cranes, but only refers to the design standards, which also do not take into account the dynamic component of wind in the calculations. This does not take into account not only the design and operational features of cranes, as well as the sailing of cargoes and the speed of the crane elements, which can increase the total loads on the mechanisms during their movement against the wind.

In the work of Yerofeeva M. I. [2] it is shown that it is not necessary to use the entire set of observations over the wind to determine the maximum wind speeds of various capacities, and it is sufficient to limit itself to constructing an integral curve of the repeatability distribution of lunar highs. It is proposed to take into account the design wind speeds depending on the type of facility and the designed duration of its operation.

Ivanenko O. I. [3] proposed a mathematical model of the mode of operation of portal cranes under the dynamic influence of wind. The method of studying the main performance indicators of portal cranes and justification of permissible wind loads for their working condition by numerical methods is proposed. Method of calculation of dynamic characteristics of crane structures by finite elements method is proposed, which allows to determine dynamic influence of wind on crane load stability at design stage.

Other aspects of studies of the impact of wind loads on tower cranes and structures are given in the work of Grigorov O. V. [4]. It proposes a method for optimizing design wind speeds for non-operating and operating states of tower cranes, based on the conditions of minimum annual operating costs and the cost of lifting one ton of cargo, in which the crane weight is expressed by the value proportional to the square of the wind speed.

METHODOLOGY

The main document for calculating the wind load of cranes is the standard of Ukraine DSTU ISO 4302:2017 [5], which establishes the norms and methods for calculating cranes in non-operating and operating conditions. Another document containing the procedure for calculating the wind load of cranes is the International standard ISO 4302-1981 [6], where two groups of indicators are established: wind speed and design pressure; coefficient of aerodynamic force (drag coefficient), depending on the type of structure and wind direction.

The estimated wind speed is taken as the average value for a certain period of time, the so-called mediation period of 1-2 minutes. For the non-operating condition of cranes, the wind speed of the parallel ground surface is taken once every five years as the value determined by a two-minute measurement in the area of installing cranes at a height of 10 m above the ground surface.

The correct choice of wind speed for the idle condition of the crane is important in terms of cost savings. If the calculations take a large load from the wind, and therefore, out of the appearance of high-speed wind, on the one hand, the probability of capsizing will decrease, and the associated losses will decrease. On the other hand, this will lead to an increase in the weight of the crane, the cost of its manufacture and operation.

For the operating condition of cranes, the wind speed at a height of 10 m above the ground for construction, installation, as well as boom-type self-propelled cranes should be taken equal to 14 m/s, and for cranes that are installed at facilities that exclude the possibility of interruption of work, 28,5 m/s. The static component of the wind load on the crane should be taken into account in all design cases.

Normal operation of all cranes requires ensuring their stability under the influence of forces during operation with or without load.

One of the main groups of cranes requiring detailed stability studies are free stationary tower cranes. For them, the results of calculations are used when choosing a counterweight, determining the total weight of the crane, as well as when arranging mechanisms.

The stability of tower cranes is ensured only by their own weight. Tipping moments create loads acting outside the reference circuit: wind load, horizontal component of weight of cargo and inertia force during start-up or braking of lifting mechanism.

Stability shall be ensured at any combination of loads and all crane positions. Under normal operating conditions and the occurrence of any allowable loads, tipping should not occur.

General provisions of calculation of stability of boom tower cranes are set out in NPAOP 0.00-1.80-18 "Occupational safety rules during operation of lifting cranes, lifting devices and corresponding equipment" [7].

In accordance with DSTU ISO 4302:2017 [5], when calculating the load stability, the torque created by the weight of the cargo is taken as the tipping moment; at calculation of own stability - moment created by wind of idle state. The holding moment is created by the weight of the crane and can be reduced by the influence of the crane tilt, as well as by the action of inertia forces and wind in the working state of the crane.

Close to this method is the method of determining the load stability of the crane by the position of all the forces acting on the crane relative to the supporting circuit of the crane.

The criterion for crane stability is the stability factor, which characterizes the degree of approximation of the point of application of the supporting loop equal to the rib. Point of application of resultant vertical reference pressures is taken as point of intersection of directions of this resultant with plane of reference contour.

The stability factor of the crane in a certain direction is the ratio of the size of the reference circuit measured in the analyzed direction at a distance from the point of application of the resulting vertical reference pressures to the furthest edge of the reference circuit when measured in the same direction.

This method also takes into account additional actions on the crane: inertia forces, wind, site slope, etc., and the numerical value of the crane load stability factor is determined by the formula:

$$k = \frac{2l}{l + b'} \geq 1{,}2\,, \qquad (1)$$

where b – distance from the axis of rotation to the line of direction of all loads acting on the stability of the loaded crane, l – distance from crane rotation axis to tipping rib.

This method has not been recognized due to the uncertainty of the value of the load stability coefficient, depending on the distance between the crane supports. Therefore, cranes with different distances between the tipping ribs must have different load stability factors, although the actual stability will be the same.

The method was further developed in the works, where it is shown that the static stability of the crane is ensured provided that the center of gravity of the crane is located during operation with 40% overload within the reference circuit.

For a rigid model, the use of the energy stability criterion is proposed:

$$\frac{A_{con}}{A_{tip}} \geq k_a\,, \qquad (2)$$

where A_{con} – limit value of operation, which is necessary for tipping the crane (holding work), A_{tip} – operation of all operating forces causing crane transfer (transfer operation).

The value of the holding work without taking into account the base plate:

$$\begin{aligned} A_{con} &= \int\limits_{0{,}5\pi-\alpha R}^{0{,}5\pi+\alpha R} R\rho_R \cos\varphi d\varphi = \\ &= R\rho_R(1-\cos\alpha_R) = Rx_R tg 0{,}5\alpha_R \end{aligned}\,, \qquad (3)$$

where $R = \sum G_j$ – equivalent to vertical static forces, α_R, ρ_R –polar coordinates of the tipping point R relative to the received origin of the tipping edge, x_R – Cartesian coordinate of the rollover point R.

Crane tipping operation:

$$A_{tip} = \int_{\pi-\beta_K}^{\pi-\beta_K+\alpha_K} (Q+G_b)\rho_Q \cos(\pi-\varphi)d\varphi = \tag{4}$$
$$= (Q+G_b)\sin\alpha_K (x_Q + \varphi_Q) tg 0{,}5\alpha_R .$$

In the case of evaluation of static stability, the condition for rollover during calculation by these formulas becomes:

$$Q + G_b = \frac{G_K}{k_a} \cdot \frac{x_K - y_K tg 0{,}5\alpha_R}{x_Q + y_Q tg 0{,}5\alpha_R}, \tag{5}$$

where G_b – boom weight reduced to her tip, x_K, y_K, x_Q, y_Q – coordinates of the center of gravity of the crane and cargo, α_R – polar coordinate of the adjoining point of the resulting vertical static forces.

Any stability calculation method shall determine the minimum crane weight required to ensure its operability under specified operating conditions [8].

The wind effect on the steel structure of the crane is characterized by the following main parameters: the average wind speed, mediated over a certain interval of time; maximum wind speed with repeatability over a certain period of time; wind gusts (gusts); duration of gusts (periods) and wind direction.

The average wind speed, the value is mediated over a certain interval of time. This parameter is initial in the calculations of cranes for wind resistance.

In this work, consider the maximum wind speed during squally and gusty winds, which will be close to the air shock wave, respectively, in the fourth and fifth zones of destruction.

First of all, consider the gusty wind. Characteristic of wind gusts, gust coefficient K_g is equal to the ratio of maximum speeds in gusts $V_{\max}$ to average speed V_m:

$$K_g = \frac{V_{\max}}{V_m}. \tag{6}$$

The inertia of existing wind speed measurement devices leads to an inevitable error in the records of such pulsations [9]. Therefore, the wind speeds $V_{\max}$ and $V_{\min}$ are not determined by the instantaneous value, but by the average value in a small (not more than a few seconds) time interval, usually τ =3-5 s.

The squalor of the wind – frequent and sharp increases in average speed, which is determined by a fairly long period of time. In the tasks related to the study of the main indicators of crane operation, it is necessary to allocate two types of winds: sustained gusty wind and squally wind. In sustained, vomiting winds, the change in velocity over time is short-lived, lasting a little more than a few seconds of pulsations, around a roughly constant mean. With squally wind, in addition to short-term pulsations, there is a sharp increase in the average wind speed, determined in a fairly long period of time. The increase in pressure and speed to full value at strong squalls can occur in one or even a fraction of a second. It can be assumed that the moment of tipping is applied to the crane suddenly.

Due to the fact that fluctuations in wind speed near the average value do not cause changes in signs of force and stress in most structural elements, the wind load is represented as a static sum and dynamic components:

$$V(t) = V_{st} + \beta, \tag{7}$$

where V_{st} – static component of wind speed corresponding to the mediated wind speed in a 2-minute time interval, β – dynamic component of wind load.

The dynamic component of wind load is determined either by the results of field measurements of wind speed, or by the dependence of the dynamicity factor ξ, and the coefficient taking into account the pulsation component of wind load m_p, $\beta = m_p \cdot \xi$. In the work of Grigorov [4] for generalized crane structures, approximate values of coefficients

$m_p = 0{,}12...0{,}0004 \cdot H$, where H is the height of the tower, $\xi = f(T)$, where $T = 2 + 0{,}02 \cdot L$; where L is the length of the crane boom, T is the free oscillation period of the crane. The relationship between T and ξ is shown in Table 1.

Table 1. Relationship between T and ξ

T, s	1	2	3	4	5	6	7	8
ξ	1,75	2,25	2,65	2,95	3,16	3,22	3,26	3,3

In [10] the dynamic component of wind load is investigated, due to wind gusts, the probabilistic characteristics of which are determined by natural measurements of wind speed. Table 2 shows the dependence of the value of the gusty coefficient on the value of the average speed in the fourth and fifth zones of air shock wave destruction and the concentration interval with the maximum wind speed.

Table 2. Gust factor K_g versus average wind speed V_m

V_m, m/s	Annealing interval τ, s		
	2	5	10
12.5	1,44	1,41	1,26
30	1,29	1,27	1,26
40	1,26	1,24	1,26
50	1,25	1,21	1,26

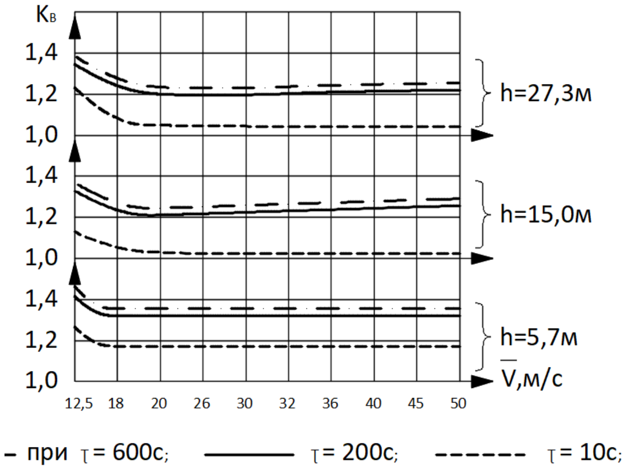

Fig. 1. Dependence of gust coefficient on height and average wind speed

According to NPAOP 0.00-1.80-18, in the table we repel the average speed of 12,5 m/s because at this speed there should be a stop of the tower crane. We see that with an average wind speed of more than 15 m/s, the value of the coefficient K_g does not exceed 1,4 and with an increase in the average speed gradually stabilizes around the average value of 1,23. As you can see, the value K_g from a height of more than 15 m does not depend on the concentration interval and the height of the crane. Therefore, this value can be assumed constant in crane height at speeds up to and greater than 33 m/s, which corresponds to the fourth zone of destruction from an air shock wave.

The dynamic component of wind load can be represented as:

$$\Delta V(t) = \sum_{i=1}^{n} V_i \eta_i(t), \qquad (8)$$

where V_i – decomposition factor; η_i – coordinate functions, ordinary non-random functions.

Receiving for wind flow:

$$\eta_i(t) = \sin \omega_i t, \qquad (9)$$

where ω_i – circular frequencies of gusts (pulsations) of wind.

Finally, the wind speed definition expression, taking into account the dynamic component, will be:

$$V = V_m[1 + \sum_{i=1}^{n} (K_g - 1) \sin \omega_i t], \qquad (10)$$

where K_g and ω_i – random static dependent quantities.

Dependency K_g and ω_i defined by the following expression:

$$\omega_i = \frac{0{,}02\pi}{K_g - 1} \text{ or } \tau_i = \frac{K_g - 1}{0{,}01} \qquad (11)$$

In tasks related to the study of the main indicators of crane operation under the influence of air shock waves, it is necessary to allocate two types of excessive air load: stable gusty wind (fifth zone of destruction) and squally wind (fourth zone of destruction). With both types of air load, the change in speed over time is short-lived, lasting a little more than a few seconds of pulsations, around an approximately constant average. Predicting average wind speed and excessive air load from waves in a squall presents a difficult task.

CONCLUSION

The analysis of studies of stationary tower cranes under the influence of wind load showed that previous work does not give a holistic approach to accounting and the effect of wind loads on the operation of lifting cranes, especially the effect of air shock waves. It has been found that a change in the dynamics of wind flow, and therefore the force of wind action, leads to a change in the response to the excitation action expressed by a decrease or increase in the drag coefficient. For sustained gusty wind, with an average wind speed of more than 12,5 m/s, the value of the gusty coefficient does not exceed 1,4. As the average speed increases, the gust coefficient gradually stabilizes around the average value of 1,23.

In the future, it is necessary to investigate the impact of wind load and determine the behavior of a stationary tower crane from the impact of the angle of attack of wind flow. This will allow the driver of the tower crane in the future to orient the crane with a turn around its axis to ensure its stability.

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Аналіз досліджень стаціонарних баштових кранів при вітрових навантаженнях

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Анотація. Навантажувально-розвантажувальні роботи є невід’ємною складовою технологічного процесу будівництва. Для виконання цих робіт здебільшого застосовують крани різних типів.

В сучасному промисловому та цивільному будівництві широко застосовуються баштові крани стаціонарного типу, які використовуються при спорудженні різних типів споруд та будівель.

Сьогодні неможливо уявити собі панораму міста і досить великого сільського селища без спрямованих увись, легких ажурних силуетів баштових кранів. Вони добре помітні на тлі нових житлових забудов, всюди, де відбуваються прогресивні зміни, де йде будівництво. На будівництвах країни сьогодні використовують понад 200 тис. баштових кранів.

Але під час використання баштових кранів особливу увагу необхідно приділяти їх експлуатації в несприятливих умовах, тому що вони є механізмами підвищеної небезпеки.

Одним із важливих факторів несприятливих умов при повномасштабному російському вторгненні в Україну стали ударні хвилі, які виникають в результаті ракетних ударів. Ці ударні хвилі спричиняють, в свою чергу, повітряний тиск та коливання на земній поверхні та зумовлюють певну сейсмічність.

Для забезпечення безаварійної роботи і підвищення надійності баштових кранів при розрахунках конструкцій і комплектуючих елементів їх робочого обладнання важливо враховувати динамічні навантаження, які в декілька разів перевищують статичні навантаження.

Забезпечення стійкості стаціонарних баштових кранів, особливо в умовах воєнного стану, є одним із важливих теоретичних і практичних завдань. Найважливішим аспектом вирішення цього завдання є забезпечення стійкості за умов повітряних ударних хвиль, що зумовлюють дію динамічних навантажень на металоконструкції крану.

Ключові слова: баштовий кран, повітряна ударна хвиля, стійкість, динамічні навантаження.