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# DEVELOPMENT OF AN ANALYTICAL MODEL OF TRANSIENT AERODYNAMIC LOADING FOR ASSESSING THE STABILITY OF TOWER CRANE METAL STRUCTURES

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***This study investigates metal structures of tower cranes that are subjected to intense dynamic impact of the high-speed pressure of extreme wind flow.***

***The task addressed relates to the insufficient adaptability of existing engineering standards (in particular EN 13001-2) to the assessment of crane stability under short-term extreme aerodynamic loads (squall gusts and remote explosion effects). Classical methods use averaged quasi-static coefficients and do not take into account the synergistic effect of the coincidence of the sudden flow vector with the dynamics of pendulum oscillations of the load.***

***The results include the analytical model of velocity head built to describe dynamic loads on the boom, tower, and crane load depending on their position. Aerodynamic coefficients for lattice structures have been determined by taking into account a change in the Reynolds number when the flow front passes.***

***It is shown that the loss of stability is due to the nonlinear interaction of the velocity head with pendulum oscillations of the load and the resistance of the lattice. The maximum overturning moment (up to 451 kNm at a flow velocity of 33 m/s) occurs when the flow velocity vector coincides with the movement of the cargo. Special features of the results involve modification of the classical formula of aerodynamic pressure by integrating the quadratic set of relative velocities. This, in contrast to static approaches, makes it possible to analytically describe the nonlinear amplification of the overturning moment due to the kinetic energy of the swinging cargo under conditions of unsteady flow.***

***The scope of and conditions for practical implementation of the results include engineering and supervisory organizations. The model could be integrated into automated design systems for developing emergency protection algorithms at facilities with an elevated risk of extreme wind loads***

***Keywords: tower crane, unsteady aerodynamics, extreme gust, overturning moment, analytical modeling***

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## 1. Introduction

One of the important mechanisms behind increased danger at a modern construction site is tower cranes. During their design and operation, special attention is paid to resistance to external influences, among which wind load traditionally dominates. However, under conditions of increased danger, in particular in wartime or at critical infrastructure facilities, there is a threat of exposure to extreme squall gusts. The process of interaction of extreme squall gusts with metal structures of tower cranes is significantly different from the action of natural wind.

Current methodologies for calculating the stability of lifting cranes are focused mainly on wind loads of natural origin and do not fully take into account the specifics of the action of non-stationary aerodynamic loads. This specificity consists in a sharp (instantaneous) increase in pressure, short duration of action, and extremely high values of velocity head. The squall front creates a powerful dynamic shock, which is accompanied by a change in the aerodynamic flow around the lattice structures and the occurrence of pendulum oscillations of the load.

According to international supervisory organizations, more than 30% of fatal tower crane accidents are caused by a sudden loss of global stability under the influence of extreme wind gusts or impulse loads. Existing design standards apply simplified quasi-static correction factors for wind gusts. However, these standards do not provide tools for assessing the instantaneous synergistic effect when the peak of aerodynamic pressure coincides with the antiphase of the swing of the suspended load.

The urgency of solving this problem is due to the fact that the lack of adapted analytical models for assessing the impact of extreme wind flow velocity pressure creates a serious risk of cranes losing stability (overturning) during emergency and extreme wind impacts. This threatens not only the loss of expensive equipment but also the safety of personnel and the integrity of the surrounding infrastructure.

## 2. Literature review and problem statement

The results of research on automated analysis of tower crane stability under wind action for safe selection of their location are reported in [1]. It is shown that taking into account the wind direction is a critical factor. However, issues related to the influence of sudden shock loads with a high pressure gradient remain unresolved. A likely reason is the authors' focus exclusively on natural wind gusts.

In [2], the dynamic behavior of cranes under the influence of various laws of load application, in particular, abrupt and impulse, is investigated. The effectiveness of using nonlinear calculation methods to estimate the overturning moment is shown. However, the specificity of the aerodynamic flow around lattice structures of land tower cranes are not taken into account, which makes the direct transfer of these results to the influence of extreme wind incorrect.

In [3], the anti-collapse behavior of steel frame structures under the influence of intense flow at close range is analyzed. The mechanisms behind destruction of load-bearing elements have been established but the issues of global stability (overturning) of "crane" type structures have remained unresolved because of the fundamental impossibility of taking into account the dynamics of pendulum oscillations of the load in static frames.

Study [4] proves the high ability of hybrid lattice structures to absorb the energy of impulse loading. An option for overcoming the corresponding difficulties for cranes may be the adaptation of these laws for the analysis of lattice towers and booms under the action of high-speed pressure.

In work [5], the aerodynamic forces acting on fast-erect cranes were experimentally and numerically estimated. It was proven that the aerodynamic coefficients significantly depend on the configuration. However, the peculiarities of the change of these coefficients at flow speeds characteristic of extreme wind were not revealed because of the objective difficulties in modeling such speeds.

In [6], an analysis of variations in aerodynamic loads and vibrations of tower cranes at different wind angles was conducted. However, the fundamental impossibility of applying this approach to extreme wind is due to the difference in the duration of the compression phase and the absence of the effect of an instantaneous dynamic shock.

Textbook [7] provides a detailed description of the basics of designing metal structures for construction machines. In [8], an assessment of the reliability indicators of tower cranes was conducted and it was shown that their supporting metal structures operate under conditions of random loading modes (overload, irregularity of cycles), where the main characteristics obey certain distribution laws (exponential, normal, Weibull). However, the issues of assessing the reliability and stability of cranes under extreme, instantaneous overloads, such as the high-speed pressure of extreme wind, remained unresolved. A likely reason is the focus of existing methodologies on long operational periods (wear, aging), while the expense of conducting full-scale experiments with the demolition of real cranes makes the relevant practical studies difficult to access.

Thus, our review of the literature revealed a key unsolved problem: existing methodologies mostly focus on the influence of natural wind gusts with quasi-static flow or consider the general anti-collapse behavior of frame buildings. At the same time, the issue of maintaining the global stability of flexible lattice structures of the crane type during instantaneous extreme gusts with a high velocity gradient remains unsolved. The main reason for this is the impossibility of using standard constant coefficients to describe the synergistic effect arising from the interaction of intense velocity pressure and kinetic energy of pendulum oscillations of the load. The need to solve this problem requires the construction of an adapted analytical model.

It is this approach, based on the construction of an analytical model of velocity pressure taking into account the changed aerodynamic coefficients and pendulum dynamics of the load, that is most appropriate for solving the set task.

## 3. The aim and objectives of the study

The aim of our study is to build an analytical mathematical model of the velocity head induced by an extreme wind flow, for calculating dynamic loads on the metal structures of a tower crane. This will make it possible to increase the safety of operation of tower cranes and objectively assess the risk of their overturning in case of emergency impacts.

To achieve this aim, the following objectives were accomplished:

– to derive an analytical dependence for determining the overturning moment, which would integrate the relative flow speeds and pendulum oscillations of the load.

– to conduct a preliminary assessment of the natural and load stability of a typical tower crane using the model built.

## 4. The study materials and methods

The object of our study is the metal structures of tower cranes, which are subjected to intense dynamic effects of the high-speed head induced by an extreme wind flow.

The principal hypothesis associates the loss of crane stability during an intense flow with two factors. The first factor is the peak value of the flow pressure. The second factor is the nonlinear interaction of the high-speed head with pendulum oscillations of the load and the changed aerodynamic characteristics of lattice structures.

The assumptions adopted in the work are as follows:

1) the extreme gust front at the calculated distance from the epicenter is considered flat;

2) the metal structure of the crane is modeled as a system of rigid and flexible bodies;

3) the interaction of the flow with the load is considered under the condition of its maximum windward area.

The simplifications accepted in the work are as follows:

1) the thermodynamic (temperature) effects of the flow on the properties of the metal are not taken into account in the calculation model;

2) only the horizontal vector of flow propagation is considered, without taking into account the effects of reflection from urban development or terrain.

Our study was conducted using analytical mathematical modeling methods. For an adequate description of the loads, the apparatus of theoretical mechanics (rigid dynamics to determine vibrations on a flexible suspension), gas dynamics, and aerodynamics of lattice structures was applied.

To calculate the total overturning moment, the principle of superposition of loads acting on the boom, tower, and crane load in dynamics was applied.

The use of analytical mathematical modeling methods, rather than numerical methods, is justified by the need to design a "first approximation" engineering toolkit. This approach allows us to obtain basic functional dependences and estimate the stability limits without significant computational costs, which is a necessary stage before further detailed numerical or experimental verification. A rigid body system was adopted for modeling, which is a deliberate simplification; the real flexibility of the tower and the deformability of the rope system are left outside the scope of this stage of our study.

The study is based on a model of velocity head, which is similar in physical properties to squall wind gusts. The characteristic of gustiness is the coefficient $K_g$, which is equal to the ratio of maximum speed $V_{\max}$ to average speed $V_{avg}$

$$K_g = \frac{V_{\max}}{V_{avg}}. \tag{1}$$

Taking into account the inertia of measuring devices, the speed is determined as averaged over a time interval $\tau = 3–5$ s. The wind load is represented by the sum of the static ($V_{avg}$) and dynamic ($\beta$) components

$$V(t) = V_{avg} + \beta. \tag{2}$$

The physical meaning of the resulting dependence (2) is that the total load makes it possible to take into account both the basic effect of the wind flow and sudden velocity fluctuations.

For the analysis of the interaction of the flow with the elements of the crane (tubular rods), the critical parameter is the Reynolds number (Re), which determines the flow regime (laminar or turbulent) and the value of the drag coefficient

$$\mathrm{Re} = \frac{vl}{\nu}. \tag{3}$$

where $l$ is the characteristic size, $\nu$ is the kinematic viscosity.

When the gust front passes, a "resistance crisis" is observed (at Re > $10^5$), when $C_x$ drops sharply. However, to ensure a safety margin, the $C_x$ values according to European standards [9] were used in our calculations, which, in the range $10^2 < \mathrm{Re} < 10^5$, are conservative (overestimated by 5–10%).

## 5. Results of the construction of an analytical model of velocity head

### 5. 1. Deriving an analytical dependence for determining the overturning moment, which would integrate the relative flow velocities and pendulum oscillations of the load

The calculation scheme in Fig. 1 takes into account the effect of wind load on the mechanism for changing the crane's reach and rotation through the generalized coordinates U (position on the boom) and $\varphi$ (angle of rotation).

The resultant wind load $P_{R1}$, reduced to the load suspension point, is defined as

$$P_{R1} = \frac{C_{R1} \pm C_{M1}}{C_{X_1}} \cdot \frac{l_1}{L} \cdot q \cdot A_U, \tag{4}$$

where $q = \frac{\rho V^2}{2}$ is the dynamic pressure, $A_U$ is the windward area. Taking into account the crane rotation angle $\varphi$ and the spatial position of the boom, the horizontal component of the load $P_{B1}$ takes the form

$$P_{B1} = \sqrt{C_{X1}^2 + C_{Y1}^2} \cdot \frac{C_{X1} \pm C_{M1}}{C_{X1}} \cdot \frac{l_1}{L} \cdot \frac{\rho V^2}{2} A_U \times$$
$$\times \cos\left( \arcsin \frac{U - r_0}{L} - \arctan \frac{C_{Y1}}{C_{X1}} \right) \cos^2 \varphi. \tag{5}$$

The total moment from wind pressure on the rotating part relative to the axis of rotation $Z$ ($M_B$) is calculated as the difference of the moments on the boom and the counterweight/tower

$$M_B = M_2 - M_3 = \frac{\rho}{2}\left(C_{M2} - C_{M3}\right) V^2 A_\varphi U. \tag{6}$$

To calculate the total load, taking into account the inherent speed of movement of the crane elements and the load, integral dependences were used, which are consistent with modern approaches to assessing the dynamic response under the influence of extreme winds [10–12] (7) to (11)

$$P_B = \int_{h_0}^{h} \frac{\rho}{2} C_X K b \left( \dot{U} \cos^2 \varphi \frac{h_i - h_0}{3} + \frac{2\dot{U} \cos \varphi V}{h - h_0} + V^2 \right). \tag{7}$$

By analogy, for the vertical component of wind pressure reduced to the point of suspension of the load "*a*" is equal to

$$P_{Bh} = \int_{h_0}^{h} \frac{\rho}{2} C_X K b \left( \dot{U}^2 \cos^2 \varphi \frac{h_i - h_0}{3} + \frac{2\dot{U} \cos \varphi V}{h - h_0} + V^2 \right). \tag{8}$$

The wind pressure on the boom is determined by taking into account the rotation speed. The projection of the velocity vector of the *i*-th point of the boom onto the direction of the wind pressure velocity vector is equal to

$$V_{i\varphi} = U \dot{\varphi} \sin \varphi \frac{h_0 - h}{h - h_0}. \tag{9}$$

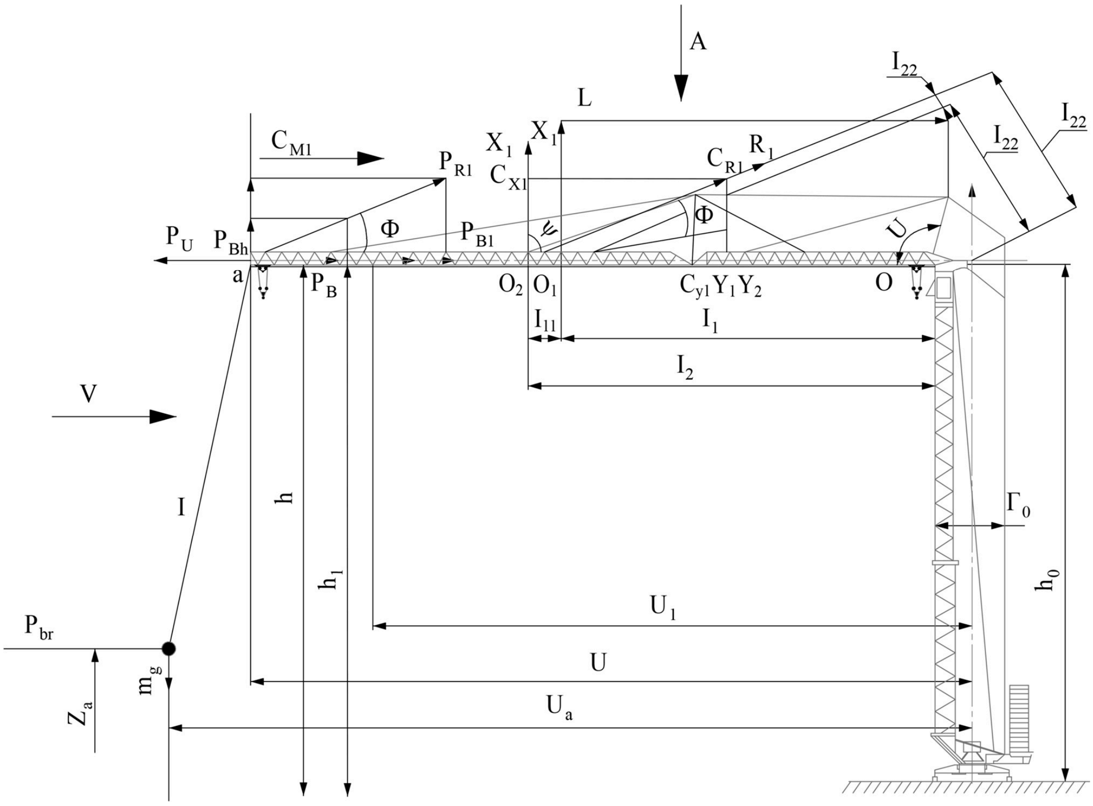

Fig. 1. Calculation scheme of the action of wind loads on crane structural elements: $U_i$ – current coordinate of the $i$-th element of the boom; $o_1$ – origin of the coordinate system $x_1$, $y_1$, $z_1$; $o_2$ – point of application of the full wind load on the boom device; $R_1$ – resultant wind load in the plane of the boom swing; R – resultant wind load in the horizontal plane; $X_1$ – component of the wind load, perpendicular to the axis of symmetry of the boom; $Y_1$ – component of the wind load on the boom, parallel to the axis of symmetry of the boom; $C_{x1}$, $C_{y1}$, $C_{R1}$, $C_{M1}$ – aerodynamic coefficients, respectively, of the forces $X_1$, $Y_1$, $R_1$ and the moment $M_1$ relative to the point $o_1$, which depend on the type of crane, the boom extension, and its angle of rotation; $l_1$ – distance from the axis of the boom swing 00 to the origin of the coordinate system $x_1$, $y_1$, $z_1$; $l_2$ – distance from the axis of the boom swing 00 to the point $o_2$ of application of the resultant wind load $R_1$; $l_{11}$ – displacement along the boom axis of the point of application $R_1$ relative to $x_1$, $y_1$, $z_1$; $l_{22}$ – displacement of the arm of application of the force $R_1$ relative to the origin of the coordinate system $x_1$, $y_1$, $z_1$; $l_{12}$ – arm of application of the component of the force $R_1$ relative to the axis of the boom swing 00; $l_{21}$ – arm of application of the force $R_1$ relative to the axis of the boom swing 00; $\upsilon$ – angle of inclination of the boom from the vertical; Φ – angle of inclination of the resultant $R_1$ to the horizontal plane; $\psi$ – angle between the forces $X_1$ and $R_1$; $P_{R1}$ – resultant wind load, reduced to the point of suspension of the load "*a*"; $P_{B1}$ – horizontal component of the wind load on the boom, reduced to the point of suspension of the load "*a*"; $P_B$ – horizontal component of wind load on the boom reduced to the point of suspension of the load "*a*" taking into account the aerodynamic effect of the rotary platform (tower) on the boom; $P_{h1}$ – vertical component of wind load on the boom, reduced to the point of suspension of the load "*a*"; $P_{Bh}$ – vertical component of wind load on the boom, reduced to the point of suspension of the load "*a*", taking into account the aerodynamic effect of the rotary platform (tower) on the boom

The load induced by the wind flow in the rolling plane of the boom on the load, taking into account movements along the coordinate $U_\alpha$

$$P_{P_{load}} = \frac{\rho}{2} C_{x\_load} A_{load} \left( \begin{array}{l} \dot{U}^2 + 2\dot{U}V\beta\cos\varphi + \\ +V^2\beta^2\cos^2\varphi \end{array} \right), \qquad (10)$$

where $C_{x\_load}$ is the coefficient of aerodynamic resistance of the load. This coefficient is taken as maximum, since the load under the action of the wind flow occupies a normal position, thereby ensuring the maximum value of the windward area; $A_{load}$ is the windward area of the load.

The moment relative to the axis of rotation of the crane from the action of the wind load on the load, taking into account its movement

$$M_{B\_load} = \frac{\rho}{2} C_{x\_load} A_{load} U \left( \begin{array}{l} \dot{\varphi}^2 U^2 + 2\varphi UV\beta\sin\varphi + \\ +V^2\beta^2\sin^2\varphi \end{array} \right). \qquad (11)$$

The derived equation (11) is a modified analog of the classical formula for the aerodynamic overturning moment. Instead of the static flow velocity, a quadratic complex of relative velocities is used. The total moment from the load is formed not only due to the direct flow pressure. It is significantly amplified by the pendulum oscillations of the load and a change in the angle of its deflection. This indicates a pronounced nonlinearity of the process. The maximum overturning moment occurs when the direction of the load movement coincides with the velocity vector of the flow front. Such a state could lead to the loss of the global stability of the crane.

### 5. 2. Preliminary assessment of the natural and load stability of a typical tower crane using the model built

To conduct an analytical assessment and verification of the constructed model, calculations were performed for the parameters of a typical LIEBHERR 63K tower crane (load capacity 6 t, maximum boom reach 40 m, crane mass $G_{crane} = 432.4$ kN). The stability assessment was carried out for the conditions of the velocity head, which corresponds to air flow speeds of 14, 21, 27, and 33 m/s at a height of 10 m above the ground.

Assessment of loads on the turning part and natural stability of the crane. At the first stage, the load $P_B$ and the overturning moment $M_B$ were determined for the non-operating state of the crane (without load) at a maximum flow speed of 33 m/s depending on the angle of attack $\varphi$. The results of our calculations are given in Table 1.

It was established that the maximum overturning moment ($M_B$ = 451 kNm) occurs when the boom is perpendicular to the flow front. For the non-working state of the crane, the holding moment ($M_r$) is created by its own weight and, for this model, is $M_r$ = 821.6 kNm. Taking into account the standard load factor, which is confirmed by the results of the stability assessment of tower cranes using software packages [12, 13], the check of its natural stability showed

$$K_{sf} = \frac{M_r}{M_{ot}} = 1.42 > 1.15. \qquad (12)$$

The condition of natural stability ($K_{sf} \geq 1.15$) at a speed of 33 m/s and the worst angle of attack (90°) is not met, which confirms the critical danger of an extreme gust compared to natural wind.

Table 1

Dependence of horizontal load ($P_B$) and overturning moment ($M_B$) on angle of attack ($\varphi$) at $V$ = 33 m/s

| Angle of attack, $\varphi$ | 33 m/s | |
|---|---|---|
| | $P_B$, kN | $M_B$, kNm |
| 90 | 45.9 | 451.0 |
| 80 | 48.0 | 436.3 |
| 70 | 50.4 | 397.1 |
| 60 | 52.6 | 340.1 |
| 50 | 50.9 | 263.0 |
| 40 | 49.2 | 186.3 |
| 30 | 44.0 | 113.5 |
| 20 | 38.3 | 52.8 |
| 10 | 34.7 | 13.7 |
| 0 | 32.8 | – |

*Note: $\varphi$ = 90° corresponds to the perpendicular position of the boom equipment relative to the wind flow; $\varphi$ = 0° corresponds to the position of the boom equipment downwind.*

During the assessment of the load stability of the simulation of the impact of the high-speed flow on the crane with the load, even more critical zones were identified. Fig. 2 shows the calculated load scheme.

To determine the stability, the overturning moments relative to different edges $M_{ot1}$ and $M_{ot2}$ were calculated, as well as the torque $M_t$ for speeds of 14, 21, 24, 27, and 33 m/s. The obtained calculated data are visualized in Fig. 3–5. These arrays of values were calculated exclusively analytically using the derived equations of the total moment (6) and (11) without conducting full-scale experiments. Fig. 3–5 demonstrate a quadratic increase in the overturning moment with increasing flow velocity at constant angle values (which is physically explained by the proportionality of the dynamic pressure to the square of velocity $V^2$). Local deviation (spike) of the curve is shown in Fig. 3.

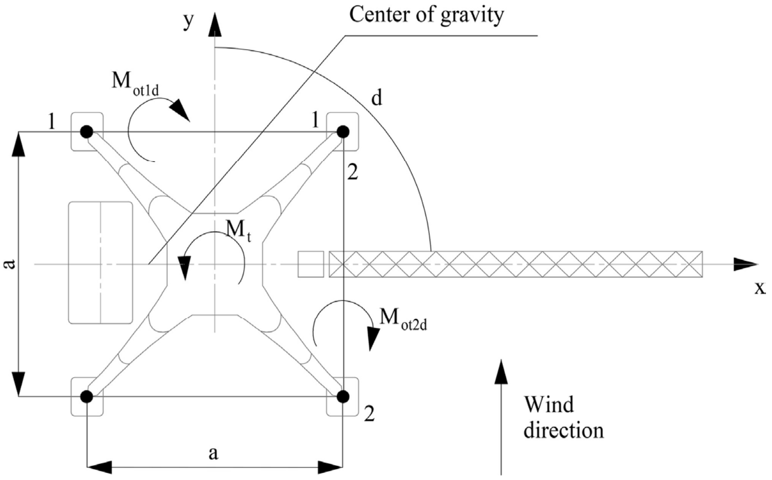

Fig. 2. Wind load calculation scheme for determining load stability: 1-1 — forward tipping edge (towards the boom); 2-2 — backward tipping edge; $M_{ot1}$ — moment relative to edge 1-1; $M_{ot2}$ — moment relative to edge 2-2; $M_t$ — torque relative to the vertical axis of the crane

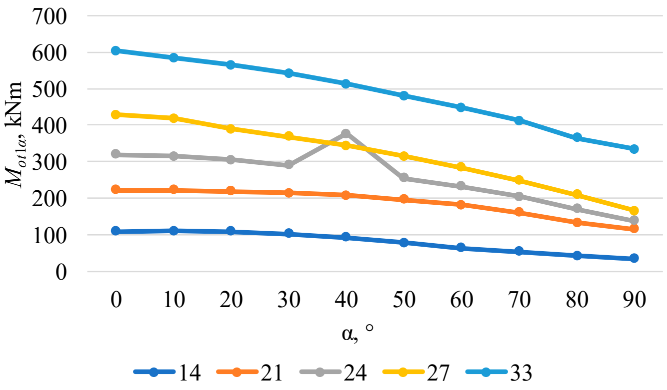

Fig. 3. Dependence plot of the overturning moment $M_{ot1\alpha}$, kNm, relative to the front edge 1-1 on the angle $\alpha$ of the boom rotation at different air flow speeds ($V$ = 14...33 m/s)

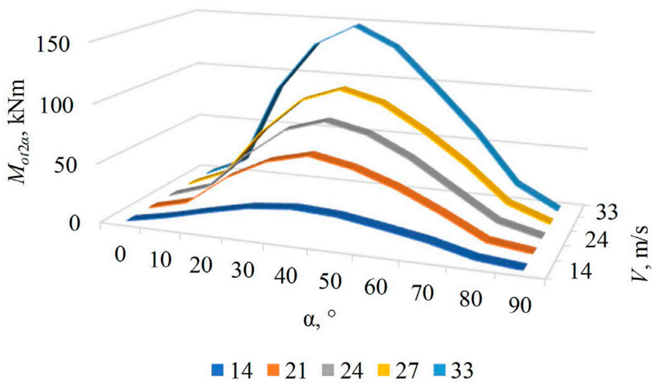

Fig. 4. Diagram of dependence of the overturning moment $M_{ot2\alpha}$, kNm, relative to the rear edge 2-2 on the angle $\alpha$ of the boom rotation at different flow speeds $V$ = 14...33 m/s

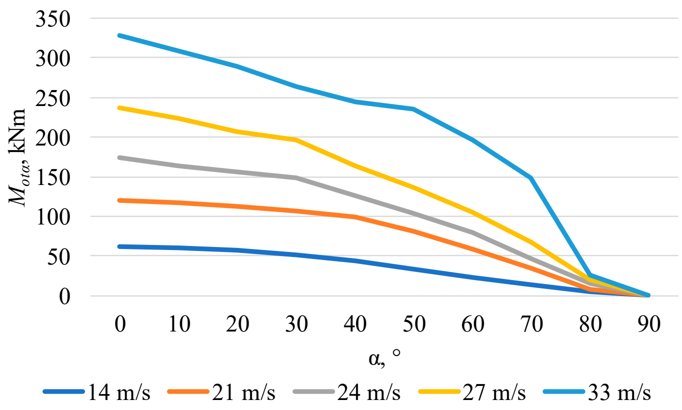

Fig. 5. Diagram of dependence of the overturning moment $M_{t\alpha}$, kNm, relative to the axis of rotation of the crane on the angle α of the boom rotation at different flow speeds $V$= 14...33 m/s

The local deviation (spike) of the curve for the flow velocity $V = 24$ m/s at an angle $\alpha \approx 40°$ (Fig. 3) is explained by the nonlinear nature of equation (11). Under these specific conditions of the spatial position of the boom, the most unfavorable coincidence of the aerodynamic flow velocity vector with the pendulum oscillation vector of the load occurs. This creates a short-term synergistic effect (maximization of the quadratic complex of relative velocities), which generates a local peak of the overturning moment. At higher speeds (27 and 33 m/s), the direct aerodynamic pressure on the metal structures becomes absolutely dominant, so the influence of the pendulum dynamics of the load on the general background is smoothed out. Based on the results of determining the overturning moments and the corresponding holding moments, the stability reserve coefficient $\psi_{1\text{-}1}$ for the non-operating state was calculated (Table 2).

Table 2

Change in the stability reserve coefficient ($\psi_{1\text{-}1}$) for the non-operating state at wind speeds of 24, 27, 33 m/s relative to edge 1–1

| α, degree | $\psi'_{1-1}$ | | |
|---|---|---|---|
| | Wind speed, m/s | | |
| | 24 | 27 | 33 |
| 0 | 1.17 | 0.87 | 0.61 |
| 10 (–10) | exceeding 1.15 | 0.94 (0.89) | 0.66 (0.63) |
| 20 (–20) | | 1.01 (0,91) | 0.70 (0.63) |
| 30 (–30) | | 1.10 (0.94) | 0.75 (0,64) |
| 40 (–40) | | 1.21 (0.98) | 0.81 (0.66) |
| 50 (–50) | | 1.34 (1.05) | 0.88 (0.69) |
| 60 (–60) | | 1.51 (1.14) | 0.99 (0.75) |
| 70 (–70) | | 1.74 (1.28) | 1.13 (0.84) |
| 80 (–80) | | 2.08 (1.51) | 1.37 (1.0) |
| 90 (–90) | | 2.6 (1.9) | 1.72 (1.24) |

From Table 2 it is seen that the maximum safe position is achieved when the boom device is located downwind $\alpha = 80°$ (–80°), which is primarily due to the minimum value of the windward area. Analysis of these coefficients allowed us to obtain a complex dependence of the safe zones (Fig. 6). The shaded zone ($1.0 < \psi < 1.15$) corresponds to the critical level of stability. Below this limit ($\psi < 1.0$), there is a guaranteed overturning of the crane.

For the operating condition, the most dangerous event is determined to be the movement of a load weighing 6 tons at a reach of 13 m. At a flow speed of 24 m/s, the stability coefficient falls below the safe value of 1.15. This is typical for almost all angles of attack. The exception is a narrow sector when the boom is directed strictly along the flow.

This proves that under the action of extreme loads from an extreme gust, ensuring global stability is possible only by quickly turning the boom into the plane of action of the flow velocity vector.

Calculation of the load stability reserve coefficients ($\psi_{1\text{-}1}$ and $\psi_{2\text{-}2}$) for this operating condition at extreme flow front speeds of 24 and 27 m/s is given in Table 3.

Analysis of the data in Table 3 reveals that at a flow front speed of 24 m/s, the stability coefficient falls below the regulatory safe value (1.15) for almost all angles of attack, except for the narrow sector when the boom is directed strictly along the flow ($\alpha = 60°$). At a speed of 27 m/s, the safety zone narrows even more.

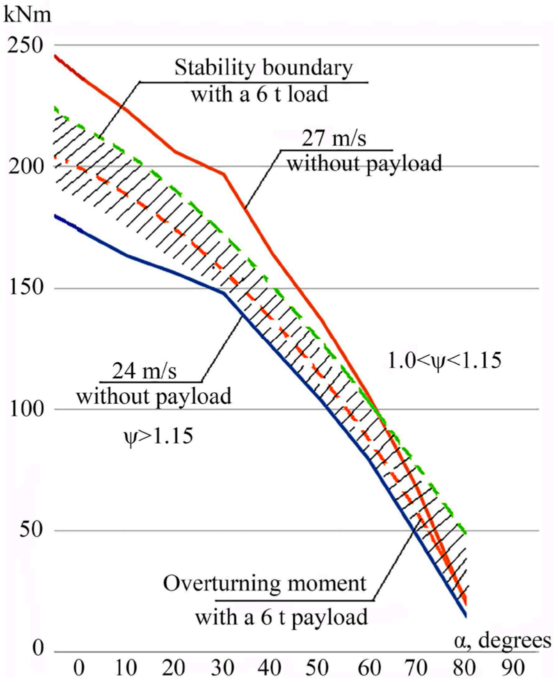

Fig. 6. Integrated dependence of stability margin and torque on boom position

Table 3

Change in the stability reserve coefficient for the operating condition at wind speeds of 24 and 27 m/s, at $\alpha < 90°$

| α, degree | 24 | | | | 27 | | | |
|---|---|---|---|---|---|---|---|---|
| | $\psi_{1\text{-}1}$ | | $\psi_{2\text{-}2}$ | | $\psi_{1\text{-}1}$ | | $\psi_{2\text{-}2}$ | |
| | Q, kN | | | | Q, kN | | | |
| | 11 | 40 | 11 | 40 | 11 | 40 | 11 | 40 |
| 0 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 |
| 10 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 |
| 20 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 |
| 30 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 |
| 40 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 | < 1.15 |
| 50 | < 1.15 | < 1.15 | 1.19 | < 1.15 | < 1.15 | < 1.15 | 1.16 | < 1.15 |
| 60 | 1.37 | 1.17 | 1.67 | 1.39 | 1.29 | < 1.15 | 1.63 | 1.34 |
| 70 | 1.76 | 1.49 | 2.14 | 1.77 | 1.66 | 1.4 | 2.08 | 1.7 |
| 80 | 2.13 | 1.8 | 2.58 | 2.11 | 2.02 | 1.7 | 2.53 | 2.05 |
| 90 | 2.47 | 2.46 | 2.92 | 2.38 | 2.36 | 1.98 | 2.8 | 2.3 |

This conclusively proves that under extreme loads from an extreme gust, ensuring global stability is possible only by quickly turning the boom into the plane of action of the flow velocity vector.

## 6. Discussion of results based on constructing the analytical model and assessing stability of the tower crane

As evidenced by our results (Fig. 3–5) and the data from analytical calculations (Tables 1–3), the obtained critical drop in the stability reserve coefficient ($\psi_{1\text{-}1} < 1.15$) and the exponential growth of the overturning moment ($M_B$ to 451 kNm) are explained by the specificity of the nonlinear interaction of the flow and the structure. Unlike existing regulatory approaches [9] in which the dynamics are taken into account by averaged coefficients, the analytical model built (11) shows that the mass of the cargo under conditions of unsteady flow acts as a kinetic accumulator. If the direction of movement of the cargo coincides with the flow vector, a synergistic effect occurs, which is capable of instantly overturning the crane even at speeds of 24 m/s.

A distinctive feature of the devised analytical approach is the modification of the classical formula of aerodynamic pressure by introducing a quadratic complex of relative velocities. The peculiarity of the results is the adaptation of the known laws from theoretical mechanics to the specific problem of nonlinear interaction of flow and load on a flexible suspension.

The scope of practical use of the proposed model covers automated design systems for crane equipment. The practical expectation from its implementation is the possibility of integrating equation (11) into microcontrollers of active safety systems for cranes. Knowing the mass of the load, its angle of deviation, and the current speed of the anemometer, the system could be capable of calculating the instantaneous risk and giving a signal for emergency braking of the winch or forced turn of the boom.

At the same time, this study has a number of limitations:

1. The model is a theoretical basis of the «first approximation» and at this stage has no experimental verification or confirmation by numerical methods (CFD/FEM).
2. The assumption of absolutely rigid bodies is accepted. In reality, the flexibility of the tower and the elasticity of the ropes significantly change the spectrum of the natural frequencies of the structure and damp part of the kinetic energy.
3. Our calculations were performed only for one crane size (LIEBHERR 63K), which does not make it possible to extrapolate the results to all classes of lifting machines without additional parametric analysis.
4. The aerodynamic load is modeled as an extreme short-term gust of wind in open space. The complex effects of diffraction and reflection of the flow in urban areas were not taken into account.

Further research should be aimed at verifying the proposed analytical dependences in ANSYS software packages or scaled wind tunnels.

## 7. Conclusions

1. A nonlinear mathematical model of the overturning moment due to the action of an intense flow has been built. The equation connects the input variables (flow velocity, cargo mass, deflection angle) with the output value of the total moment. The main advantage of the model is the use of a quadratic complex of relative velocities. This makes it possible to estimate the nonlinear load amplification. The coincidence of the flow front velocity vector with the direction of motion of the swinging cargo has the greatest significance and influence on the system. Such a synergistic effect forms a critical overturning moment and proves that the cargo mass acts as a kinetic accumulator capable of destroying the stability of the system.
2. A numerical analytical assessment of the stability of metal structures in a typical tower crane (LIEBHERR 63K) has been carried out. A direct dependence of safety on the angle of attack of the flow front has been proven. Unlike static methods, it has been shown that the loss of stability occurs instantly at angles other than the vane position. The maximum windward area of the boom generates an overturning moment that significantly exceeds the holding moment from the crane's natural weight (for example, 451 kNm versus 821.6 kNm for the selected model, which eliminates the necessary margin). A critical drop in the stability margin coefficient (to values below standard 1.15) has been quantitatively proven during a perpendicular extreme gust. The time of passive self-turning of the crane downwind significantly exceeds the duration of the peak gust (which is 3–5 seconds), which requires the introduction of forced active stabilization systems.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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## Data availability

The data will be provided upon reasonable request.

## Use of artificial intelligence

Disclosure of delegation of tasks to generative AI.

The authors declare the use of generative AI in the research and manuscript preparation process. According to the GAIDeT taxonomy (2025), the following tasks were delegated to generative AI tools under full human supervision:

- literature search and systematization;
- grammar editing.

Generative AI tool used: Gemini 3.

The authors bear full responsibility for the final manuscript.

The generative AI tools are not identified as authors and are not responsible for the final results.

## Authors' contributions

**Ievgenii Gorbatyuk**: Conceptualization, Methodology; **Oleg Bulavka**: Software, Formal analysis; **Oleksandr Terentiev**: Validation, Writing – original draft; **Vitalii Borodynia**: Visualization, Writing – review & editing; **Volodymyr Sliusar**: Supervision, Project administration.

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