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Estimation of simulation of high-speed pressure of blast wave of tower crane

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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.

Keywords: tower crane, air shock wave, stability.

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 [1, 2].

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.

Since the beginning of the large-scale invasion of the territory of Ukraine, many areas have been damaged during shelling. In particular, active hostilities took place on the territory of the Kyiv region within the settlements: Irpin, Bucha, Borodyanka, Makariv, Gostomel, Vorzel, etc. The result was the destruction and damage of a large number of buildings and structures and various equipment on construction sites and, accordingly, also tower cranes. The tower cranes suffered damage to their metal structures from shock-explosive damage, and stationary cranes fell on the rails, which is not typical for further operation in peacetime conditions. Therefore, first of all, damage to the metal structures of tower cranes and the direct impact of an air blast wave on the stability of these cranes should be analyzed, which will allow a more systematic approach to solving this problem [3, 4].

There are studies on the stability of tower cranes under conditions of wind loads, strong gusts of wind, which can be close to an explosive wave in a certain area of damage.

So, for example, work [5] does not take into account the dynamic effect of wind load on tower cranes, but only refers to their design standards, which do not take into account the dynamic component of the wind in the calculations. At the same time, the design and operational features of cranes are not taken into account.

In work [6], there was a study of the movement of cranes under the influence of wind loads, the parameters of cranes under the influence of wind were determined. A calculation method is proposed to find the highest speed of movement of a crane by the wind and to predict the movement of the crane according to wind maps. Such work can be close to the study of the effect of an air shock wave on the stability of tower cranes on a rail track or on quick-mounting cranes.

The above-mentioned works complement each other, but, unfortunately, do not provide a holistic approach to accounting for the impact of wind loads on the work of cranes, and especially the impact of air shock waves.

PURPOSE OF THE ARTICLE

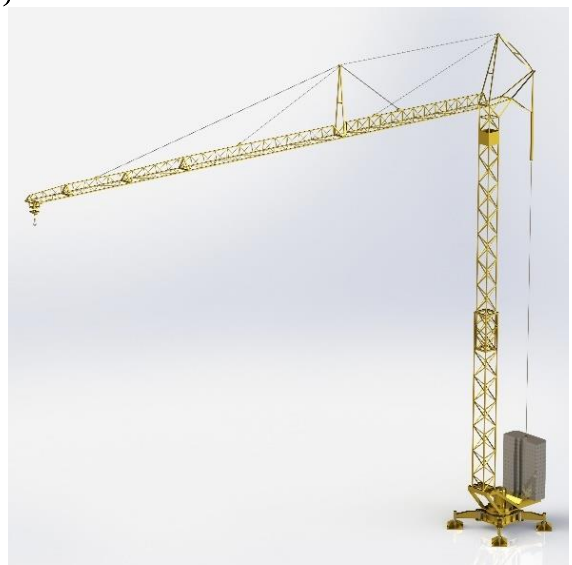
The purpose of the work is to analyze the nature of damage to metal structures of tower cranes under the influence of an air shock wave.

PRESENTING MAIN MATERIAL

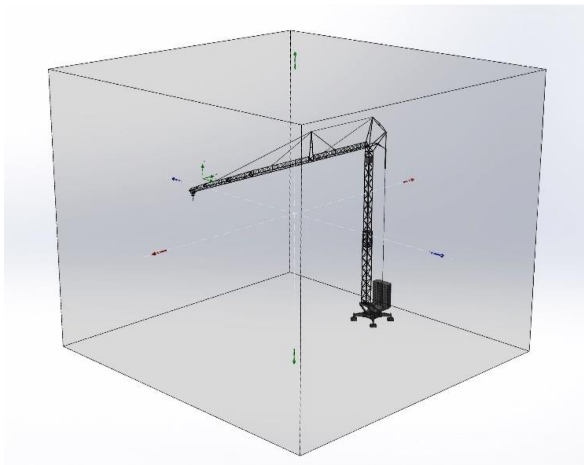
The necessary information on the distribution of wind loads on the metal structure of tower cranes can be obtained using analytical dependencies, numerical computer or physical modeling in wind tunnels [7].

The existing norms for calculating cranes for wind load, as noted above, are based on coefficients that take into account drag, change in dynamic pressure in height, dynamic pressure and windward area of the structure [7].

Preparation of a mathematical model describing the effect of wind load on the metal structure of the tower crane is carried out in several stages. At the first stage, a three-dimensional monolithic model of the crane is built without taking into account the fineness of the structural elements and the internal structure (Fig. 1, *a*). The deformed monolithic structure of the tower crane is then subtracted from the volume of the airspace model (Fig. 1, *b*).



a



b

Fig. 1. Object model: *a* – 3D crane model; *b* – airspace model

The result is a hollow mathematical model with gaps that determine the design of the crane. By setting the boundary conditions of the resulting three-dimensional model, the characteristics of the real physical object of the tower crane and the air environment are assigned.

The next, most laborious step is to create a mesh consisting of approximating a solid model of airspace with finite elements (volume). Two methods are used: the finite volume method, which is determined by the dependence of the Reynolds number on the drag coefficient when studying the dynamics of wind flow, and the finite element method when studying modeling the wind loads of cranes.

Let's take a closer look at the features of building a finite volume model. The finite volume method is based on approximating the integral form of the equilibrium equation of the problem to the finite volume of spacetime, each of which contains the boundary of a certain node of a regular or irregular grid. Sampling of integral equations is performed using piecewise polynomials or kinematic difference approximations of solutions.

Let us consider in more detail the general states of the method of finite volumes set forth in [8], using the example of the equation of balance of the quantity of φ in the control volume Ω bounded by a surface $S = \Sigma S_k$ with an external normal $\vec{n}$:

$$\int_{\Omega} \frac{\partial \rho \varphi}{\partial t} d\Omega + \sum_{\Omega} \int_{S_k} \vec{n}\vec{q} dS = \int_{\Omega} Q d\Omega, \qquad (1)$$
$$\vec{q} = \rho \vec{V} \varphi - \alpha \vec{V} \varphi,$$

where q – flux density vector φ of a quantity including convective and diffusion components; Q – distribution density of volumetric sources; $\vec{V}$ – velocity vector; ρ – medium density; α – diffusion coefficient. The quality φ can include, for example, the internal energy of the current medium, the concentration of impurities, the kinetic energy of turbulence and so on.

According to the finite volume method, spatial sampling of the problem is performed by dividing the computational area into small tangential volumes and writing the corresponding equilibrium relations (1). In each control volume, the desired mesh solution has 1 "binding" point. Most products focused on solving 3D-zadach in areas of complex geometry use cells in the computational grid as control volumes. The grid node is located at the top of the polyhedron, the grid line runs along its edges, and the value of the desired value comes from the geometric center of the cell (Fig. 2).

To obtain a discrete analogue of the balance equation in the selected cell, it is necessary to calculate the integrals included in (1) using quadrature formulas:

$$\int_{S_e} \vec{n}\vec{q} ds \approx \overrightarrow{S_{e}\vec{q_e}}, \qquad (2)$$
$$\int_{\Omega} Q d\Omega \approx Qp\Omega,$$

where $\overrightarrow{S_e} \equiv S_e \overrightarrow{n_e}$ – conditional vector of the face plane, calculated as a vector derivative of its diagonals, $\overrightarrow{q_e}$ – vector of flux density φ at the center of the face.

For tangent cells, the surface integral over their common face S_k was calculated identically. This requirement ensures the conservatism of the numerical scheme, that is, the exact observance of the balance φ according to equation (1) for the entire region of the current [9]. The method of approximation of integrals affects such important properties of a numerical scheme as accuracy, stability, monotony, etc. In this work, the finite volume method is used to approximate the cylinder model when constructing a relationship between the Reynolds number and the drag coefficient (Fig. 3).

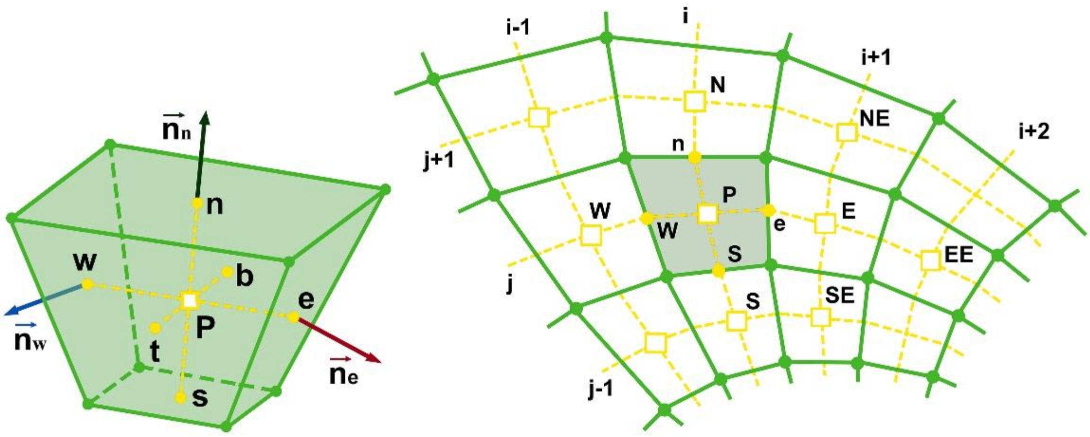
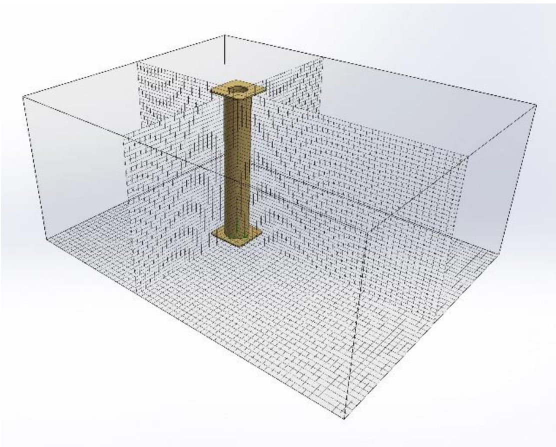
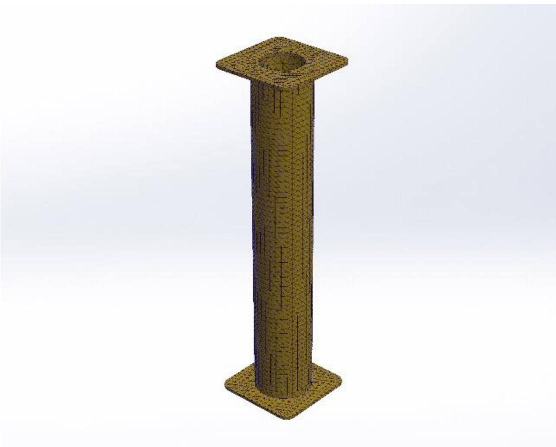


Fig. 2. A structured grid of control volumes with the "binding" of variables to the center of the cell: ● – the node of the grid; □ – the center of the cell; ● –the center of the face



a



b

Fig. 3. 3D model preparation sequence: *a* – block structure; *b* – mesh

Next, consider the main provisions of the finite element method. The main idea of the finite element method is any continuous value (displacement, temperature, pressure, etc.). It can be approached using a model consisting of individual elements. In the finite element method, the entire field matrix consists of a matrix of individual elements represented as a function of unknown nodes. For each of these elements, the continuous quantity under study is approximated as a piece-continuous function based on the value of the continuous quantity under study at the endpoints of this element. The variational formulation of the initial boundary value problem is used to define the decomposition [10, 11].

Further consideration of the main limiting conditions leads to a constant change in the overall matrix. Similarly, the value set in the element node creates a vector of generalized node loads. To additionally take into account the resulting system of equations, determine the value of the desired function in the node.

The main stages of implementation of this method are:

1. Discretization of the problem, that is, the representation of the region (volume) V as a set of finite elements connected by nodes.
2. Get the matrix of elements.
3. Constructing a common matrix of all field and charge vectors.

The first stage of the finite element method is to divide the space occupied by the body into several elements. Discretization of regions (units) includes the number, size, and shape of subdomains used to construct models of discrete entities. The smaller the linear size of the finite element h, the greater the number of elements in the model, exponentially increasing the calculation time and reducing the analysis error (Fig. 4) [12].

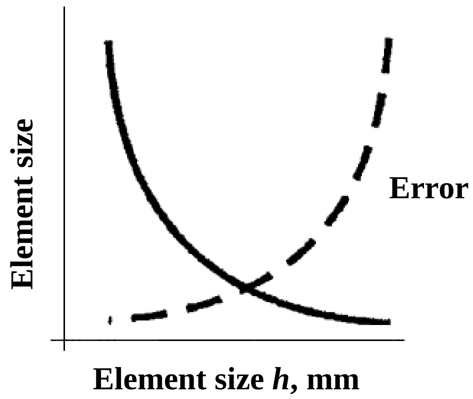


Fig. 4. Element size and solution duration dependency

Two basic methods are used to construct a finite element lattice: constructing an arbitrary lattice and constructing an ordered lattice. Neighboring elements can vary greatly in size, but any mesh will be created automatically. An ordered mesh is created by dividing the geometric elements of the model into several parts. In an automatically generated grid with a large number of elements, the number of nodes takes precedence over the number of elements (Fig. 5).

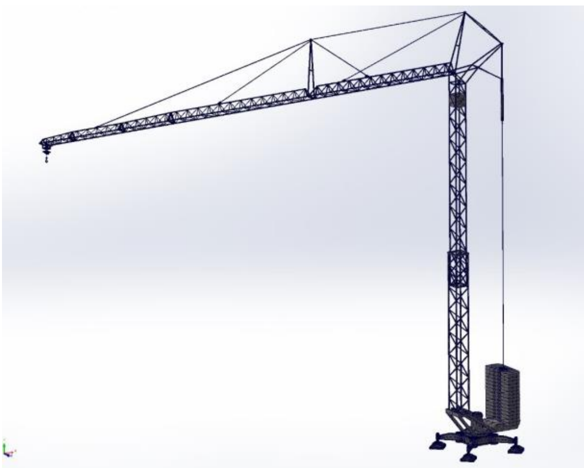


Fig. 5. Unstructured finite element airspace grid

From Fig. 5. it can be seen that the size of the finite elements changes as it approaches the cavity describing the stationary tower crane. The value of the maximum and minimum finite element is set to manual.

The ratio between nodes and elements is approximately 2:1 for flat arbitrary grids and 6:1 for arbitrary three-dimensional grids with tetrahedral elements [8]. The finite elements may be linear (first order elements) or parabolic (second order elements). Linear elements have straight sides and nodes only in the corners. Thus, the minimum number of nodes of a three-dimensional element is 4. Parabolic elements can have intermediate nodes along each side. With an equal number of elements, parabolic elements give greater accuracy of calculations, since they more accurately reproduce the curved geometry of the model and have more accurate shape functions (approximating functions). However, calculation using higher order finite elements requires more computer resources and more machine time.

Generation of grids, both of course volumetric and of course elemental, in the SOLIDWORKS software complex is carried out at the software level by the universal net generator SOLIDWORKS Flow Simulation.

After building the grid, it is necessary to set boundary conditions describing the behavior of the environment, external disturbing actions, physical properties of the object under study, and so on. Note that the boundary conditions for these methods are set identically in the SOLIDWORKS Flow Simulation preprocessor. The placed airspace model in the preprocessor acts as a domain to which general physical properties and environmental behavior (density, temperature, turbulence model, initial speed, pressure, etc.) are assigned. Boundary conditions describing external actions and properties of the investigated object are applied to the domain. The boundary conditions are: an inlet (surface or face) with a certain parameter of the inlet flow velocity, an outlet (surface or face) with a certain specified parameter of the outlet pressure, a Flo function that assigns physical properties to an object of a surface that simulates it.

Consider the most important parameter of the domain – the turbulence model. As noted above, wind loading should be considered as a turbulent current due to the small kinematic viscosity of the air. Turbulent currents are characterized by fluctuations in the velocity field. When solving the Navier-Stokes equation describing such currents, an approach

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based on the use of time-averaged quantities is used. As a result, solving modified equations requires less machine resources, but additional unknowns appear.

Various turbulence models are used to close the resulting equations. The choice of the optimal turbulence model depends on the type of flow of a specific class of problems, the required accuracy of the solution, the available computing resources, and the like. The most commonly used models of turbulence in COSMOS Works are: standard $k-\varepsilon$ model; low-Korenolds $k-\varepsilon$ model; a quadratic $k-\varepsilon$ model and a group of $k-w$ models (SST model – Shear – Stress Transport) and the Spalart-Almaras model (SA model) [6].

The $k-w$ model group is represented by the SST model (Shear - Stress Transport). The standard $k-w$ model takes into account the low-field effects of compressibility and the propagation of shear perturbations, but it is significantly inferior in breadth of application to models of the $k-\varepsilon$ group. The SST stress shift transfer model uses a $k-w$ model in the wall region and a transformed $k-\varepsilon$ model away from the wall.

It should be noted that the usual element grid of the tetrahedron allows you to create cells that are similar in shape to the boundaries of the calculated region and zones of large gradients, which allows you to expand the boundary layers well. At the same time, creating a tetrahedron mesh is very laborious. Of course, the volume grid allows you to create rectangular cells, which can lead to a worse resolution of the boundary layer.

There are a number of ways to expand the areas of boundary layers and high gradients. Examples of such methods are adaptive locally shredded mesh technology and subnet geometry expansion technology implemented in the SOLIDWORKS Flow Simulation mesh generator. Technology adaptive locally crushed mesh allows you to split the selected cells in all directions in a given number of times (adapt to a given level). In this case, the cells located next to the crushed one are ground so that the size of the two adjacent cells does not differ by more than 2 times.

Grinding cells can be set both in volume and on the surface. Subnet geometry expansion technology allows you to automatically accurately reproduce the shape of the surface. In this work, studies of the effect of wind load on the metal structure of the crane were carried out using the SST turbulence model. The choice of this model is based on the studies conducted by the authors [8], from which it turns out that when modeling the flow around poorly flowing bodies with an unfixed breakaway point, it is necessary to use the SST turbulence model, since with sufficiently large parameters $y+$, calculation errors can reach narrow limits and, as a result, due to the complexity of the tower crane design, calculation errors are minimal.

Below, we give the results of numerical modeling of the cylinder flow obtained using the SOLIDWORKS Flow Simulation postprocessor (Fig. 6), (Fig. 7).

Figure 6 shows the current lines, which show that at a small value of Reynolds number ($R_e \approx 10$) the wind flow is laminar. A slight increase in the Reynolds number leads to turbulence of air jets and the formation of turbulent swirls.

The obtained results of modeling the flow around a cylindrical body, presented on Fig. 8, indicate that mathematical numerical modeling using the finite element method and the finite volume method gives accurate results, subject to the rules for constructing volumetric meshes, setting boundary conditions and choosing a turbulence model.

CONCLUSION

In matters related to the study of the aerodynamics of tower cranes, it is advisable to use finite-element mathematical models, since all design features are taken into account.

As a model of turbulence, it is preferable to use the SST (Shear – Stress Transport) model, designed for the study of complex shapes and structures.

When flowing around the tower and the head of the boom in the wind position, the wind flows turbulently swirl, loading the metal structure of the boom along the entire length.

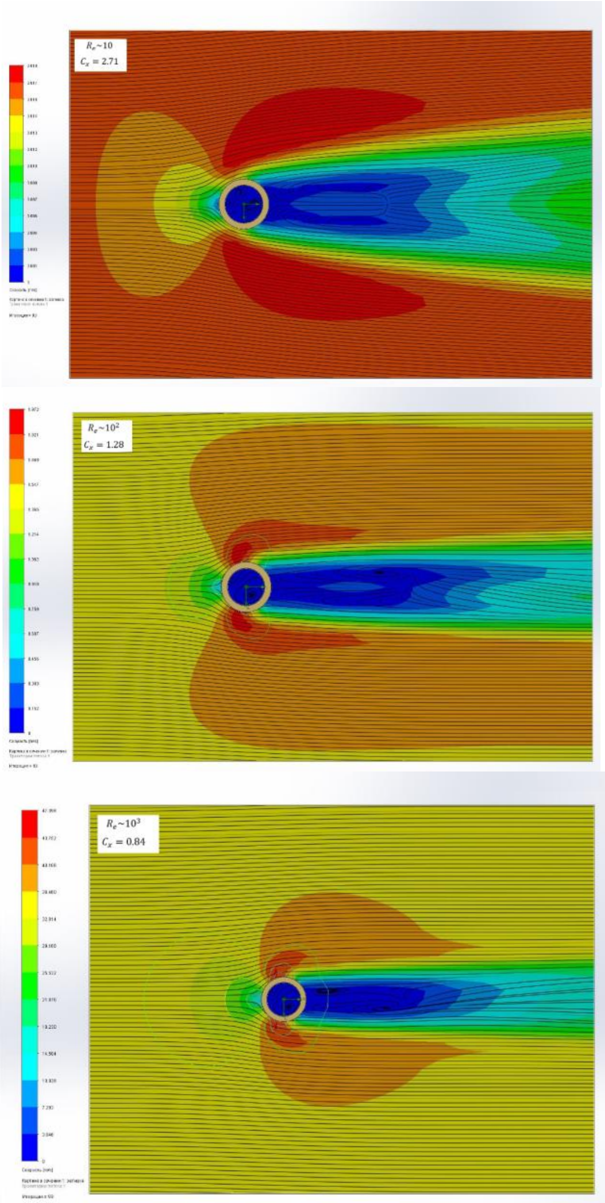

Fig. 6. Formation of turbulent vortices when a cylindrical body flows around

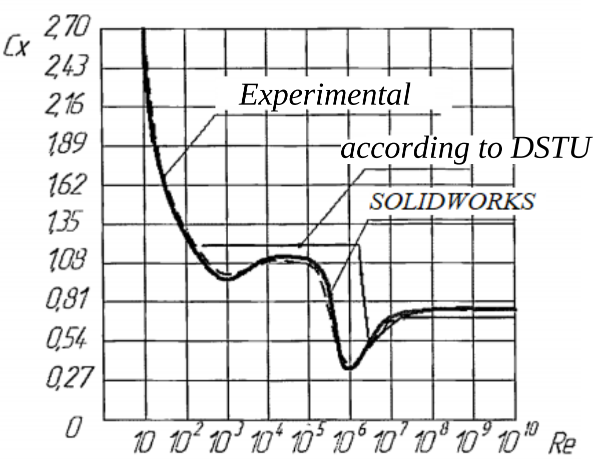

Fig. 7. Dependence of drag coefficient on Reynolds number $C_X(R_e)$

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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.

На будівництвах різних країн сьогодні використовують понад 200 тис. баштових кранів.

Під час використання баштових кранів особливу увагу необхідно приділяти їх експлуатації в несприятливих умовах, тому такі системи 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.

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