

A study of run onto the wheel contact crane stops of tower cranes

Vadim Rabey

Abstract—The processes of load-lifting crane's interactions with impact and non-impact end stops are still at the research level due to the simplified approaches that are used. The use of the wheel contact crane stops to smoothly slow tower cranes has demonstrated an alarming tendency to run over the wheel contact crane stops, and additionally, potential decreases in the stability of the cranes may result. The existing standards for load-lifting cranes and the scientific studies devoted to this problem have prevented the evaluation of the spatial behavior of tower cranes when cranes run onto the wheel contact crane stops due to flat computational models with few degrees-of-freedom. The present work was devoted to a study of the interaction of tower cranes with the wheel contact crane stops based on a numerical method analysis, i.e., a finite element method. With the help of a finite element model reflecting the actual metal construction of the tower crane, a series of computational experiments were performed to determine the theoretical spatial behavior of a tower crane when the crane runs onto the wheel contact crane stops. This behavior is important to determine the actual stability of tower cranes.

Keywords—Tower crane, wheel contact crane stops, run-on, finite element method.

I. INTRODUCTION

ACCORDING to one study [1], the maximum number of load-lifting crane accidents occur in tower cranes. In general, the primary cause of tower crane accidents is the malfunction of breaks, crane safety systems and runway rails.

As opposed to the bumper contact crane stops [2], the wheel contact crane stops (WCCS) are designed to smoothly dampen the remaining velocity of tower cranes at the end of runway rails and prevent their derailment during accident situations, such as the failure of limit switches, brakes of travelling mechanisms and response to strong winds. In practice, the WCCS are often not effective as an emergency device. The WCCS can be carried away or run over by the tower cranes, leading to their overturning due to the noncompliance by personnel to regulations for the design and safe operation of load-lifting cranes or crane operation during strong winds. Experts have published case studies of damaged WCCS and their further operation after such damages occurred, despite

the fact that the consequences of tower cranes running onto such crane stops may be unpredictable (Fig. 1).

The problem of tower cranes running onto the WCCS is known. The theoretical and practical basics of this problem have been detailed by P.Z. Petukhov [3], A.V. Martynov [4], V.G. Zhukov [5] and others (Fig. 2). However, the main problem of the use of the WCCS has not been solved: namely, the stability assessment of the position of a tower crane in space. This failure was due to an oversimplification of the calculation-dynamic models of the studied cranes; models of 2-3 degrees-of-freedom were used [6]. The actuality of the present problem has also been confirmed by few degrees-of-freedom calculation models of tower cranes in well-known standards on calculations of tower cranes [7], which cannot evaluate the actual spatial behavior of the metal construction of tower cranes when they run onto the WCCS. Furthermore, many standards do not account for loads (in the sections concerning loads and load combinations), which act on a tower crane as the result of a crane running onto the WCCS.

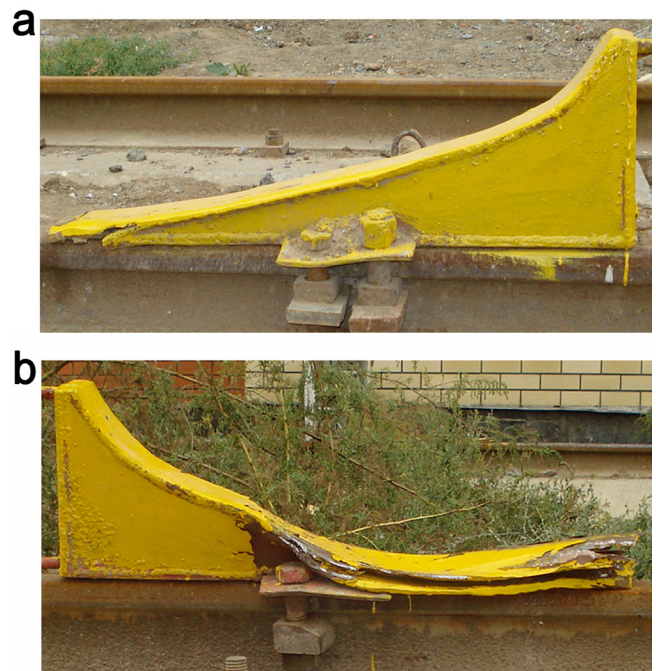


Fig. 1 tower crane KB-408's WCCS in service:
a-serviceable; b- fractured

Vadim Rabey, Department of Lifting-and-Transport Machines, Industrial Logistics and Mechanics of Machines, Astrakhan State Technical University, Astrakhan, Russia (phone: +79050604270, +79881799256; e-mail: vadimbey@hotmail.com).

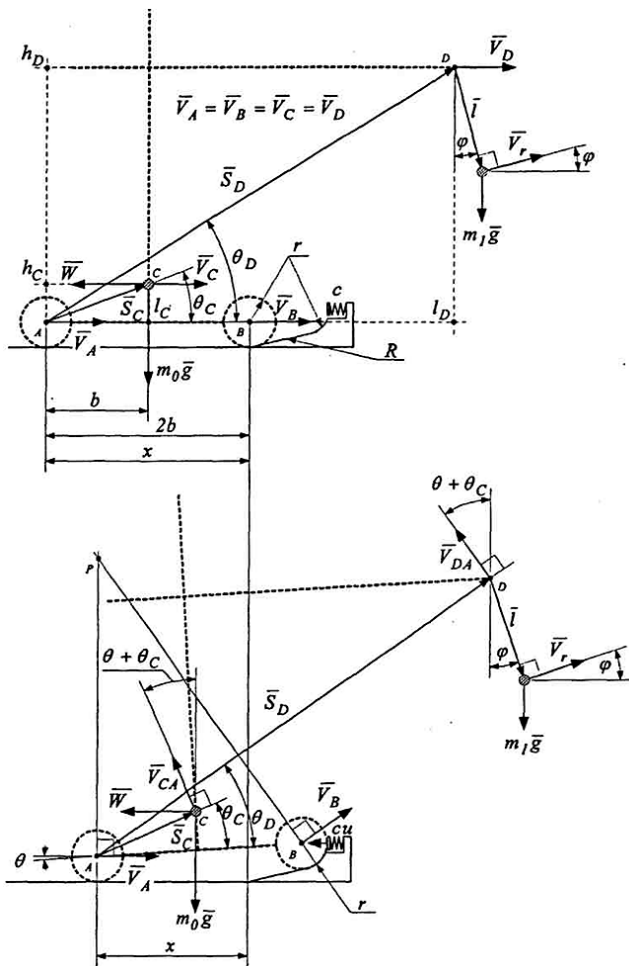


Fig. 2 a calculation model of tower crane's run onto the WCCS (by V.G. Zhukov [5])

II. FINITE ELEMENT MODELING OF TOWER CRANES' RUN ONTO THE WCCS

Based on the aforementioned information, present work have attempted to study this problem at a higher mathematical level by developing a spatial finite-element dynamic calculation model that reflects the actual interaction processes of tower cranes KB-408.21 (Nyazepetrovsky Zavod CJSC, 2008 year made) with the WCCS [8].

A movable track-mounted tower crane KB-408.21 reg.№ 39340 (Fig. 3) was designed for the mechanization of construction-and-installation processes to construct buildings that were 72.7 m tall from mounted elements that were 10 t maximum in mass at an ambient air temperature of $\pm 40^\circ\text{C}$. The classification group is A4 according to ISO 4301/1-86.

Beam, shell and solid finite elements (FE) were considered as the base FE of the model. The finite element model (FEM) of tower crane KB-408.21 of a loading capacity of 10 t (Fig. 4) consisted of 1151 beam FE, 1236 shell FE and 3850 solid FE. The number of degrees-of-freedom of the system, n , was 26370.



Fig. 3 tower crane KB-408.21 reg.№ 39340 of a loading capacity of 10 t

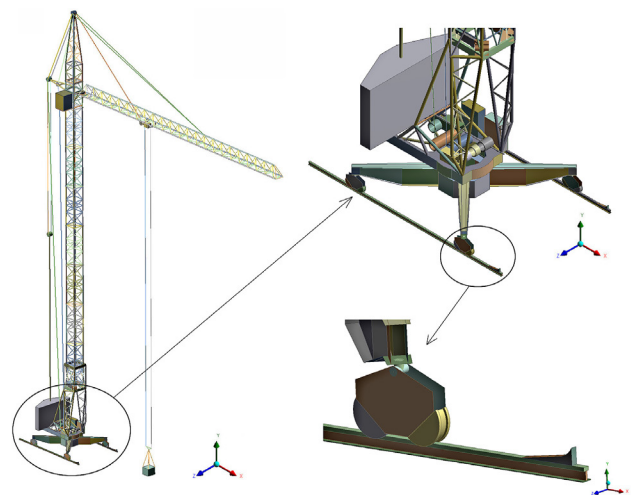


Fig. 4 structural model of a tower crane KB-408.21 reg.№ 39340 of a loading capacity of 10 t

The process of a tower crane running onto the WCCS was described by a matrix equation of motion of n -th order:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{R(x, \dot{x})\} = \{F(t)\}, \quad (1)$$

where $[M], [C]$ and $[K]$ are the mass, damping and stiffness matrices; $\{F(t)\}$ is the vector of external loads; $\{\ddot{x}\}, \{\dot{x}\}, \{x\}$ are the unknown vectors of acceleration, velocities and displacements of discrete nodes of the FEM of a crane; $\{R(x, \dot{x})\}$ are non-linear restoring forces and friction forces.

Because the values of the matrices $[M]$ and $[K]$ are known, the damping matrix $[C]$ can be expressed as follows:

$$[C] = \alpha_M [M] + \beta_K [K], \quad (2)$$

where α_M and β_K are Rayleigh damping coefficients ($\beta_K=0,001$), which are connected to the damping ratio ($\xi=0,02-0,04$) by the following equation:

$$\alpha_M / 2\omega + \beta_K \omega / 2 = \xi, \quad (3)$$

where ω is the carrier natural oscillation frequency of the FEM, and ξ from (3) is connected to the logarithmic decrease δ_d by the following relationship:

$$\xi = \frac{\delta_d}{\sqrt{(2\pi)^2 + \delta_d^2}} \approx \delta_d / 2\pi \quad (4)$$

where $\delta_d = \ln(A_1 / A_2)$, A_1 and A_2 are taken the 1st and 2nd amplitudes of the principal modes of a crane's metal construction. At any point in time $t = t_{i+1} = (i+1)h$, where h is the time step of integration of (1), the accelerations of masses of the FEM can be determined via the values of displacements, velocities and applied forces. Thus, the accelerations from (1) takes the following form:

$$\ddot{x}(t_{i+1}) = -[M]^{-1} \left[[C]\dot{x}(t_{i+1}) + [K]x(t_{i+1}) + \{R(x(t_{i+1}), \dot{x}(t_{i+1}))\} - \{F^{ext}(t_{i+1})\} \right] \quad (5)$$

Equation (1) is solved by the unconditionally stable, one step, Newmark- β time integration scheme:

$$\ddot{x}_{i+1} = \frac{\Delta x}{\beta h^2} - \frac{\dot{x}_i}{\beta h} - \frac{1}{\beta} \left(\frac{1}{2} - \beta \right) \ddot{x}_i, \quad (6)$$

$$\dot{x}_{i+1} = \dot{x}_i + h(1-\gamma)\ddot{x}_i + \gamma h \ddot{x}_{i+1}, \quad (7)$$

$$x_{i+1} = x_i + \Delta x, \quad (8)$$

where β и γ are the free parameters of Newmark's time integration. For $\gamma = 1/2$ and $\beta = 1/4$, the Newmark method becomes the constant average acceleration method. For $\gamma = 1/2$ and $\beta > 1/4(1/2 + \gamma)^2$, numerical damping is in the solution, which leads to a loss of energy and momentum.

III. REAL EXPERIMENTS OF TOWER CRANE RUN ONTO THE WCCS

A series of real experiments were performed to determine the tower crane's real movements when it runs onto the WCCS to check the adequacy of the FEM for the behavior of a crane. One of the most important things to determine was the distance travelled by the wheels of the bogies of a crane's chassis over the WCCS as a function of the crane's velocity for different parameters. Due to lack of information on the codes and standards concerning permissible parameters (including speed limits) of tower cranes running onto the WCCS, a series of real experiments were performed using unloaded crane at minimal velocities. Tower crane KB-408.21 was used to run onto the WCCS without a payload (m_p) at a velocity (V_c) of 0.12 m/s (Fig. 5). At these parameters, the real experiment showed that

the front wheels of the bogies of the crane's chassis travelled an average distance of 0.170 m over the WCCS. A computational experiment using the same parameters determined this value to be 0.154 m. This difference (approximately 9.5%) was most likely due to an absence of rotating masses in the finite element model of the bogies wheels of the crane's chassis, which were substituted by the theoretical friction of crane wheels and slip coefficients in the FEM. Therefore, this magnitude of error of divergence of the practical value from the theoretical value was considered in the FEM calibration to the experimental tests.

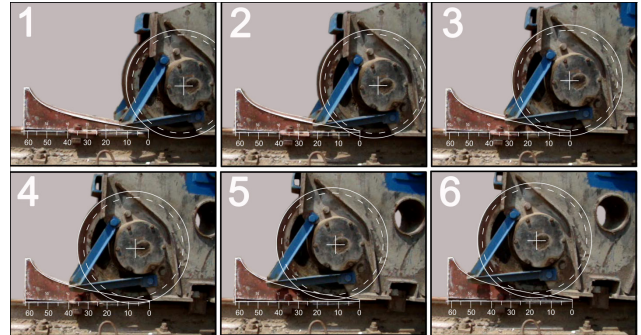


Fig. 5 a study of a tower crane KB-408.21 reg.№ 39340's run onto the WCCS ($V_c=0.12$ m/s, $m_p=0$ t) under conditions of "Stroitel Astrakhani" JSC

IV. RESULTS AND DISCUSSION OF COMPUTATIONAL EXPERIMENTS

To obtain a broad picture of a tower crane's interaction with the WCCS, a series of computational experiments were performed that considered the following operational states of the crane:

- 1) Position of the payload with jib's outreach (L_j) of 16 m or 40 m;
- 2) Mass of the payload is 10 t;
- 3) The payload is 2 m above a ground level (H_s);
- 4) An initial run-on velocity of 0.3 m/s or 0.9 m/s;
- 5) Position of crane's jib is parallel or orthogonal to runway rails.

A complete picture of the tower crane's spatial behavior during the interaction with the WCCS was obtained from the computational experiments. Specifically, these experiments yielded the following findings: 1) the velocity characteristics of the tower crane's run onto the WCCS; 2) the crane's stability characteristics; 3) a deformational state of the crane's metal construction; 4) the behavior of the payload on a flexible suspension.

Fig. 6 shows animated process of the bogies of the crane's chassis run onto the WCCS at a maximum crane velocity of 0.3 m/s (according to the crane's passport) and at a three-fold higher velocity of 0.9 m/s, which can occur when cranes are influenced by strong winds, for example. When a tower crane runs onto the WCCS at a velocity of 0.3 m/s, the velocity is completely arrested when the wheels of the bogies of the crane's front chassis were at approximately 0.339 m of the

WCCS. The computational experiment shows that the crane will likely run over the WCCS at a velocity of 0.9 m/s (see Fig.6b, the 5th frame).

The results of the computational experiments indicated the wheels of the bogies of the crane's back chassis lift off after tower crane runs onto the WCCS. Fig. 7a shows the heights of wheel liftoff when the crane runs onto the WCCS at a maximum crane velocity of 0.3 m/s (according to the crane's passport) at different payload and jib outreach values. Fig. 7a indicates that the most unfavorable values of rear wheel liftoff occur when the tower crane runs onto the WCCS when the run-on parameters were set to (4) and (5). At these parameters, the crane's wheels are likely to derail. According to the behavior of the FEM at other parameters (see Fig. 7a, relations (1)-(3)), the crane's wheels contacted the rails again after liftoff.

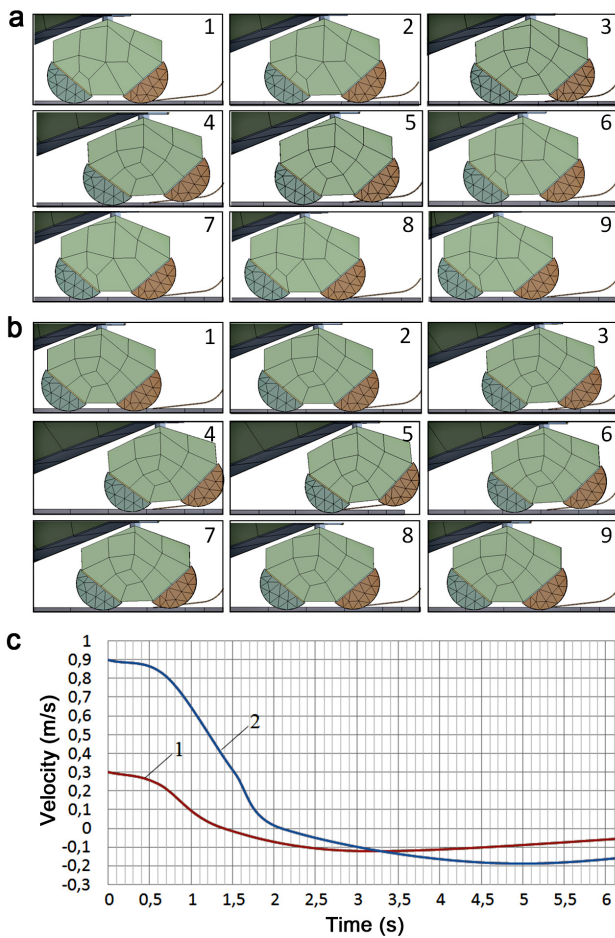


Fig. 6 a theoretical process of a tower crane KB-408.21's run onto the WCCS when a jib is situated along travelling of a crane ($m_p=10$ t, $H_s=2$ m, $L_j=16$ m) with a velocity of: a- $V_c=0.3$ m/s; b- $V_c=0.9$ m/s; c- a variation of a crane's velocity in the process: 1- $V_c=0.3$ m/s; 2- $V_c=0.9$ m/s

The charts in Fig. 7a indicate that the mass of a payload and its position along the length of a crane's jib play a crucial role in the liftoff of a crane's rear wheels when the crane interacts with the WCCS (see run-on parameters (3) and (4) and

parameters (1) and (2)). As such, the rear wheels do not only lift off during WCCS run-on using parameter (1), as indicated by the computational experiment. Computational experiments were also performed for a tower crane's interaction with the WCCS when the crane's jib was orthogonal to the crane's traveling direction. Thus, when $V_c=0.3$ m/s, $M_p=10$ t and $L_j=16$ m the crane ran onto the WCCS and the rear wheels lifted to a height of 15 mm. In comparison, this liftoff height was 20 mm when all other parameters remained the same but the jib was parallel to the traveling direction (see Fig. 7a relation (2)). This finding indicates that run-on is most unfavorable when the jib is parallel to the crane's traveling direction [9].

The spatial deformation state of a crane's metal construction during a crane's interaction with the WCCS was determined (Fig. 8) in addition to the rear wheel liftoff and its influence on a crane's stability. The maximum deformations of a crane's tower and jib did not occur at the same time because of oscillation processes that occur in the tower crane's metal construction when the crane interacts with the WCCS. Therefore, the maximum deformation states of a crane's metal construction in Fig. 8 a, b are shown as a function of the maximum deformations of a crane's tower. The oscillation processes of crane's tower are presented in Fig. 9.

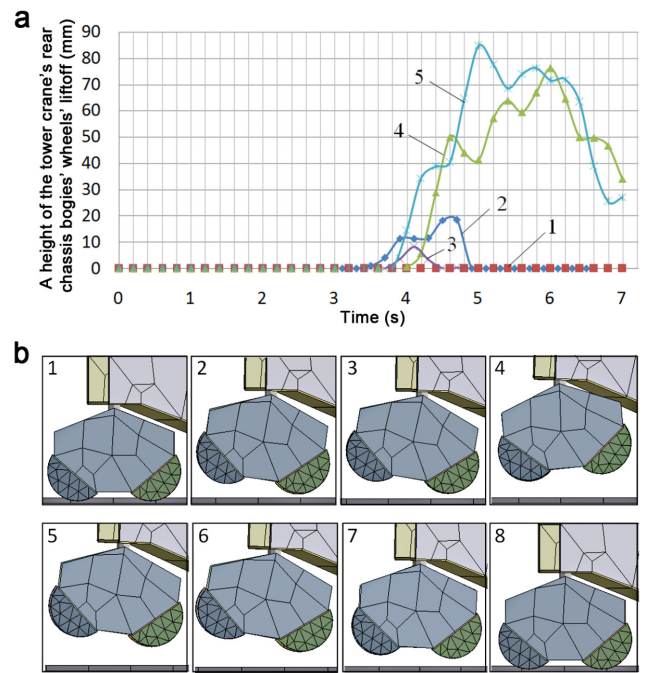


Fig. 7 a theoretical height of tower crane KB-408.21's rear chassis bogies' wheels' liftoff as the result of crane's run onto the WCCS when a position of crane's jib is along travelling direction of a crane: a-charts of the height of the wheels' liftoff with respect to time depending on different load and velocity parameters of crane run-on: 1- $V_c=0.3$ m/s, $M_p=1$ t, $L_j=16$ m; 2- $V_c=0.3$ m/s, $M_p=10$ t, $L_j=16$ m; 3- $V_c=0.3$ m/s, $M_p=1$ t, $L_j=40$ m; 4- $V_c=0.3$ m/s, $M_p=3$ t, $L_j=40$ m; 5- $V_c=0.9$ m/s, $M_p=10$ t, $L_j=16$ m; b- an animation process of rear wheels' liftoff under working condition (5)

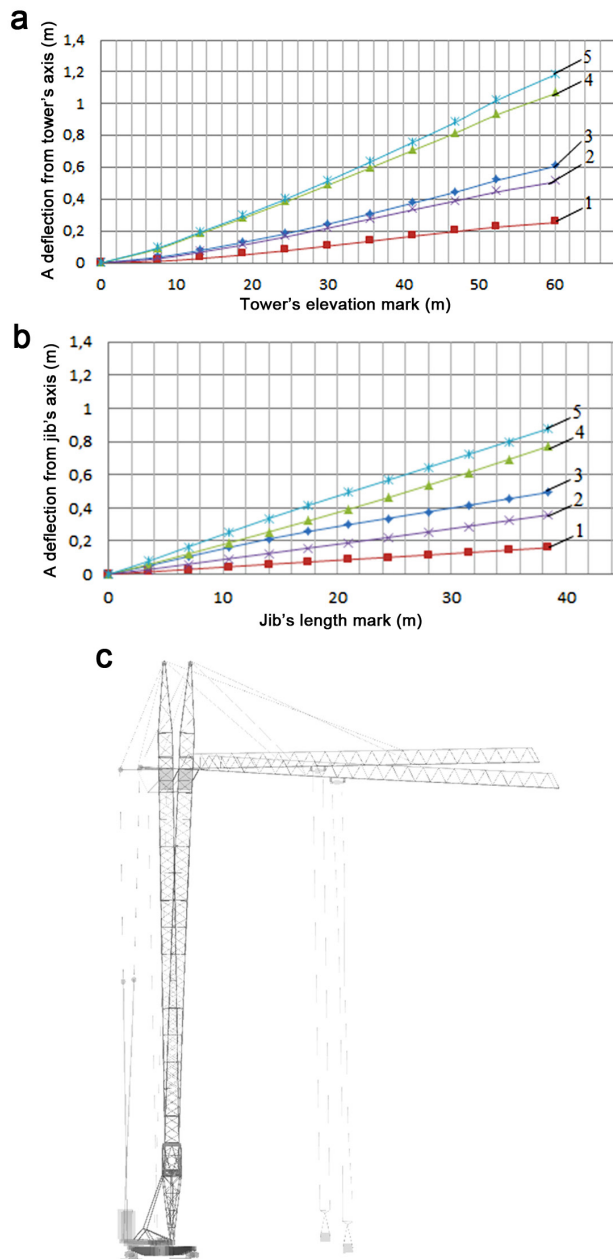


Fig. 8 a maximum deformation state of a tower crane KB-408.21's metal construction as the result of crane's run onto the WCCS: a – deformation state of crane's tower; b-deformation state of crane's jib: 1- $V_c=0.3$ m/s, $M_p=1t$, $L_j=16$ m; 2- $V_c=0.3$ m/s, $M_p=1t$, $L_j=40$ m; 3- $V_c=0.3$ m/s, $M_p=10t$, $L_j=16$ m; 4- $V_c=0.3$ m/s, $M_p=3t$, $L_j=40$ m; 5- $V_c=0.9$ m/s, $M_p=10t$, $L_j=16$ m; c-full deformation state of a crane's metal construction

Thus, the FEM of a tower crane enabled the determination of the theoretical spatial behavior and inertia processes of tower crane KB-408.21's metal construction as a result of the crane's run onto the WCCS, which is important to understand the actual stability of tower cranes during their interaction with the WCCS. The FEM also showed that oscillation processes that occur in a tower crane's metal construction when the crane runs onto the WCCS are unstable and cannot be reflected by plane models with 2-3 degrees-of-freedom [3-5].

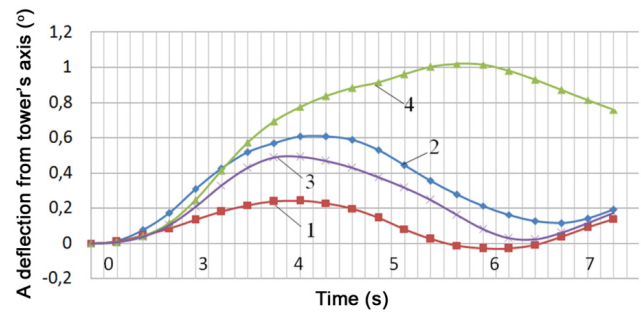


Fig. 9 values of tower's deflection of a tower crane KB-408.21 as the result of a crane's run onto the WCCS (see Fig. 8c): 1- $V_c=0.3$ m/s, $M_p=1t$, $L_j=16$ m; 2- $V_c=0.3$ m/s, $M_p=10t$, $L_j=16$ m; 3- $V_c=0.3$ m/s, $M_p=1t$, $L_j=40$ m; 4- $V_c=0.3$ m/s, $M_p=3t$, $L_j=40$ m

V. CONCLUSION

In conclusion this study showed that the WCCS type shown in Fig. 1 is not sufficient to smoothly dampen a tower crane's remaining velocity. An examination of a tower crane's run onto the WCCS based on a FEM that reflects the actual metal construction of the crane showed the presence of considerable inertial forces. Due to these forces, the top part of the crane's tower with a jib continues to travel forward when the crane brakes, which leads to tilting of the crane and results in rear wheel liftoff (see Fig. 7). According to the theoretical calculation, a run onto the WCCS may be dangerous if the crane's load exceeds 1 t at maximum crane velocity and any jib orientation. These conditions could result in rear wheel liftoff or derailment. Nevertheless, the FEM did not indicate a loss in stability or turnover of the crane as a result of the crane's run onto the WCCS, even at the most unfavorable conditions of run on within the limits of maximum parameters according to crane's specifications ($V_c=0.3$ m/s, $M_p=3t$, $L_j=40$ m). The influence of wind load on the crane's run on is still important because the WCCS may not be an effective protection facility in this case because it may be overrun by the crane due to its high acceleration. The computational experiment showed that when the tower crane traveled at 0.9 m/s, it likely overruns the WCCS, which may result in a loss of crane stability and crane failure.

In addition to the main behavior of a tower crane's metal construction, the stress-strain state of load elements of the WCCS was determined. According to the obtained results, the stresses that occur in the weld seams of the box section of the WCCS during run-on exceed double the yield limit of the WCCS material. Therefore, the metal construction of the WCCS needs to be reinforced and its technical conditions need to be closely controlled.

ACKNOWLEDGMENT

The author would like to thank Prof. Dr. Nikolai Panasenkov and Candidate of Science Aleksei Sinelshchikov at Astrakhan State Technical University, Russia. The author also wishes to thank Astrakhan State University for support.

REFERENCES

- [1] V. Kotelnikov, V. Martynjuk, *Analysis of Breakages and Accidents in Lifting Constructions*. Moscow: Analiz Opasnostei LLC, 2008 (in Russian).
- [2] V. Rabey, "The study of a stress-strain state of bridge cranes' metal constructions in the process of a collision with the end stops," *FME Transactions*, vol. 41, no 3, pp. 195-201, May 2013.
- [3] P. Petukhov, "A Protection of Cranes from Impacts Due to Run onto the End Stops," Ph.D. dissertation, Dept. Load-Lifting Machines, UPI, Sverdlovsk, 1950 (in Russian).
- [4] A. Martynov, "A Study of Gravitational Slow-Down of Bridge Cranes and Crane Trolleys," Candidate of Science dissertation, Dept. Load-Lifting Machines, NPI, Novocherkassk, 1976 (in Russian).
- [5] V. Zhukov, "Safety Improving of Track-Mounted Tower Cranes' Operation," Candidate of Science dissertation, Dept. Load-Lifting Machines, NPI, Novocherkassk, 2004 (in Russian).
- [6] N. Panasenko, V. Rabey, "The condition of the studies concerning dynamics of collision between load-lifting cranes and the end stops," *Innovative Technologies in Machine Construction: Problems, Tasks, Solutions*, vol. 1, no 1, pp. 186-192, Jan. 2012 (in Russian).
- [7] *Construction Tower Cranes, Codes of Design*, RD 22-166-86 Standard, 1986 (in Russian).
- [8] V. Rabey, "A study of the processes of run onto the end stops of tower cranes," *Proc. 5th Scientific-Tech. Conf. Youth-Led Innovations – Potential for Development of Oil and Gas Sector*, Astrakhan: Gazprom Dobycha Astrakhan LLC, 2013, pp. 251-252 (in Russian).
- [9] V. Rabey, "Analysis of the problem of interaction with the wheel contact crane stops of tower cranes," in *Proc. 5th Int. Scientific Symposium Shock-and-Vibration systems, Machines and Technologies*, Orel: State University – Education-Science-Production Complex, 2013, pp. 279-283 (in Russian).

Vadim Rabey was born in Astrakhan, Russia, in October 1987. In 2009, he graduated from Astrakhan State University with honors from the Department of Physics and Electronics, and received the qualification of "Engineer of Equipment and Technology of Welding Production." Parallel in 2009, he received the second diploma of "Translator in the Sphere of Professional Communications" from the Department of English Language and Technical Translation. In 2008-2009, he worked on a shipbuilding factory, Kasnye Barrikady Ltd., as a welding engineer of the 2nd category. In 2009, he entered a PhD programme at Astrakhan State Technical University, in the department of Lifting-and-Transport Machines, Industrial Logistics and Mechanics of Machines. Since 2009, he has worked in the expert organization Podjemnie Sooruzhenia, LLC. as an expert of industrial safety in the sphere of lifting machines, especially load-lifting cranes.

Currently, he is an Assistant Lecturer at Department of Material Science and Welding Technology, Astrakhan State University and at Department of Lifting-and-Transport Machines, Industrial Logistics and Mechanics of Machines, Astrakhan State Technical University. His research interests are in steel construction technology and dynamics and seismic stability of buildings and lifting structures.