UNIVERSITY OF NIŠ
The scientific journal **FACTA UNIVERSITATIS**
Series: **Mechanical Engineering** Vol.1, N° 6, 1999 pp. 695 - 702
Editor of series: Nenad Radojković, e-mail: radojkovic@ni.ac.yu
Address: Univerzitetski trg 2, 18000 Niš, YU
Tel: +381 18 547-095, Fax: +381 18 547-950
http://ni.ac.yu/Facta

ELEMENTS THAT INFLUENCE THE CHANGE OF LOADS IN DRIVING MECHANISMS OF THE CRANES

UDC 621.869.87

Mijajlović Radić, Marinković Zoran, Jovanović Miomir

Mechanical Faculty, University of Niš, Str. Beogradska 14, 18000 Nis, Yugoslavia

Abstract. *This paper presents the procedure of the analysis of the influential factors in the change of the loads - torsion moments of the shafts of the crane mechanisms during the transient modes of the function (periods of the acceleration and braking) using the relevant equivalent dynamic and mathematical models.*

Key words: *crane, mechanism, load, elasto-kinetic model, torsional moment*.

1. INTRODUCTION

Cranes are complex transport machines with stop movements. Their characteristic is a cyclic change of a number of different operations and movements of their driving gears during space transfer of loads during the single functional cycle. Their work has the large number of startings of the driving gear, braking and pauses. Every movement, in principle, is a combination of the phases of acceleration, stationary movement and braking. Because of the fast exchange of these phases, elements of mechanisms are exposed to the change of the loads which in some cases may create the fatigue, crack of elements and malfunction of the mechanism, that is, the malfunction of the crane itself. Also, the characteristics and performances of the chosen components (electromotors, brakes, reductors etc.), as well as the conditions of the function and the intention of the crane, influence the character of the change of the loads that occur during the process of function.

2. THE EQUIVALENT AND MATHEMATICAL MODELS OF THE DRIVING MECHANISMS

During the investigation of the dynamic conduct of the driving mechanisms of the cranes (for lifting, moving etc.) the different types of the equivalent models can be used.

Received October 11, 1999

Here, for the analysis of the influential factors in the load change, that is, the analysis of the torsional moments of the referring shafts of the crane mechanisms, the torsional elasto-kinetic model with the two degrees of freedom.

The Fig. 1. presents this model which is, in general, made of two reduced masses of the known moments of inertia (J_1 and J_2) and of the elastic connections between them. Those connections have the defined rigidity (c_1), dumping (b_1) and gap (φ_G) (Fig. 1.c). The reduction of the masses and the elastic connections in the model is done for the referent shaft of the mechanism (i.e. the first-driving shaft, the last, or any other shaft). This reduction is based on the equality of the energy of the real system and of the equivalent model. The first mass is the driving one and it consists of all the masses that are in front of the referent shaft. The second mass is the driven one and it consists of all the masses that are behind the shaft. The first - driving mass is influenced by the moment of the electromotor $M_1 = M_{EM}$ during the period of acceleration. During the period of braking, it is influenced by the moment of the brake $M_1 = M_{BR}$. The second – driven mass is influenced by the moments of the resistance to motion $M_2 = M_W$. Those moments have the relevant signs (+ or –) which depend on the type of the mechanism and its movements (i.e. mechanism for lifting during the lifting or dropping; mechanism for moving forwards or backwards etc.). The values $\varphi_j, \dot{\varphi}_j, \ddot{\varphi}_j$ are the generalized coordinates (of the angle, of the velocity and of the acceleration) of the driving (j = 1) and of the driven (j = 2) masses.

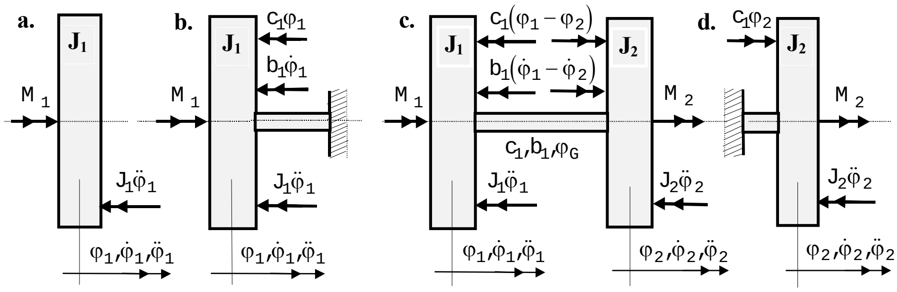

Fig. 1. Torsional elasto-kinetic model with two degrees of freedom and its modifications

The modifications of the model which refer to the certain phases of the moving during the periods of acceleration and braking are given in the same figure 1. In the most general case, the phases for the one movement of the mechanism are:

a) moving of the first - driving mass - from the state of rest in order to overcome the gap in the mechanism, stretching the loose rope etc. (Fig. 1.a.),
b) further moving of the first mass and the deformation (torsion) of the elastic connection until the second - driven mass starts to move (Fig. 1.b.),
c) simultaneous asynchronous moving – acceleration of the both masses until the mechanism starts to move stationary (Fig. 1.c.),
d) stationary - synchronous moving of the both masses till the electromotor turns off and the working brake starts to function,
e) braking - slowing down of the mechanism till the stopping moment of the first mass which is influenced by the working brake (Fig. 1.c. with the relevant sign of the

disturbing moments),

f) oscillation of the second - free mass around the balance position until it finally rests, that is, until the whole system rests (Fig. 1.d.).

Those phases are present in mechanisms whose driving shaft is balanced before the electromotor starts to function and moves the shaft. The example for this case is the mechanism for lifting the load with the loose rope etc. Some of the listed phases may not occur and that depends on the type of the mechanism, type of its function, position of the load, type of the handling etc. For example, with the short turning on of the electromotor of the lifting mechanism, the gap and the looseness of the rope can be eliminated. Also, in the case of starting the mechanism when the load is already lifted, the third phase is realized immediately.

The mathematical model means that the differential equations of the moving in all phases are set, and they are established in order to get the laws for the moving of the masses $\varphi_1(t)$ and $\varphi_2(t)$ for the one movement of the mechanism, that is, to get the change of the deformation $\Delta\varphi(t) = \varphi_1 - \varphi_2$ and the torsional moment of the elastic connection $M_t = T_t = c\ \Delta\varphi(t)$. The general differential equations for the movements of the masses in phases (for the one movement of the mechanism) are [1, 2]:

a) phase: $J_1\ddot{\varphi}_1 = M_1$, that is $\ddot{\varphi}_1 = M_{EM}/J_1$, (1)

b) phase: $J_1\ddot{\varphi}_1 + b_1\dot{\varphi}_1 + c_1\varphi_1 = M_{EM}$, that is $\ddot{\varphi}_1 + 2\delta_1\dot{\varphi}_1 + \omega_1^2\varphi_1 = M_{EM}/J_1$, (2)

c) phase: $\begin{array}{l} J_1\ddot{\varphi}_1 + b_1\dot{\varphi}_1 + c_1\varphi_1 = M_{EM} \\ J_2\ddot{\varphi}_2 - b_1\dot{\varphi}_2 - c_1\varphi_2 = M_2 \end{array}$, that is $\Delta\ddot{\varphi} + 2\delta_0\Delta\dot{\varphi} + \omega_0^2\Delta\varphi = h_{EM}$, (3)

d) phase: there are no differential equations for the moving because the masses move synchronous, that is, the deformation of the elastic connection is:
$\Delta\varphi(t) = \varphi_1(t) - \varphi_2(t) = -M_2/c_1 = \text{const.}$,

e) phase: $\begin{array}{l} J_1\ddot{\varphi}_1 + b_1\dot{\varphi}_1 + c_1\varphi_1 = -M_{BR} \\ J_2\ddot{\varphi}_2 - b_1\dot{\varphi}_2 - c_1\varphi_2 = M_2 \end{array}$, that is $\Delta\ddot{\varphi} + 2\delta_0\Delta\dot{\varphi} + \omega_0^2\Delta\varphi = h_{BR}$, (4)

f) phase: $J_2\ddot{\varphi}_2 + c_1\varphi_2 = -(\text{sign}\dot{\varphi}_2)\,|\,M_2\,|$, that is $\ddot{\varphi}_2 + \omega_2^2\varphi_2 = -(\text{sign}\dot{\varphi}_2)\,|\,M_W/J_2\,|$, (5)

where: $\delta_1 = b_1/2J_1$, $\delta_2 = b_1/2J_2$, $\omega_1^2 = c_1/J_1$, $\omega_2^2 = c_1/J_2$,

$\delta_0 = (b_1/2)(1/J_1 + 1/J_2) = \delta_1 + \delta_2$, $\omega_0^2 = c_1(1/J_1 + 1/J_2) = \omega_1^2 + \omega_2^2$,

$h_{EM} = M_{EM}/J_1 - M_2/J_2$, $h_{BR} = -M_{BR}/J_1 - M_2/J_2$, $(\text{sign}\ \dot{\varphi}_2) -$ is multiplier which has value (+) when $\dot{\varphi}_2 > 0$ and (−1) when $\dot{\varphi}_2 < 0$. The moment $M_2 = M_W$ has the relevant sign.

The shape of the listed differential equations mostly depends on the law of the change of the disturbing moments M_1 and M_2. In this analysis it can be accepted that the moment of the resistance to motion on the driven mass ($M_2 = M_w$) is constant. The moment of the brake M_{BR} is also constant (Fig. 2). The analytical description of the moment of starting the asynchronous electromotors $M_{EM} = f(\dot{\varphi})$ is linearized and given in the equation of the line. This is illustrated in the Fig. 3. for the i^{th} line of the "saw diagram" of the slide-ring electromotor and, also, in the Fig. 4. for the i^{th} line of the broken infinite natural linearized characteristic of the cage electromotors.

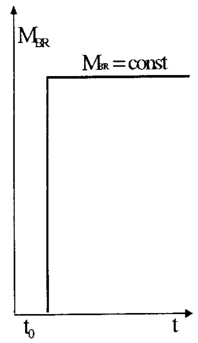

Fig. 2. Moment of brake M_{BR}

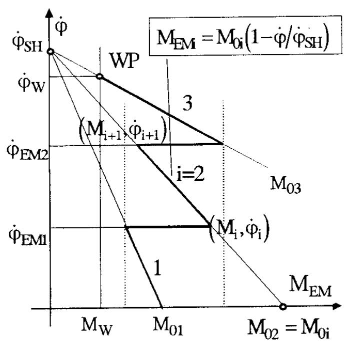

Fig. 3. Moment of the starting starting M_{EM} of the slide ring elektromotor

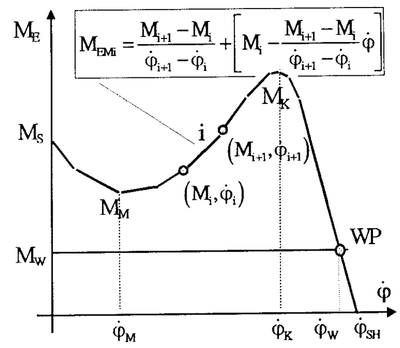

Fig. 4. Moment of the the starting M_{EM} of the cage elektromotor

When we change the described disturbing moments of the electromotor $M_{EM}=f(\dot\varphi)$, of the brake M_{BR} = const. and the moment of the resistance to motion M_W = const. the listed differential equations don't become very complex, except the equation (3) which transforms into the inhomogeneous differential equation of the order 3 [3, 5]:

$$a_{0i}\Delta\dddot\varphi_i(t)+a_{1i}\Delta\ddot\varphi_i(t)+a_{2i}\Delta\dot\varphi_i(t)+a_{3i}\Delta\varphi_i(t)=b_{0i}\,, \tag{3.a}$$

where: $a_{0i}=1$, $a_{1i}=2\delta_0+\rho_{1i}$, $a_{2i}=2\delta_2\rho_{1i}+\omega_0^2$, $a_{3i}=\rho_{1i}\omega_2^2$, $b_{0i}=-\rho_{1i}(M_2/J_2)$, $\rho_{1i}=M_{0i}/J_1\dot\varphi_{SH}$.

3. The analysis of the factors that influence the change of the load

For the purpose of the analysis of the loads, that is, the change of the torsional moment of the referent shaft, the differential equations for the starting terms should be solved and linked into the single movement of the mechanism. The solutions to these linearized equations can be obtained in the closed shape or by using the numerical methods (Runge-Kutta) they can be obtained by the computer and the functions of the torsional moment can be drawn $M_t=T(t)=c_1\Delta\varphi(t)$ as shown in the Fig. 5. and Fig. 6.

The Fig. 5. presents the simulated torsional moment of the driving shaft of the mechanism for the moving of the single bridge crane with the slide-ring electromotor which has three lines of the starting. The periods of the acceleration, stationary moving and slowing down which is realized by the electric – reversible and mechanical braking and, finally, the resting of the system are clearly recognized. The rapid change of the starting moment of the electromotor from the first line to the second one (Fig. 3.) is demonstrated by the occurrence of the great values of the first amplitudes and by the considerable dumping of the periodical change of the torsional moment $M_t=T(t)$ between the two engagements (Fig. 5.). This dumping is not the result of the viscose friction in the system, that is, of the coefficient of the dumping b_1, but, it is the result of the negative inclination of the electromotor line $(-M_{0i}/\dot\varphi_{SH})$. The same relies to the period of the electric braking. During the period of resting of the system the first amplitudes are considerable, because $J_2 >> J_1$. In figure 6, the change $M_t = T(t)$ of the output shaft of the second mechanism for the moving is different from the previous one, because the cage electromotor with the mechanical brake is used.

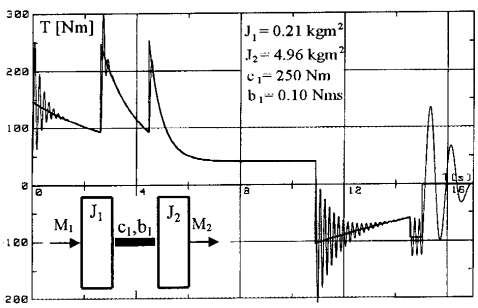

Fig. 5. The function T(t) of the driving shaft of the mechanism for the moving with the slide-ring motor

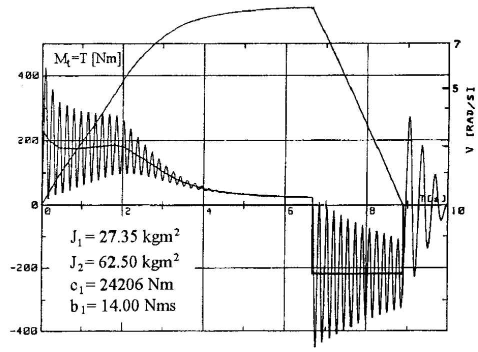

Fig. 6. The function T(t) of the output shaft of the mechanism for the moving with the cage motor

The investigation of the change $M_t = T(t)$ can be realized by using the simulations and varying of the influential factors. In the first case, the so-called "one-factor experiment" can be used, and then, all of the factors keep the same values, except the one which is varied as shown in the Fig. 7. From this figure it can be seen the influence of the dumping (b_1), the rigidity (c_1) and the gap (φ_G) of the elastic connection on the change of the torsional moment of the driving shaft of the crane mechanism in the case of the braking of the safety brake during the dropping of the empty traverse. In the second case the so-called "many-factors experiment" can be used, that is, the Box-Wilson's method of planning and conducting of the certain number of the simulations with the simultaneous varying of the large number of the influential factors as shown in the previous example in this paper [4].

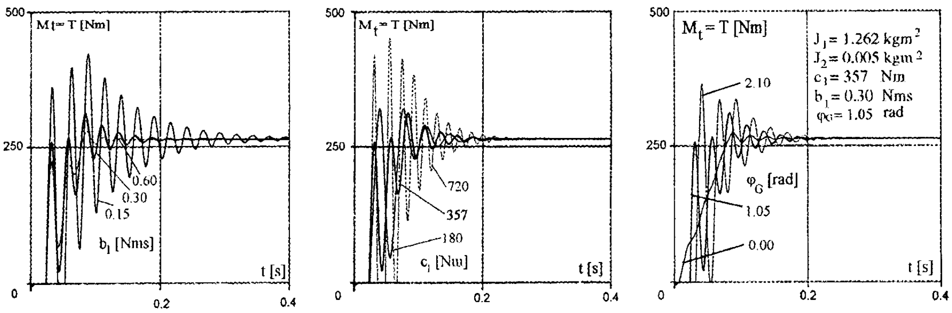

Fig. 7. Analysis of the influential factors on the change T(t) using the simulations ("simple experiment")

The analysis of the change $M_t = T(t)$ and their influential factors can be done using the expressions which are set by analytical solution to the differential equations following the phases of the moving in closed shape. In the first phase (1), the time of overcoming the gap φ_G and, also, the values of the characteristics of the moving of the driving mass in the moment of the gap creation are important because they present the starting values for the second phase of the moving. It is desirable that this phase finishes in a short period of time, that is, during the creation of the moment of the electromotor in the first line of the "saw diagram" (i = 1 in the Fig. 3.), so that the values of the velocity and acceleration in the moment of the stroke would be very small. In the second phase, the first mass goes on moving and it deforms - twists the elastic connection. Since it lasts very short, the law of the change $M_t = T(t)$ is not so important as the characteristics of the moving at the end of the phase when M_t equals M_W because they are the starting values for the next phase of the moving.

The change $M_t = T(t)$, in the third phase of the moving, during the creation of the moment of the electromotor along the ith line is obtained by solving the differential equation (3.a.), as $M_t = T(t) = c_1 \cdot \Delta\varphi$. Its characteristic equation is $\lambda_i^3 + a_{1i}\lambda_i^2 + a_{2i}\lambda_i + a_{3i} = (\lambda_i - \alpha_{0i}) \cdot [(\lambda_i - \beta_{0i})^2 + p_{0i}^2] = 0$, whose one root is real, and two others are conjugate and complex: $\lambda_{1i} = \alpha_{0i}$ and $\lambda_{2i,3i} = \beta_{0i} \pm p_{0i} \cdot i$, where $\alpha_{0i} = -\rho_{Ri}$, $\beta_{0i} = -(a_{1i}+\alpha_{0i})/2$ and $p_{0i} = \sqrt{\omega_0^2 - \beta_{0i}^2}$. Here, the new signs $\rho_{Ri} = M_{0i}/(J_R \dot{\varphi}_{SH})$ and $J_R = J_1+J_2$ have been taken. Because of the listed reasons, the law of the change of the torsional moment of the elastic connection in the third phase during the period of acceleration [2, 3] will be:

$$M_{ti} = T_i(t) = M_{1ai} + M_{2ai} \cdot \exp(\alpha_{0i}(t - t_{0i}))\ |\ + M_{3ai} \cdot \exp(\beta_{0i}(t - t_{0i})) \cdot \cos(p_{0i} + (t - t_{0i}) - \psi_{0i}), \quad (6)$$

where: M_{1ai}, M_{2ai} and M_{3ai} are the constants dependable on the characteristics of the dynamic model and on the starting conditions, ψ_{0i} - phased angle and t_{0i} - starting time.

The obtained change of the torsional moment consists of the two parts: low-frequent component and high-frequent component. The first one is until the vertical line (constant and e-function) and it presents the average value of the moment with the slight dropping ($\alpha_{0i} = -\rho_{Ri}$). The second one oscillates (product of the e- and cos- functions) around the first one with the considerable dumping ($\beta_{0i} = -(a_{1i} + \alpha_{0i})/2$) (Fig. 5.). The analysis of the influential factors on the low-frequent component can be done by using the values of the constants:

$$\begin{gathered} M_{1ai} = M_2, \\ M_{2ai} = (J_2/J_R)[M_{EMi}(\Delta\dot{\varphi}_{0i} = \dot{\varphi}_{EMi}) + M_2] = (J_2/J_R)[M_{0i}(1 - \dot{\varphi}_{EMi}/\dot{\varphi}_{SH}) + M_2], \end{gathered} \quad (7)$$

where: $\Delta\dot{\varphi}_{0i} = \dot{\varphi}_{EMi}$ is the velocity on the beginning of the ith line of the electromotor (Fig. 3.).

For the high-frequent component, the expression for the constant M_{3ai} is much more complex. However, for its analysis, among other data, the values of the first maximum amplitude T_{ai} and the complex coefficient of the dumping β_{0i} [3]:

$$T_{ai} = | M_{3ai}\cos(-\psi_{0i}) | = c_1 \left| -\frac{\rho_{Ri}(3\rho_{Ri} + \rho_{1i})}{m_{0i}^2}\Delta\varphi_{i0} - \frac{1}{m_{0i}^2}\Delta\ddot{\varphi}_{i0} - \frac{2\rho_{Ri}\rho_{1i}M_2}{\omega_{01}^2 m_{0i}^2 J_2} \right|, \quad (8)$$

where: $\Delta\varphi_{0i}$, $\Delta\ddot{\varphi}_{0i}$ - are the starting values, $m_{0i}^2 = (\alpha_{0i} - \beta_{0i})^2 + p_{0i}^2$.

$$\beta_{0i} = -(a_{1i} + \alpha_{0i})/2 = -[\delta_0 + (\rho_{1i} - \rho_{Ri})/2] = -\left(b_1 \frac{J_R}{J_1 J_2} + \frac{1}{2} \frac{M_{0i}}{\dot{\varphi}_{SH}} \frac{J_2}{J_1 J_R} \right). \quad (9)$$

The obtained analytical expressions (7, 8 and 9) make the solid base for analyzing of the influential factors on the change of the torsional moment of the shaft of the driving mechanisms during the period of acceleration (6).

The change of the torsional moment for the period of braking is easily obtained by solving the differential equation (4), because $M_1 = -M_{BR}$ = const., as [2]:

$$M_t = T(t) = c_1 \cdot \Delta\varphi(t) = M_{1b} \,| + M_{2b} \cdot \exp(\beta_b (t - t_0)) \cdot \cos(p_b (t - t_0) - \psi_b) \ , \quad (10)$$

where: $\beta_b = -\delta_0$, $p_b^2 = \omega_0^2 - \delta_0^2$, ψ_b – phased angle, t_{0i} – starting time, $\Delta\varphi_0 = M_W/c_1$, $\Delta\dot{\varphi}_0 = 0$,

$$M_{1b} = c_1 (h_{BR} / \omega_0^2)$$
$$M_{2b} = c_1 [(\Delta\varphi_0 - (h_{BR}/\omega_0^2)^2 + ((\Delta\dot{\varphi}_0 - \beta_b (\Delta\varphi_0 - h_{BR}/\omega_0^2))/p_b)^2]^{1/2}. \quad (11)$$

The analysis of the obtained change (10) shows that it is also made of the low-frequent component in the shape of the constant and of the high-frequent oscillatory component with the dumping which can be seen more clearly in the Fig. 6. Using the analysis of the constants M_{1b} and M_{2b} (11) the influential factors on this change during the period of the braking is obtained.

4. Conclusion

From the whole paper, it can be concluded that the analysis of the influential factors on the change of the torsional moment of the shaft of the driving mechanisms of the crane may be realized in two ways:

– by using the simulations by varying the influential values ("one- or many-factors experiment"),

– by studying the obtained analytical expressions (6-11) and their influential factors.

The knowledge of the influential factors and their simulation enables the obtaining of the lighter and more reliable mechanisms. The ability to deal with the driving moment, also, enables the programmed moving which presents a step towards the automatization and towards the more efficient crane function.

References

1. Trapp, H.J., *Eine rechnerische Prognose der Betriebsfestigkeit von Bauteilen in elastischen, durch Scheifringläufermotore einggetriebenen System*, Dissertation, TH Darmstadt, Düsseldorf, 1974.
2. Marinković, Z., *Probable-Statistical Model of the Life-Time Calculation of the Crane Driving Mechanism Elements*, (in Serbian), Ph. D. Thesis, Mechanical Faculty University of Nis, Nis, 1993.
3. Mijajlović R., Marinković Z., Mijajlović D., *Analyses of crane driving mechanism acceleration by means of sliding-ringe electric motors*, Ninth World Congress on the Theory of Machines and Mechanisms, Proceedings Vol. 2, Politecnico di Milano, Italy, 1995., pp. 866–870.
4. Mijajlović R., Marinković Z., *Factor Experiment and Crane Load Simulations by Means of a Computer*, (in Serbian), Tehnika, No 1/95, Savez mašinskih i elektrotehničkih inženjera i tehničara Jugoslavije, Beograd, 1995., str. M14–M19.

5. Marinković, Z., Mijajlović, R., Jovanović, M., Đorđević, T., Marković, S., *Modelling and simulation of accelerating period at lifting driving mechanisms with sliding rings (Part 1 and 2)*, XIV International Conference on Material Handling and Warehousing, Proceedings, Mechanical engineering faculty University of Belgrade, 1996, pp. 2.37–2.42 and pp. 4.88–4.92.

FAKTORI KOJI UTIČU NA PROMENU OPTEREĆENJA POGONSKIH MEHANIZAMA KRANOVA

Mijajlović Radić, Marinković Zoran, Jovanović Miomir

U radu se daje postupak analize uticajnih faktora na promenu opterećenja - torzionog momenta vratila mehanizma krana u prelaznim režimima rada (periodi ubrzavanja i kočenja) korišćenjem odgovarajućih dinamičkih i metamatičkih modela.

Ključne reči: *kran, mehanizam, opterećenje, elasto-kinetički model, torzioni moment*