Modeling of dynamic loadings on a tower crane jib

Evgenij Kudryavtsev, Alexander Gavrilenko*, and Mostafa Jafari
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. Article describe processes of modeling of dynamic loadings on a tower crane jib and represent their in analytic and, graphic kinds with using of modern computer technologies. Complexity of such tasks is concluded in depending these characteristics from load characteristics of the crane, weights and inertial parameters of elements of the mechanism of the lifting of loads, having a nonlinear appearance. The proposed procedures of modeling allow to reduce time and costs of such calculations at least in several hundred times and effectively to carry out researches in any usage mode and on all design stages of tower cranes, providing good visual presentation of received results.

1 Introduction

Article describe process of modeling of dynamic loadings on a tower crane jib. It is necessary originally: to simulate the load characteristic of the tower crane in an analytical kind; to define the resulted moments of inertia of rotating bodies and lifted load to an engine rotor; to define time, a way and acceleration of dispersal of load at its lifting, depending on a load site on a jib and representation their in analytic and graphic kinds in MathCad system. [1][2]

The proposed procedures of modeling and calculations allow to reduce time and costs of such calculations at least in several hundred times and effectively to carry out researches in any usage mode and exploitation of transport means, providing good visual presentation of received results.[3]

2 Statement of the problem

The load characteristic of the tower crane in a graphic kind is known, as a rule, looks how is shown on fig. 1.

* Corresponding author: sdm@mgsu.ru

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).
In an analytical kind the load characteristic of the tower crane can be presented such expression.

- In the range \( r_1 - r_2 \)

\[ Q_{1-2}(r) = Q_2, \]

- In the range \( r_2 - r_3 \)

\[ Q_{2-3}(r) = \frac{M_{cr} + M_{cl} - M_{wcl} - M_{wl} - M_{im} - M_{cfl}}{K_{sscr} \cdot ((g + aa) \cdot (r - 0.5 \cdot B + H_5 \cdot \sin(\alpha)))}. \] (1)

where:
- \( M_{cr} \) - moment from constructive weight of the crane in working status, kN·m;
- \( M_{cl} \) - moment from weight of counterload in working status kN·m;
- \( M_{wcr} \) - moment from wind loading on the crane in working order, kN·m;
- \( M_{wl} \) - moment from wind loading on load in working order, kN·m;
- \( M_{imcr} \) - inertia moment at crane dispersal, kN·m;
- \( M_{imla} \) - inertia moment at load dispersal along, kN·m;
- \( M_{imlv} \) - inertia moment at load dispersal on a vertical, kN·m;
- \( M_{cfl} \) - moment from centrifugal force of load, kN·m;
- \( K_{sscr} \) - factor of a stock of stability of the crane in working status;
- \( B \) - base of the crane, m;
- \( \alpha \) - maximal gradient angle, degree;
- \( H_5 \) - height of a heel of an arrow, m.

In an analytical kind can define the resulted moments of inertia of rotating bodies and lifted load to an engine rotor.

\[ Inp(r) = (\delta \cdot (I_r + 0.5 \cdot I_c) + \frac{0.5 \cdot I_c + I_1}{\eta_1} + \frac{I_2}{i_1^2 \cdot \eta_1 \cdot \eta_2} + \frac{I_{scd}}{i_1^2 \cdot i_2^2 \cdot \eta_1 \cdot \eta_2 \cdot \eta_3} + \frac{1000 \cdot (QR(r) \cdot (1 + K_{vl}) + 0.05 \cdot QR(r))}{\eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_p \cdot \eta_{bl}^{abl}} \cdot \left( \frac{V_{ll}}{\omega m} \right) \] (2)

where:
- \( \delta \) - factor influence of inertial weights of the mechanism of lifting of loads;
- \( I_r, I_c \) - inertia moments of engine rotor and coupler, kgm²;
- \( I_1, I_2 \) - inertia moments of reducer shafts, kgm²;
- \( I_{scd} \) - inertia moments of reducer shaft, coupler and drum, kgm²;
- \( QR(r) \) - capacity of tower crane, tone
- \( K_{vl} \) - factor of variability of loads;
- \( V_{ll} \) - speed of lifting of loads, m/s;
- \( \eta_1, \eta_2, \eta_3 \) - reducer shafts efficiency;
In an analytical kind, the load characteristic of the tower crane can be presented in the following expression:

\[ Q(r) = \begin{cases} Q_2, & \text{in the range } r_1 - r_2 \\ M_{cr} \sin(\alpha - \beta) + M_{cl} \cos(\alpha - \beta) + M_{wcr} \sin(\alpha) + M_{wl} \cos(\alpha) + M_{im} \theta + M_{cfl} \sin(\alpha) + \frac{K_{sscr} \cdot b \cdot H_5}{\sqrt{\alpha}} , & \text{otherwise} \end{cases} \]

where:
- \( M_{cr} \) - moment from constructive weight of the crane in working status, kN·m;
- \( M_{cl} \) - moment from weight of counterload in working status, kN·m;
- \( M_{wcr} \) - moment from wind loading on the crane in working order, kN·m;
- \( M_{wl} \) - moment from wind loading on load in working order, kN·m;
- \( M_{im} \) - inertia moment at crane dispersal, kN·m;
- \( M_{iml} \) - inertia moment at load dispersal along, kN·m;
- \( M_{imlv} \) - inertia moment at load dispersal on a vertical, kN·m;
- \( M_{cfl} \) - moment from centrifugal force of load, kN·m;
- \( K_{sscr} \) - factor of a stock of stability of the crane in working status;
- \( B \) - base of the crane, m;
- \( \alpha \) - maximal gradient angle, degree;
- \( H_5 \) - height of a heel of an arrow, m.

In an analytical kind, we can define the resulted moments of inertia of rotating bodies and lifted load to an engine rotor.

\[ \delta \eta_1 \eta_2 \eta_3 = \frac{\eta_1 \eta_2 \eta_3}{n_{bl}} \]  

where:
- \( \delta \) - factor influence of inertial weights of the mechanism of lifting of loads;
- \( \eta_{1}, \eta_{2}, \eta_{3} \) - efficiencies of the reducer shafts;
- \( n_{bl} \) - number of by-pass blocks.

3 Modeling algorithm in system Mathcad

This paragraph shows the program in the MATHCAD system in the form of screenshots of the computer screen.[4][5] This program can be used to calculate and simulate dynamic loads on the jib of a tower crane. In fig. 2,3 shows modelling of load characteristics of the tower crane process.

**Fig. 2.** The initial data for modeling of load characteristics.

**Fig. 3.** Algorithm of calculation load characteristics.

\[ Q(R) = \begin{cases} Q_1(R), & \text{if } r_2 \leq R \leq R_1 \\ Q_2(R), & \text{if } r \leq r_2 \text{ or } R \leq r \leq R_1 \end{cases} \]

where:
- \( Q_1(R) \) - load characteristic of the crane in the form of two lines,
- \( Q_2(R) \) - load characteristic of the crane in the form of three lines,
- \( r_1 = \frac{B}{2} + \frac{H_5 \sin(\alpha \cdot \deg)}{r_2} \)
- \( r_2 = \sqrt{(Q_2(R) - Q_2) \cdot R_1 \cdot R_1} \)
- \( Q_3(R) \) - load characteristic of the crane in the form of three lines,
- \( R_1 = 40 \).
The second paragraph of the program shows calculation the acceleration of lifting loads. In the figures 4-8 initial data and calculation algorithm are shown.

2. Calculation of acceleration of lifting of loads

**Initial data:**
- effort in a rope going on a drum of lifting of loads, $H$
- speed of lifting of loads, $m/s$
- polispast multiplicity $q_p = 2$
- block efficiency $\eta = 0.9$
- number of by-pass blocks $n_b = 2$
- polispast and coupler efficiency $\eta_p \approx 0.9$, $\eta_c \approx 0.99$
- factor of variability of loads $V_f \approx 0.06$
- transfer number of the stages of a reducer $i_1 = 4.16$, $i_2 = 3.92$
- reducer shafts efficiency $\eta_1 = 0.99$, $\eta_2 = 0.99$
- factor influence of inertial weights of the mechanism of lifting of loads $f \approx 1.2$
- inertia moments of engine rotor and coupler, $kgm^2$, $J_r = 2.9$, $J_c = 4.8$
- inertia moments of reducer shafts, $kgm^2$, $J_{1m} = 4.8$, $J_{2m} = 6.711$
- inertia moments of reducer shaft, coupler and drum, $kgm^2$, $J_{ed} \approx 164.242$
- average diameter of rope winding on a drum, $m$, $D_{wr} = 0.501$
- calculated value of transfer number of a reducer $i_{sp} = 18.711$
- actual value of transfer number of a reducer $i_p = 16.3$
- nominal number of turns of an engine rotor, $rpm$ $n_{m} = 715$
- capacity on an engine shaft (грн ПВ = 40%), $kW$, $N_{en} = 55$
- reloading ability of an engine $\lambda = 2.9$
- admissible acceleration of loads lifting at engine dispersal, $m/s^2$, $g_{ed} = 0.4$

**Fig. 4.** Calculation of acceleration of lifting loads. Initial data.

**Calculation algorithm**

1. Nominal angular speed of rotation of an engine rotor, rad/s
   \[
   \omega_n = \frac{2 \pi \cdot n_m}{60}
   \]
   $\omega_n = 74.373$

2. Nominal moment of an engine rotor, $Nm$
   \[
   M_n = \frac{1000 \cdot N_m}{\omega_n}
   \]
   $M_n = 734.581$

3. Critical moment of an engine rotor, $Nm$
   \[
   M_c = M_n \lambda
   \]
   $M_c = 2.13 \times 10^3$

4. Reduced moment of inertia of rotating bodies and lifted load to an engine shaft, $kgm^2$
   \[
   I_{sp}(r) = \left( \frac{0.5 \cdot J_c + H_l}{\eta_1} \right) + \frac{I_2}{i_1^2 \cdot \eta_1 \cdot \eta_2} + \frac{I_{ed}}{i_2^2 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4} \\
   + 1000 \cdot \left( \frac{Q_{Bm}}{r} \cdot (1 + K_v) - 0.05 \cdot Q_{Bm} \right) \left( \frac{V_{II}}{\omega_n} \right)^2
   \]

**Fig. 5.** Calculation of acceleration of lifting loads. Points 1-4.
5. Moment of static resistance, $Nm$
$$M_{sr} = \frac{Srd \cdot Der}{2l1 \cdot l2 \cdot q1 \cdot q2 \cdot q3 \cdot q4 \cdot b \cdot l}$$
$$M_{sr} = 1.06 \times 10^3$$

6. Average starting moment, $Nm$
$$M_{as} = \frac{M_{re} + 1.1 \cdot M_{n}}{2}$$
$$M_{as} = 1.469 \times 10^3$$

7. Time of dispersal of lifted load, $s$
$$t_{dl}(r) = \frac{Imp(r) \cdot \omega_{m}}{M_{as} - M_{sr}}$$

![Graph showing the calculation of acceleration of lifting loads for points 5-7.](image)

Fig. 6. Calculation of acceleration of lifting loads. Points 5-7.

8. Actual speed ($m/s$) and acceleration of dispersal ($m/s^2$) of lifting of loads,

$$V_{oa} = V_{r} \cdot \frac{EP}{ip}$$
$$a_{dl}(r) = \frac{V_{oa}}{t_{dl}(r)}$$
$$V_{oa} = 0.605$$

![Graph showing the calculation of actual speed and acceleration for points 8-9.](image)

Fig. 7. Calculation of acceleration of lifting loads. Points 8,9.
Fig. 8. Calculation of acceleration of lifting loads. Point 10.

4 Conclusion

The proposed procedures of modeling of dynamic loadings on a tower crane jib allow to reduce time and costs of such calculations at least in several hundred times and effectively to carry out researches in any usage mode and all design stages of tower cranes, providing good visual presentation of received results.

The reported study was funded by RFBR according to the research project № 20-38-90168

References

1. Vahlamov V. K. Structures, calculation and operational properties of cars. - M: Academy. 2007. - 560 p.
2. Krajcinovic D 1995 Continuum Damage Mechanics: when and how? Int. J. Damage Mechanics 4 pp 217-229
3. Y Kudryavtsev and A Gavrilenko 2019 IOP Conf. Ser.: Mater. Sci. Eng. 698 022081.
4. Y Kudryavtsev and A Gavrilenko 2020 IOP Conf. Ser.: Mater. Sci. Eng. 753 042076.
5. E. Kudryavtsev, A. Gavrilenko 9/2020 Construction and road building machinery journal., pp 40-43.