Study of the crawler crane stability affected by the length of compensating ropes and platform rotation angle in the mode of movement with payload

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Abstract. Payload uncontrolled oscillations arising during movement of a loaded self-propelled crawler crane at a construction site were reduced by equipping the crane with two additional compensating ropes equal in length and connecting the rotating platform to the load gripping device. This also increased the stability of the entire system. The stability margin moment was used to evaluate the crane stability at individual tipping axes of the crawler support contour. While moving along a random microrelief surface, under the varied length of the compensating ropes and the platform rotation angle, the length reduction increased the mathematical expectation of the stability margin moment for the most loaded lateral tipping axis. The smallest values of the stability margin moment were obtained at the platform rotation angle close to 90 degrees, with the crane stability index being most affected by the compensating rope length. At a zero platform rotation angle, the compensating rope length effect on the stability at the most loaded lateral axis was insignificant. The regression equation of the average stability margin moment affected by the compensating rope length and the platform rotation angle was obtained. The results can be used in the design of advanced self-propelled cable electric crawler cranes.

Keywords: crawler crane, compensating rope, payload oscillations, microrelief

1. Introduction
Jib cranes represent systems with non-linear dynamics [1]. Having an advantage over other types of cranes, in particular, overhead and gantry cranes, crawler self-propelled jib cranes (CC) are widely used. The design of CCs allows them to move loaded along an unprepared supporting surface over significant distances [2]. At the same time, any movement of the upper suspension point in the crane system of any type, where the load is suspended using a flexible payload rope, cause the payload to swing [3]. The latter has a negative impact on both the productivity and safety of the work process [4]. The problem of suppressing uncontrolled oscillations of the payload on a flexible rope suspension is important not only for CCs, but also for overhead [5], gantry [6], tower slewing [7] and other cranes.
An increase in the carrying capacity of a CC raises the question of its stability. On the other hand, increased CC stability implies an increase in the CC carrying capacity [8]. It was proposed to increase the stability of CCs by applying additional compensating ropes oriented in directions close to horizontal [9]. These ropes were shown to be capable of suppressing oscillations of the payload transported by a CC.

The aim of this study was to investigate the effect of the length of compensating ropes and the angle of the platform rotation on the stability of a loaded crawler crane moving along a construction site.

2. Formulation of the problem

The task is to develop a mathematical simulation model for a CC dynamic system with a payload. The system includes the following parts: a base chassis with a mass of \( m_1 \), a rotation platform with a mass of \( m_2 \), a jib arm with a mass of \( m_3 \) and a payload with a mass of \( m_4 \) (see figure 1).

![Figure 1. Crawler self-propelled jib crane with additional compensating ropes.](image)

The model must take into account all \( q_i \) degrees of freedom for the CC mechanical system, which have a significant impact on its movement, as well as \( F_1 \) and \( F_2 \) additional unstable force constraints from the ropes, which are introduced in the CC design. These additional ropes perform the function of compensating the payload by reducing the amplitude of its uncontrollable oscillations. The model should provide for force excitation of spatial angular displacements of the CC base chassis affected by the irregularities in the microrelief of the supporting surface, along which the CC track moves. The developed model will be subsequently used for investigating the effect of the length of the compensating rope and the platform rotation angle on the CC stability in the mode of loaded movement at a construction site. All other design and technological parameters of the model, except for those indicated, must take fixed values during the computational experiment.

3. Theoretical part

In developing the CC mathematical model, the following assumptions were made [10, 11]:
- CC is an articulated spatial multi-unit machine;
- constraints superimposed on the CC dynamic system are holonomic and stationary;
- elements of metal structures and the main payload rope are described as absolutely rigid rods;
- the mass-inertial properties for the elements of the CC metal structures are characterised by masses, coordinates of the mass centres, moments of inertia and centrifugal moments of inertia;
- no backlash is presented in the articulated joints;
- no dry friction forces in the hydraulic cylinders and the CC track assembly are presented;
- normal reactions from the side of the supporting surface microrelief to the CC base chassis are given to 4 concentrated forces applied in the corners of the CC basic chassis;
- the Voigt bodies are used to describe the elastic and dissipative properties for the elements of the track assembly in the base chassis and the ground under it, the angular displacements of the main payload rope and the extension of additional compensating ropes.

![Diagram](image-url)

**Figure 2.** Loading diagram for a dynamic system of a crawler self-propelled jib crane equipped by additional compensating ropes.
Figure 3. Simulation mathematical model of a self-propelled jib crane with additional compensating ropes in MATLAB Simscape Multibody

The CC mechanism in the developed simulation model has 8 degrees of freedom. The \( q_1 \ldots q_8 \) corresponding generalised coordinates of the CC mechanical system are given in Table 1. This combination of coordinates with a sufficient degree of accuracy describes the linear and angular displacements of the CC when moving loaded along the supporting surface microrelief with constant velocity.

### Table 1. Generalised coordinates of the crawler crane (CC).

| №  | Generalised coordinates | Description of the generalised coordinate                      |
|----|------------------------|----------------------------------------------------------------|
| 1  | \( q_1 \)              | Displacement of the CC base chassis along the \( Y_0 \) vertical axis |
| 2  | \( q_2 \)              | Rotation of the CC main chassis around the \( X_0 \) axis        |
| 3  | \( q_3 \)              | Rotation of the CC main chassis around the \( Z_0 \) axis        |
| 4  | \( q_4 \)              | CC platform rotation around the \( Y_1 \) axis                   |
| 5  | \( q_5 \)              | Jib arm rotation around the \( Z_3 \) axis                      |
| 6  | \( q_6 \)              | Rotation of the main payload rope around \( X_4 \) axis          |
| 7  | \( q_7 \)              | Rotation of the main payload rope around \( Z_5 \) axis          |
| 8  | \( q_8 \)              | Payload movement along \( Y_4 \) axis                           |

According to the proposed loading diagram of the CC dynamic system with additional compensating ropes (see figure 2), the corresponding simulation mathematical model was developed in the Simscape Multibody application of the MATLAB system (see figure 3).

The following notations are used in the loading diagram: \( l_k \) is the equilibrium length for each of the two additional compensating ropes; \( c_1 \ldots c_8 \) are the stiffness coefficients of the Voigt bodies (No. 1 \ldots 4 - for supporting elements, No. 5, 6 - for the main payload rope, No. 7, 8 - for the additional compensating ropes); \( b_1 \ldots b_8 \) are the viscous friction coefficients of the corresponding Voigt bodies; \( F_{m1} \ldots F_{m4} \) are the gravity of the units; \( F_{R1} \ldots F_{R4} \) are the forces of normal reactions from the microrelief of the supporting surface to the CC base chassis. The magnitude of the \( F_{R1} \ldots F_{R4} \) reaction forces is determined by the vertical coordinates of the microrelief at the \( y_1(t) \) left and \( y_2(t) \) right ruts, respectively:
where \( l_i = y_{vi} - y_{hi} \) are the small deviations in the lengths of the Voigt bodies for the CC track assembly relative to their own equilibrium positions; \( y_{vi} \) is the value of the vertical coordinate for the attachment point of the Voigt body in the unit of the base chassis; \( y_{hi} \) is the value of the vertical coordinate for the surface microlrelief under the corresponding reference element (for example, the left rut), \( i \in [1; 2; 3; 4] \). Dots indicate the time derivatives of the parameters.

Using the values for the forces of the chassis support normal reactions, the values of the CC stability indicators, i.e. the stability margin moments along the individual tipping axes of the track support contour, are calculated [12]:

\[
M_{\text{front}} = (F_{R3} + F_{R4}) \cdot L; M_{\text{rear}} = (F_{R1} + F_{R2}) \cdot L;
\]

\[
M_{\text{left}} = (F_{R2} + F_{R4}) \cdot B; M_{\text{right}} = (F_{R1} + F_{R3}) \cdot B.
\]

\( M_{\text{front}}, M_{\text{rear}}, M_{\text{left}} \) and \( M_{\text{right}} \) designate the stability margin moments relative to the front, rear, left and right axes of the CC support contour, respectively.

The magnitude of the \( F_1, F_2 \) internal forces of unstable constraints for the additional compensating ropes are determined by the expression:

\[
F_i = \begin{cases} 
-c_i l_i - b_i \dot{l}_i, & \text{при } l_i > 0; \\
0, & \text{при } l_i \leq 0,
\end{cases}
\]

where \( l_i = l_{vi} - l_{ki} \) are the small deviations in the lengths of the Voigt bodies for additional compensating ropes relative to their own equilibrium positions; \( l_{vi} \) is the actual value for the length of a separate additional compensating rope, \( i \in [1; 2] \).

With the rope length under the \( l_{vi} \leq l_{ki} \) equilibrium value (which is identical to \( l_i \leq 0 \)), no force is exerted by the rope on the moving inertial units of the dynamic system. The subsystem of the model simulating the Voigt body for an additional compensating rope is presented in figure 4(a). Switching the method of calculating the value of the constraint force is carried out using the Switch block.

The subsystem of the model simulating the Voigt body for the chassis support element is shown in figure 4(b). The current value of the \( y_{hi} \) vertical coordinate for the surface microlrelief under the support element is used as an input signal. In order to calculate the microlrelief vertical coordinates by the left and right ruts, the following sequence of formulas is used [13]:

\[
h = v \cdot dt_{op}; \quad \gamma_k = \alpha_k \cdot h; \quad \gamma_0 = \beta_k \cdot h; \quad \rho = e^{-\gamma_0}; \quad c_0 = \rho (\rho^2 - 1) \cos \gamma_0; \quad c_1 = 1 - \rho^4; \]

\[
q_1 = 2 \cdot \rho \cdot \cos (\gamma_0); \quad q_2 = -\rho^2; \quad c = \sqrt{\frac{c_1^2 + 4 \cdot c_0^2}{2}}; \quad a = \frac{\sigma_k \cdot c_0}{c}; \quad Q = \sigma_k \cdot c;
\]

\[
y_{hi, 1, 2}(n) = Q \cdot x(n) + a \cdot x(n-1) + q_1 \cdot y(n-1) + q_2 \cdot y(n-2),
\]

where \( v \) is the velocity of the base chassis, \( m/s; \); \( dt_{op} \) is the time step between two adjacent profile reference points, \( s; \) \( h \) is the profile step, \( m; \) \( a_k \) and \( \beta_k \) are the constant coefficients depending on the profile type; \( x(n) \) is a sequence of normally distributed random numbers with \( m = 0 \) mathematical expectation and \( \sigma = 1 \) standard deviation; \( n \) is the serial number of the current profile point; \( \alpha_k \) is the standard deviation for the points of the formed profile, \( m. \)
Figure 4. Subsystems for modelling Voigt bodies of an (a) additional compensating rope and (b) supporting elements of the chassis.

As the main mechanical blocks of Simscape Multibody in the simulation model, the following blocks were used: solids - *Solid*, joints - *Joint*, specified constant shifts and rotations - *Rigid Transform* [14].

4. Experimental results

In order to investigate the effect of the compensating rope length and the platform rotation angle on the CC stability in the mode of loaded movement, a computational experiment was conducted on the basis of the developed simulation model. The \( l_e \) equilibrium length of the compensating ropes ranged from 2.5 to 7.5 m in increments of 1 m. The \( q_4 \) platform rotation angle ranged from 0 to 1.8 rad. (103°) in increments of 0.1 rad.

The remaining parameters of the model were assigned fixed values: the \( v=1 \) km/h velocity of the base chassis translational movement; the masses for the units of the chassis, platform, jib arm and payload equal to 15000, 2000, 1680 and 1000 kg, respectively; the \( L=4.053 \) m chassis base size in the longitudinal direction; the \( B=2.773 \) m width of the chassis in the transverse direction; 0.5 m height above the ground level of the mass centre for the chassis and the platform joint; the 2.0025 m distance between the mass centre of the chassis and the rear corner points of the chassis support contour in the longitudinal direction; the \( c_{op}=1000000 \) N/m reduced stiffness coefficient of the Voigt body for the individual angular support of the chassis; the \( b_{op}=100000 \) N/(m/s) reduced viscous friction coefficient of the Voigt body for a separate angular support of the chassis; the 1 rad. (57.3°) jib arm lifting angle; the jib arm joint coordinates in the \( O_2X_2Y_2Z_2 \) coordinate system: \( x_{com2}=0.7 \) m, \( y_{com2}=0.4 \) m; the coordinates of the attachment points for the additional compensating ropes relative to the jib arm joint point in the \( O_2X_2Y_2Z_2 \) coordinate system: \( x_{cm3}=0.4, y_{cm3}=-0.2, z_{cm3}=\pm 0.8 \) m; the \( c_k=100000 \) N/m reduced stiffness coefficient of the Voigt body for the additional compensating rope; the \( b_k=10000 \) N/(m/s) reduced viscous friction coefficient of the Voigt body for the additional compensating rope; the \( l_s=12 \) m jib arm length; the \( q_e=10 \) m length of the main payload rope; \( \sigma_k=0.054 \) m, \( \alpha_k=0.5, \beta_k=0 \)
microrelief parameters of the supporting surface. The supporting surface with a random microrelief profile was formed unvariative in accordance with the correlation function given below and subsequently used as a test in the entire computational experiment.

The correlation function of the microrelief vertical coordinates is approximated by the expression

$$R(t) = \sigma_k^2 \cdot e^{-\alpha t} \cdot \cos(\beta_k \cdot t),$$

where $t$ is the value of the correlation time.

The functional dependences of the average stability margin moment for the left tipping axis on the $q_4$ platform rotation angle are obtained as a result of the described computational experiment, as well as an example of the time dependences for the stability margin moments of all axes, are shown in figure 5.

5. Discussion

The displacement of the dynamic system was simulated for $110$ s. In the period from 0 to $10$ s, impacts on the elements of the track assembly from the side of the supporting surface microrelief were set to zero (see figure 5(a)). An oscillation subsidence of the moving units under the action of gravity was observed. The calculation of stability indicators was carried out from $10$ s to $110$ s of the dynamic process time. Thus, the time of studying the CC stability in the steady-state mode of movement comprised a constant value of $100$ s in the considered computational experiment.

The functional dependences of the average stability margin moment for the most loaded left tipping axis on the $q_4$ platform rotation angle were obtained for different $l_k$ lengths of compensating ropes.

The obtained functional dependences of the average stability margin moment were identified to be accurately approximated by regression equations

$$\bar{M}_{left} = \sin(q_4) \left( \frac{b_1}{e^{b_2(b_2-l_k)}} + 1 \right) + b_4,$$

where $b_1, b_2, b_3, b_4$ are the regression coefficients.

With the values of the coefficients equal to $b_1=145300, b_2=0.40344, b_3=1.41876$ and $b_4=263438.59$, found by the least squares method using the Levenberg-Marquardt algorithm [15], the relative approximation error for the regression equation (1) was less than $1.5\%$. The absolute error of equation
(1) comprised 2056 N/m with the $R^2=0.99936$ and $R^2=0.99934$ determination and adjusted determination coefficient, respectively.

6. Conclusions
1. The smallest values of the mathematical expectation for the stability margin moment are obtained at the platform rotation angle close to 90 degrees.
2. A decrease in the length of the compensating ropes increases the average value of the stability margin moment, ceteris paribus.
3. When using compensating ropes, the average value of the stability margin moment increases most significantly at the CC platform rotation angle close to 90°. In this case, the increase comprises 33% with a decrease in the length of the compensating ropes from 7.5 to 2.5 m. At a zero platform rotation angle, the increase in the average moment of stability margin is only 0.6%.
4. With an increase in the length of the compensating ropes over 7.5 m, no significant effect on the CC stability is observed, since their actual length in payload swinging basically does not exceed the equilibrium value. In addition, the length of the compensating ropes cannot be reduced to that shorter than 2.5 m due to the danger of deformation, which will exceed the tensile strength of steel products. This is determined by the design limitations: the lengths of the jib arm and the main payload rope.
5. The use of additional compensating ropes will always increase the stability of a loaded CC moving along an uneven surface. It is advisable to use additional compensating ropes of the smallest possible length allowed by the CC design (jib arm length) and the current length of the main payload rope. In this case, a maximum increase in stability can be achieved.

The obtained results may be of interest to researchers involved in the design of advanced self-propelled crawler cranes.

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