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RESEARCH AND ANALYSIS OF TOWER CRANE LOAD BEHAVIOR WHEN THE ROPE BREAKS

The object of research is the behavior of the load of the tower crane during the break of the sling. One of the most problematic areas is the safety of work and the prevention of emergency situations. Despite the presence of mandatory safety measures, during cargo transportation, one of the sling branches may be destroyed due to the presence of a dynamic component during the operation of the crane, or errors of the slinger when securing the cargo. Also, the presence of hidden internal or unnoticed defects in the sling construction itself cannot be ruled out. Also, one of the most problematic places is the chaotic fluctuations of the load, which negatively affect the stability of the crane and safety. The paper describes the case of the destruction of one of the branches of a two-rope sling during the transportation of a long product by a tower crane.

The proposed method of cargo behavior analysis is based on the use of a dynamic description of cable system failure modes within the framework of setting and solving differential-algebraic equations. This makes it possible to more accurately describe the behavior of the cargo when the sling breaks.

The obtained results show that the application of the proposed method makes it possible to bring the mathematical model of the two-link mathematical pendulum significantly closer to the actual mutual oscillations of the load during the sling break. This is due to the fact that the proposed method has a number of features, in particular, high sensitivity to changes in the behavior of the cargo and a quick reaction to a rope break.

These results can be used in practice in the design and operation of tower cranes. Thanks to the application of the proposed method, it is possible to obtain accurate values of cargo behavior indicators and timely detection of a rope break. Compared to similar known methods, this method has such advantages as high efficiency, reliability and safety of operation.

Keywords: *tower crane, sling break, two-link pendulum, load swinging, Lagrange equation, nonlinear differential equations.*

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1. Introduction

To connect the transported cargo with the hook suspension of the crane, such load-catching devices as slings are successfully used. Slings are special products designed to fix the load, which ensure its preservation during lifting, carrying and transportation. Depending on the technological process (location of the crane, temperature of the environment/cargo, weight of the cargo, etc.), slings can be made of synthetic materials, steel channels or round-link chains [1–3].

The number of branches in the sling can be from one to four, depending on the cargo being transported. For the transportation of long products with a small cross-section, traverses are required (which, unfortunately, are not universal, have a significant own weight, reduce the total height of lifting the load), or additionally – two-rope slings.

When lifting a load with a single-branch sling, the load is, as a rule, equal to the weight of the load. However, when using, for example, a double-pronged sling, this rule does not apply, after tensioning, the sling grows with an increase in the angle between the needles. It also follows that when the angle between the needles increases, the probability of rupture increases, but the compressive force that affects the load increases, which can lead to its wear or destruction [4, 5].

All types of slings have a margin of strength in relation to the breaking load from 4 to 6, depending on the material from which they are made. The margin of strength is necessary to prevent damage or breakage of slings under dynamic loads, which may be several times higher than static ones [6] (for example, when one of the branches of a multi-link sling is suddenly lifted or broken).

During such works, one of the main requirements is their safety. in accordance with the «Rules of labor protection during loading and unloading operations», as well as the requirements of NPAOP 0.00-1.80-18 [7], before using lifting slings or other relevant persons, they are required to inspect them.

But, despite the presence of such mandatory safety measures, during cargo transportation, one of the sling branches may be destroyed due to the presence of a dynamic component during the operation of the crane, or errors of the slinger when attaching the cargo. It is also not possible to exclude the presence of hidden internal or unnoticed defects in the construction of the sling itself.

In the work, there is a case of destruction of one of the branches of a two-rope sling during the transportation of a long product by a tower crane.

Today, various systems are being developed that function to increase the safety of using tower cranes. The task of reducing the swinging of the load when the rope breaks has been studied in many works by scientists around the world [6, 8–11]. At the same time, it should be noted that in known studies, insufficient attention is paid to the dynamic description of failure modes of cable systems within the framework of establishing and solving differential-algebraic levels (hereinafter DAR), which determines the relevance of this work.

The aim of research is to apply the effect of vibration damping on the relative deflection angles of flexible stretched links of a two-link pendulum in the vertical plane.

2. Materials and Methods

The calculation services.mscdiagram of the break of one branch of the sling is shown in Fig. 1 where $AB = l_1 = 0.3$ m and $BC = l_2 = 0.3$ m are models of stretched weightless cable links, and the point masses of the bodies are $m_B = m_1 = 0.01$ kg and $m_c = m_2 = 0.15$ kg. There is no friction at the suspension points. To build a nonlinear mathematical DAR model, let's use Lagrange equations of the second kind [8–10]. In our case, the coordinates are generalized q_i and generalized speeds dq_i/dt let's take the relative deviation angles of the stretched pendulum threads β and γ, and relative angular velocities of the links $d\beta/dt$; $d\gamma/dt$.

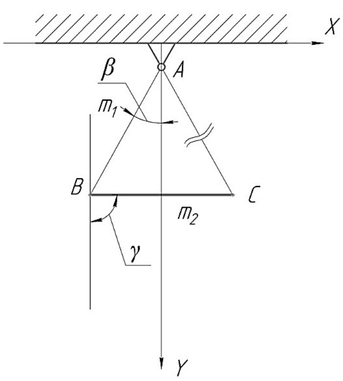

Fig. 1. Model of a sling break

Let's introduce the Cartesian coordinate system Oxy, the origin of which coincides with the suspension point of the cable AB. The coordinates of the oscillating masses are determined by the following relations for the holonomic geometric restraining bonds in this problem:

$$x_1 = l_1\sin(\beta);\; y_1 = l_1\cos(\beta);$$
$$x_2 = -l_1\sin(\beta) + l_2\sin(\gamma);$$
$$y_2 = l_1\cos(\beta) + l_2\cos(\gamma), \qquad (1)$$

where x_1 – the abscissa of the position of point B in the Cartesian coordinate system; x_2 – the abscissa of the position of point C in the Cartesian coordinate system; y_1 – the ordinate of the position of point B in the Cartesian coordinate system; y_2 – the ordinate of the position of point C in the Cartesian coordinate system.

Kinetic T_1 and potential V_1 energy of the first pendulum are expressed by formulas:

$$T_1 = \frac{m_1 l_1^2 \dot\beta^2}{2};$$
$$V_1 = m_1 g l_1 (1 - \cos(\beta)), \qquad (2)$$

where $\dot\beta$ – the first-time derivative of the deflection angle of pendulum I; g – acceleration of gravity 9.81 m/s^2.

Kinetic T_2 and potential V_2 energy of the second pendulum are expressed by the formulas:

$$\dot x_2 = -l_1\cos(\beta)\dot\beta + l_2\cos(\gamma)\dot\gamma;$$
$$\dot y_2 = -l_1\sin(\beta)\dot\beta - l_2\sin(\gamma)\dot\gamma;$$
$$\dot x_2^2 = l_2^2\cos^2(\gamma)\dot\gamma^2 + l_1^2\cos^2(\beta)\dot\beta^2 - 2l_1l_2\dot\beta\dot\gamma\cos(\beta)\cos(\gamma);$$
$$\dot y_2^2 = l_2^2\sin^2(\gamma)\dot\gamma^2 + l_1^2\cdot\sin^2(\beta)\dot\beta^2 + 2l_1l_2\dot\beta\dot\gamma\sin(\beta)\sin(\gamma);$$
$$\dot x_2^2 + \dot y_2^2 = l_1^2\dot\beta^2 + l_2^2\dot\gamma^2 - 2l_1l_2\dot\beta\dot\gamma s\cos(\beta+\gamma);$$
$$V_2 = m_1 g(l_1 + l_2) - m_2 g y_2 =$$
$$= m_2 g(l_1 + l_2) - m_2 g l_1\cos(\beta) - m_2 g l_2\cos(\gamma), \qquad (3)$$

where $\dot x_2$ – the first-time derivative of the abscissa of point C; $\dot y_2$ – the first-time derivative of the ordinate of point C; $\dot\gamma$ – the first-time derivative of the deflection angle of pendulum II.

Then the Lagrangian L has the following form:

$$L = \frac{m_1 l_1^2\dot\beta^2}{2} + \frac{m_2 l_1^2\dot\beta^2}{2} + \frac{m_2 l_2^2\dot\gamma^2}{2} - m_2 l_1 l_2\dot\beta\dot\gamma\cos(\beta+\gamma) +$$
$$+ m_1 g l_1\cos(\beta) + m_2 g l_1\cos(\beta) + m_2 g l_2\cos(\gamma). \qquad (4)$$

The first Lagrange equation (HDE I):

$$\frac{\partial L}{\partial \beta} = -m_1 g l_1\sin(\beta) - m_2 g l_1\sin(\beta) + m_2 l_1 l_2\dot\beta\dot\gamma\sin(\beta+\gamma);$$
$$\frac{\partial L}{\partial \dot\beta} = m_1 l_1^2\dot\beta + m_2 l_1^2\dot\beta - m_2 l_1 l_2\dot\gamma\cos(\beta+\gamma);$$
$$\frac{d}{dt}\frac{\partial L}{\partial \dot\beta} = m_1 l_1^2\ddot\beta + m_2 l_1^2\ddot\beta - m_2 l_1 l_2\ddot\gamma\cos(\beta+\gamma) +$$
$$+ m_2 l_1 l_2\dot\gamma\sin(\beta+\gamma)(\dot\beta+\dot\gamma), \qquad (5)$$

where $\ddot\beta$ – the second derivative of the time of the angle of deviation of the pendulum I; $\ddot\gamma$ – the second derivative of the time of the angle of deviation of the pendulum II.

Lagrange's second equation (HDE II):

$$\frac{\partial L}{\partial \gamma} = -m_2 g l_2\sin(\gamma) + m_2 l_1 l_2\dot\beta\dot\gamma\sin(\beta+\gamma);$$
$$\frac{\partial L}{\partial \dot\gamma} = m_2 l_2^2\dot\gamma - m_2 l_1 l_2\dot\beta\cos(\beta+\gamma);$$
$$\frac{d}{dt}\frac{\partial L}{\partial \dot\gamma} = m_2 l_2^2\ddot\gamma - m_2 l_1 l_2\ddot\beta\cos(\beta+\gamma) +$$
$$+ m_2 l_1 l_2\dot\beta\sin(\beta+\gamma)(\dot\beta+\dot\gamma). \qquad (6)$$

By shortening HDE I an $m_1 l_1^2 \neq 0$ and HDE II an $m_2 l_2^2 \neq 0$ a system of differential equations is obtained:

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$$\begin{cases} \ddot{\beta}\left(1+\dfrac{m_2}{m_1}\right)-\dfrac{g-m_2 g}{l_1}\sin(\beta)+\dfrac{m_2 l_2}{m_1 l_1}(-\ddot{\gamma}\cos(\beta+\gamma)+\dot{\gamma}^2\sin(\beta+\gamma)=0; \\ \ddot{\gamma}-\dfrac{g}{l_2}\sin(\gamma)-\dfrac{l_2}{l_1}(\ddot{\beta}\cos(\beta+\gamma)-\dot{\beta}^2\sin(\beta+\gamma))=0. \end{cases} \quad (7)$$

Using system (7), the trajectory of the double pendulum was obtained as a result of the break of one branch of the sling (Fig. 2).

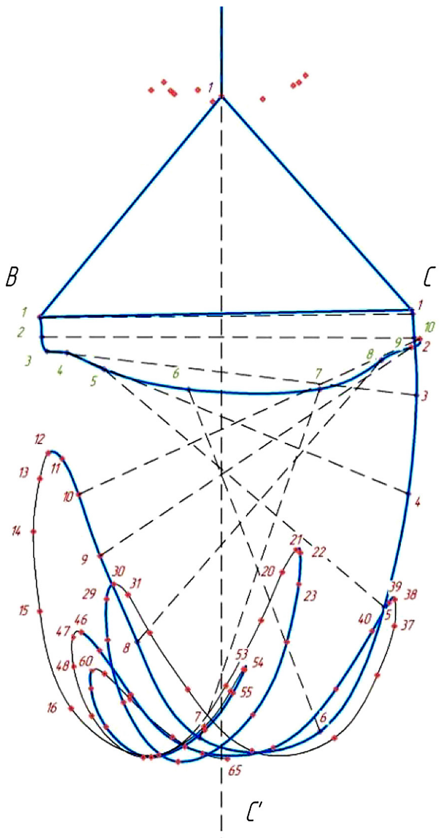

Fig. 2. Trajectory of cargo movement when one branch of the sling is broken

Point C' is the final position of point C before the moment of rest of the double pendulum system.

3. Results and Discussion

As a result of the study of a separate case of damping oscillation of a double pendulum (Fig. 3), it was established that the main «leading» link of oscillations is pendulum II due to its greater mass compared to pendulum I. Upon further observation, the system passes into the state of a single pendulum. The value $\gamma \approx 0$ and does not contribute to the oscillations of pendulum I.

Therefore, the system has the form of a single pendulum with the length of suspension l1 and mass m_1+m_2.

The obtained results of the study make it possible to analyze the behavior of the cargo in the event of a sling break, which is an emergency situation, and to implement increased criteria for checking equipment before operation and unconditional compliance with everyone's safety rules. Also, by analyzing the cargo behavior, it is possible to implement a plan of actions that the crane operator should perform in the event of a sling break.

The result in the form of relative deviation angles is obtained by solving the system of differential equations (7), and is a special case of the solution. Since this system of differential equations describes the oscillations of a double pendulum regardless of friction, this system will move infinitely long and will not decay, as the pendulums will significantly influence each other's behavior.

The main limitations of this method are considering the double pendulum system not as a joint movement of pendulums, but two separate pendulums connected in series. Taking into account their mutual influence in the transient moments of oscillation, as the pendulums move in antiphase. Also, in the considered method, pendulums represent a concentrated mass at the ends of weightless inextensible suspensions.

The introduction of martial law in Ukraine had a significant impact on research activities. Due to the closure of some roads and railways, difficulties arose with the delivery of equipment and materials for the experiment. It was also more difficult to ensure the safety of the experiment participants during their movement. Blocking of some Internet resources limited participants' access to necessary information. It was more difficult to analyze the obtained results due to the change in mood of the participants. Martial law led to increased anxiety and stress in many people, which may have affected the results. Despite these difficulties, the study was carried out in full.

The direction of the following studies is the selection of the main transitional moments of damping of the oscillation of a two-link mathematical pendulum, namely the time when the value of the angle of deviation takes the maximum value – extrema.

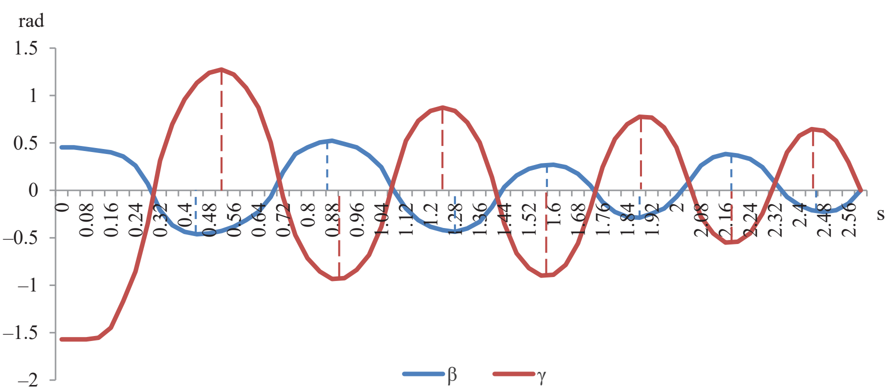

Fig. 3. Angles of deflection of pendulums

The prospect of further research is to increase the scope of the study, namely to consider the tower crane as a whole and to analyze the behavior of the tower, boom and cart at the moment of breaking the sling.

4. Conclusions

In the work, a nonlinear mathematical model of a two-link mathematical pendulum oscillating in a vertical plane under the action of gravitational forces is constructed and numerically analyzed. The analysis of the conducted experiment revealed the influence of the angle of deflection of the pendulum two γ on the angle of deflection of the pendulum one β due to the significant difference in masses. Based on the obtained values of the relative angles of deviation, it can be seen that the difference between the extrema β and γ becomes smaller and smaller over time.

As the numerical simulation of a separate case of damping oscillation of a double pendulum showed, pendulum II takes part in oscillation not immediately after the interruption of the *AC* section, but after an hour of 0.12 seconds, which is 13.6 % of the oscillation period of pendulum I. This allows to conclude that there is a possible considering the simultaneous start of the movement of pendulums.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

This manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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