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CONSTRUCTION OF PHYSICAL MODEL OF JIB CRANE ROTATION MECHANISM, PROGRAM AND DESCRIPTION OF EXPERIMENTAL STUDIES

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Abstract. This article outlines the main provisions of the program, methodology, description of the object of experimental studies and construction of a physical model of the jib crane rotation mechanism.

A real QTZ 80 crane has been chosen for the study, which differs from the laboratory installation (physical model) of the jib crane rotation mechanism by structural, power and energy parameters, for this reason, experimental studies used physical modeling, which usually changes the scale and leaves the physical nature of phenomena. Therefore, similarity theory is used to determine the characteristics of the physical model.

A physical model (laboratory unit) of the jib crane rotation mechanism was designed to conduct experimental studies on the similarity theory. This model is prepared for experimental studies of the dynamics of the rotation mechanism during the start-up process. To determine the similarity criteria, equations of motion were used that reflect the operation of the jib crane rotation mechanism, namely the three-mass dynamic model of the rotation mechanism, which is a system of three second-order differential equations.

Using the obtained ratios of similarity criteria, the numerical values of the similarity coefficients of the real rotation mechanism of the jib crane and its physical model are determined.

Based on the parameters obtained, a physical model of a full-scale jib crane rotation mechanism was constructed.

The results obtained in this study can be further used to refine and improve existing engineering methods for calculating the mechanisms of rotation of cranes, both at the stages of their design/construction, and in real operation.

Key words: rotation mechanism, experimental studies, dynamic loads, oscillations, physical model, similarity coefficients, jib crane.

Introduction

During the operation of the jib crane rotation mechanism, load oscillations on the flexible suspension occur, and significant dynamic loads can be observed in the structure and drive [1]. To minimize these processes, the process of start-up of the rotation mechanism of jib crane was optimized [2-4].

Formulation of problem

Optimization made it possible to minimize unwanted processes in the drive, metal structures and load oscillations [5]. To confirm the studies, it is necessary to conduct experimental studies on a physical model (laboratory installation) of a jib crane with a rotation mechanism. For this, it is necessary to develop a model of the rotation mechanism. To create an experimental setup, we apply the theory of similarity, based on which we determine the coefficients of similarity to a real jib crane.

Analysis of recent research results

Physical modeling is widely used in experimental studies. Physical modeling preserves the physical nature of phenomena, but changes their scale.

In order for the processes that arise in the process of loading and unloading operations in the metal structures and mechanisms of jib cranes to be similar to the original, the model must meet a number of requirements of the theory of modeling [6-16], which follow from the main theorems and provisions of the theory of similarity.

The basis of physical modeling is the theory of similarity, which is based on dimensional analysis [17]. A necessary and sufficient condition of similarity is the equality of all the same criteria of similarity for two physical phenomena. Dimensionless similarity criteria must be equal. Under the condition of known equations describing the physical process, the similarity criteria are formed by reducing these equations to a dimensionless criterion form [18]. Considerable attention is paid to the construction of physical and mathematical models of technical systems in the articles [17, 18, 19]. The general theory of dimensions of physical quantities, the theory of mechanical and physical similarity, as well as the theory of modeling are given in the article [20]. The book [21] contains the basics of theory and recommendations for practical applications of experimental studies on full-scale objects, as well as on physical, analog, digital and mathematical models. General principles of analysis of physical similarity and its connection with the construction of mathematical models are set out in the article [22].

The article [23] considers the construction of interpolation models, the study of the kinetics and mechanism of phenomena, and optimization of processes.

The article [24] provides information about science, methods to justify the topic of theoretical and experimental research, means and methods of measurements, analysis and features of the processing of research results, methods of implementation and calculation of economic efficiency. The issues of planning and organization of scientific studies are highlighted.

Purpose of research

The aim of the work is to determine the coefficients of similarity of the model to the jib system with the rotation mechanism of a real crane using the similarity theory for further experimental study.

Research results

The obtained theoretical results in the articles [1-5] require confirmation and experimental verification, so there is a need for experimental studies of the dynamics of the mechanism of rotation of the jib crane at different control modes.

The purpose of experimental studies is to measure the actual parameters and dependences of the kinematic, dynamic and energy characteristics during the operation of the mechanism of rotation of the jib crane, as well as the oscillations of the load on a flexible suspension.

Since the use of a full-scale model of a real jib crane for a number of certain reasons is difficult and practically impossible, it is recommended to conduct experimental studies on a physical model of a jib crane, which will reproduce the rotation process of the crane. The QTZ-80 jib crane was chosen as a prototype [25]. The QTZ-80 jib crane was chosen as the prototype [25]. Based on similarity theory, the coefficients of the similarity of a real jib crane are determined and its physical model is constructed.

The experimental research program is divided into several stages:

- building of a physical model of the jib crane rotation mechanism and determination of similarity coefficients;
- construction of a physical model of a jib crane for experimental studies;
- planning experiments to study the dynamics of the jib crane rotation mechanism under various control modes (manual and optimal)
- selection of measuring and recording equipment for studying the dynamics of movement of the jib crane rotation mechanism under various control modes;
- writing a program and selection of equipment that provides the implementation of optimal modes of movement when controlling the jib crane rotation mechanism.

Physical modeling is the process of creating a material model that has the same physical nature (the same physical meaning) as the actual studied phenomenon, based on the criteria of geometric, kinematic and dynamic modeling [26].

The task of physical modeling is to determine the characteristics of a full-scale object according to the characteristics of the physical model. The peculiarity of physical modeling is that to determine the characteristics of a full-scale object, a mathematical description of the processes is not required, it is enough just to have an idea of the mechanism (physical nature) of the phenomena in order to correctly calculate the parameters of a full-scale object according to the test data of the physical model. In physical modeling, the physical nature of the phenomena occurring in a full-scale object and model is unchanged. The physical modeling is based on the theory of similarity. Separate types of physical similarity are: geometric (similarity of similar geometric elements); kinematic (similarity of the velocity fields for the two considered motions); dynamic (similarity of systems of acting forces or force fields of different physical nature – gravity, pressure, etc.); mechanical (assumes the presence of geometric, kinematic and dynamic similarity).

Physical modeling consists of two stages:

- theoretical reproduction on the model of the investigated physical phenomenon or technical device (including constructions and structures) similar to a full-scale sample;
- construction of the models and performing the necessary observations and measurements on them.
- the theory of modeling based on the theory of similarity [26-28].

“Physical phenomena of one class are called similar, when all characteristic quantities are similar, i.e. all vector quantities are geometrically similar, and all scalar quantities are correspondingly proportional.

Necessary and sufficient conditions of similarity:

phenomena that are similar in one sense or another (complete, approximate, physical, mathematical, etc.), have certain combinations of parameters, called similarity criteria, and which are numerically identical for similar phenomena;

any complete equation of a physical process, which is written in a certain system of units, can be represented by a functional dependence between the similarity criteria, which are formed from the parameters that characterize the process;

necessary and sufficient conditions for the similarity of phenomena that are then compared are the proportionality of the relevant parameters included in the single-valuedness conditions of mathematical models of these phenomena, as well as the equality of criteria for the similarity of these phenomena"[29].

To conduct experimental studies, a physical model of the jib crane rotation mechanism was constructed [30], the 3D model of which is shown in Fig. 1 and the scheme of the jib crane is shown in Fig. 2.

For the study, a real QTZ-80 crane was selected, which differs from the laboratory installation (physical model) of the jib crane rotation mechanism by its structural, power and energy parameters, therefore, physical modeling was used in experimental studies, which usually changes the scale and leaves the physical nature of the phenomena. Therefore, the similarity theory is applied to determine the characteristics of the physical model.

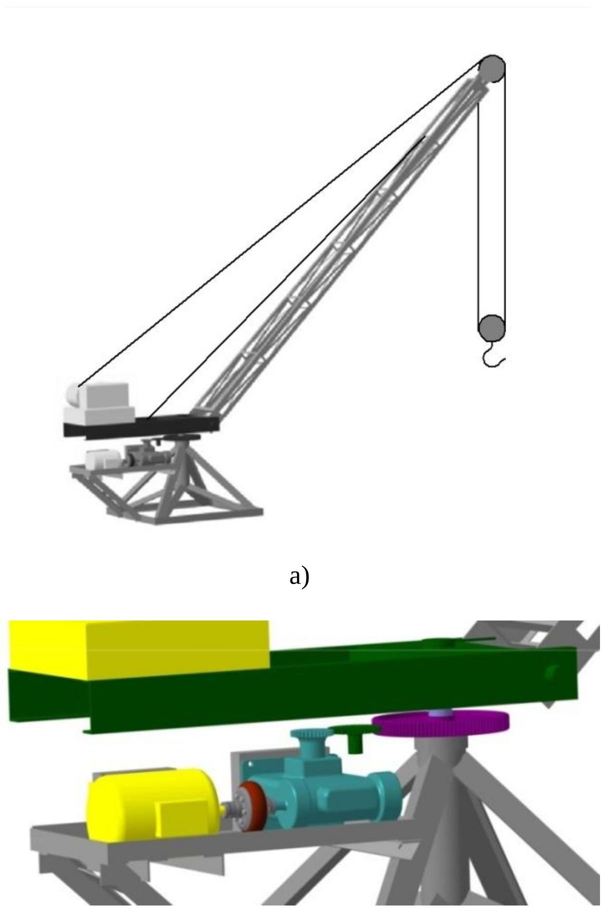

Fig. 1. Scheme of the laboratory installation of the jib crane: a) general view of the crane; b) the mechanism of rotation of the jib crane.

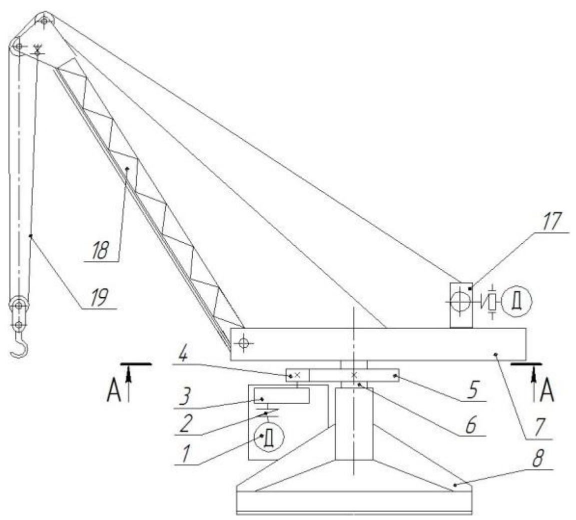

Fig. 2. Jib crane: 1 – engine; 2 – elastic coupling; 3 – reducer; 4 – gear; 5 – slewing ring; 6 – rotary shaft; 7 – rotary part; 8 – frame.

A three-mass dynamic model of the jib crane rotation mechanism was used (Fig. 3).

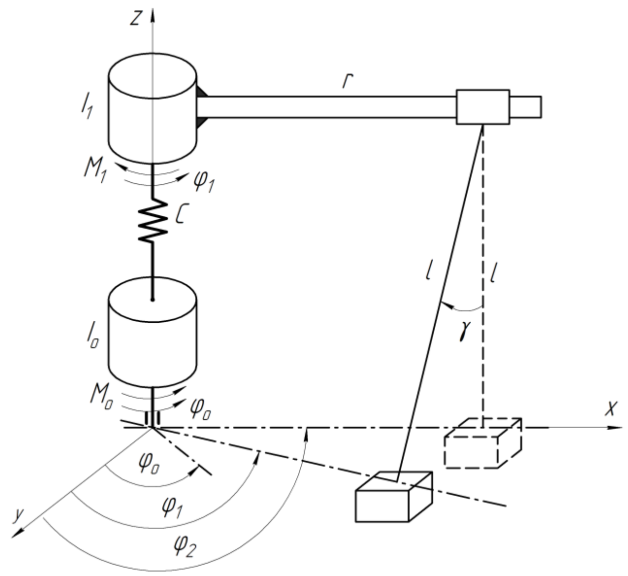

Fig. 3. Dynamic model of the rotation mechanism.

In this model the following designations are accepted: m – weight of load on a flexible suspension; I_O, I_1 – moments of inertia of the drive mechanism and the rotary part are reduced to the axis of rotation of the crane; M_O, M_1 – the driving moment on the motor shaft and the moment of resistance forces are reduced to the axis of rotation of the crane; φ_O, φ_1, φ_2, – angular coordinates of rotation of the rotor of the electric motor, rotary part of the crane and load, which are taken as generalized coordinates; C – the stiffness coefficient of the drive mechanism, reduced to the axis of rotation of the crane; r – derricking mechanism; l – length of a flexible suspension of load; γ –the angular coordinate of the deviation of the traction rope from the vertical; g – free fall acceleration.

Based on the dynamic model, a mathematical model was compiled, which is a system of three second-order differential equations:

$$\begin{cases} I_0 \dfrac{d^2\varphi_0}{dt^2} = \dfrac{M_n \lambda u \eta}{2} - c(\varphi_0 - \varphi_1); \\ I_1 \dfrac{d^2\varphi_1}{dt^2} = c(\varphi_0 - \varphi_1) - mr^2 \dfrac{g}{l}(\varphi_1 - \varphi_2) - M_1; \\ \dfrac{d^2\varphi_2}{dt^2} = \dfrac{g}{l}(\varphi_1 - \varphi_2). \end{cases} \quad (1)$$

The parameters in the system of equations are designated by the following indices for a real crane "n", for a physical model "m".

Expressing the parameters of a real system through the corresponding parameters of its physical model and similarity coefficients, it was obtained:

$$\begin{cases} I_{0n} = \nu_I I_{0m}; I_{1n} = \nu_I I_{1m}; \\ M_{nn} = \nu_M M_{nm}; M_{1n} = \nu_M M_{1m}; \\ m_n = \nu_m m_m; l_n = \nu_l m_l; r_n = \nu_l r_m; \\ \lambda_n = \nu_\lambda \lambda_m; u_n = \nu_u u_m; \eta_n = \nu_\eta \eta_m; c_n = \nu_c c_m; t_n = \nu_t t_m; \\ \varphi_{0n} = \nu_\varphi \varphi_{0m}; \varphi_{1n} = \nu_\varphi \varphi_{1m}; \varphi_{2n} = \nu_\varphi \varphi_{2m}. \end{cases} \quad (2)$$

where ν_I; ν_m; ν_M; ν_λ; ν_u; ν_η; ν_c; ν_l; ν_t; ν_φ – similarity coefficients; I_{0n}; I_{1n}; m_n; M_{nn}; M_{1n}; λ_n; u_n; η_n; c_n; l_n; r_n; t_n; φ_{0n}; φ_{1n}; φ_{2n} – parameters of the real crane; I_{0m}; I_{1m}; m_m; M_{nm}; M_{1m}; λ_m; u_m; η_m; c_m; m_l; r_m; t_m; φ_{0m}; φ_{1m}; φ_{2m} – parameters of the crane model.

Equation (1), taking into account expressions (2) for a full-scale sample and a physical model of the rotation mechanism, have the form:

$$\begin{cases} I_{0n}\dfrac{d^2\varphi_{0n}}{dt_n^2}=\dfrac{1}{2}M_{nn}\lambda_n u_n\eta_n - c_n(\varphi_{0n}-\varphi_{1n}); \\ I_{0m}\dfrac{d^2\varphi_{0m}}{dt_m^2}=\dfrac{1}{2}M_{nm}\lambda_m u_m\eta_m - \\ - c_m(\varphi_{0m}-\varphi_{1m}). \end{cases} \tag{3}$$

$$\begin{cases} I_{1n}\dfrac{d^2\varphi_{1n}}{dt_n^2}=c_n(\varphi_{0n}-\varphi_{1n}) - \\ - m_n r_n^2\dfrac{g}{l_n}(\varphi_{1n}-\varphi_{2n}) - M_{1n}; \\ I_{1m}\dfrac{d^2\varphi_{1m}}{dt_m^2}=c_m(\varphi_{0m}-\varphi_{1m}) - \\ - m_m r_m^2\dfrac{g}{l_m}(\varphi_{1m}-\varphi_{2m}) - M_{1m}. \end{cases} \tag{4}$$

$$\begin{cases} \dfrac{d^2\varphi_{2n}}{dt_n^2}=\dfrac{g}{l_n}(\varphi_{1n}-\varphi_{2n}); \\ \dfrac{d^2\varphi_{2m}}{dt_m^2}=\dfrac{g}{l_m}(\varphi_{1m}-\varphi_{2m}). \end{cases} \tag{5}$$

We divide the components of equations (3), (4) and (5) for a real mechanism and a physical model and equate them, as a result we get:

$$\begin{cases} \dfrac{I_{0n}\dfrac{d^2\varphi_{0n}}{dt_n^2}}{I_{0m}\dfrac{d^2\varphi_{0m}}{dt_m^2}}=\dfrac{\frac{1}{2}M_{nn}\lambda_n u_n\eta_n}{\frac{1}{2}M_{nm}\lambda_m u_m\eta_m}= \\ =\dfrac{c_n(\varphi_{0n}-\varphi_{1n})}{c_m(\varphi_{0m}-\varphi_{1m})}; \\ \dfrac{I_{1n}\dfrac{d^2\varphi_{1n}}{dt_n^2}}{I_{1m}\dfrac{d^2\varphi_{1m}}{dt_m^2}}=\dfrac{c_n(\varphi_{0n}-\varphi_{1n})}{c_m(\varphi_{0m}-\varphi_{1m})}= \\ =\dfrac{m_n r_n^2\dfrac{g}{l_n}(\varphi_{1n}-\varphi_{2n})}{m_m r_m^2\dfrac{g}{l_m}(\varphi_{1m}-\varphi_{2m})}=\dfrac{M_{1n}}{M_{1m}}; \\ \dfrac{\dfrac{d^2\varphi_{2n}}{dt_n^2}}{\dfrac{d^2\varphi_{2m}}{dt_m^2}}=\dfrac{\dfrac{g}{l_n}(\varphi_{1n}-\varphi_{2n})}{\dfrac{g}{l_m}(\varphi_{1m}-\varphi_{2m})}. \end{cases} \tag{6}$$

After that, we express the parameters and characteristics of the real rotation mechanism through the parameters and characteristics of the physical model, using for this the dependencies (2), which give:

$$\begin{aligned} &\dfrac{\nu_I I_{0m}\dfrac{d^2(\nu_\varphi\varphi_{0m})}{d(t_m\nu_t)^2}}{I_{0m}\dfrac{d^2\varphi_{0m}}{dt_m^2}}=\dfrac{\nu_M M_{nm}\nu_\lambda\lambda_m\nu_u u_m\nu_\eta\eta_m}{M_{nm}\lambda_m u_m\eta_m}= \\ &=\dfrac{\nu_c c_m(\nu_\varphi\varphi_{0m}-\nu_\varphi\varphi_{1m})}{c_m(\varphi_{0m}-\varphi_{1m})}; \\ &\dfrac{\nu_I I_{1m}\dfrac{d^2(\nu_\varphi\varphi_{1m})}{d(t_m\nu_t)^2}}{I_{1m}\dfrac{d^2\varphi_{1m}}{dt_m^2}}=\dfrac{\nu_c c_m(\nu_\varphi\varphi_{0m}-\nu_\varphi\varphi_{1m})}{c_m(\varphi_{0m}-\varphi_{1m})}= \\ &=\dfrac{\nu_m m_m(\nu_l r_m)^2\dfrac{1}{\nu_l l_m}(\nu_\varphi\varphi_{1m}-\nu_\varphi\varphi_{2m})}{m_m r_m^2\dfrac{1}{l_m}(\varphi_{1m}-\varphi_{2m})}=\dfrac{\nu_M M_{1m}}{M_{1m}}; \\ &\dfrac{\dfrac{d^2(\nu_\varphi\varphi_{2m})}{d(t_m\nu_t)^2}}{\dfrac{d^2\varphi_{2m}}{dt_m^2}}=\dfrac{\dfrac{1}{\nu_l l_m}(\nu_\varphi\varphi_{1m}-\nu_\varphi\varphi_{2m})}{\dfrac{1}{l_m}(\varphi_{1m}-\varphi_{2m})}. \end{aligned} \tag{7}$$

In the resulting equations (7), we remove the differentiation operations, since they do not affect, after which we will have:

$$\frac{\nu_I I_{0m}\frac{\nu_\varphi \varphi_{0m}}{t_m^2\nu_t^2}}{I_{0m}\frac{\varphi_{0m}}{t_m^2}} = \frac{\nu_M M_{nm}\nu_\lambda\lambda_m\nu_u u_m \nu_\eta \eta_m}{M_{nm}\lambda_m u_m \eta_m} = \frac{\nu_c c_m(\nu_\varphi\varphi_{0m}-\nu_\varphi\varphi_{1m})}{c_m(\varphi_{0m}-\varphi_{1m})};$$

$$\frac{\nu_I I_{1m}\frac{\nu_\varphi\varphi_{1m}}{t_m^2\nu_t^2}}{I_{1m}\frac{\varphi_{1m}}{t_m^2}} = \frac{\nu_c c_m(\nu_\varphi\varphi_{0m}-\nu_\varphi\varphi_{1m})}{c_m(\varphi_{0m}-\varphi_{1m})} = \frac{\nu_m m_m(\nu_l r_m)^2\frac{1}{\nu_l l_m}(\nu_\varphi\varphi_{1m}-\nu_\varphi\varphi_{2m})}{m_m r_m^2\frac{1}{l_m}(\varphi_{1m}-\varphi_{2m})} = \frac{\nu_M M_{1m}}{M_{1m}};$$

$$\frac{\frac{\nu_\varphi\varphi_{2m}}{t_m^2\nu_t^2}}{\frac{\varphi_{2m}}{t_m^2}} = \frac{\frac{1}{\nu_l l_m}\nu_\varphi(\varphi_{1m}-\varphi_{2m})}{\frac{1}{l_m}(\varphi_{1m}-\varphi_{2m})}. \tag{8}$$

As a result of certain mathematical transformations and reductions, we obtain the ratio between the similarity coefficients [30]:

$$\frac{\nu_I\nu_\varphi}{\nu_t^2} = \nu_M\nu_\lambda\nu_u\nu_\eta = \nu_c\nu_\varphi; \tag{9}$$

$$\frac{\nu_I\nu_\varphi}{\nu_t^2} = \nu_c\nu_\varphi = \nu_m\nu_l\nu_\varphi; \tag{10}$$

$$\frac{\nu_\varphi}{\nu_t^2} = \frac{\nu_\varphi}{\nu_l}. \tag{11}$$

Analyzing expressions (9), (10) and (11), the following dependences were obtained:

$$\begin{cases} \frac{\nu_I\nu_\varphi}{\nu_t^2} = \nu_m\nu_\lambda\nu_u\nu_\eta; \frac{\nu_I\nu_\varphi}{\nu_t^2} = \nu_c; \\ \frac{\nu_I}{\nu_t^2} = \nu_m\nu_l; \frac{1}{\nu_t^2} = \frac{1}{\nu_l} \rightarrow \nu_t^2 = \nu_l. \end{cases} \tag{12}$$

A system of four equations (12) was obtained with eight unknown similarity coefficients. Therefore, the four similarity coefficients are set arbitrarily, and the remaining four coefficients are determined from the system of equations (12). The numerical values of all eight similarity coefficients are summarized in table 1.

Thus, the obtained ratios of the coefficients of similarity of the rotation mechanism of the jib crane make it possible, according to the parameters of a real crane, to read the parameters of its physical model.

Table 1. The value of the similarity coefficients of the physical model of the jib crane

Parameter name	Value of the similarity coefficient
Jib length	10.6
Length of a flexible suspension	18.5
Weight of load	50
Time	4.3
Gear ratio	1.205
Efficiency	1.25
Moment of the inertia of the rotation part of the crane	12052.668
Moment of the inertia of the rotation mechanism drive	8.42

Based on the parameters obtained, a physical model of the full-scale rotation mechanism of the QTZ 80 jib crane was constructed (Fig. 4), the main parameters of which are given in Table. 2.

Fig. 4. Physical model of the jib crane rotation mechanism

Table 2. The main parameters of the physical model of the mechanism of rotation of the jib crane

Parameter name	Unit of measurement	Parameter value
Jib length	m	3.75
Length of a flexible suspension	m	2.7
Weight of load	kg	40
Gear ratio	-	1124.9
Efficiency	-	0.69
Moment of the inertia of the jib	kg·m^2	408.27
Moment of the inertia of the drive	kg·m^2	8503.5

Conclusions

1. A physical model of the jib crane rotation mechanism has been developed to conduct experimental studies on similarity theory. To determine the similarity criteria, the equations of motion dynamics were used, which reflect the process of operation of the jib crane rotation mechanism.

2. Using the similarity criteria, the numerical values of the similarity coefficients of the real rotation mechanism of the jib crane and its physical model are determined.

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КОНСТРУКЦІЯ ФІЗИЧНОЇ МОДЕЛІ МЕХАНІЗМУ ОБЕРТАННЯ КРАНА, ПРОГРАМА ТА ОПИС ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ

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Анотація. У цій статті викладено основні положення програми, методику, опис об’єкта експериментальних досліджень та побудову фізичної моделі механізму обертання стрілового крана.

Для дослідження було обрано справжній кран QTZ 80, який відрізняється від лабораторної установки (фізичної моделі) механізму повороту стрілового

крана за конструктивними, силовими та енергетичними параметрами, тому в експериментальних дослідженнях використовувалося фізичне моделювання, яке зазвичай змінює масштабу і залишає фізичну природу явищ. Тому для визначення характеристик фізичної моделі використовується теорія подібності.

Для проведення експериментальних досліджень теорії подібності розроблено фізичну модель (лабораторний блок) механізму обертання стрілового крана. Ця модель підготовлена для експериментальних досліджень динаміки механізму обертання в процесі пуску. Для визначення критеріїв подібності використано рівняння руху, що відображають роботу механізму повороту стрілового крана, а саме тримасову динамічну модель механізму обертання, що є системою трьох диференціальних рівнянь другого порядку.

Використовуючи отримані співвідношення критеріїв подібності, визначено чисельні значення коефіцієнтів подібності реального механізму повороту стрілового крана та його фізичної моделі.

На основі отриманих параметрів побудовано фізичну модель натурного механізму обертання стрілового крана.

Результати, отримані в даному дослідженні, можуть бути в подальшому використані для уточнення та вдосконалення існуючих інженерних методів розрахунку механізмів обертання кранів, як на етапах їх проектування/конструювання, так і в реальній експлуатації.

Ключові слова: механізм обертання, експериментальні дослідження, динамічні навантаження, коливання, фізична модель, коефіцієнти подібності, стріловий кран.

КОНСТРУКЦИЯ ФИЗИЧЕСКОЙ МОДЕЛИ МЕХАНИЗМА ВРАЩЕНИЯ КОНСОЛЬНОГО КРАНА, ПРОГРАММА И ОПИСАНИЕ ЭКСПЕРИМЕНТАЛЬНЫХ ИССЛЕДОВАНИЙ

В. С. Ловейкин, Ю. А. Ромасевич, И. А. Кадыкало

Аннотация. В данной статье изложены основные положения программы, методика, описание объекта экспериментальных исследований и построение физической модели механизма поворота стрелового крана.

Для исследования был выбран реальный кран QTZ 80, который отличается от лабораторной установки (физической модели) механизма поворота стрелового крана конструктивными, силовыми и энергетическими параметрами, по этой причине в экспериментальных исследованиях применялось физическое моделирование, которое обычно изменяет масштаб и оставляет физическую природу явлений. Поэтому для определения характеристик физической модели используется теория подобия.

Для проведения экспериментальных исследований по теории подобия была создана физическая модель (лабораторная установка) механизма поворота стрелового крана. Данная модель подготовлена для экспериментальных исследований динамики механизма вращения в процессе пуска. Для определения критериев подобия использовались уравнения движения, отражающие работу механизма поворота стрелового крана, а именно трехмассовая динамическая модель механизма поворота, представляющая собой систему трех дифференциальных уравнений второго порядка.

С помощью полученных соотношений критериев подобия определяются численные значения коэффициентов подобия реального механизма поворота стрелового крана и его физической модели.

На основе полученных параметров построена физическая модель натурного механизма поворота стрелового крана.

Результаты, полученные в данном исследовании, могут быть в дальнейшем использованы для уточнения и совершенствования существующих инженерных методов расчета механизмов поворота кранов, как на этапах их проектирования/строительства, так и в условиях реальной эксплуатации.

Ключевые слова: механизм вращения, экспериментальные исследования, динамические нагрузки, колебания, физическая модель, коэффициенты подобия, стреловой кран.

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