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EXPRESS MONITORING OF TECHNICAL CONDITION OF TOWER CRANE ON THE BASIS OF INTEGRAL-DIFFERENTIAL APPROACH

ЭКСПРЕСС-МОНИТОРИНГ ТЕХНИЧЕСКОГО СОСТОЯНИЯ БАШЕННОГО КРАНА НА ОСНОВЕ ИНТЕГРАЛЬНО-ДИФФЕРЕНЦИАЛЬНОГО ПОДХОДА

The article presents a method for calculating the technical condition of the tower crane on the basis of integrated monitoring of the mechanisms of the lifting structure using a digital model. The use of information technologies allows to take a new look at the issues of ensuring the safe operation of lifting mechanisms. Due to the application of these technologies, a qualitatively new method of calculating the technical condition of tower cranes on the basis of an integral-differential approach, which takes into account the score of defects, according to the regulatory documentation, is proposed. The concept of the technical condition index of the tower crane (TCItc), as an integral indicator reflecting the general condition of the nodes and mechanisms of the crane, is introduced. The use of information technologies to calculate the technical condition index of tower cranes makes it possible to integrate the geometric parameters of the tower crane and a mathematical algorithm for their evaluation, which results in a quantitative assessment of defects formed during the operation of tower cranes.

Keywords: technical condition of tower crane, defects, TCItc, information model, digital technologies, BIM-technology, technical condition index of tower cranes, integral-differential approach.

Представлен метод расчета технического состояния башенного крана на основе комплексного мониторинга механизмов подъемного сооружения с использованием цифровой модели. Использование информационных технологий позволяет по-новому взглянуть на вопросы обеспечения безопасной эксплуатации грузоподъемных механизмов. Благодаря применению данных технологий предложен качественно новый метод расчета технического состояния башенных кранов на основе интегрально-дифференциального подхода, который учитывает балльные показатели дефектов согласно нормативной документации. Введено понятие индекса технического состояния башенного крана (ИТСбк) как интегрального показателя, отражающего общее состояние узлов и механизмов крана. Использование информационной технологии для расчета индекса технического состояния башенных кранов даст возможность интегрировать геометрические параметры башенного крана и математический алгоритм для их оценки, в результате чего достигается количественная оценка дефектов, образовавшихся во время эксплуатации башенных кранов.

Ключевые слова: техническое состояние башенного крана, дефекты, ИТСбк, информационная модель, цифровые технологии, BIM-технология, индекс технического состояния башенных кранов, интегрально-дифференциальный подход.

Introduction

Using of digital technologies in construction allows us to take a new look at the situation related to the control of production processes. Technical progress leads to the search and application of new methods for assessing the safety systems and technical condition of tower cranes, which can reduce injuries associated with the use of lifting mechanisms. The tower crane is an integral part of any construction, it finds application both in civil, and in industrial construction; at erection of power and hydraulic engineering constructions, installation of designs of all types assignment. Modern construction of residential buildings involves the use of tower cranes working on rails, stationary or attached ones.

Cranes are used at unlimited heights at construction of future buildings, which involves additional risks in the field of safety and requires careful control. Regardless of the type of crane, it is necessary to carefully monitor the operation of all mechanisms and components, as well as keep up registration and systematization of identified defects in order to forecast the operation of the tower crane in the future.

Considering the research carried out on this topic [1–5], it can be concluded that tower cranes are serious sources of danger and, in the process of improper operation, they can provoke an accident and cause damage to life and health, as well as property.

In the article “Tower crane safety” ([website]. URL: <http://www.ehsdb.com/tower-crane-safety.php>) the tower crane is considered as a balancing mechanism consisting of identical parts attached to a concrete base plate, which requires careful control.

The author [6] regards such actions as installation and dismantling of tower cranes as the most dangerous tasks which may cause the loss of workers' lives or damage to buildings under construction. At the same time, the author notes that the technical condition of the tower crane and the correct operation are among the factors improving the safety of workers' life.

The authors [7] propose to optimize the location of tower cranes on construction sites by integrating geographic information systems (GIS) and building information modeling (BIM). Determining the optimal number and location of tower cranes is an important issue that can reduce conflicts between

groups of tower cranes. Using GIS facilitates the analysis of large amounts of spatial data used in the process of optimizing the location of tower cranes. In addition, the integration of GIS analysis results with three-dimensional visual models allows managers to visualize potential conflicts with tower cranes in detail. BIM helps managers to visualize a building before the process is implemented using a virtual model built digitally.

The authors [8], based on the QTZ630 tower crane, use the APDL parameter language of the software for finite element analysis of ANSYS direct modeling. Then, setting of the basic parameters of the material, mesh and static analysis is carried out. Thus, the use of modern calculation systems allows calculating the load on the tower crane during operation.

In works [9–17] the authors consider possibilities of application of digital technologies in system of data collection in regard of the tower crane condition, as well as implementation of a complex of actions allowing to prevent collision at concentration of a large number of cranes on a construction site.

At the same time, a number of authors suggest using wireless systems for remote control of tower crane operation parameters. In particular, in order to monitor the state of operation in real time and solve the problems of tower crane overload, the critical parameters are analyzed and the structure of the tower crane safety monitoring and protection system based on ARM (Advanced RISC Machine) processors is developed [11]. Thanks to this, the key information of the tower crane operation systems can be displayed in real time.

Analyzing the causes of accidents involving tower cranes, it becomes clear that the human factor is one of the most critical ones. Ensuring proper maintenance of tower crane systems, as well as employing qualified personnel, can be regarded as positive factors improving the safety of tower crane operation. However, in practice, companies sometimes employ people to work with a tower crane who are not properly trained in the basics of safe operation of lifting mechanisms.

In this regard, the authors [10] propose to use the simulation system of the tower crane based on virtual reality. This implies the use of virtual reality in the system simulate operation of the tower crane with its operational characteristics, including the following: building virtual semi-physical models

of a tower crane on the basis of three-dimensional optical measurement, the implementation stage and multi-channel display screen, work of tower crane high above the ground, a virtual simulation of the dynamics and trajectory planning of the body motion and cable tower and cargo lift in the case of multiple loads, the virtual installation and dismantling of a tower crane, an expert system for simulation and verification of the fault. All this is aimed at achieving the safe operation of tower cranes [18–25].

According to Federal Environmental, Industrial and Nuclear Supervision Service of Russia (Rostekhnadzor) for the year 2016, (Report on the activities of the Federal service for environmental, technological and nuclear supervision in 2016 [website]. URL: <https://ohranatruda.ru/news/899/585992/>), the number of deaths in accidents in the operation of lifting equipment exceeds the number of accidents approximately three times, while the “leaders” in this anti-rating are tower cranes, where 10 victims were registered for 17403 units of equipment, and the fatal injury rate was 0.57; the second place is taken by mobile cranes, respectively, 61875 units – 6 people dead, the frequency rate is 0.10; in the third place are bridge cranes — 71 648 units — 7 people dead, frequency rate — 0,10; other — on 37 984 units technology — 4 people dead, the rate of injuries — 0.31.

Referring to the statistics on the accident rate of lifting structures (Fig. 1), you can see that most of the

accidents occur on tower cranes, which may indicate the neglect of the heads of operating organizations of industrial safety rules and the requirements of norms and instructions for the safe operation of tower cranes, while injuries among workers is about 37 % of the total number of deaths on cranes [1, 26].

Analyzing the current situation with low production discipline and control over safe operation of tower cranes, and given the important role of human factor in accidents and introduction of a risk-based approach by the state in oversight and enforcement, we need qualitatively new methods of assessing the technical condition of the crane during operation with the use of modern information technology.

Existing technologies and techniques do not always allow to assess the technical condition of the tower crane, as well as to prevent a risky situation development that may lead to a stop of the tower crane and its decommissioning. This increases the relevance of monitoring the safe operation of tower cranes at hazardous production facilities. The solution to this problem can be the use of modern information systems for rapid diagnosis and prediction of risk during operation of the lifting mechanism.

The paper proposes an integral-differential approach to the assessment of the technical condition of the tower crane using modern information technology based on the software product of

Fig. 1. Distribution of accidents by types of equipment for 2016

Autodesk. According to research [27–29], BIM technology is a universal tool that can be applied in this area [30, 31].

Method

The new method of calculating the technical condition of the tower crane is based on the use of an information model, namely a 3D model of the tower crane, where this model acts as a platform that allows to integrate three-dimensional graphics with the possibility of detailing the elements of the tower crane with information systems capable of processing. Thus, we have obtained a digital model of a tower crane with specified control factors and an algorithm for their calculation.

The algorithm for creating a digital model of a tower crane is considered in detail in [31], here we note the key steps for its creation (Fig. 2).

The algorithm proposed by the author [31] for creating a digital model of a tower crane allowed filling each checked element of a tower crane with relevant information. The result of such control is a quantitative assessment of the defects, expressed in the form of an index of technical condition of the tower crane (TCItc). However, the calculation method itself is not presented.

Calculation of the technical condition index of the tower crane (TCItc) is based on the score of identified defects formed during operation. TCItc is formed from indexes of technical condition of nodes (TCIn) and mechanisms (TCIm), which reflects the technical condition of the tower crane. Assessing the TCItc allows to estimate relative physical deterioration, requirements for the equipment and reliability of separate knots and elements, and also specifies correctness of operation of the load-lifting mechanism. Since the tower crane consists of mechanisms, the calculation of the index of

technical condition of mechanisms (TCIm) is based on the calculation of their operating hours, in comparison with normative indicators. This index shows the residual share of the operating time of the mechanism.

Calculating the TCImi of individual mechanisms (movement, rotation, lifting, etc., in fractions of a unit) produces the following formula:

$$TCImi = (Tri - Toi) / Tri, i = 1, \dots, n \quad (1)$$

where

Tri — assigned resource of the individual mechanism;

Toi — operating time of the individual mechanism from the date of commissioning. Resource (expressed in the form of hours) mechanisms is determined according to the manufacturer's documentation, regulatory or technical documentation.

The basis for the assessment of the technical condition of units not associated with operating time (measured in hours), calculation of units of tower crane (TCIu) in this paper, a method of differential wear on a group of defects is proposed D, where D — some finite set of inherent (possible) node defects {di}.

Calculation of technical condition index of tower crane (TCItc) is carried out by the formula:

$$TCItc = \min \{TCImi, i = 1, \dots, n; \\ TCIu, j = 1, \dots, m\}. \quad (2)$$

Define $D = \{di\}$, where $i \in I$,

where I — the set of indices (ordinal numbers), $[1, \dots, N]$ group members D.

Each $di \in D$ let's match his score λ_i ($di \rightarrow \lambda_i$), $\lambda_i > 0$, so all scores are positive.

The method assumes that when inspecting a technical node, a subset of defects is selected from the set D θ from the list of defects ($\theta \subset I$). Thus, $D\theta \subset D$ — a subgroup of defects found during the examination. Let us compare the set D with the absolute value characterizing the sum of the points corresponding to it: $|D| = \sum_{i \in I} \lambda_i$ — sum of points of the whole group of defects. We introduce the same value for an arbitrary subset $\theta \subset I$. $|D\theta| = \sum_{i \in \theta} \lambda_i$ which represents the sum of the points of the detected defects. Then

$$TCIu = 1 - \sum_{i \in \theta} \lambda_i / \sum_{i \in I} \lambda_i, \text{ or } TCIu = 1 - |D\theta| / |D|.$$

Let's bring to a common denominator

Fig. 2. Algorithm for creating a digital model of a tower crane

$$TCI_{Iu} = \frac{\sum_{i \in I} \lambda_i - \sum_{I \in \emptyset} \lambda_i}{\sum_{i \in I} \lambda_i} = \frac{|D| - |D\emptyset|}{|D|} \quad (3)$$

Then for $TCI_{Im} = \frac{Tri - Toi}{Tri}$, it turns out that both forms are equivalent. Thus, it is possible to introduce the concept of wear differential for components and mechanisms, in which the indices of technical condition take the form:

$$TCI_{Iu} = \frac{\Delta|D\emptyset|}{|D|} : TCI_{Im} = \frac{\Delta|Toi|}{|Tri|} \quad (4)$$

Considering the integral form, we assume the following:

let n be the number of all mechanisms,

m — number of all nodes,

TCI_{Imi} — defect index of the i -th mechanism,

TCI_{Iu} — the defect index of the j -th node.

Then,

$$TCI_{Imi} = (Tri - Toi(t)) / Tri \quad (5)$$

Tri — the assigned resource mechanism;

$Toi(t)$ — operating time of the mechanism at the time t .

Note that the forms of expression of operating time of nodes and mechanisms are equivalent:

$$Tri \sim \sum_I \lambda_i = |D| \text{ and } Toi(t) \sim \sum_{\emptyset} \lambda_i = |D\emptyset| —$$

equivalent forms of operating time of mechanisms and devices.

Given the equivalence property of forms, one can establish the equivalence of differential forms:

$$\Delta T = Tri - Toi \sim |D| - |D\emptyset| = \Delta|D\emptyset|. \quad (6)$$

Write down the differential form:

$$TCI_{Imi} = \Delta T_{im} / TCI_{Iu} = \frac{\Delta|D\emptyset|}{|D|}, \quad (7)$$

Where ΔT and $\Delta|D\emptyset|$ — differentials of wear of mechanisms and knots.

The integral form will have the form:

$$TCI_{Imi} = \min_{im} \frac{\Delta|T_{mi}|}{|T|} \quad \text{and} \quad TCI_{Inj} = \min_{\emptyset} \frac{\Delta|D\emptyset|}{|D|}. \quad (8)$$

The criterion for assessing the state of the tower crane is the distribution of indices TCI_{Imi} and TCI_{Inj} on intervals (semi-intervals) of the segment $[0,1]$ formed by boundary (threshold) values of levels of safety of the tower crane.

For example, the adopted gradation of safety levels implies three intervals on a point scale according to the regulatory document RD 10-112-2-09 p. 8 p. 8.1.5, which says: «The decision on the possibility of

further operation is made by the Commission taking into account the following recommendations:

– at total number of points less than 5, after repair the crane can be operated with passport loading capacity;

– with the total number of points from 5 to 10 inclusive, in cases where there are defects of at least 3 points, the load capacity of the crane after repair on all departures must be reduced by at least 25 % (the crane must be transferred to a lower size group), and the relevant cargo characteristics are attached to the passport, and the Load Capacity Limiter must be reconfigured accordingly (in necessary cases, the counterweight must be reduced);

– at total number of points more than 10, the crane is subject to removal from operation and write-off or replacement of the defective knot has to be made».

Based on the above, we denote the threshold values:

0-4-safe operation level of tower crane;

5-9-satisfactory level of tower crane operation;

10 and more unsatisfactory level of operation of the tower crane.

When displaying threshold values on the interval $[0,1]$ and by the formula $TCI_{Inj} = \frac{\Delta|D\emptyset|}{|D|}$, three disjoint components of the half-interval $[0,1]$ are displayed. At the same time, $\Delta|D\emptyset|$ correspond to the boundaries of the intervals of security levels on a point scale.

Consider an example of calculating the technical condition of a tower crane. First, let's form a table of defects and their score indicators obtained during monitoring (Table 1).

According to the proposed methodology, the threshold values TCI according to the list of defects will be as follows:

– for the period of commissioning (the sum of points is 70.2):

$$TCI_{Imi} \sim TCI_{Inj} = 1 - 4/|D| = 1 - 4/70,2 = 0,9 \rightarrow (0,9-1) — \text{interval of serviceability};$$

$$TCI_{Imi} \sim TCI_{Inj} = 1 - 9/|D| = 1 - 9/70,2 = 0,87 \rightarrow (0,86-0,89) — \text{interval of limited serviceability};$$

$$TCI_{Imi} \sim TCI_{Inj} = 1 - 10/|D| = 1 - 10/70,2 = 0,85 \rightarrow (0-0,85) — \text{interval of failure};$$

– during operation (the sum of points is 93.2):

Table of defects and their score

Type of defect	Characteristics of defects	
	Manufacturing or installation of defects	Defects arising during normal operation
Violation of paint and varnish coating	0,5	
Corrosion of critical elements: up to 5% of element thickness inclusive; up to 10% of element thickness inclusive; more than 10% of the thickness of the element.	0,2 1 10	
Cracks, breaks in seams or in the parotid zone	1	4
Cracks, gaps in the zones remote from the weld	1	5
Loosening of bolted connections in which bolts work on tension (and also wear of a thread of screw supports)	0,5	1
Loosening bolt connections in which the bolts work on the cut	2	
Deformations of elements of lattice structures exceeding the limit values: belts; the elements of the lattice.	1 0,5	5 2
Deformation of elements of sheet structures, in excess of the limit	1	5
Metal bundle	5	
Crushing of eyelets and development of holes in hinges exceeding limit values	1	3
Any defects that occurred at the site of the previous repair	1	5
Defects of rope-block mechanisms and other mechanisms: - cracks, chips, wear on the Creek rebord blocks; - wear of gears, joints.	9 4	
Defects in ropes: - breakage of wires, strands, reduction of the cross-sectional area of the rope, surface and internal wear, corrosion; - mechanical deformation of the rope, the temperature effect.	5 10	
Cracks and chips, exposing the reinforcement of foundations. Draft (drawdown, roll) foundations. Crumpling, cracks of anchor bolts (studs), weakening of bolted connections.	2 10 3	
Method of elimination of defects: - repair; - replacement.	1 0,5	

$$\begin{aligned}
 &TCI_{mi} \sim TCI_{nj} = 1 - 4/|D| = \\
 &= 1 - 4/93,2 = 0,95 \rightarrow (0,95 - 1) \text{ — interval} \\
 &\quad \text{serviceability;} \\
 &TCI_{mi} \sim TCI_{nj} = 1 - 9/|D| = \\
 &= 1 - 9/93,2 = 0,90 \rightarrow (0,90 - 0,94) \text{ — interval} \\
 &\quad \text{of limited serviceability;} \\
 &TCI_{mi} \sim TCI_{nj} = 1 - 10/|D| = \\
 &= 1 - 10/93,2 = 0,841 \rightarrow (0 - 0,89) \text{ — interval} \\
 &\quad \text{of failure.}
 \end{aligned}$$

The part of structural elements of the tower crane consisting of 30 elements (the enlarged breakdown of the tower crane in the digital model) was examined). The operating time of the mechanism was 5600

moto-hours. At the same time the following defects were found on 3 elements:

Element 1.

Violation of the paint coating-0.5.

Crack, gap in the seams or parotid zone-4.

Deformation of elements of lattice structures-5.

$$TCI_n = 1 - 9,5/93,2 = 0,89.$$

Element 2.

Violation of the paint coating-0.5.

Corrosion of critical elements-0,2.

Metal bundle-5.

$$TCI_n = 1 - 5,7/93,2 = 0,93.$$

Element 3.

Violation of the paint coating-0.5.

Loosening of bolted connections in which bolts work on a slice-2.

Crumpling of eyelets and development of holes-3.

Any defects that occurred in the place of the previous repair-5.

$$TCIn = 1 - 10,5/93,2 = 0,88.$$

Mechanism

The actual operating time is 5600 hours.

Assigned resource — 7000 hours.

According to the methodology we calculate the TCI For each identified element:

$$TCIm = (7000 - 5600) / 7000 = 0,2$$

The TCItc assessment takes the minimum of the identified and assessed defects, in our case:

$$TCIm \min = 0,2 — \text{faulty,}$$

$$TCIn \min = 0,88 — \text{faulty.}$$

Thanks to this approach to assessing the safe operation of tower cranes, it was possible to differentiate the defective areas and timely repair or replacement of damaged elements. This approach will allow to react in due time to the revealed serviceability and to provide safety of operation of the tower crane.

When considering the report on the results of the bypass, the responsible person, guided by the normative document, can make decisions on the further operation of certain nodes of the tower crane. The practical application of the tower crane survey methodology on the basis of information technology has shown that it is possible to use it for effective control of the technical condition of tower cranes with the construction of an information model of the tower crane. The data obtained during monitoring can be visualized, presented in the form of a detailed report and shared with stakeholders.

Results and discussions

The result of the analysis and the possibility of using the research to understand the effectiveness of digital technologies in assessing the technical condition of the tower crane is as follows:

- information modeling technology is the tool through which you can create a digital double of the tower crane being tested or a digital model;

- the digital model of the tower crane allows to receive to the potential checking, the user, etc.

all technical characteristics of the load-lifting mechanism;

- the digital model contains all the entered information on the result of inspection of the technical condition both at the pre-start stage after installation at the facility, and before dismantling and transfer to the base, so that, responsible for the safe operation of the lifting mechanism, it is possible to track: how the mechanism was operated?

Thanks to the use of a digital model of the lifting mechanism, it is possible to switch to a digital design of all documentation, which will preserve the history of the lifting mechanism and its technical characteristics.

Conclusion

Thus, within the framework of the goals and objectives, we can sum up the following:

1. A new method for calculating the technical condition of tower cranes using a digital model and an integral-differential approach, which assumes a point estimation of defects, is proposed.

2. The use of information technology to calculate the technical condition index of tower cranes makes it possible to integrate the geometric parameters of the tower crane and a mathematical algorithm for their evaluation, which results in a quantitative assessment of the defects formed during the operation of tower cranes.

3. The use of information technologies in the field of labor protection in the operation of lifting mechanisms will allow to collect and accumulate in-depth statistical data related to the influence of specific factors during operation. Subsequent processing of information will allow to reveal dependence of influence of defects on those or other violations and to specify their weight values. Accounting for the identified defects and patterns of their formation, when comparing them with the forecast values, will be able to carry out not only the operating organizations themselves, but also their controlling parts.

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