Mathematical modeling of overhead crane under conditions of stress-strain state of metal structure as a control object

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Abstract. The article considers an example of the application of the existing mathematical model of an overhead crane to equipment with irreversible structural defects. The course of the solution of the problem is considered: obtaining primary data, finding the existing mathematical model of the crane, adapting it to the problem in question, building a computational model, modeling and analyzing the results obtained. The peculiarity of a crane as a control object is the non-typical state of the metal structure. The overhead crane is in this state after prolonged operation of the equipment with incorrect loading and control modes. As a result of such operating modes, significant wear of the wheels and the rail track take place. Worn elements must be replaced. The frequency of wheel replacement is very intensive, and is about twice a year. The process of replacing wheels with corner boxes is a very expensive procedure – it is necessary to buy equipment, stop the warehouse for a few days and attract staff. To eliminate such costs, it is proposed to conduct a simulation of the crane in order to identify methods of controlling it. The result of the first stage of modeling is the answer to the question: is it possible to operate the crane that is deformed using the correctly selected control mode.

1. Introduction
The intensification of construction production imposes very strict requirements on the safety of construction machines. When carrying out lifting and hoisting operations using overhead cranes, production safety is primarily determined by the technical condition of the crane mounting and crane runways. Malfunctions of the undercarriage or changes in the geometry of the crane metal structures, happening due to imprecise control procedures, significantly reduce the service life of the rail track. Travel wheels have lower performance properties and their service life is further reduced. In addition to high economic costs, such violations in crane operation are associated with the occurrence of emergency situations - crane derailment.

2. Problem statement
Crane construction. The authors adopt a two-girder overhead crane (Fig. 1), working at the technological stage of unloading raw materials at a plant producing building materials, for consideration. It has the following main technical characteristics [1]:

- crane physical dimensions: crane span - 34500 mm, crane base – 5000 mm, wheel diameter – 500 mm, distance between bumpers (extreme points) of the crane - 6710 mm;
drive characteristic of the travel mechanism: two electric motors MTF-311-6 (power - 11 kW, rotational speed - 945 rpm), two gearboxes 1Ц2У-250-12.5-12 / 21 (reduction ratio 12.5);
- crane mass (design) - 21 t, trolley mass - 1.5 t, cab mass - 1 t, grab mass - 1.9 t, crane lifting capacity - 10 t;
- maximum load of the crane wheel on the rail (calculated) - 185 kN.

Figure 1. Design scheme of an overhead crane.

**Analysis of the condition of the overhead crane.** Inspection of the crane condition showed: there is significant wear on the flanges of one of the driving wheels, wear on the flanges of the second driving wheel is within normal limits; wear of the flanges of driven wheels is even, exceeding the norm; wear of rails - along one of the end parts of the rail head.

After analyzing the survey results, it is not difficult to come to the following conclusions. First, there is a violation of the crane geometry, leading to the uneven distribution of the load from the crane weight on three wheels, the fourth wheel is less loaded. Secondly, intensive wear of the flanges on one side of the running wheels is caused by the uniformity of the travel of the loaded grab. Thirdly, long-term, significant misalignment of the crane led to the wedging of the bridge and to the irreversible stretching of the elements of the metal structure.

**Problem statement.** For the overhead crane described above, it is required to carry out mathematical modeling of the undercarriage, taking into account the stress-strain state of the metal structure of the crane frame. Moreover, it is required to identify the most rational methods for controlling the movement of the crane, which can reduce wear on wheels and rails, on the obtained model.

When setting the problem, the existing devices and methods for controlling such cranes were analyzed. The analysis of these solutions showed the impossibility of their application on an overhead crane with a large span, or their low energy or functional efficiency.

3. **Results and discussion**
The mathematical model of an overhead crane of a pallet storage area was adopted as a prototype [2]. This model is similar to the considered crane. The undercarriage has the same design, but the differences are in the bridge design and the hooking of the moving load.
In the construction of the bridge, elastic-dissipative elements were taken into account, which were calculated by the method of finite-difference modeling in the previously considered structure. For modeling, the load will be considered concentrated and located in the middle of the bridge.

The mathematical model of the crane given in [2] and [3] is supplemented by the preliminary deformation of the crane bridge, which is expressed by the displacement of the position of one girder relative to the other. Further, these positions are indicated by coordinates $x_1$ and $x_2$. In addition, for the adequacy of the model with a deformed bridge, the form of nonlinearities has been changed. In the model of an overhead crane [2], nonlinearities with symmetry relative to zero (in the range from 0 to $+\infty$) are applied, in the model corresponding to the crane under consideration, total nonlinearities in the range from $-\infty$ to $+\infty$ are taken into account.

Based on the mathematical description and block diagram (Fig. 2), given in [2, 4], as well as taking into account the previously described changes, a computational model was built, shown in Fig. 3.

Figure 2 shows the block diagram of an overhead crane as a control object. Moreover, at that the control object is multidimensional [5]. Here, $\omega_1$ and $\omega_2$ are the frequencies of the voltages supplied to asynchronous motors with transmission mechanisms DPM1 and DPM2, $F_{T1}$ and $F_{T2}$ are the traction forces for DPM1 and DPM2 supplied to the mechanical part - MCh. $F_{TP1}$ and $F_{TP2}$ - friction forces. The rest of the output coordinates are required to set up the model.

Figure 3 shows a computational model of an overhead crane as a control object. It can be seen here that DPM1 and DPM2 are represented by asynchronous motors (AD1, AD2), gearboxes with appropriate reduction ratios (ired, ired3) and wheel model (1/Rk, 1/Rk3). Chains Jdv, Derivative1, Derivative, ired1, 1/Rk1 and Jdv1, Derivative3, Derivative2, ired2, 1/Rk2 are necessary to form the static load torque of the linearized mathematical model of an asynchronous motor [6]. Scope blocks are designed to display graphs of changes in the corresponding values: $F$ - traction forces, $X$ - overhead crane displacements, Mdv - motor torques, Wdv - motor shaft rotation frequencies, Wz - frequency difference in voltages supplied to motors, Wk - crane wheel rotation frequencies, dX - crane bridge misalignment, Scope3 - frequency difference in voltages supplied to motors. Defining parameters: $w_o$ is the base voltage frequency supplied to the motors, Constant is the initial frequency mismatch of the supply voltages of the two motors, Step 3 is the frequency difference of the supply voltages of the motors.

The mathematical model of an asynchronous motor was adopted on the basis of paper [6], its computational model is shown in Figure 4. The computational model of the mechanical part, based on
the description [2] and the previously described changes, is shown in Figure 5. Here the Constant block defines the initial misalignment of the crane bridge.

The parameters of the variables shown in Figures 3-5 are calculated according to known laws [2, 6, 7]. The technical characteristics of the crane were taken as the initial data.

![Figure 3. Computational scheme of an overhead crane.](image)

**Modeling**

Initially, the experiments were carried out confirming the adequacy of the model, which was evaluated by the speed of the crane, the time of its acceleration and deceleration and the response to input parameters. The model was validated. Further, the existing methods of managing multidimensional control objects were analyzed and a series of experiments were conducted [8].

*In the first series of experiments*, the frequencies of the supply voltages on the motors are equal and amount to 241 rad/s. The initial displacement ΔX is set at first at 0.15 m, then at 0.5 m. At 30 s, the voltage frequency of the second motor is increased by 20%. In this case, the motors torques change and come to a steady-state value of 300 Nm, the displacement ΔX changes sign, and is 0.18 m, which signals the rotation of the crane bridge and friction of the wheel flanges against the rails.

*In the second series of experiments*, the frequencies of the supply voltages on the motors are equal and amount to 241 rad/s. At 30 s, the frequency of the supply voltage of the second motor is decreased by Δω (5, 10, 15, 20, 30, 35%) Initial displacement ΔX = 0 m. The experiment determined torques for the motors M, bridge misalignment ΔX, transient time t and readjustment σ. The results of the experiment are summarized in Table 1, and, for convenience, graphs are drawn for M (Δω) (Fig. 6a), ΔX (Δω) (Fig. 6b), t (Δω) (Fig. 6c) and σ (Δω) (Fig. 6d). With a further increase in Δω, stable self-induced vibrations appear.

*In the third series of experiments*, we will introduce non-linearity of the "dead zone" type into one of the drives. This nonlinearity will simulate bridge wedging when the joints are irreversibly stretched. In this case, we will supply equal voltage frequencies to the motors (241 rad/s). At 30 s, the frequency of the supply voltage of the second motor will be increased by Δω = 30%. Initial displacement ΔX = 0.15 m.

The experiment showed that there is no change in the position of the bridge (ΔX remains at the same level).
Figure 4. Computing scheme of subsystems AD1 and AD2

Figure 5. Computational scheme of the mathematical model of crane subsystem
Table 1. Results of the second series of experiments

| Δω, rad/s | M, N m | ΔX, m | t, s | σ, % |
|-----------|--------|-------|------|------|
| 0.05      | -224   | 240   | -0.1814 | 8   | 0.00 |
| 0.1       | -437   | 449   | -0.197  | 6   | 0.00 |
| 0.15      | -623   | 630   | -0.21   | 4   | 0.00 |
| 0.2       | -770   | 785   | -0.22   | 3   | 0.00 |
| 0.3       | -937   | 950   | -0.233  | 4   | 0.13 |
| 0.35      | -957   | 963   | -0.234  | 10  | 1.71 |

Figure 6. Results of the second series of experiments

Based on the results of the first series of experiments, it can be concluded that the crane is controllable under normal operating conditions and is capable of returning to its original state.

Based on the results of the second series of experiments, it can be concluded that:
- the crane, as a control object, achieves the best speed of operation at a speed difference in the range of 15 ... 30%;
- with an increase in the frequency mismatch of the supply voltages of the drives, the torque increases, which then leads to wear of the rails and wheel flanges;
- when the frequency mismatch of the supply voltages of the drives is more than 35%, stable self-induced vibrations occur and the crane does not straighten.

According to the results of the third series of experiments, it can be concluded that when modeling crane jamming, the change in the position of the bridge does not occur (ΔX = const), and therefore the effort developed by the motor with a difference in the frequencies of the supply voltages of 30% is not enough to overcome the obstacles created by the deformation of the joints.

4. Conclusion
The method of modeling an overhead crane considered in the article based on the results of observation and keeping records of the state of individual nodes of crane equipment (wheels and rail track) is of great practical importance in the operation of lifting and transporting equipment. Namely,
the application of the described method gives an answer to the question of the need for the fastest repair of mechanical equipment and metal structures. This is achieved by the fact that during the modeling, it is possible to test various modes of crane control and some of them can ensure the operation of the deformed crane in a safe mode, with the minimum possible wear of crane undercarriage components. In this case, it is possible to ensure the operation of the crane up to the scheduled maintenance and repair time.

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