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Transformation of Pick-And-Carry Cranes into Robots

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Abstract: The design and operational preconditions for transformation of special hoisting cranes with a rigid suspension of cargo into pick-and-carry cranes-robots have been thoroughly investigated. Position-accuracy, structural, functional-cost and dynamic analyses of main drives of special bridge cranes have been carried out. The results of the study allowed us to consider justified the creation of pick-and-carry cranes-robots as well as redesigning the whole line of existing special cranes into cranes-robots provided they are equipped with automatic control systems.

The rather modern concept of combining in a crane-robot generalized displacements from the controlled drives in use, such as transport, and movements with high accuracy of positioning at the expense of introduction of unprofitable degrees of motion has been suggested.

Keywords: pick-and-carry crane-robot, multidisciplinary analysis, position accuracy, functional-cost analysis, dynamic research, accuracy of positioning, unprofitable degrees of motion.

Reduction of the production technological cycle, to some extent, is associated with mechanization and automation of pick and carry, assembly and warehousing tasks. Transporting and reloading operations still remain a weak point in the implementation of complete automation of production. In modern industries, one of the effective means of automation is robotics. Design and development of pick-and-carry industrial robots (PCIR) lags behind the general development of industrial robots (IR), the load capacity of which is still limited. Alongside, there exist and successfully perform PCIR functions other special technological cranes, such as stacker cranes, balance cranes, dogging cranes, stripping cranes, turnaround charging crane, pratzen cranes (claw cranes), container cranes and others. Some of them, equipped with software control, can provide automatic grabbing, holding and transporting of various objects, and, if necessary, manipulating them. Structural, dynamic, position-accuracy and functional-cost analyses of manipulation systems of such cranes should confirm that the principles of their construction and technical characteristics correspond to manipulation systems of IR. Such manipulator cranes have from 3 to 6 degrees of motion. Besides, it should be comprehensively proven that these cranes can be used as a base for creating heavy and super-heavy PCIR, which can operate with both sufficient and high positioning accuracy. This is the main purpose of this article.

1. Structural accuracy analysis

There is a wide class of bridge cranes with rigid suspension of cargo which are used at the majority of enterprises as the main equipment to perform transporting and reloading operations. They are, in fact, manipulator systems with the number of degrees of motion of three or more, which operate in rectangular and cylindrical coordinate systems. Development of methods and means of software control of these cranes will allow to transfer them to the class of industrial robots and exclude the presence of humans in dangerous zones.

A metallurgical dogging crane with rigid suspension of cargo was used for multidisciplinary research. This crane at the Zaporizhstal plant loads steel ingots weighing Q = 20 tons into pit furnaces, and moves the heated ingots from the pits to the ingot trolley, which feeds them into the cogging mill. The layout of pit furnaces, fixed arrangement of ingots in furnaces, positioning of platforms to achieve precise coordination of location of ingots, self-guided ingot trolley − all these factors create prerequisites and the need to move the dogging crane into the category of crane-robots.

To carry out a position accuracy analysis, a schematic diagram (Fig. 1) of the dogging crane was drawn according to the principle of an open-loop kinematic chain of the manipulation system (MS) of IR.

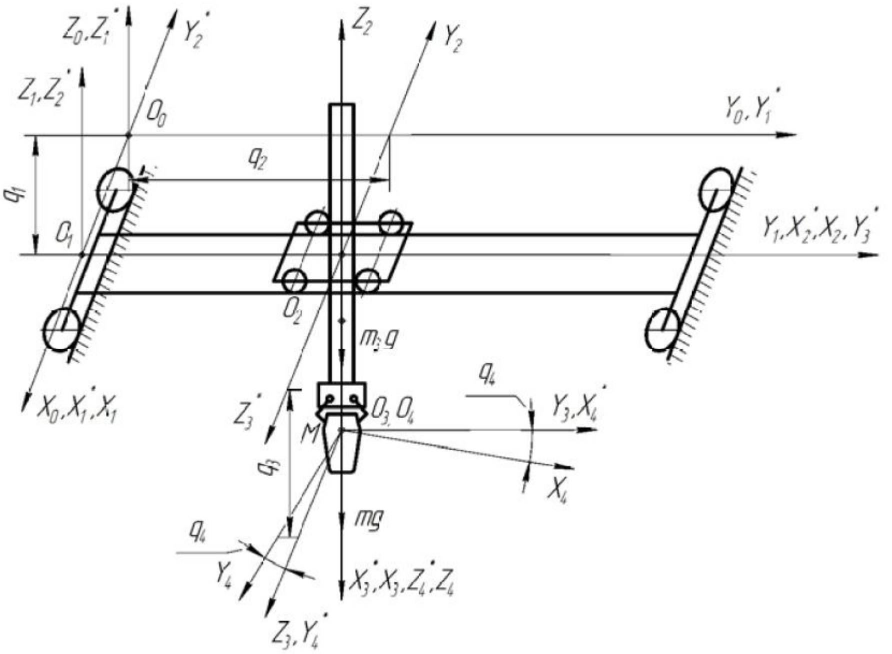

Figure 1 – Schematic diagram of pick-and-carry metallurgical dogging crane-robot

The diagram shows the following: X_0, Y_0, Z_0 is a system of absolute Cartesian coordinates, the first octant; X_i, Y_i, Z_i is a system of relative coordinates after the i-th generalized displacement; X_i^*, Y_i^*, Z_i^* is transition coordinate system; q_1, q_2, q_3, q_4 are generalized displacements of degrees of motion (movements of crane drives); m_3g, mg are gravity forces, respective to the third chain of the MS (crane posts) and the load in the gripper (ingot in the crane tongs).

All movements of the M point of the gripper, which provide the drives of the degrees of motion in a real dogging crane, are performed with deviations from the program movements (with errors), which affects the accuracy of positioning of the ingot (point M) in the Cartesian coordinate system. The accuracy of positioning is influenced by: errors in working out generalized coordinates, gaps in the joints, wear of contact elements of kinematic pairs, static errors of elastic deformations from weight influence, dynamic errors in the transient processes of actuation of drives.

Errors of the dogging crane were used to collect the statistical material in production conditions and to get reference data. Weight and rigidity data of each chain of the MS are obtained from the design documentation for the crane and by calculation.

In the general outline, the position function (1) of the M point (the attachment point of the core of the dogging crane to the ingot) is made for the structural diagram of the MS.

$$r_M^{(0)} = \left(\begin{array}{l} \left[X_e(\alpha\varphi - \cos\alpha\cos\varphi) + Y_e(\varphi\cos\alpha + \alpha\cos\varphi)\right]\sin(q_4 + \Delta q_4) - \\ \left[X_e(\alpha\cos\varphi + \varphi\cos\alpha) + Y_e(\cos\alpha\cos\varphi - \alpha\varphi + (\beta+\theta)\cos\varphi)\right]\sin(q_4 + \Delta q_4) + \\ \left[Z_e(1 - (\beta+\theta)\cos\alpha) - X_e\alpha(\beta+\theta)\right]\sin(q_4 + \Delta q_4) - \end{array} \right.$$

$$\begin{aligned}
&-\left[X_e\left(\varphi\cos\alpha+\alpha\cos\varphi\right)+Y_e\left(\cos\alpha\cos\varphi+\alpha\varphi\right)\right]\cos\left(q_4+\Delta q_4\right)+\\
&+\left[X_e\left(\alpha\varphi-(\beta+\theta)\cos\varphi-\cos\alpha\cos\varphi\right)+Y_e\left(\alpha\cos\varphi+\varphi\cos\alpha\right)\right]\cos\left(q_4+\Delta q_4\right)+\\
&-Y_e\alpha(\beta+\theta)+X_e\left(1-(\beta+\theta)\cos\alpha\right)\cos\left(q_4+\Delta q_4\right)-\\
&\left.\begin{aligned}
&+Z_e\gamma\left(\varphi\cos\alpha+\alpha\cos\varphi\right)+\left(q_1+\Delta q_1\right)\\
&+Z_e\cos\varphi\left(\gamma\cos\alpha-\beta-\theta\right)-\left[\left(H+q_3+\Delta q_3\right)(\beta+\theta)+\left(q_2+\Delta q_2\right)\right]\cos\varphi\\
&-Z_e\left(1-\gamma(\beta+\theta)\cos\alpha-H-\left(q_3+\Delta q_3\right)\right)
\end{aligned}\right),
\end{aligned}$$

(1)

where $\Delta q_1, \Delta q_2, \Delta q_3, \Delta q_4$ are errors in working out generalized coordinates, m, rad;

H is the maximum lifting height of the ingot, m;

X_e, Y_e, Z_e are coordinates of the ingot gravity center eccentricity concerning the M point, m;

φ, α, k are skews of the crane, trolley, post, m, rad;

$\beta+\theta$ are errors (reference deviation) in installation of crane and trolley rails, including static ones, m, rad.

By decomposing the position function (1) into a Taylor series and subsequent partial differentiation by generalized coordinates q_i and by errors Δq_i, a vector column of point *M* positioning errors was obtained for the dogging metallurgical crane-robot in general. After substituting into the column vector real design parameters of the dogging crane Q = 20 t of "Zaporizhstal" plant the following maximum values of positioning errors of the grasp point *M* were obtained: ΔX = 175 mm; ΔY = 75 mm; ΔZ = 61 mm.

The studied values of errors fully satisfy the feasible accuracy of positioning of metallurgical ingots at all stages of work with them in the furnace departments of Zaporizhstal and Dniprospetsstal plants, etc.

2. Functional-cost analysis

Since the largest positioning errors occur along the axes of the longitudinal movements of the crane and the trolley, the drives of travel mechanisms of bridge cranes should be subjected to a deeper multidisciplinary analysis.

Transformation of the bridge crane into IR is accompanied by expansion of its functionality. IR must provide controlled positioning, execution of the control program, the specified positioning accuracy, etc. However, these functions are typical mainly of stationary IR, while the crane-robot is an object that moves in a horizontal plane. The bridge crane-robot must have such an important consumer characteristic as positioning accuracy, especially necessary for operations of loading materials into a vehicle with stable dimensions, as well as for assembly of construction projects, machines, ships, etc.

Previous comparative functional and structural analysis of the IR and the bridge crane showed that along with the general functions characteristic of these machines, there are significant differences due to the purpose of the main function of the IR and the crane. Therefore, the formal reclassification of the bridge crane into a crane-robot is impossible, as the change of functions with the invariable structure in technical systems, as a rule, is unrealistic. Redesigning of the bridge crane into a robot crane is accompanied by an increase in the number of correction functions of the control program. But such functions as: position accuracy, movement in the preset direction and response speed to control commands of the processor make up an inherent property only in the crane-robot, which is controllability. At the same time, the mechanisms of the crane-robot must have a high level of reliability and operational safety, which ensure its functioning as an automatic manipulator. Thus, the consumer characteristics of the crane-robot imply high structural perfection of all its units operating in the IR mode, and the level of controllability that corresponds to modern technologies.

The most problematic in terms of ensuring the precise position accuracy of the crane-robot, as can be seen from the research, is the longitudinal movement of the crane.

To substantiate the possibility of transforming a bridge crane into a crane-robot, a multidisciplinary analysis of several structural schemes of crane travel mechanisms was performed (Fig. 2). Functional completeness is intrinsic to the travel mechanism with a central drive for a bridge crane with Q = 20 t capacity, L = 28.5 m span (Fig. 2 scheme 1). This scheme is accepted as a basis for functional analysis. The choice of the object of analysis is due to its importance in terms of ensuring the controllability of the crane-robot, as the design of the travel mechanism determines its dynamic characteristics, which define the execution of the control program and position accuracy. The controllability of the crane-robot, in turn, is one of the main factors affecting the daily performance of the crane in automatic mode. Other technical properties of the considered schemes of the travel mechanism are adequate.

The complexity of the task of redesigning a bridge crane into a crane-robot requires for functional and structural analysis of the travel mechanism to be completed by calculations of its functional organization and quantitative assessments of its dynamic characteristics, as well as determining the positioning accuracy.

At the information stage of the research of the travel mechanism, its structural-cost scheme (Table 1) and functional-structural matrix of the mechanism (Table 2) are worked out.

Characteristics of the structural-cost scheme indicate a significant difference in quantitative estimates of the initial cost and current repair costs. The considered model of travel mechanism acts as a starting point for establishment and formulation of function of the travel mechanism with the central drive and operating units that make it up (tab. 2).

Defined and systematized functions together with structural elements are evaluated for their importance in ensuring the efficiency of the crane travel mechanism. In addition, the functional matrix must be supplemented with new functions inherent in the crane-robot: execution of the control program, positioning with a preset accuracy, speed.

Comparison of the structural-cost model (Table 1) with the functional-structural matrix (Table 2) of the travel mechanism allowed us to establish the costs of performing functions and identify sources of costs. According to table 2 functions F7, F8 and F12 can be completely excluded, and with them and such structural units as a transmission shaft and couplings.

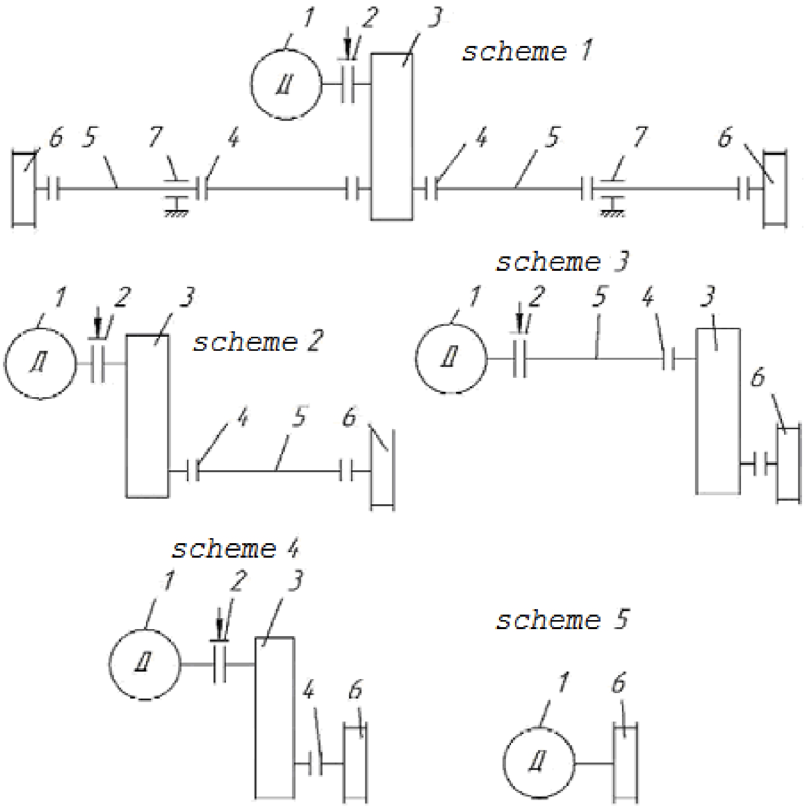

Figure 2 − Structural diagrams of bridge crane drives:
1 − engine; 2 − brake; 3 − gearbox; 4 − coupling; 5 − transmission shaft;
6 − running wheels; 7 − intermediate bearer

Table 1 − Structural-cost scheme of the travel mechanism with a central drive

Specific weight of the operating units,%	Electric motor	Gearbox	Brake	Transmission shaft	Couplings	Running wheels
In the cost of the mechanism	17	26	8	9	15	25
In operating costs	10	15	12	13	23	27

Cost savings in conventional units can be calculated by the formula

$$C = Э_{TB} + Э_{M} + Э_{p} - Э_{y}, \tag{2}$$

where C is saving costs on production, operation and modernization of the travel mechanism (cost of functions F_7, F_8, F_{12} and F_6, F_9, F_{10});

$Э_{TB}$ is the cost of the transmission shaft;

$Э_{M}$ is the cost of the coupling;

$Э_{p}$ is the cost of repairing shafts and couplings;

$Э_{y}$ is the cost of the microprocessor control device of the drive.

The final cost estimate of the travel mechanism can be performed by choosing the best design of the travel mechanism of the crane-robot.

Technical implementation of functions of the crane-robot in the morphological matrix is considered in four possible variants of design solutions for the drive travel mechanism (Fig. 2) in conjunction with the basic one.

The transmission of torque from the gearbox 3 to the wheel 6 is carried out via the transmission shaft 5 and the coupling 4 (Fig. 2, schemes 1 and 2). In addition, intermediate bearers 7 are used in scheme 1 to support the transmission shafts. This circuit is centrally driven. In scheme 2, the gearbox transmits rotation to one driving wheel 6 via the coupling 4 and the shaft 5.

In schemes 3 and 4, the rotation from the gearbox 3 is transmitted through the coupling 4 to the wheel 6 without transmission shafts. Schemes 2, 3, 4 and 5 are circuits with distribution drives.

Table 2 − Composition of functions of the travel mechanism and their carriers

Types of functions		Index	Name of the function	Function carrier
Main		F_0	Crane travel	The travel mechanism of the crane
Basic (operating)		F_1	Crane movement	Running wheel
		F_2	Creating torque	Electric motor
		F_3	Crane braking	Brake
		F_4	Support	Running wheel
Complementary	Supplying	F_5	Torque transmission	Transmission shaft
		F_6	Revolutions drop	Gearbox
	Connecting	F_7	Connection of the engine and the gearbox	Coupling
		F_8	Connection of the gearbox and the running wheel	Couplings and transmission shaft

	Fixing	F_9	Fixation of alignment of the output shaft and the gearbox	Coupling
		F_{10}	Fixation of alignment of shafts of the gearbox and the running wheel	Couplings and transmission shaft
		F_{11}	Alignment of the engine shaft and the transmission shaft	Gearbox
		F_{12}	Fixing the travel mechanism on the main beam	Platform (bench)

Scheme 5 has an engine 1 with a built-in brake 2. The torque is directly transmitted to the driving wheel 6 without transmission elements. This scheme is the one with transmission-free drive and can have a modular design.

The multidisciplinary assessment of the rational variant of the crane-robot travel mechanism drive was performed in two steps: the study of constructive (organizational) perfection, and then the dynamic characteristics of all five variants of the morphological matrix were calculated.

As a result of systematic study of the functional-structural model of the travel mechanism we have obtained quantitative assessments of designs, which allow a more reliable assessment of technical characteristics for compliance with new functions that make up the property of the crane-robot − controllability.

The level of functional organization of the design of the travel mechanism for the crane-robot is determined using a set of coefficients of the level of functional organization *I*; the coefficient of organization of the system $K_{орг}$; the coefficient of functional embodiment $K_{фв}$ and the coefficient of functional diversity $K_{фр}$. Numerical values of the coefficients (Table 3) reflect the degree of technical perfection of the morphological matrix designs under consideration in relation to the basic one.

Parameter *I* characterizes the degree of information practicability of the technical system, the coefficient $K_{орг}$ shows the level of functional load, $K_{фр}$ reflects the actualization of functions (specific weight of basic functions), $K_{фв}$ measures the degree of concentration of basic functions.

The dynamics of parameters of the functional organization of structural diagrams of the drives decreases, thereby characterizing the growing level of order in the system. It is accompanied by an increase in the structural perfection of the travel mechanism, as the performance of necessary functions is carried out by fewer parts.

Numerical design parameters were supplemented by a pair-wise correlation analysis of their dynamics from the number of complementary functions in the operating unit.

The obtained characteristics of the organization of the considered schemes prove that the most perfect design of the travel mechanism for the crane-robot is the scheme 5 (Fig. 2).

Table 3 − Assessment of the organization of the structures of the travel mechanism for the crane-robot

Index	Scheme number (Fig. 2)				
	1	2	3	4	5
The number of elements in the system	17	16	16	10	4
I	4,08	4,0	4,0	3,32	2,0
$K_{орг}$	0,24	0,25	0,25	0,33	0,5
$K_{фр}$	0,051	0,052	0,052	0,09	0,33
$K_{фв}$	0,065	0,055	0,055	0,1	0,5

3. Dynamic analysis

To most fully meet the consumer functions of controllability and positioning accuracy, the crane-robot system must have effectors, especially actuators, with good dynamic properties.

Dynamic properties without taking into account damping of various schemes of cranes drives can be estimated by dynamic errors and dynamic factors in elements of drives during transient and constant operating modes. It is convenient to carry out dynamic analysis on multimass chain models of drives (fig. 3).

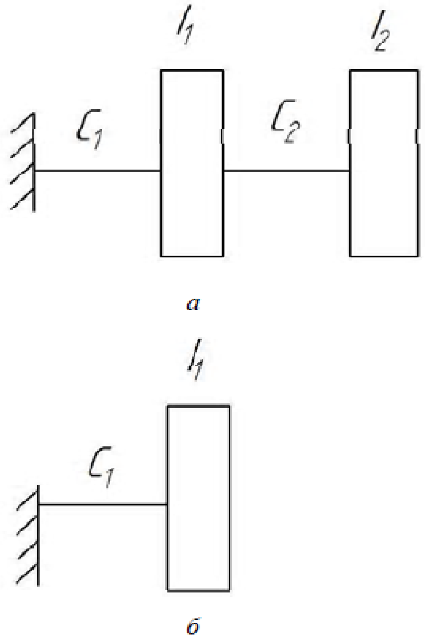

Figure 3 − Chain drive models:
a − two-mass model; b − single-mass model

The first three schemes of drives (Fig. 2) of travel mechanisms of bridge cranes are presented in the form of two-mass chain system with a clamped end (Fig. 3, a), while the other two − in the form of single-mass ones. In models C_1, C_2 represent induced rigidity of elements of the drive to the engine shaft of, whereas I_1, I_2 designate induced moments of inertia of masses of the drive and the crane to the same shaft.

Natural frequencies and shapes of masses of chain systems are determined by solving the differential equation of free oscillations

$$I\ddot{\varphi} + C\overline{\varphi} = 0, \tag{3}$$

where I is diagonal matrix of moments of inertia of masses;
C is band matrix of rigidity of the chain system.

After substituting the solution into equation (3) and simplification, the expression is obtained

$$\left(C - Ik_m^2\right)\overline{h}_m = 0, \tag{4}$$

where k_m are natural frequencies of mass oscillations;
$\overline{h}_m$ are amplitudes of mass oscillations (natural modes).

The natural frequencies k_m are worked out from the frequency determinant

$$C - Ik_m^2 = 0. \tag{5}$$

Substituting frequencies k_m into equation (4), natural modes can be determined $\bar{h}_m$.

The natural frequencies and forms of oscillations of masses of chain systems are necessary to determine dynamic errors, that is deviations from the program motions which are determined by the equation

$$\psi_s = -\sum_{m=1}^{n} k_m \rho_s^m A_m, \tag{6}$$

where ρ_s^m is amplification coefficient;

A_m is the amplitude of mass oscillations.

Amplification coefficient equals

$$\rho_s^m = \frac{h_{ms} c}{k_m^4 \sum_{l=1}^{n} I_l h_{ml}^2}. \tag{7}$$

The amplitude of oscillations can be determined using the Duhamel's integral

$$A_m = \int_0^t \sin k_m (t-\tau) \varepsilon(\tau) d\tau, \tag{8}$$

where $\varepsilon(\tau)$ is programme acceleration of the executive drive engine rotor;

τ is the period of the oscillating system.

Table 4 – Results of the drives dynamic analysis

Drive scheme	Induced				Natural frequencies k_m, c^{-1}	Errors φ, 1 × 10		Dynamic factor k_∂	
	Rigidity, rad × 10^4		moment of inertia, kg/m			Mass I_1	Mass I_2	with gaps	without gaps
	01	02	I_1	I_2					
1	1,04	0,14	0,03	22,89	31	0,017	0,141	2,4	1,8
2	0,69	0,25	0,014	11,49	14	2,83	9,62	2,4	1,66
3	5,46	0,6	0,024	11,49	22	0,48	4,8	2,2	1,6
4	0,6	-	11,49	-	23	-	4,46	2,56	1,65
5	512,3	-	11,49	-	103	-	0,023	2,8	1,63

As an illustration for all five schemes the rectangular law of engine rotor acceleration is accepted. Dynamic analysis (Table 4) shows that drives with intermediate transmission elements, which are schemes 1, 2, 3 (Fig. 2) have the biggest errors. Transmission-free schemes 4 and 5 (Fig. 2) produce small deviations from programme movement of the actuator. The drive wheel (Fig. 2, Scheme 5) performs program movements most accurately and with a high natural frequency, which contributes to the fastest attenuation of disturbances. In this regard, the power wheel should be considered the most suitable drive for programme automatic control of the movement of bridge cranes, as the most accurately fulfilling the programme law of motion.

The elements of such drives have a slightly higher dynamic stress during transient operating modes, which was determined by dynamic factors after the numerical solution of differential equations of oscillations of two-mass models. The presence of gaps in the drive elements increases the dynamic stress and inaccuracy of the travel. Reducing the number of intermediate elements in the drive transmission reduces the effect of inaccuracy in the manufacture and assembly of the drive on the accuracy of positioning of the crane-robot.

To achieve the highest dynamic accuracy and minimum dynamic stress, the transmission-free drive requires high precision manufacturing and assembly, as well as the selection of the most acceptable law of acceleration and braking of high-torque engines.

The parameters of such a travel mechanism drive, obtained through dynamic analysis, allow us to establish the presence of the most important quality − controllability, which complies with the statement of the task.

Given the urgent need for high hoisting capacity cranes-robots with increased accuracy of cargo positioning, which is especially difficult to achieve in the horizontal plane, for example, when installing turbines, large-scale assembly of ships, loading fuel elements of nuclear reactors and other critical machines, it is proposed to combine orthogonally related movements in the horizontal plane with less positioning accuracy with precise highly accurate positioning of the load grab point, which means to use unprofitable degrees of motion, controlled with high accuracy.

It is proposed to redesign, for example, the above-recommended crane with a transmission-free modular travel drive with frequency control by equipping it with a trolley with eccentric connected rotating platforms, onto which the gripping device, gripper or tongs are fixed (Fig. 4).

Upon receipt of signals for processing, eccentric platforms 2, 3, 4 receive rotational movements from the drives 8-9; 10-11; 12-13. Since platforms 2 and 3 have eccentricities e_1 and e_2, and the gripper is attached to the platform 4 with eccentricity e_3, the mutual rotation of platforms leads to movement of the gripper in the plane, that is its positioning in the plane occurs.

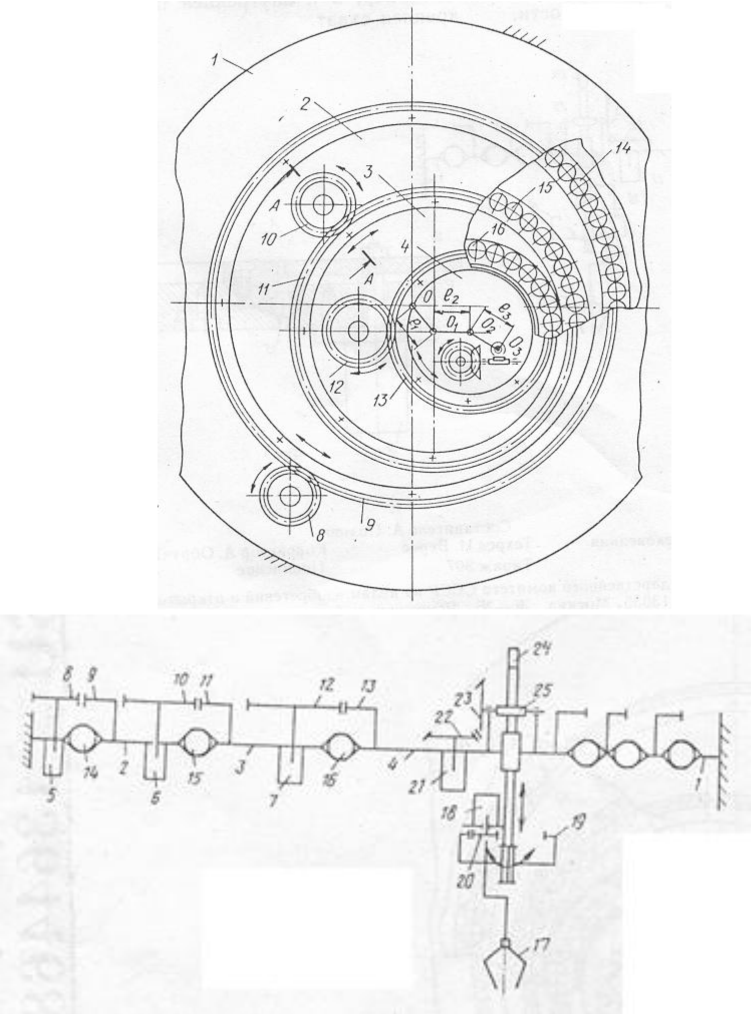

Figure 4 − Rotational unprofitable degrees of motion of the gripper of the crane-robot

At the same time the crane passes from the PCIR working in Cartesian system, to the PCIR class with a cylindrical coordinate system. The position accuracy of eccentric platforms is significantly higher, and for platforms with the same eccentricity e is determined by the formula

$$\left.\begin{aligned}\Delta x &= e\left[-2\sin\delta_1(2n_1+1)\cdot\sin\delta_1 - 2\sin\delta_2(2n_2+1)\cdot\sin\delta_2\right]\\ \Delta y &= e\left[2\sin\delta_1\cdot\cos\delta_1(2n_1+1) + 2\sin\delta_2\cdot\cos\delta_2(2n_2+1)\right]\end{aligned}\right\}, \qquad (9)$$

where $\Delta x, \Delta y$ are coordinate-wise errors of plane-linear movements, m;
e is eccentricity of rotating platforms, m;
δ_1, δ_2 are indexing increments of rotations of platforms, rad;
n_1, n_2 are the number of spent increments of platforms rotations.

Since the length of the functional units of each platform (eccentricity) is significantly less than the radius of the platform, this combination allows us to combine in the cranes quite proven, albeit modern, mechanics of Cartesian movements with angular rotation of eccentric platforms, which is always significantly more accurate and has no "dead zones", which occur in all MS with a cylindrical coordinate system.

The accuracy of PCIR positioning depends on increment and accuracy of execution of control signals when drives fine-tune generalized displacements. It is problematic for hoisting cranes to ensure the accuracy of horizontal movements of gripping devices with the load.

The use of functional units in the form of eccentric full-circle platforms allows us to increase the technological capabilities and accuracy of the manipulator by obtaining a full working area and by reducing increments and positioning errors of the gripper. In addition, the combination of units with circular movable bearers provides greater static and dynamic rigidity on the gripper, which further increases the accuracy of its positioning.

Conclusion

Design values of characteristics of the travel mechanism of bridge cranes show that the greatest design perfection is inherent in the transmission-free modular drive. It enables us to change the bridge crane into the crane-robot with controlled automatic mode of operation. Moreover, maintainability of the travel mechanism increases while its steel intensity decreases. The relevance of the obtained conclusions is enhanced by the desire of the world's leading crane companies to use gearless drives with frequency and other control.

Transformation of bridge cranes with rigid suspension of cargo into pick-and-carry industrial robots (PCIR) can be carried out by using modular drives with frequency control. To achieve high position accuracy of the gripper with the load in the horizontal-plane direction, it is advisable to add unprofitable angular generalized displacements of the gripper, for example, in the form of eccentric interconnected rotating platforms.

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