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SYSTEM CRITERIA ANALYSIS AND FUNCTION OPTIMIZATION OF INDUSTRIAL ROBOTS

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Summary. For objects of a set-modular structure, such as industrial robots (IR), the interconnected sequence of procedures is offered to achieve multi-criterion evaluation of design data and functional-technological optimization. A system of the boundary filtration of quality criteria set for some types of IR is offered, and an example of an optimum trajectory selection by two criteria for IR such as SCARA is resulted.

Key words: industrial robot, criteria of quality, system model, functional optimization

INTRODUCTION

Efficiency of modern machinery is largely limited to the fast-acting, carrying capacity, exactness of positioning, universality of application and reliability in exploitation of IR mechanisms. Mass limiting of constructions gives the possibility to decrease action moments, and to promote the fast-acting and carrying capacity of the manipulator systems. However such constructions of manipulators are more subject to deformations, decrease their exactness of positioning and operating reliability. In addition, the IR competitiveness is determined also by a possibility of varying the functional modes of the spatial positioning. Modern scientific researches [Gutyrya and Derevianchenko 2001, Gutyrya *et al.* 2004, 2005] allow to estimate the quality of a project in the initial stages, at the same time to optimize its structure and other parameters, using the methods of system qualimetry of technical objects, on the basis of integral criterion of quality and typical algorithms of multi criterion optimization.

OBJECTS AND PROBLEMS

The optimum choice of the mode of functioning of a particular IR construction by a certain number of quality criteria is an important condition of providing a prolonged life cycle of such machines [Eliseev *et al.* 1999, Yaglinsky and Iorgachov 2004]. During the choice and development of a particular model it structure and parameters of component parts are analyzed above all things, especially of drive, run-time mechanical system, control systems, typical objects of manipulation. It is necessary to take into account also descriptions of external power cooperation, obstacles to IR movement, complication and intensity of functional-technological mode of operation.

On the basis of researches conducted on the enterprises of Japanese industry, the basic consumer requirements to IR constructions were determined. [Kotsuhiconoda 1995]. Also the statistical research of parameters of 156 IR operating constructions was carried out (Tab. 1). As known, the exactness of IR positioning is related to the range of drawing out of hand manipulator, by a carrying capacity, by spatial configuration in the point of positioning, and by elastic-absorber parameters of links. With the purpose of increase of productivity and saving of certain requirements of technological process it is expedient to multiply the speed of separate motions and to combine them at implementation. However, due to non-rigidity of manipulator construction and necessity of limitation of accelerations for providing certain techno-resources and exactness of positioning, some restrictions are imposed on the parameters of motion: the way of braking makes no less than 10–15% of the complete range of displacement, here the normative sizes of accelerations are 4,0–9,0 $\mathrm{m/s^2}$ [Eliseev *et al.* 1999].

Technological IR possibilities are characterized by the coefficient of service and coefficient of mobility. For an integral estimation of geometrical properties of manipulator in a given point of the working area and for the selection of the most convenient areas in the IR working space the coefficient of service k_θ is used, which is determined by the relation of servo angle in this point to the solid angle 4π. For an estimation of IR possibility to orientate the objects in all the working zone (working space V_w) the mean coefficient of service is calculated

$$k_m = \frac{1}{V_w}\int_{V_w} k_\theta dV_w = \frac{1}{V_w}\int_{V_w} \frac{\theta}{4\pi} dV_w \in [0.1...1.0]. \quad (1)$$

An increase of nomenclature of processing details results in a relative growth of the losses of time while adjusting the IR systems. Expedience and speed of a IR functional unit adjustment is estimated by the coefficient of equipment flexibility, which represents the degree of the use of balance of working hours, and is determined as

$$k_f = \left[1 + \frac{\sum_{i=1}^{n} t_n^{(i)}}{Q} \cdot P_c \right]^{-1}, \quad (2)$$

where:

$t_n^{(i)}$ – the middle duration time on over adjusting of the functional unit *i*;

s, n – amount of devices or mechanisms, for which the periods on over adjusting are unconnected in time;

P_c – cyclic productivity of equipment, s^{-1};
Q – quantitative volume of details. It is considered, that the automatic equipment satisfies high conditions in case k_f = 0.5…1.0.

Table 1. Statistical data concerning the IR parameters and proper user priorities [Kotsuhiconoda 1995]

Parameter, dimension	Data of study			Priorities	
	Number of specimens	Range of determination	Sample %	Range of determination	Sample %
1. Working space V_w, m^3	1 9 22 27 1	0.009 0.01 ... 0.09 0.1 ... 0.99 1 ... 9.99 10.0	1.7 15 36.6 45 1.7	– – – – –	– – – – –
2. Vertical displa-cement h_v, cm	– – – –	– – – –	– – – –	< 50 50 ... 100 100 ... 200 > 200	32.9 34.1 15.9 18.3
3. Horizontal displacement h_h, cm	– – – –	– – – –	– – – –	< 50 50 ... 100 100 ... 200 > 200	18.3 39.0 23.2 20.7
4. Angle of rotation φ, grad	– – – –	– – – –	– – – –	< 90 90 ... 180 180 ... 240 > 240	13.4 45.1 35.4 7.3
5. Speed of the linear moving V, m/s	23 45 20	0.10 ... 0.49 0.50 ... 0.99 1.00 ... 2.00	26.1 51.1 22.8	< 0.50 0.50 > 1.00	35.4 48.8 13.4
6. Angular speed ω, s^{-1}	11 13 51 23	0.76 0.78 ... 1.55 1.57 ... 3.11 3.13	11.2 13.3 52.1 23.4	– – – –	– – – –
7. Absolute error of positioning Δ, mm	8 19 25 48 7 4	0.09 0.1 ... 0.49 0.5 ... 0.99 1 ... 2.49 2.5 ... 4.00 5.00	7.2 17.1 22.6 43.2 6.3 3.6	< 1 1 ... 5 > 5.0	41.5 51.2 7.3
8. Amount of cy-cles of positioning n_{cp}	– – –	– – –	– – –	< 100 100 > 100	51.2 31.7 20.7

9. Amount of degrees of mobility N	1 13 23 43 24 11 2 1 1	1 2 3 4 5 6 7 8 9	0.8 10.8 19.2 35.8 20.5 9.7 1.6 0.8 0.8	< 3 3 ... 5 5 ... 7 > 7	13.4 46.3 26.8 6.1
10. Carrying capacity m_c, kg	16 23 31 18 21 21	0.99 1 ... 4.99 5 ... 14.99 15 ... 29.99 30 ... 49.99 50	12.3 17.7 23.8 13.8 16.2 16.2	< 5 5 ... 30 30 ... 100 > 100	39.0 40.2 26.8 7.3

METHOD OF MODELING

On the basis of the executed analysis of characteristic parameters and the proper user requirements of IR constructions (Tab. 1) the multi-parametric, multi-criterion and multi-level maintenance of the problem of reflection and management by technical perfection of similar products and projects of system complication is confirmed. The necessary and sufficient nomenclature of functional properties of typical IR constructions is set (Tab. 2), and the proper group indexes are represented as tops $q'_j\ \forall j=\overline{1.6}$ of the graph (Fig. 1), the prototypes of which are the single indexes of quality, that are bound by the fuzzy set of relations $\{ q_i \Leftrightarrow q_j \}$. For the data given by the circuit, some composition of relations is offered as a nucleus model and a few different shells. At the same time, the indexes at every level are not the composition of indexes of other levels [Gutyrya *et al.* 2005].

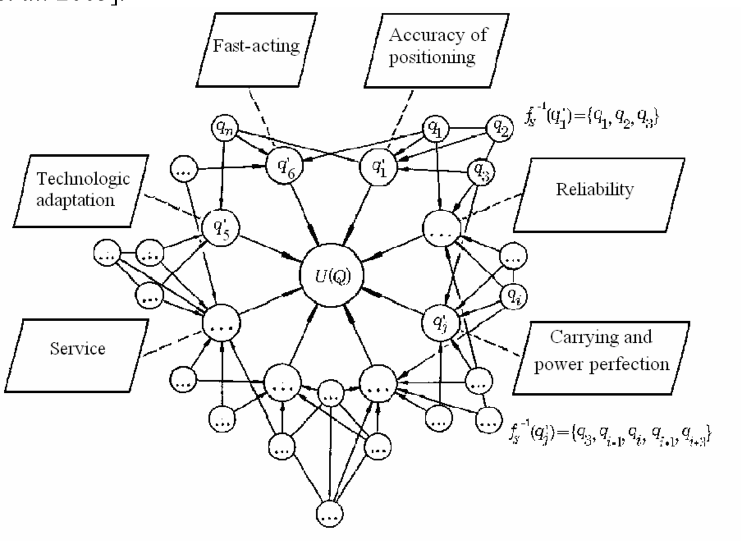

Fig. 1. Graph of a system model of IR quality indexes

Table 2. Systematization and norm setting of IR quality indexes

Functional property	Index of quality, dimension	Range of determination y^-, y^+	Gradient of useful function	Absolute y_i /rationed q_i values of the index for some IR type		
				Universal 20.02	PUMA 600	SCARA
1.Reliability	1.1. Work till the first failure, *hours*	1000 … 5000	+	1500 0.25	3500 0.75	4500 0.9
2. Carrying and power perfection	2.1. Relative carrying capacity m_c / m_r, (m_r – mass of robot)	0.01... 0.10	+	0.06 0.45	0.06 0.67	0.08 0.87
	2.2. Relative power capacity $\gamma_p = m_c / N_e$, (N_e – total engine power), kg/kWt	0.2 ... 1.0	+	0.5 0.52	0.7 0.75	0.9 0.93
3. Accuracy of positioning	3.1. Absolute error of positioning Δ, mm	0.1 ... 2.5	-	1.5 0.31	1.5 0.31	0.5 0.72
	3.2. Dynamic error of the angular rotation $\Delta\varphi$, rad	0.01 ... 0.04	-	0.03 0.31	0.03 0.31	0.01 0.8
	3.3. Dynamic error of the linear displacement δ, mm	1.0 ... 5.0	-	3.5 0.29	1.5 0.71	1.2 0.88
4.Technologic adaptation	4.1. Time of running approach to nominal speed Δt_r, s	0.1 ... 0.7	-	0.6 0.48	0.3 0.62	0.3 0.62
	4.2. Time of vibration calming of grab pole, *s*	1 ... 5.0	-	4 0.35	2.4 0.55	1.1 0.88
	4.3. Number n_{cp}	100 … 300	+	150 0.39	250 0.84	280 0.94
	4.4. Coefficient k_f	0.5 … 1.0	+	0.6 0.33	0.7 0.55	0.9 0.88
5. Fast - acting	5.1. Nominal angular speed ω, s^{-1}	1.0 ... 3.5	+	2.0 0.55	2.5 0.73	3.2 0.93
	5.2. Nominal speed of getting up, m/s	0.4 ... 1.0	+	0.5 0.52	0.6 0.75	0.8 0.93
	5.3. Nominal horizontal speed, m/s	0.4 ... 1.0	+	0.5 0.52	0.7 0.80	0.9 0.97
	5.4. Maximal angular acceleration ε, s^{-2}	3 ... 30.0	+	15 0.51	15 0.51	22 0.64
	5.5. Maximal acceleration of translational motion a_x, m/ s^2	0.4 ... 2.0	+	1.0 0.38	1.2 0.45	1.5 0.56

6. Service	6.1. Space V_w, m^3	0.1…10	+	1.9 0.22	5.1 0.60	8.7 0.92
	6.2. Displacement h_v, m	0.3 ... 2.0	+	0.5 0.26	1.0 0.55	1.7 0.68
	6.3. Displacement h_h, m	0.3 ... 2.0	+	0.5 0.26	1.2 0.58	1.8 0.86
	6.4. Angle θ, sterad	1.6 ... 4.2	+	120 0.33	180 0.73	220 0.88
	6.5. Amount N	4 ...7	+	5 0.48	6 0.79	6 0.79
	6.6. Coefficient k_m	0.1 ... 1.0	+	0.5 0.59	0.6 0.70	0.9 0.94

Consequently, on each level of the model a new functional property of each of IR subsystem can be taken into account, and also complex criteria of quality, that users of the construction as a whole pull out.

The method of qualimetry Allows to coordinate a certain amount m of IR functional properties with the necessary altitude l_m of a model, and sufficient power of group index set $q'_j \; \forall j = \overline{1.6}$. The canon form of the structure of a model responds to the conditions $l_m = m$; $n = \sum_{k=0}^{m}(m-k)$, and the proper display on the plane of „property – altitude" has the triangular form of $(m \times n)$ – matrices of elements $\{Q\} = \{q_1, q_2, ..., q_n\}$. Unity and stability of decision of such heterogeneous systems of linear equalizations is provided

$$\begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} & q_{15} & q_{16} & -1 \\ 0 & q_{22} & q_{23} & q_{24} & q_{25} & q_{26} & -1 \\ 0 & 0 & q_{33} & q_{34} & q_{35} & q_{36} & -1 \\ 0 & 0 & 0 & q_{44} & q_{45} & q_{46} & -1 \\ 0 & 0 & 0 & 0 & q_{55} & q_{56} & -1 \\ 0 & 0 & 0 & 0 & 0 & q_{66} & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ U \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \tag{3}$$

(U – system criterion of quality; $\lambda = \{\lambda_1, \lambda_2, ..., \lambda_6\}$ – column of weighing unknown coefficients) is provided by the condition of order of matrix Q elements in the following form

$$1{,}0 > q_{k+1,j} > q_{k,j} > 0{,}1 \; \forall k = \overline{1, j} \wedge j = \overline{1, m}.$$

Adequacy of application of the given condition is confirmed by the sequence of forming of such IR properties as service possibilities, fast-acting, exactness of positioning, and others like that, the intensity of which diminishes in direction from the level of design of separate details, assembling units, subsystems, and others like that, to the level of IR on the whole. On the basis of hyperbolical function th$y$, that represents reduction of priority for the user of any absolute index of quality $y_i \; \forall \, i = \overline{1,n}$ with growth of its value, for setting of various physical scales in range $[0.1; 1.0]$, the following equalizations are offered:

– reflect without the change of gradient

$$q_i = 0.1 + 1.18 \cdot \text{th}\left[\left(y_i - y_i^-\right) / \left(y_i^+ - y_i^-\right)\right];$$

– with change of gradient on opposite one

$$q_i = 1 - 1.18 \cdot \text{th}\left[\left(y_i - y_i^-\right) / \left(y_i^+ - y_i^-\right)\right],$$

where:

y_i^-, y_i^+ – accordingly lower and overhead borders of range of change of certain index of quality, that is determined taking into account statistical data and priorities of users (Tables 1, 2).

The necessary completeness of a model (3) and no redundancy of database Q are assured aiming at a quantification of a design up to the level of mapping by certain indexes of quality. An objective criterion for the selection of certain indexes of quality is information content [Gutyrya *et al.* 2005].

RESULTS OF INVESTIGATIONS

By applying the model (3) decisions the following values of system criterion of quality are set: for IR type Universal 20.02 U = 0,34; for PUMA – 600 U = 0,57; for SCARA U = 0,71. It is exposed, that for IR SCARA the most values of weighing coefficients answer such functional properties as a fast-acting, technological adaptation and exactness of positioning. Subsequent technical improvement of IR SCARA is considered on the basis of invariability of its structure, design, elasticity, absorber and mass-inertial parameters. The set of such variable parameters, which form certain criteria of quality of the working of a trajectory is exposed [Yaglinsky and Iorgachov 2004], and the process of multi-criterion functional-technological IR synthesis, which enables to estimate the alternative variants of functioning and choose the best from them for subsequent introduction in production, is considered.

The task of functional-technological IR synthesis is parted into two: at first – form the set of alternative variants of engines operation mode with the criteria of minimum technological time of the working of a necessary trajectory t_T with restriction by coefficient of overload of engines k_E, that affects reliability of IR functioning; secondly – select the best from them with additional criteria of quality – the minimum of relative power capacity by IR functioning. It is consequently needed to choose one of a few possible trajectories of functioning IR (Fig. 2, marked the initial C_0 and eventual C_k

positions of grab pole), when the time of the working of a trajectory, absolute error of positioning Δ , and also the coefficient of overload of engines k_E were minimum among the legitimate maximal values (it is accepted as k_E =1.6). The permanent IR parameters are: structural diagram; design, mass-inertial, and elastically-absorber parameters of links; parameters of engines and control system; carrying capacity $\mathrm{m}_c = 5\,\mathrm{kg}$; initial and eventual configuration of robot.

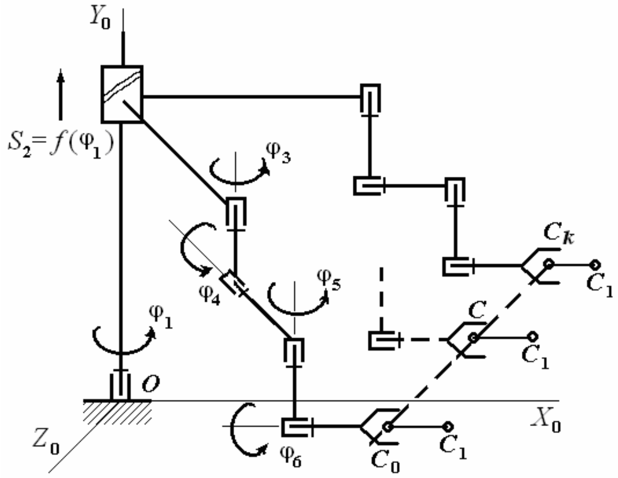

Fig. 2. Structural-kinematics model of the IR type SCARA

At linear overloads a typical diagram of angular speed of the engine has the following sections: an output on rated speed (time of starting Δt_{ri}), work on a nominal mode (time Δt_{ni}), braking time ($\Delta t_{bi} = \Delta t_{ri}$). At the moment of the work start the engine *i* corresponds to the value t_{0i} , and the moment of switching-off – to the value $t_{si} = t_{0i} + \Delta t_{ri} + \Delta t_{ni}$. Angular moving of each degree of IR mobility φ_i is determined by the area of the speed diagram $\omega_i = f(t)$. Alternative variants of functioning differs also according to consecutive or simultaneous work of engines 1, 3, 5. At variation the control parameters of synthesis $t_{0i}, t_{si}, t_{ri}, t_{ni}$ (Tab. 3) the area of each speed diagram remains constant. Thus, the duration of the working of a trajectory and dynamic errors of IR functioning $\Delta\varphi$ and δ should be minimal, and the overload of engines does not exceed allowable values.

Time of the working of a functional trajectory by an engine *i*

$$\Delta t_i = t_{si} - t_{0i}\,; \quad \Delta t_{ni} = \Delta t_i - 2t_{ri} \geq 0\,. \tag{4}$$

Technological time of the working of a functional trajectory *j* is determined by a stopping moment of all engines

$$t_{Tj} = \max{}_j \left(t_{si} \right)$$
$$t_{Tj} = \max{}_j \left(t_{si} \right). \tag{5}$$

Table 3. The control parameters of IR functional-technological synthesis

Parameter	Variant j of trajectory				
	1	2	3	4	5
t_{0i}, s	(0; 0; 0.8; 0; 1.7; 0)	(0; 0; 0; 0; 0.4; 0)	(0; 0; 0.07; 0; 0.07; 0)	(0; 0; 0; 0; 0; 0)	(0; 0; 0.3; 0; 0.3; 0)
t_{ri}, s	(0.3; 0; 0.2; 0; 0.1; 0)	(0.3; 0; 0.2; 0; 0.1; 0)	(0.7; 0; 0.6; 0; 0.6; 0)	(0.7; 0; 0.1; 0; 0.2; 0)	(0.2; 0; 0.1; 0; 0.2; 0)
t_{ni}, s	(0.3; 0; 0; 0; 0.61; 0)	(0; 0; 0.65; 0; 1.2; 0)	(0; 0; 0; 0; 0.75; 0)	(0.22; 0; 0.5; 0; 0.4; 0)	(0.32; 0; 0.47; 0; 0.91; 0)
t_{si}, s	(0.9; 0; 0.9; 0; 2.51; 0)	(0.4; 0;1.05; 0; 1.8; 0)	(1.4; 0; 1.27; 0; 2.02; 0)	(1.62; 0; 0.7; 0; 0.8; 0)	(0.72; 0; 0.97; 0; 1.61; 0)
t_{Tj}, s	2.51	1.22	2.02	1.62	1.61
E_{ij}, kJ	23.4	25.6	32.3	30.1	44.0
q_T	1.000	0.488	0.808	0.648	0.644
q_E	0.532	0.582	0.732	0.684	1.000
ψ_A	0.579	0.573	0.740	0.681	0.964
ψ_B	0.579	0.497	0.800	0.651	0.700
Note: function ψ_A determined when $\xi_1 = 0.1 \wedge \xi_2 = 0.9$; ψ_B – $\xi_1 = 0.9 \wedge \xi_2 = 0.1$					

The first criterion of optimization of IR function is

$$t_T = \min(t_{Tj}) = \min\lfloor \max_j (t_{si}) \rfloor \Rightarrow q_T = \min\left(\frac{t_{Tj}}{T_0}\right), \qquad (6)$$

where:

T_0 – maximally possible duration of technological operation (Fig. 3).

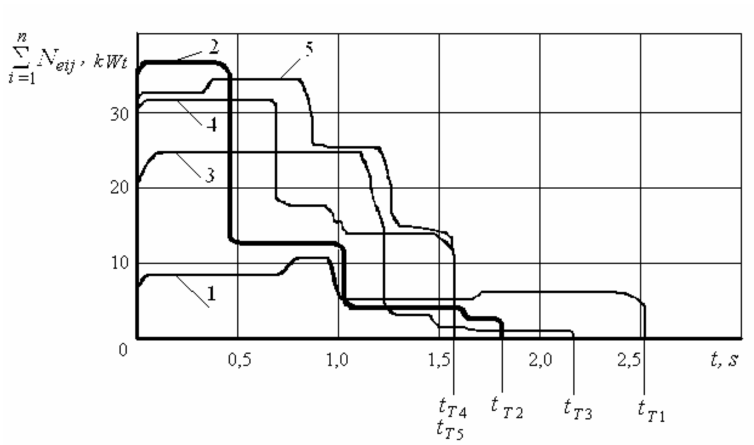

Fig. 3. Diagram of IR engines power consumption by execution of the certain trajectory

Nominal angular speed ω_{ni}, s^{-1}, and nominal moments M_{ni}, N·m, of engines is considered unchanging:

$$[\omega_n]=\left(\omega_{n1},\omega_{n2},\omega_{n3},\omega_{n4},\omega_{n5},\omega_{n6}\right)=\left(2.51;\,0;\,2.51;\,0;\,2.74;\,0\right),$$

$$[M_n]=(M_{n1},M_{n2},M_{n3},M_{n4},M_{n5},M_{n6})=(26.4;0;21.2;0;3.4;0)\,.$$

The program of IR movements is set as a system of algebraic equalizations – functions of the generalized coordinates of vector $\vec{\varphi}$ from the parameter of time t

$$[\varphi]=\{\varphi_{n1},\varphi_{n2},..,\varphi_{n6}\}\forall\,\varphi_{ni}=\varphi_{ni}(t)\wedge i=\overline{1.6}. \tag{7}$$

In this case the position of the grab pole and its orientation (Euler's angles) are determined simply by the matrices of the coordinates'transformation. The first and second direct tasks of kinematics are used, and further differential equalizations of motion to determine the generalized forces on the axes of degrees of mobility, necessary for such motion, necessary motive moments, reaction (internal power factors) in kinematics pairs and in certain cuts of links [Kotsuhiconoda 1995].

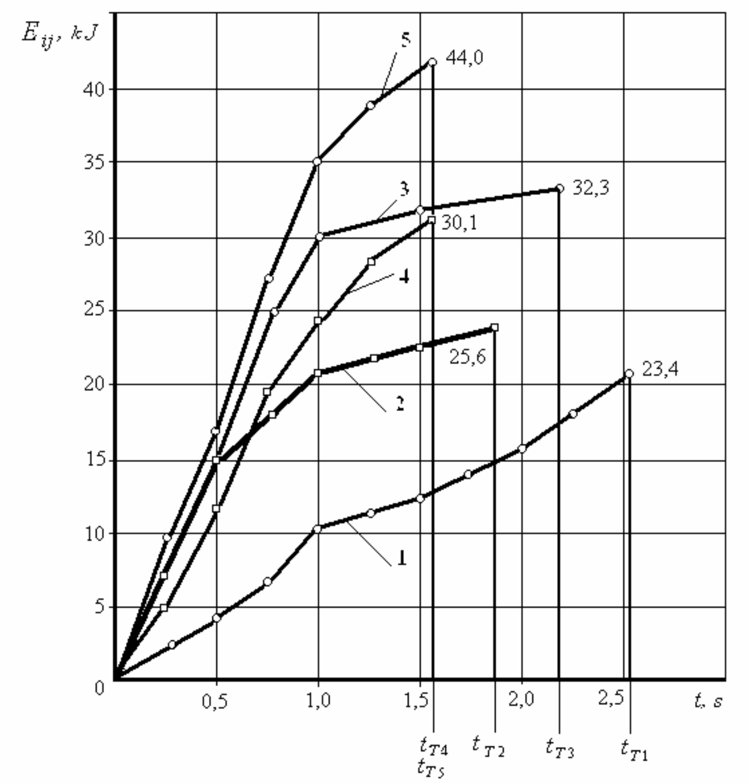

Fig. 4. Diagram of IR energy consumption by an execution of a certain trajectory

The reduction of technological time t_T is set by a reduction of time of achievement of nominal speed (time of starting Δt_{ri}), that simultaneously multiplies accelerations of links, that is multiplies moments on the axes of engines. For every variant *j* of a trajectory, the maximal values of moments of engines $\max M_i$ are determined.

The second criterion of optimization of IR — minimum of relative power capacity by IR functioning

$$q_E = \min\left(\sum_{j=1}^{6} E_{ij} / E_0\right), \tag{8}$$

where:

E_0 – maximal energy consumption by realization of alternative variants of trajectories (Fig. 4).

The calculations of the proper IR parameters are conducted by the program complex of dynamic processes modeling [Kotsuhiconoda 1995].

For the functional optimization the same IR model a useful function was formed as the weighed sum of two partial quality criteria

$$\psi = f_j(x) = \xi_{1i} q_T + \xi_{2i} q_E \;\; \forall\, i = \overline{1.9} \wedge j = \overline{1.5}\,, \tag{9}$$

where:

ξ_1, ξ_2 – weighing coefficients of partial criteria;

i, *j* – number of weighing coefficients variations and amount of alternative variants of trajectories.

Varying the value of weighing coefficients in a range from 0.1 to 0.9 with a permanent step, the set of alternative variants of trajectories (Tab. 3), from which a variant 2 (most perspective for the subsequent working) is selected as a result.

CONCLUSION

The results of a systematic evaluation of IR constructions quality and further functional optimization confirmed a high efficiency of the developed methods and technologies, which allows for their recommendation for the choice of tasks to analyze – synthesis of machinery constructions with system complication.

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