STATIC LOAD STUDY OF INDUSTRIAL ROBOTS OF ARTICULATED TYPE

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Abstract: *The paper deals with the calculation algorithm of the structure elements static loads of an industrial robot of articulated type – RRR used in welding. For calculation, the general architecture and the constructive variant of the robot are known. The calculation relations of the kinematic radii, gravity and dynamic forces that act in the mass centers, gyration radii, and the resultant torsor are presented. On the basis of the working space, functional characteristics, and integration characteristics in a welding cell, the reciprocal position and orientation of the motion axes of each robot joint are established.*

The application supplies the numerical values of the parameters that define the robot loads. The loads knowledge (forces and moments) is necessary in elemental and mechanism calculations and also in driving motor selecting. The disadvantageous robot configurations can be emphasized.

Keywords: *robot, kinematic structure, joints, constructive structure, forces, moments, static load,*

1. INTRODUCTION

In the conception and achievement of an industrial robot, as for every machine and equipment, some stages are covered. Among them one can mention the study, design, modelling and simulation [1, 4], execution, setting in motion, and certification. All these have on the basis specific methods and techniques.

In the design stage some imposed functional characteristics are analysed and the kinematic variant [2, 3], nature and value of loads, constructive solutions, driving manner, control system, etc. are established. The simplified kinematic diagram, working space, and motion parameters (strokes, speeds, accelerations) that define the analysed robot correspond to the operating requirements: the welding operations with speeds determined by the process parameters, possibility of including the robot in a welding cell.

2. CALCULATION METHOD

The establishing of the static and dynamic load values [3, 5, 6] is necessary for the component calculations and component and mechanism stiffness calculation, and also for driving motor and robot structure joint selection.

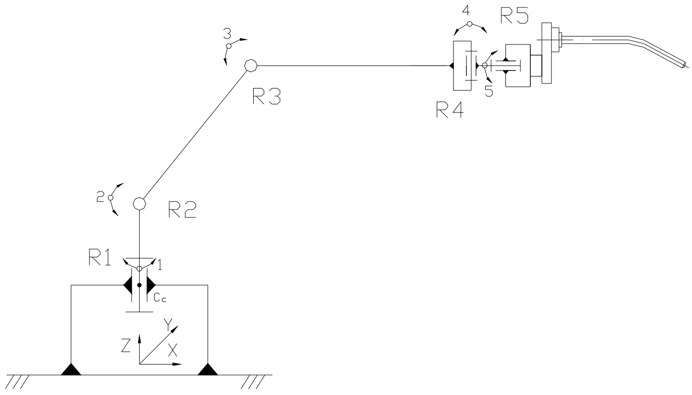


Fig. 1. Kinematic structure of am articulated robot

Working space: sphere. The constructive variant is compact. The robot is of articulated type and has three rotation joints ($R1$, $R2$, $R3$), the structural kinematic diagram being depicted in Fig. 1. The orientation system is parameterised Roll-Pitch, and has an adapted welding head for continuous, in points or on plane or spatial trajectories welding.

The reduced resultant torser $(F, M)_R$ [7] expresses the reduction of the gravity and inertial forces at the level of the designed assembly.

The components of the force (F_x, F_y, F_z,) and moments (M_x, M_y, M_z) correspond to a reference system attached to the assembly. For the torser component establishing it is considered a reference system characteristic for each material point, with the axes parallel and identically oriented to the frame attached to the robot basis. The torser components are considered applied in the calculation centre C_c.

For the component establishing that express the load the followings are considered: the value and orientation of the gravity and inertial forces represented in the calculation scheme (Table 1, Fig. 2); constructive parameters specific to the robot variant that influence the spacial distribution of the mass centres of each assembly considered in calculation in the current axis design; maximum values of the kinematic parameters characteristic for each movement achieved in joints.

For this purpose the coordinates of the mass centres of the mobile elements [7], direction of the gravity and inertial forces, robot reference system axis orientation, the value of the dimensions used for reducing the gravity and inertial loads.

Reducing the loads in form of a resultant torser that loads the mobile assembly is done in a point belonging to it named calculation centre C_c of the reduced loads applied to the assembly.

In the calculation algorithm each mentioned force is considered, their reduction being done as they were acting alone. Finally, by superimposing the effects the resultant expression of the reduced torser components is established.

In the calculation method application the followings are considered:

- inertial forces that appear as effect of a variable motion and are considered in the mass centres of the directly or indirectly driven elements (the mobile element *k* induces the inertial forces in all elements or assemblies that allow the materialisation of the degrees of freedom $k+1, \ldots, n$);
- the inertial force is considered on parallel direction to the motion axis of the mobile joint in opposite direction of the element motion;
- the inertial forces due to a rotation motion in the joint *k* are grouped as follows:
  - centrifugal F_{cg} oriented along the revolution radius direction, obtained as the line perpendicular from the mass centre of the material point to the revolution axis;
  - tangential F_{tg} oriented along a direction perpendicular to that of the force F_{cg} and having an opposite direction in regard with the rotation motion;
- for all material points considered directly or indirectly and driven in rotation motion by joint *k*, the pair of forces F_{cg} and F_{tg} are allocated;
- for establishing the unfavourable case of robot loading the inertial forces projection is oriented in the action direction properly to the cumulative effect of them. Thus, it is obtained a sum of individual forces. All these forces appear in a transitory functioning regime, their calculation is achieved considering from case to case either the starting or stopping of a mobile element with R/T motion so that to obtain the maximum cumulative effect previously mentioned.

It is considered all gravity and inertial loads that appear as result of:

- specific spacial distribution of the masses characteristic to each assembly belonging to the numerical controlled axes $k + 1, \ldots, n$, end effector, and manipulated object;
- spacial distribution of the inertial forces that appear in every designed assembly and are induced by the motions in the joints $k + 1, \ldots, n$, end effector, and manipulated object respectively.

All spacial distributed gravity and inertial loads are considered allocated in the mass centres of the assembly.

For the manipulated object, end effector, and orientation system it is considered the whole mass concentrated in the mass centre, the whole assembly being replaced with a material point (Fig. 2).

Table 1. Establishing of the static loads in elements of an industrial robot of articulated type.

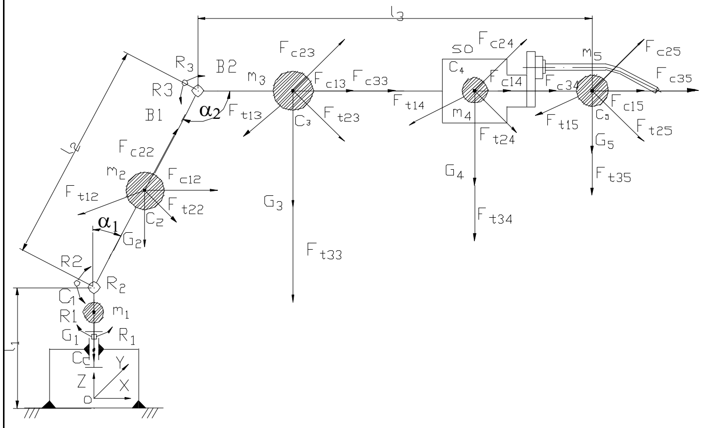
Stages	**Calculation relations**	*Notation meaning*
1	2	3
1. Gravity forces reduction	 Fig.2. Static load diagram $\sum F_x^{(G_i)}=0;\ \sum F_y^{(G_i)}=0;\ \sum F_z^{(G_i)}=-\sum_{i=1}^{5} m_i g;$ (1) $\sum M_x^{(G_i)}=\sum_{i=1}^{5} G_i\cdot y_i;\ \sum M_y^{(G_i)}=0;\ \sum M_z^{(G_i)}=0.$ (2)	F_{tji} - tangential inertial forces, in N; F_{cji} - centrifugal inertial forces, in N; i = 1…5, - mass centres; j = 1...3 – joints; $F_{x,y,z}^{(G_i)}$ – weights on the axes *X*, *Y*, and *Z*, in N; $M_{x,y,z}^{(G_i)}$ – weight moments about *X*, *Y*, and *Z*, in N·m; m_i – element mass, in kg; g – acceleration due to gravity, in m/s^2; G_i – weight in mass centre *i*, in N; x_i, y_i – force arm on *X* and *Y*, in m.
2. Inertial force reducing due to the segment *B*2 motion	$\sum F_x=0;\ \sum F_y=-\sum_{i=1}^{4} F_{ci}^{(3)}=-\sum_{i=1}^{4} m_i\cdot\omega_3^{(2)}\cdot(y_i-\Delta y);$ $\sum F_z=-\sum_{i=1}^{4} F_{ti}^{(3)}=-\sum_{i=1}^{4} m_i\cdot\varepsilon_3\cdot(y_i-\Delta y);$ (3) $\sum M_x=\sum_{i=1}^{4} F_{ci}^{(3)}\cdot(y_i-\Delta y);$ $\sum M_y=0;$ $\sum M_z=0.$ (4) $y_i-\Delta y=R_{cin}$ (R_{cin} = kinematic radii, in m).	$F_{x,y,z}$ - forces on *X*, *Y*, and *Z*, in N; $M_{x,y,z}$ -moments about *X*, *Y*, and *Z*, in Nm; $\sum_{i=1}^{n} F_{ti}^{(j)}$ - tangential forces sum in mass centre *i*, joint *j*; $\sum_{i=1}^{n} F_{ci}^{(j)}$ - centrifugal forces sum in mass centre *i*, joint *j*; ω_i ,- angular velocity, in rad/s, ε_i - angular acceleration, in rad/s^2;
3. Inertial force reducing due to the segment *B*1 motion	$\sum F_x=0;$ $\sum F_y=\left[\sum_{i=1}^{5} F_{ci}^{(2)}\cdot\cos(90^0-\theta_i)+\sum_{i=1}^{5} F_{ti}^{(2)}\cdot\sin(90^0-\theta_i)\right];$ $\sum F_z=\left[\sum_{i=1}^{5} F_{ci}^{(2)}\cdot\sin(90^0-\theta_i)-\sum_{i=1}^{5} F_{ti}^{(2)}\cdot\cos(90^0-\theta_i)\right];$ (5) $\sum M_x^{F_{ci}^{(2)},F_{ti}^{)2)}}=\sum_{i=1}^{4} F_y^{F_{ci}^{(2)},F_{ti}^{(2)}}\cdot z_i+\sum_{i=1}^{5} F_z^{F_{ci}^{(2)},F_{ti}^{(2)}}\cdot y_i;$ $\sum M_y=0;\ \sum M_z=0;$ (6)	$\sum M_{x,y,z}$ – Force moment sum acting about *X*, *Y*, and *Z*, in N·m; z_i - force arm on *Z*, in m; θ_i – stroke of segment *i*, in grd;
4. Inertial force reducing due to the rotatio module	$\sum F_x=-\sum_{i=1}^{5} F_{ti}^{(1)}=-\sum_{i=1}^{5} m_i\cdot\varepsilon_1\cdot y_i;$ $\sum F_y=-\sum_{i=1}^{5} F_{ci}^{(1)}=-\sum_{i=1}^{5} m_i\cdot\omega_1^{(2)}\cdot y_i;\ \sum F_z=0;$ (7) $\sum M_x=\sum_{i=1}^{5} F_{ci}^{(1)} z_i;\ \sum M_y=\sum_{i=1}^{5} F_{ti}^{(1)} z_i;\ \sum M_z=\sum_{i=1}^{5} F_{ti}^{(1)} y_i;$ (8	x_i, y_i, z_i – force arms on axes *X*, *Y*, and *Z*, in mm;

Table 1 *Continuation*

1	2	3
5. Compo-nents of the reduced resultant torsor	$F_{x_R}^{(R)} = \sum F_x^{(G_i)} + \sum F_x^{F_{ci}^{(1)},F_{ti}^{(1)}} + ... + \sum F_x^{F_{ci}^{(3)},F_{ti}^{(3)}} + \sum F_x^{F_i^{(0)}};$ $F_{y_R}^{(R)} = \sum F_y^{(G_i)} + \sum F_y^{F_{ci}^{(1)},F_{ti}^{(1)}} + ... + \sum F_y^{F_{ci}^{(3)},F_{ti}^{(3)}} + \sum F_y^{F_i^{(0)}};$ $F_{z_R}^{(R)} = \sum F_z^{(G_i)} + \sum F_z^{F_{ci}^{(1)},F_{ti}^{(1)}} + ... + \sum F_z^{F_{ci}^{(3)},F_{ti}^{(3)}} + \sum F_z^{F_i^{(0)}};$ (9) $M_{x_z}^{(R)} = \sum M_x^{(G_i)} \cdot x_i + \sum M_x^{F_{ci}^{(1)},F_{ti}^{(1)}} \cdot x_i + ... + \sum M_x^{F_i^{(0)}} \cdot x_i;$ $M_{y_R}^{(R)} = \sum M_y^{(G_i)} \cdot y_i + \sum M_y^{F_{ci}^{(1)},F_{ti}^{(1)}} \cdot y_i + ... + \sum M_y^{F_i^{(0)}} \cdot y_i;$ $M_{z_z}^{(R)} = \sum M_z^{(G_i)} \cdot z_i + \sum M_z^{F_{ci}^{(1)},F_{ti}^{(1)}} \cdot z_i + ... + \sum M_z^{F_i^{(0)}} \cdot z_i;$ (10)	$F_{x,y,x}^{(R)}$ – resultant forces on *X*, *Y*, and *Z*, in N; $M_{x,y,z}^{(R)}$ – moments of the resultant forces on *X*, *Y*, and *Z*, in N·m;
6. Kinematic radii	•*Joint R*1: $R_{cin}^{(1)}$ = pr($\overline{C_1C_5}$)$_{ox}$ = $l_2 \cdot \sin\alpha_1 + l_3 \cdot \cos(\alpha_1-\alpha_2-90^0)$; $F_c^{(1)} = m \cdot \omega_1^2 \cdot R_{cin}^{(1)}$; $\varepsilon_1 = \frac{\omega_{1\max}}{t_a}$; $a_t^{(1)} = \varepsilon_1 \cdot R_{cin}^{(1)}$; $F_t^{(1)} = m \cdot a_t^{(1)}$; (11) •*Joint R*2: $R_{cin}^{(2)} = \overline{R_2C_2} = \sqrt{l_2^2 + l_3^2 - 2 \cdot l_2 \cdot l_3 \cdot \cos\alpha_2}$; $F_c^{(2)} = m \cdot \omega_2^2 \cdot R_{cin}^{(2)}$; $\varepsilon_2 = \frac{\omega_{2\max}}{t_a}$; $F_t^{(2)} = m \cdot a_t^{(2)}$; $a_t^{(2)} = \varepsilon_2 \cdot R_{cin}^{(2)}$; (12) •*Joint R*3: $= \overline{R_1C_5} = R_{cin}^{(3)} = l_3$; $F_c^{(3)} = m \cdot \omega_3^2 \cdot R_{cin}^{(3)}$; $\varepsilon_3 = \frac{\omega_{3\max}}{t_a}$; $F_t^{(3)} = m \cdot a_t^{(3)}$; $a_t^{(3)} = \varepsilon_3 \cdot R_{cin}^{(3)}$; (13)	$R_{cin}^{(j)}$ - kinematic radii, in m; t_a – accelerating time, in s; a_t – tangential acceleration, in m/s^2; l_1, l_2, l_3 – robot arm dimensions, in m;
7. Gyration radii	• *Centre m*$_1$: $R_{gir\,1}^{(5)} = R_{cin}^{(1)}$; $R_{gir\,1}^{(4)} = R_{gir\,1}^{(5)} - (x_{gE} + x_{gSO})$ $R_{gir\,1}^{(3)} = \sin\alpha_1 \cdot l_2 + x_{gB2}$; $R_{gir\,2}^{(2)} = \sin\alpha_1 \cdot x_{gB1}$; $R_{gir\,1}^{(1)} = 0$; (14) • *Centre m*$_2$: $R_{gir\,2}^{(5)} = R_{cin}^{(2)}$; $R_{gir\,2}^{(4)} = \left[l_2^2 + \left(l_3 - \frac{x_{gSO} + x_{gE}}{\cos(90^\circ + \alpha_1 - \alpha_2)} \right)^2 + 2 \cdot l_2 \cdot \left(l_3 - \frac{x_{gSO} + x_{gE}}{\cos(90^\circ + \alpha_1 - \alpha_2)} \right) \cdot \cos\alpha_2 \right]^{1/2}$; $R_{gir\,2}^{(3)} = \sqrt{l_2^2 + x_{gB2}^2 + 2 \cdot l_2 \cdot x_{gB2} \cdot \cos\alpha_2}$; $R_{gir\,2}^{(2)} = x_{gB1}$ (15) • *Centre m*$_3$: $R_{gir\,3}^{(5)} = l_3$; $R_{gir\,3}^{(4)} = l_3 - (x_{gSO} + x_{gE})$; $R_{gir\,3}^{(3)} = x_{gB2}$ (16)	$R_{cin\ j}^{i}$ - gyration radii considered from joint *j*, in m; x_{gE}, x_{gSO} – distance between the mass centre of the effector and the orientation system related to the connection point from *E* to *SO* on *X* in m; x_{gB1}, x_{gB2} – distance from segment joint to the mass centre, in m.

3. NUMERICAL APPLICATION

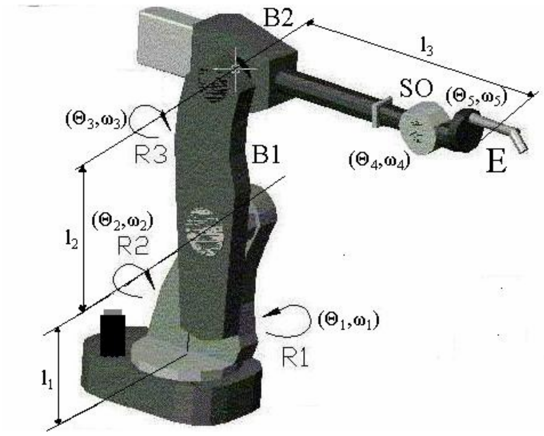


Fig.4. Constructive variant of the industrial robot

The following calculation parameters of the designed robot are considered:

- Maximum mass of the manipulated object: 10 kg;
- Geometric dimensions: l_1 = 0,265 m; l_2 = 0,7 m; l_3 = 1,23 m;
- Motion parameters: strokes, speeds on the numerical controlled axes:
  - Axis1: θ_1 = 340 grd; ω_1 = 2.0943 rad/s;
  - Axis 2: θ_2 = 205 grd; ω_2 = 2.094 rad/s;
  - Axis 3: θ_3 = 252 grd; ω_3 = 2.0933 rad/s;
  - Axis 4: θ_4 = 240 grd; ω_4 = 4.6227 rad/s;
  - Axis 5: θ_5 = 300 grd; ω_5 = 4.6227 rad/s;
- Effector positioning accuracy: ± 0,1 mm;

It was considered for calculation the arm *B*1 and *B*2 positions given by α_1 = 40 grd and α_2 = 40 grd respectively. After the calculation, according to the methodology presented in the second paragraph, the following results were obtained: kinematic radii, gyration radii, centrifugal forces, gravity forces, inertial forces. The components of the reduced resultant torser are:

$F_x^{(R)}$ = 2756.249 N; $F_y^{(R)}$ = 386.884 N; $F_z^{(R)}$ = 1819.74 N.
$M_x^{(R)}$ = 1013.72 Nm; $M_y^{(R)}$ = 2258.765 Nm; $M_z^{(R)}$ = 304.525 Nm.

4. CONCLUSION

The calculation algorithm concerns the structure elements static loads of an industrial robot of articulated type – RRR used in welding. It allows determining disadvantageous configurations in which the analysed robot could be at a moment of time concerning the static loads. On the basis of resultant torser forces and moments the selection and preliminary checking of the driving motors is done. Therefore, it is necessary for the basis revolution module a servomotor of rated torque of 12 Nm, associated with a reducer with the transfer ratio *i* = 1/30. The motor has to be verified in transitory regime conditions.

5. REFERENCES

[1] Borangiu, Th., Ionescu, Fl., (2002), Robot Modelling and Simulation. AGIR Publishing House, Romanian Academy Publishing House, Bucharest.
[2] Dorin, Al., Dobrescu, T. (1998), Bazele cinematicii roboților industriali. BREN Publishing House, Bucharest.
[3] Handra-Luca, V., Mătieş, V., Brişan, C., Tinca, T. (1996), Roboți. Structură, cinematică şi caracteristici. Dacia Cluj-Napoca Publishing House.
[4] Ionescu, Fl., (2002), Computer Aided Engineering. University of Applied Scieneces Konstanz, Konstanz, Germany.
[5] Ispas, V. (1990), Aplicațiile cinematicii în construcția manipulatoarelor şi a roboților industriali. Romanian Academy Publishing House, Bucharest.
[6] Nicolescu, A. (1997), Proiectarea roboților industriali. University POLITEHNICA of Bucharest.
[7] Rădoi, M., Deciu, E. (1994) – Mecanică. Ediția a III-a. Didactic and Pedagogical Publishing Houese, Bucharest.