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APPROPRIATE CHOOSING THE CROSS-ROLLER RING FOR ROBOTIC APPLICATIONS

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Abstract. *Cross-Roller Rings are the newest types of bearing, with optimal performances for high precision motion guidance mechanism in machine-tool and robotics design. The problem of choosing the appropriate size of the Cross-Roller Ring is very important to obtain maximum performances of the mechanical system which use this type of device. Based on specific operating conditions and data from the manufacturer's catalog, this paper represents a practical algorithm that can be used by the designers in selecting the correct size and verification of the Cross-Roller Ring which satisfy the solving of the practical problem, in the better way.*

Key words: *precision bearings, rigidity, high rigidity, robotics, Gantry robots.*

I. INTRODUCTION

Since the Cross-Roller Ring (abbreviated CRR) achieves high rigidity despite the minimum possible dimensions of the inner and outer rings, it is optimal for applications such as joints and swiveling units of industrial robots, swiveling tables of machining centers, rotary units of manipulators, precision rotary tables, medical equipment, measuring instruments and IC manufacturing machines [1], [4].

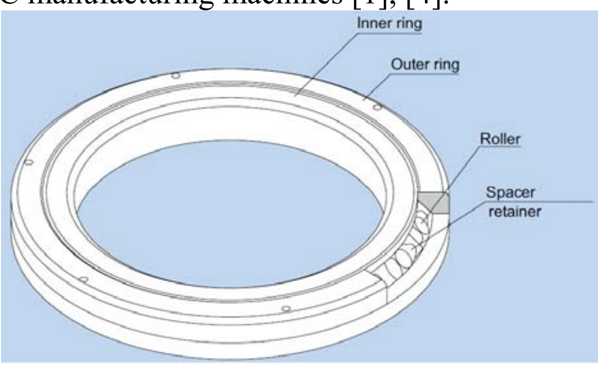


Fig.1. Structure of Cross Roller-Ring Model RB

Structure and Features. With the CRR, cylindrical rollers are arranged with each roller perpendicular to the adjacent roller, in a 90° V groove, separated from each other by a spacer retainer. This design allows just one bearing to receive loads in all directions including radial, axial and moment loads.

-High Rotation Accuracy. The spacer retainer fitting among cross-arrayed rollers prevents rollers from skewing and the rotational torque from increasing due to friction between rollers. Thus, even under a preload, the CRR provides stable rotation. Since the inner and outer rings are designed to be separable, the bearing clearance can be very easily adjusted.

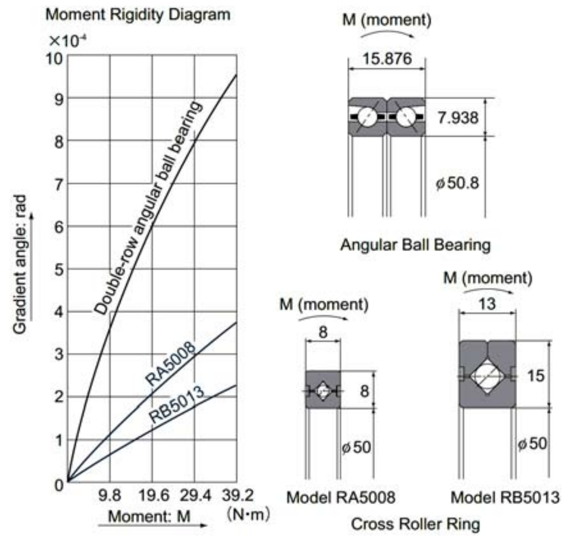


Fig. 2. Moment Rigidity Diagram of CRR

- Easy Handling. The inner and outer rings, which are separable, are secured to the Cross-Roller Ring body after being installed with rollers and spacer retainers in order to prevent the rings from separating from each other.

Thus, it is easy to handle the rings when installing the Cross-Roller Ring.

- Skewing Prevention. Moreover, the application of a preload provides a stable and accurate rotation. Thus, a preload can be applied. These features enable accurate rotation.

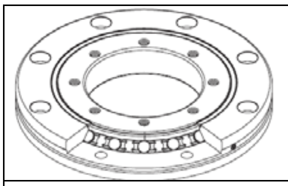
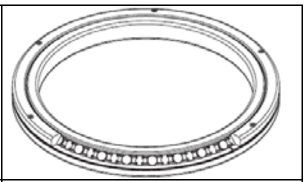
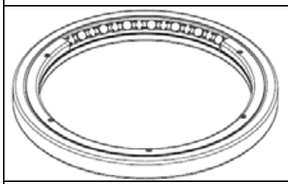
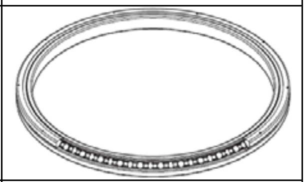
- Increased Rigidity. Unlike the thin angular ball bearings installed in double rows, the cross array of rollers allows a single CRR unit to receive loads in all directions, increasing the rigidity three to four times compared to the conventional type.

- Large Load Capacity. Compared with conventional steel sheet retainers, the spacer retainer allows a longer effective contact length of each roller, thus significantly increasing the load capacity. The spacer retainer guides rollers by supporting them over the entire length of each roller, whereas the conventional type of retainer supports them only at a point at the center of each roller.

In the Figure 2 is presented a comparison between the stiffness (measured by the angular gradient) [4] of Cross-Roller Rings and the stiffness of two angular ball bearings assembly.

Table 1 shows four of the most commonly used types of CRR:

TABLE 1

	
Model RU - Integrated Inner/Outer Ring Type	Model RB - Separable Outer Ring Type for Inner Ring Rotation
	
Model RE - Two-piece Inner Ring Type for Outer Ring Rotation	UPS Grade Series of Models RB and RE

In the case of the RU-Integrated Inner/Outer Ring Type, since holes are drilled for mounting, the need for a presser flange and housing is eliminated. Also, owing to the integrated inner/outer ring type structure with washer, there is almost no effect from installation on performance, allowing stable rotational accuracy and torque to be obtained. It can be used for both outer and inner ring rotation.

RB-Separable Outer Ring Type is the basic type, which is used in locations where the rotational accuracy of the inner ring is required, for example in the swivel portions of index tables of machine tools.

RE-Two-piece Inner Ring Type for Outer Ring Rotation is used in locations where the rotational accuracy of the outer ring is required. The rotation accuracy of the USP-Grade Series of Models RB and RE achieves the ultra precision grade that surpasses the world's highest accuracy standards, such as JIS Class 2, ISO Class 2, DIN P2 and AFBMA ABCE9.

A compact type, similar to model UPS Grade Series, with the thinnest possible inner and outer rings, is optimal for locations requiring a light-weight and compact design such as the swivel portions of robots and manipulators.

II. METHOLOGY TO SELECT A CROSS-ROLLER RING

When selecting a CRR, it is necessary to make a selection while considering various parameters of operating conditions and also forces and moments which load the bearing [4]. The procedure diagram for selecting a CRR is shown in Figure 3.

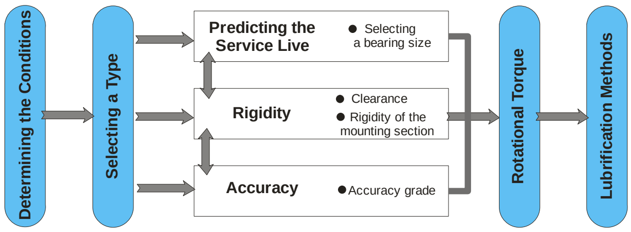


Fig. 3. procedure diagram for selecting a Cross-Roller Ring

A. Determining the Nominal Life.

Nominal life represent the total number of revolutions that 90% of a group of identical Cross-Roller Ring units independently operating under the same conditions can achieve without showing flaking from rolling fatigue [2]. The service life of the CRR is obtained from the following equation:

$$L=\left(\frac{f_T\cdot C}{f_W\cdot P_C}\right)^{\frac{10}{3}}\cdot 10^6 . \qquad (1)$$

L : Nominal life (rev)

C : Basic dynamic load rating* (N)

P_C : Dynamic equivalent radial load (N)

f_T : Temperature factor (see Fig.4)

f_w : Load factor (see Table 2)

The basic dynamic load rating (C) of the Cross-Roller Ring shows the radial load with interlocked direction and magnitude, under which the nominal life (C) is 1 million revolutions when a group of identical Cross-Roller Ring units independently operate under the same conditions. The basic dynamic load rating (C) is indicated in the specification tables.

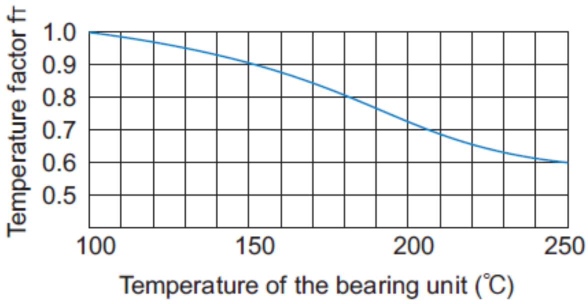


Fig. 4. Temperature factor f_T

If the temperature of the environment surrounding the operating CRR exceeds 100℃ take into account the adverse effect of the high temperature and multiply the basic load ratings by the temperature factor indicated in Fig.3. In general, reciprocating machines or industrial robots tend to involve vibrations or impact during operation. It is extremely difficult to accurately determine vibrations generated during high-speed operation and impact during frequent start and stop [2]. When loads applied on a CRR cannot be measured, or when speed and impact have a significant influence, divide the basic load rating (C or C_0), by the corresponding load factor in the Table 2.

TABLE 2

Operating conditions	f_w
Smooth motion without impact	1 to 1.2
Normal motion	1.2 to 1.5
Motion with severe impact	1.5 to 3

Loading model of a CRR is presented in figure 5. Depending on the CRR loading, the dynamic equivalent radial load of the Cross-Roller Ring is obtained from the following equation:

$$P_C = X \cdot \left(F_r + \frac{2M}{d_p} \right) + Y \cdot F_a . \qquad (2)$$

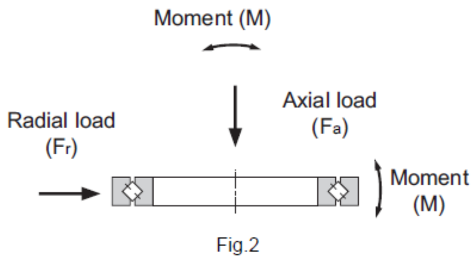


Fig. 5. Loading model of a CRR

P_C : Dynamic equivalent radial load ⟨N⟩

F_r : Radial load ⟨N⟩

F_a : Axial load (N)

M : Moment ⟨N·mm⟩

X : Dynamic radial factor (see Table 3)

Y : Dynamic axial factor (see Table 3)

d_p : Roller pitch circle diameter ⟨mm⟩

TABLE 3

Classification	**X**	**Y**
$\frac{Fa}{Fr + 2M / dp} \leq 1.5$	**1**	**0.45**
$\frac{Fa}{Fr + 2M / dp} > 1.5$	0.67	0.67

The basic static load rating C_0 (indicated as "C_0" in the supplier specification tables) refers to the static load with constant direction and magnitude, under which the calculated contact stress in the center of the contact area between the roller and the raceway under the maximum load is 4000 MPa. If the contact stress exceeds this level, it will affect the rotation. When a load is statically or dynamically applied, it is necessary to consider the static safety factor as shown below.

$$f_S = \frac{C_0}{P_0} . \qquad (3)$$

f_s : Static safety factor (see Table 4)

C_0 : Basic static load rating (N)

P_0 : Static equivalent radial load (N)

TABLE 4

Load conditions	**Lower limit of f_S**
Normal load	1 to 2
Impact load	2 to 3

The static equivalent radial load of the CRR is obtained from the following equation.

$$P_0 = X_0 \cdot \left(F_r + \frac{2M}{d_p} \right) + Y_0 \cdot F_a . \qquad (4)$$

P_0 : Static equivalent radial load (N)

F_r : Radial load (N)

F_a : Axial load (N)

M : Moment $\langle N \cdot mm \rangle$

X_0 : Static radial factor (X_0=1)

Y_0 : Static axial factor (Y_0=0.44)

d_p : Roller pitch circle diameter $\langle mm \rangle$

B. Static Permissible Moment

The static permissible moment (M_0) of the CRR is obtained from the following equation.

$$M_0 = C_0 \cdot \frac{d_p}{2} \cdot 10^{-3}. \quad (5)$$

M_0 : Static permissible moment (kN-m)

C_0 : Basic static load rating (kN)

d_p : Roller pitch circle diameter (mm)

C. Static Permissible Axial Load

The static permissible axial load (F_{a0}) of the CRR is obtained from the following equation.

$$F_{a0} = \frac{C_0}{Y_0} \quad (6)$$

F_{a0} : Static permissible axial load $\langle kN \rangle$

Y_0 : Static axial factor (Y_0=0.44)

III. EXAMPLE OF SELECTING THE CROSS-ROLLER RING, FOR A GANTRY ROBOTIC APPLICATION.

To capture the most important aspects of a CRR selection, is considered the four degrees of freedom suspended robot, presented in Figure 6, [1]. The kinematic scheme [3] is shown in Figure 7. Assuming Cross Roller Ring - model RB25025 (from THK-SUA Catalogue), is used under the following conditions:

- Known the masses and the radius of all fixed and mobile structural elements:

$m_0 = 100$ kg ; $m_1 = 50$ kg ; $m_2 = 75$ kg ;

$m_3 = 50$ kg ; $m_4 = 50$ kg ; $m_5 = 25$ kg ;

$r_{0,5} = 0.75$m ; $r_{1,2,3} = 0$ m ; $r_4 = 0.5$m ;

- Known the mass centers position on the Z axis of all fixed and mobile structural elements:

$h_0 = 1$m; $h_1 = 0$m; $h_2 = 0.5$m; $h_{3,4,5} = 0.75$m;

- It is proposed the angular speed and acceleration values:

$w_G = 2$ rad/s (w: angular velocity);

$a_x = 2\ m \cdot s^{-2}$; $a_y = 2\ m \cdot s^{-2}$; $a_z = 2\ m \cdot s^{-2}$.

- Catalog data of CRR chose (THK-SUA):

$C = 69.3$ kN; $C_0 = 150$ kN; $dp = 0.2775$ m

- The average daily work-cycle: 100 rev/hour.

a.) Axial load : Fa.

To capture the maximum axial load of cross roller ring, it is considered that all four movements taking place in the four axes, namely:

- linear displacement of the entire robot – C_0 axis, rotation around the axis OZ - (C_1), vertical travel of the sled 3 along the column 2 – (C_2), movement of the sled 5 along OX axis, on the arm 4 – (C_3).

It is considered constant movement of robot rotation around the axis OZ (angular speed w = const). The three linear movements, along OZ, OX and OY axes are accelerated movements: a_z, a_x, and a_y (constant values).

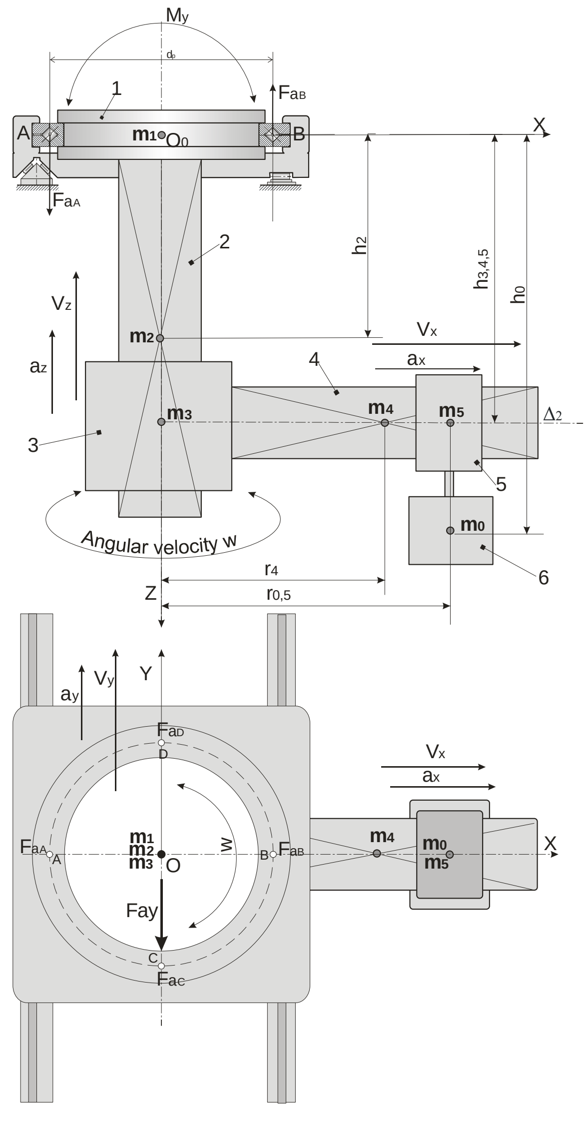


Fig. 6. Structural design of a four degrees of freedom suspended robot

To determine the correct axial loading of the CRR, the constructive robot configuration must be taken into account [3]. So, remember that d_p diameter of the rollers movement circle.

For the determination of axial loads in the two significant B and D areas, in the first stage must be written of all forces balance equation, in relation on the A point.

$$\sum_{i=1}^{k} M_{A_i} = 0; \qquad (7)$$

Thus, you get the resultant force value in the point B:

$$F_{a_B} = \left\{ \begin{array}{c} \frac{(m_1+m_2)\cdot g}{2} + \frac{(a_z+g)}{2}\cdot(m_3+m_4) + \frac{(a_z+g)}{d_p}\cdot m_4\cdot r_4 + \\ + \frac{1}{d_p}\cdot\left[(a_z+g)\cdot(m_0+m_5)\cdot(r_0+\frac{d_p}{2}) + a_x\cdot(m_5\cdot h_5+m_0\cdot h_0)\right] - \\ -\omega^2\cdot[h_4\cdot(m_4\cdot r_4+m_5\cdot r_5)+m_0\cdot r_0\cdot h_0] \end{array} \right\} \qquad (8)$$

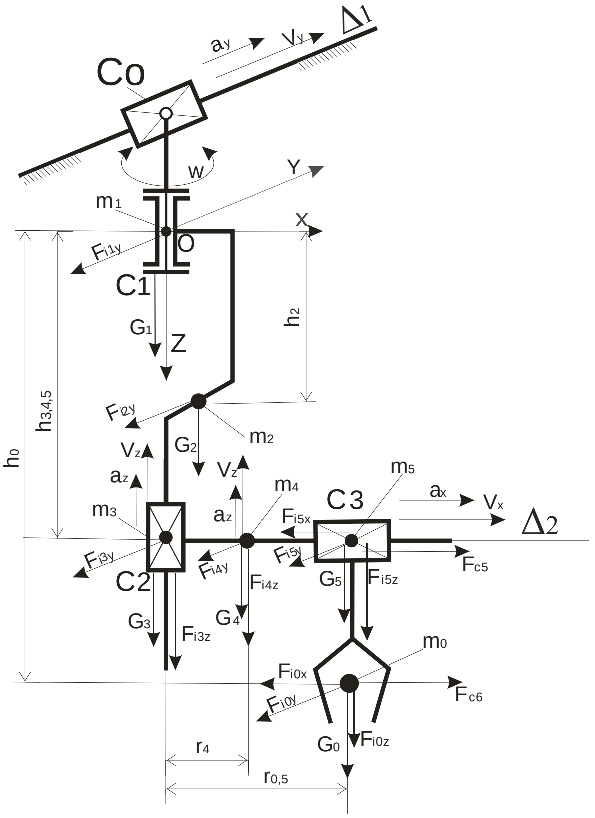


Fig. 7. The kinematical scheme of a TRRT robot

For the numeric data proposed in the example, it was obtained the value of the axial load: $F_{a_B} = 8.349 \times 10^3 \langle N \rangle$

In stage two all forces balance equation is written, in relation to the D point, (diametrically opposed to C).

$$\sum_{j=1}^{n} M_{D_j} = 0. \qquad (9)$$

Thus, you get the resultant force value in the point C:

$$F_{a_C} = \left\{ \begin{array}{c} \frac{1}{2}\left[(m_1+m_2)\cdot g + (a_z+g)(m_3+m_4+m_5+m_0)\right] + \\ + \frac{a_y}{d_p}\cdot[m_2\cdot h_2+(m_3+m_4+m_5)\cdot h_3+m_0\cdot h_0] \end{array} \right\} \qquad (10)$$

After the calculation it is obtained: $F_{a_C} = 5.533 \times 10^3 \langle N \rangle$

Because the value of the axial force differs in the two areas B and D of CRR, the average load is calculated by the relation:

$$F_a = \sqrt{F_{a_B}^2 + F_{a_C}^2} \qquad (11)$$

For numeric values, the result is: $F_a = 1.002 \times 10^4 N$

b) Radial load: F_r

Maximum radial load is due to centrifugal force of the masses m_4, m_5 and m_6, in circular motion (ω = cst.), as well as the inertial force on the arm 4 due to the accelerated movement along the OX axis, at the same time due to the accelerated movement of the entire mechanical structure along the OY.

$$F_r = \omega^2\cdot[m_4\cdot r_4+(m_5+m_0)\cdot r_0] + a_y(m_1+m_2) + a_y\cdot(m_3+m_4+m_5+m_0) - a_x\cdot(m_4+m_5+m_0) \qquad (12)$$

For proposed values, the result is: $F_r = 1.053 \times 10^4 \langle N \rangle$

c) The moment : M

Writing the equation of moment's equilibrium towards the point O_0, in the two plans: ZOX and ZOY, result:

For the ZOX plane:

$$M_y = (a_z+g)[m_4\cdot r_4+m_5\cdot r_5+m_0\cdot r_0] - \omega^2\cdot[h_4\cdot(m_4\cdot r_4+m_5\cdot r_5)+m_0\cdot r_0\cdot h_0]; \qquad (13)$$

The numeric result is: $M_y = 1.231 \times 10^3 \langle N\cdot m \rangle$

For the ZOY: plane $M_x = 0$ (14)

Equivalent torque witch acts on bearing is:

$$M = \sqrt{M_x^2 + M_y^2} = M_y; \qquad (15)$$

The numeric result is: $M_y = 1.231 \times 10^3 \langle N\cdot m \rangle$

To determine the value of X and Y factors, first is calculated the K-factor value, as follows:

$$K : \frac{F_a}{F_r + \frac{2 \cdot M_y}{d_p}} \qquad (16)$$

After calculation, the result is: $K = 0.516$

Because $K < 1.5$, (see tab. 3), is adopted: $X = 1,\ Y = 0.45$

For proposed numerical data, the dynamic equivalent radial load value is: $P_C = 23.906 \text{ x}10^3 \langle N \rangle$

For normal temperature conditions of operation, ($T < 80^\circ C$) and motion with severe impact, it will adopt: $f_T = 1$ (see fig.4) and $f_W = 2$ (see table 2) In this case, on the basis of expression (1), after the calculus, the nominal life of Cross Roller Ring is: $L = 3.442 \text{ x } 10^6$ rev.

d) Radial equivalent static load

To complete the mechanical evaluation of the Cross Roller Ring, in the following must be calculated the radial equivalent static load. On the basis of equation (4), result is: $P_0 = 2.381 \text{ x}10^4 \langle N \rangle$

e) Static safety factor

Based on the expression (3), the static safety factor is: $f_s = 6.031$

f) Static permissible moment

On the basis of expression (5), permissible moment is: $M_0 = 2.081 \text{ x}10^4 \langle N \cdot m \rangle$

g) Static permissible axial load

At the end, on the basis of expression (6), permissible axial load (Fa_0) is: $F_{a_0} = 3.409 \text{ x}10^5 \langle N \rangle$

h) Service life of Cross-Roller Ring.

If it is known the robot's work cycle, expressed by the number of cycles/hour N_{ch}, we can calculate the service life L_h of RCC:

$$L_h = \frac{L}{N_{ch}}. \qquad (17)$$

In the case of the proposed example, for an average of 600 rev/hour daily, work-cycle service life of RCC is: $Lh = 34.420$ hours..

IV. CONCLUSIONS

Compared with conventional ball bearing, using Cross-Roller Rings bring important advantages in robotic applications, the most important being: high rotation accuracy, increased rigidity, easy handling, simplification of mechanical structure.

Correct calculation of CRR durability, or service life, is a very important problem in order to complete a technical project. The performance of the robotic system is closely related to the optimum choice of CRR. If the work cycle and the duty cycle cannot be determined with precision, then, it should be appreciated the size of the all forces and all torsion moments acting on robot's joints, CRR being the most loaded joint.

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ALEGEREA ADECVATĂ A RULMENȚILOR SPECIALI CU ROLE ÎN CRUCE PENTRU APLICAȚII ROBOTICE

Rezumat: Lucrarea prezintă premisele teoretice necesare abordării problemei alegerii corecte a rulmenților speciali cu role în cruce, în baza cărora se pot realiza cele mai performante soluții de lăgăruire simultană radiala şi axiala a elementelor mecanice grele, în cazul roboților industriali, a masinilor-unelte agregat şi a centrelor de prelucrare. În baza condițiilor specifice de operare şi a datelor de catalog oferite de producător, lucrarea prezintă un algoritm practic de proiectare ce poate fi utilizat în selecția corectă şi verificarea rulmentului cu role în cruce ce poate satisface rezolvarea unei probleme practice de lăgăruire, cu exemplificare în cazul unui Gantry, de tip TRTT.

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