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CONTRIBUTIONS AT THE CALCULATION AND CONSTRUCTION OF THE SUSPENDED TTR ROBOT

Nicuşor Iosif URSA

Abstract: *In paper [1] the dynamic study of the TTR industrial robot was performed. Considering the whole robot's dynamics and the mechanical structure of each module, the actuators are calculated in this paper. This calculation involves the following steps: the identification from the established system of differential equations, the differential equation for each module; depending on the construction of each module, the relation between the driving force from the output mode and the actuator's power is established; the introduction of the driving force expression in the motion differential equation; using the imposed or calculated numerical data the report from this equation* $\frac{P_m}{n_m}$ *is determined; the determination of the actuator's moment* M_n *and choosing from an actuator's catalogue the actuator that has the moment value higher than calculated. The calculations for choosing the actuators were made for MTV, MTO and MR modules from the TTR robot structure.*

Key words: *actuators, driving force, differential equation, mechanical structure, translation module, gripping device.*

1. INTRODUCTION

The suspended industrial robot TTR (figure 1) for heat exchangers handling in the preservation operation from the brazing process, is composed of two translation modules that provide the horizontal movement (HTM), the vertical movement (VTM) and a rotation module (RM).

The robot's construction in this version of modules constructive arrangement, it provides the mobility needed to achieve the movements to be performed during the production process.

Fig. 1. The TTR serial industrial robot

Based on the dynamic study and on the dynamic equations resulted from this study, the judicious choice of the actuators robot's modules is done. The calculations necessary to identify the actuators characteristics for each module are listed below.

2. THE ACTUATOR'S CHOICE OF THE HORIZONTAL TRANSLATION MODULE

Given the horizontal translation module construction of the industrial TTR robot, (HTM, figure 2), based on yields the driving force F_a , the geometry transmission sprocket-belt synchronous gear-rack and the guides used for runway, can be determined.

The axial force (driving force) required for

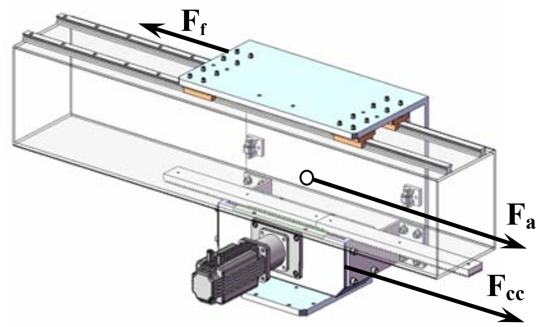

Fig. 2. The horizontal translation module

the mobile equipment movement of the HTM module, has the expression:

$$F_1 = F_a = F_{cc} - F_f\,[N] \qquad (1)$$

relation in which: F_{cc} – is the axial force developed by the transmission sprocket-belt synchronous gear-rack and F_f – is the guide's friction force. The developed transmission force F_{cc} has the expression:

$$F_{cc} = \frac{2M_p}{D_0}[N], \qquad (2)$$

in which: M_p [Nm] – is the torque at the pinion shaft, D_0 [mm] – is the division diameter of the pinion.

By noting P_p, n_p the power, respectively the pinion speed, the torque it can be determined with the relation:

$$M_p = 9550\frac{P_p}{n_p}\,[Nm]. \qquad (3)$$

The power P_p is determined as:

$$P_p = P_m \eta_c\,[kW]. \qquad (4)$$

is noted: P_m – represent the power output by the DC engine which causes the motion of the translational mobile equipment from the robot's base and by η_c the yield's coupling with elastic element.

The n_p pinion speed must satisfy the following inequality:

$$n_p \le n_m\left[\frac{rot}{min}\right], \qquad (5)$$

in which by n_m was noted the shaft engine speed.

Considering the relations (3), (4) and (5), the relation (2) becomes:

$$F_{cc.} = \frac{2\cdot 9550 P_m \eta_c}{D_0 n_m}\,[N]. \qquad (6)$$

Taking into account the relations (1), (6), the dynamic equation corresponding to the vertical translation module of the robot, identifies from the established differential equations system, presented in paper [1] and has the form:

$$\left(\sum_{i=1}^{4} m_i\right)\ddot{q}_1 = \frac{2\cdot 9550 P_m \eta_c}{D_0 n_m} - F_f. \qquad (7)$$

The friction force is calculated with the relation:

$$F_f = \left(\sum_{i=1}^{4} m_i\right) g\mu \quad [N], \qquad (8)$$

where g is noted the gravitational acceleration (g = 9.8 m/s2) and the guide's coefficient of friction μ, adopting the standardized value μ = 0.003.

The expression of the report $\frac{P_m}{n_m}$ it can be obtained from the relations (7) and (8). Thus

$$\left[\left(\sum_{i=1}^{4} m_i\right)\ddot{q}_1 + \left(\sum_{i=1}^{4} m_i\right) g\mu\right]\frac{D_0}{\eta_c \cdot 2\cdot 9550} = \frac{P_m}{n_m}. \qquad (9)$$

With the report obtained in the previous relation it can be calculated the driving moment of the engine, using the relation form:

$$M_m = 9550\cdot\frac{P_m}{n_m}[Nm], \qquad (10)$$

from where the actuator's module is chosen.

The following values are used as numerical data:

$$m_1 = 86{,}15\ kg;\quad m_2 = 53{,}90\ kg;$$

$$m_3 = 22{,}59\ kg;\quad m_4 = 81{,}21\ kg;$$

$$\ddot{q}_1 = 1{,}5\ \frac{rad}{s^2};\quad D_0 = 0{,}092\ m;\quad \eta_c = 0{,}995.$$

According to relation (8), the friction force it's calculated:

$$F_f = (86{,}15 + 53{,}90 + 22{,}59 + 81{,}21)\cdot 9{,}8\cdot 0{,}003 = 7{,}1765\ N. \qquad (11)$$

Entering the values obtained in relation (9), the report $\frac{P_m}{n_m}$ it's calculated:

$$\frac{P_m}{n_m} = 1{,}451\cdot 10^{-3}\ \frac{kWmin}{rot}. \qquad (12)$$

According to relation (10) the driving moment of the DC engine it's calculated:

$$M_m = 9550\cdot 1{,}451\cdot 10^{-3} = 13{,}86\ Nm. \qquad (13)$$

From the cataloque of Parker's company the actuator is chosen. His construction being conducted in an integrated solution, engine and planetary gear set, type GM 090, with the following characteristics:

$$M_m = 14{,}0\ Nm;\ i = 5:1;\ n_{max} = 700\ min^{-1};$$

$$m = 7{,}4\ kg;\ P_{calc.} = 1{,}026\ kW.$$

It is equipped with resolver and electrically brake. Using the actual value of the engine driving moment chosen, according to relations (1), (2) and (8), the force associated to the horizontal translation module it can be calculated:

$$F_1 = F_a = \frac{2M_{m_{CATALOG}}}{D_0} - \left(\sum_{i=1}^{4} m_i\right) g\mu\,[N]. \qquad (14)$$

Using the numerical data, the force F_1 has the value: $F_a = F_1 = 297{,}171$ N.

The kinematic chain for the translation module is consists of: an electric engine, a permanently mobile coupling with intermediate elastic element and sprocket-belt synchronous gear-rack. By using the ball guides, the assembly link with the guides elements related to the runway is achieved. The design criteria that were taken into account when designing the translation modules are: the applied moment to the pinion that will be used to obtain axial forces; the guides anointing that must be used and also ensured by an anointing mechanism of the system for preventing seizure and wear; the guides protection is made with cleaning parts of the runway provided by the manufacturer's factory; implementing technology involves choosing the constructive elements from product catalogs provided by specialized producers and their use according to the technical requirements imposed.

3. THE ACTUATOR'S CHOICE OF THE VERTICAL TRANSLATION MODULE

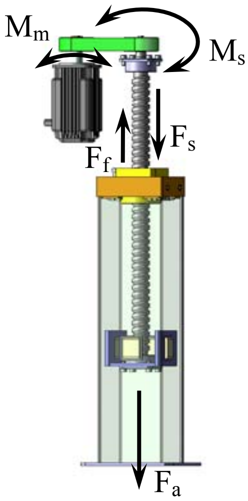

Fig. 3. The vertical translation module

Given the vertical translation module construction of the TTR industrial robot, (VTM, figure 3, [4]), the driving forces F_2 based on yields, the transmission geometry screw-nut with balls and the guides used, can be determined.

The axial force (driving force) reguired for the mobile equipment movement of the VTM module, has according to (1), the expression:

$$F_2 = F_a = F_{sb.} - F_f\,[N]. \qquad (15)$$

relation in which: F_{sb} – is the axial force developed by the ball screw transmission and F_f – is the guide's friction force.

The developed ball screw transmission force F_{sb} has the expression:

$$F_{sb.} = \frac{2M_s}{d_0 tg\left(\varphi + arctg\dfrac{k}{d_b sin\varphi}\right)}\,[N]. \qquad (16)$$

where: d_0 [mm] – is the cylinder diameter that are centers of the balls, φ [˚] – is the angle of the propeller lock on the medium cylinder, k – is the friction coefficient at the rolling, d_b [mm] – is the ball diameter, ϕ [˚] - is the contact angle between the ball and runway, M_s - is the torque of the ball screw shaft.

By noting P_s, n_s the power, respectively the ball screw speed, the torque it can be determined with the relation:

$$M_s = 9550\frac{P_s}{n_s}\,[Nm]. \qquad (17)$$

The power P_s is determined as:

$$P_s = P_m \eta_r\ [kW]. \qquad (18)$$

noting: η_r the yield's bearings pair and by P_m – represent the power output by the DC engine which causes the motion of the translational mobile equipment from the robot's base.

The n_s screw speed must satisfy the following inequality:

$$n_s \le n_m \left[\frac{rot}{min}\right], \qquad (19)$$

in which by n_m was noted the shaft engine speed. Considering the above relations, the relation (16) becomes:

$$F_{sb.} = \frac{191\cdot 10^2 P_m \eta_r}{n_m d_0 tg\left(\varphi + arctg\dfrac{k}{d_b sin\varphi}\right)}\,[N]. \qquad (20)$$

Taking into account the relation (1) and the previous relation written for the F_{sb} force, the dynamic equation deduced from paper [1], corresponding to the vertical translation module (VTM) of the robot, becomes:

$$\left(\sum_{i=2}^{4} m_i\right)\ddot{q}_2 = \frac{191\cdot 10^2 P_m \eta_r}{n_m d_0 tg\left(\varphi + arctg\dfrac{k}{d_b \cdot sin\varphi}\right)} + \sum_{i=2}^{4} G_i - F_f \qquad (21)$$

The friction force F_f is calculated with the relation:

$$F_f = \left(\sum_{i=2}^{4} m_i\right) g\mu\ [N], \qquad (22)$$

where g is noted the gravitational acceleration (g = 9.8 m/s2) and the guide's coefficient of friction μ, the adopting standardized value is μ = 0.02. The angle φ of the propeller lock on the medium cylinder is calculated with the expression:

$$\varphi = arctg \frac{p_h}{\pi d_p} [^\circ] , \quad (23)$$

where by p_h was noted the step screw leader.

From relation (21) it can obtain an expression of the report $\frac{P_m}{n_m}$. Thus ,

$$\left[\left(\sum_{i=2}^{4} m_i\right)\ddot{q}_2 - \sum_{i=2}^{4} G_i + \left(\sum_{i=1}^{4} m_i\right) g\mu\right] \frac{d_0 tg\left(\varphi + arctg \frac{k}{d_b sin\varphi}\right)}{191 \cdot 10^2 \eta_r} = \frac{P_m}{n_m}. \quad (24)$$

With the report obtained in the previous relation it can be calculated the driving moment of the engine, using the relation form:

$$M_m = 9550 \cdot \frac{P_m}{n_m} [Nm], \quad (25)$$

from where the actuator's module is chosen.

As numerical data the following values are used:

$m_2 = 53{,}90\ kg$; $m_3 = 22{,}59\ kg$; $m_4 = 81{,}21\ kg$;

$\ddot{q}_2 = 1\ \frac{m}{s^2}$; $p_h = 0{,}025\ m$; $d_0 = 0{,}025\ m$;

$d_p = 0{,}026\ m$; $k = 0{,}00001 m$; $d_b = 0{,}004\ m$;

$\varphi = 40^0$; $\varphi = 17{,}025^0$; $\eta_r = 0{,}995$.

According to relation (22), the friction force it's calculated:

$$F_f = (53{,}90 + 22{,}59 + 81{,}21) \cdot 9{,}8 \cdot 0{,}02 = 30{,}941\ N . \quad (26)$$

The angle of the propeller lock on the medium cylinder of the ball screw, it can be calculated with the relation (23):

$$\varphi = arctg \frac{0{,}025}{3{,}14 \cdot 0{,}026} = 17{,}025^0 . \quad (27)$$

Entering the values obtained in relation (24), the report $\frac{P_m}{n_m}$ it's calculated:

$$\frac{P_m}{n_m} = 6{,}993 \cdot 10^{-3} \frac{kW \cdot min}{rot} . \quad (28)$$

According to relation (24) the driving moment of the DC engine it's calculated:

$$M_m = 9550 \cdot 6{,}993 \cdot 10^{-3} = 6{,}678\ Nm , \quad (29)$$

With which it will choose the DC actuator planetary gear incorporated, from the cataloque of Parker's company, type GM 060, according to [2], with the following characteristics:

$M_m = 7{,}1\ Nm$; $i = 7:1$; $n_{max} = 780\ min^{-1}$;

$m = 2{,}8\ kg$; $P_{calc.} = 0{,}579\ kW$.

It is equipped with resolver and electrically brake. Using the actual value of the engine driving moment chosen, according to relations (16) and the measurement previously calculated, the force associated to the horizontal translation module, considering $M_s = M_{m\ catalog}$, it can be calculated:

$$F_2 = F_a = \frac{2M_{sSTAS}}{d_0 tg\left(\varphi + arctg \frac{k}{d_b sin\varphi}\right)} - \left(\sum_{i=2}^{4} m_i\right) g\mu\ [N]. \quad (30)$$

Thus, the force F_2 has the value:

$F_a = F_2 = 1752$ N.

The kinematic chain for the translation module is consists of: an electric engine, a permanently mobile coupling with intermediate elastic element and ball screw-nut. The connection between the actuator and screw driver is performed by a belt synchronous gear-rack. The yield ball screw-nut mechanism is high (η = 85-95 %). The design criteria that were taken into account when designing the translation modules are: the applied moment to the driver screw that will be used to obtain axial forces; the reversibility screw driver can not be regarded as an anti-blocking and therefore, to obtain the mobile body position of command, the system requires a torsional locking of the screw; the contact between the actuator and screw driver will be done by safety coupling for overload protection; regarding the tightening, is mention that the transmission of high precision movements and rigidity is only possible by using the ball screw with two nuts; the guides anointing that must be used and also ensured by an anointing mechanism of the system for preventing seizure and wear; the runway protection is made with cleaning parts; implementing technology involves choosing the constructive elements from product catalogs provided by profiled producers, their installation and use are according to the technical requirements imposed; the bearings are used to acquire the axial force from screw driver.

4. THE ACTUATOR'S CHOICE OF THE ROTATION MODULE

For the rotation module of the industrial robot TTR, (RM, figure 4), the engine moment M_3, can be determined, according to the indentified dynamic equation from the differential equation system established in paper [1], coresponding to the rotation module of the robot, namely:

$$\left[J_{\Delta_3}^{(3)} + J_{\Delta_4}^{(4)} + m_4 l_5^2\right]\ddot{q}_3 = M_3 . \tag{31}$$

Steiner's theorem is applied to determine the inertia moments in relation with the rotation axis, for axes parallel situatio $(\Delta // \Delta_C)$.

$$J_\Delta = J_{\Delta_C} + Md^2\left[kgm^2\right] \tag{32}$$

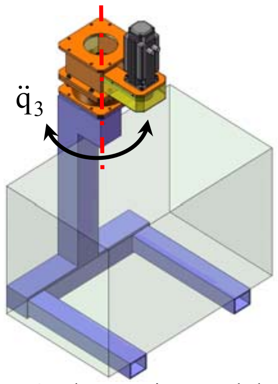

Fig. 4. The rotation module, the gripping device and the manipulated piece

where: d [m] – is the distance between the axes,
M [kg] – is the weight element.

For determine the inertia moments of the complex geometrical components shape, they are divided into simple geometric forms for simplicity, in this case the rotation module and the gripping device (figure 5).

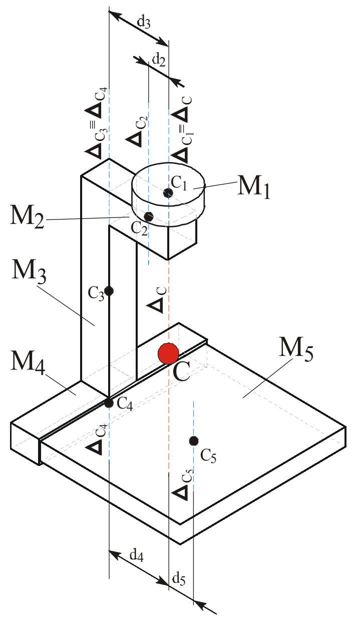

Fig. 5. The decomposition into simple geometric shaps

From figure 5, the relations can be written:

$$J_{\Delta_3}^{(3)} = J_{\Delta_C} = J_{\Delta_C}^{(1)} + J_{\Delta_C}^{(2)} + J_{\Delta_C}^{(3)} + J_{\Delta_C}^{(4)} + J_{\Delta_C}^{(5)}\left[kgm^2\right]. \tag{33}$$

$$\begin{aligned} J_{\Delta_C}^{(1)} &= J_{\Delta_{C_1}} + M_1 d_1^2\,[kgm^2] \\ J_{\Delta_C}^{(2)} &= J_{\Delta_{C_2}} + M_2 d_2^2\,[kgm^2] \\ J_{\Delta_C}^{(3)} &= J_{\Delta_{C_3}} + M_3 d_3^2\,[kgm^2] \\ J_{\Delta_C}^{(4)} &= J_{\Delta_{C_4}} + M_4 d_4^2\,[kgm^2] \\ J_{\Delta_C}^{(5)} &= J_{\Delta_{C_5}} + M_5 d_5^2\,[kgm^2]. \end{aligned} \tag{34}$$

Considering the relations (34), the relation (33) becomes:

$$J_{\Delta_C} = J_{\Delta_C}^{(3)} = J_{\Delta_{C_1}} + J_{\Delta_{C_2}} + \ldots + J_{\Delta_{C_5}} + M_1 d_1^2 + M_2 d_2^2 + \ldots + M_5 d_5^2 = \sum_{i=1}^{5} J_{\Delta_{C_i}} + \sum_{i=1}^{5} M_i d_i^2\,[kgm^2]. \tag{35}$$

Applying the relation (32) for (figure 6, [6]), it can be written:

$$J_{\Delta_4}^{(4)} = J_{\Delta_C} = J_{\Delta_C}^{(4)} = J_{\Delta_{C_6}}\,[kgm^2]. \tag{36}$$

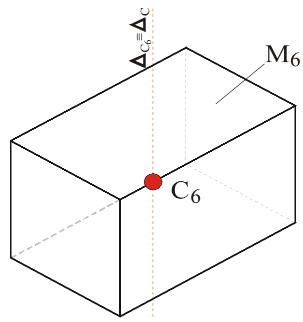

Fig. 6. The manipulated assemble

Taking into account the relations (35), (36), the indentified dynamic equation from the differential equation system established in paper [1], coresponding to the rotation module of the robot, is:

$$\left[\sum_{i=1}^{5} J_{\Delta_{C_i}} + \sum_{i=1}^{5} M_i d_i^2 + J_{\Delta_{C_6}}\right]\ddot{q}_3 = M_3 . \tag{37}$$

The following values are used as numerical data:

$J_{\Delta C1} = 0{,}070\ kgm^2$; $J_{\Delta C2} = 0{,}133\ kgm^2$;
$J_{\Delta C3} = 0{,}356\ kgm^2$; $J_{\Delta C4} = 1{,}350\ kgm^2$;
$J_{\Delta C5} = 0{,}518\ kgm^2$; $J_{\Delta C6} = 5{,}794\ kgm^2$;
$d_1 = 0{,}0\ m$; $d_2 = 0{,}105\ m$; $d_3 = 0{,}235\ m$;
$d_5 = 0{,}025\ m$; $M_1 = 10{,}072\ kg$; $M_2 = 2{,}68 kg$
$M_3 = 2{,}95\ kg$; $M_4 = 6{,}48\ kg$; $M_5 = 3{,}94\ kg$;
$M_6 = 60\ kg$; $\ddot{q}_3 = 1{,}5\ \dfrac{rad}{s^2}$.

According to relation (37) the driving moment of the DC engine it's calculated:

$$M_3 = M_m = 13{,}161 Nm. \tag{38}$$

From the cataloque of Parker's company the actuator is chosen. His construction being conducted in an integrated solution, engine and planetary gear set, type GM 090, with the following characteristics:

$$M_m = 14{,}0\ Nm;\ i = 5:1;\ n_{max} = 700\ min^{-1};$$
$$m = 7{,}4\ kg;\ \ P_{calc.} = 1{,}026\ kW.$$

It is equipped with resolver and electrically brake. The kinematic chain for the rotation module is consists of: an electric engine, a transmission belt synchronous gear, a rotation element. The bearings rotation element fully assume its axial loading. Taking into account the operational requirements and the operational safety criteria, the design of the rotation module was made, such as: the bearings are used to acquire the full axial force due to weight's gripping device and the manipulated piece and radial loads; the anointing should be used regularly and also ensured by an anointing mechanism of the rotation system for preventing seizure and wear; the simple module construction and reliability in its operation; the implementation technology involves choosing the engine, transmission and bearings capable of ensuring the imposed parameters. This is done by linking values from calculations, with product data sheets from manufacturers' catalogs.

5. CONCLUSION

Taking into account the whole dynamics of the robot and the mechanical structure of each module, the actuators are calculated.

Also, for the design of each robot's module, were taken into account the imposed requirements by the operation and the reliability criteria.

6. REFERENCES

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Contribuții la calculul şi construcția robotului suspendat TTR

Rezumat: Studiul dinamic al robotului industrial TTR a fost efectuat în lucrarea [1]. În prezenta lucrare se calculează motoarele de acționare luând în considerare dinamica întregului robot şi structura mecanică a fiecărui modul. Acest calcul presuspune parcurgerea următorilor paşi: identificarea din sistemul de ecuații diferentiale stabilite, a ecuației diferențiale corespunzătoare fiecărui modul, stabilirea relației între forța motoare de la ieşirea din modul şi puterea motorului de acționare, în funcție de construcția fiecărui modul, introducerea în ecuația diferențială a mişcării expresia forței motoare, determinarea raportului $\frac{P_m}{n_m}$ din această ecuație cu date numerice impuse sau calculate, determinarea momentului M_m a motorului de acționare şi alegerea dintr-un catalog de motoare motorul care are valoarea momentului mai mare decăt cea calculată. Calcule pentru alegerea motoarelor au fost făcute pentru modulele MTV, MTO şi MR din structura robotului TTR.

Nicuşor Iosif URSA, Drd. Ing., S.C. RAAL S.A. Bistrița