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DESIGN ANALYSES OF A ROBOT SERVING A CHANGING TOOL SYSTEM WITH RACKS

Summary. With reference to a robot for a replacing tool system with racks we pointed out the typical locations of the end effector thus relating the prescribed path with kinematic parameters and obtaining the consequent total time. Limit values of such parameters were emphasized. Also structural equations were written in order to size several structures which differenciate mainly in the assumed material. Benefits were shown for the different cases.

1 INTRODUCTION

The investigations and experiments carried out with reference to the traditional automatic tool changing systems (with revolver or chain storage) are sufficient to optimally design and utilize them, but they are very few in the field of stores with racks and a robot arm because of their recent industrial use. In fact technical experiences can only give the general design and management criteria of the latter, while specific analyses aimed to determine kinematic parameters for optimal sizing and the use of the mechanisms are up to now not frequent in the technical literature.
We may find, on this subject, general methodologies for kinematic, elastostatic and elastodynamic analyses [1] and formulations oriented to the optimal use or to the programming of robots integrated in manufacturing processes [2,3]. Furthermore, studies concerning the graphic interactive interfaces for programming robot systems [4] or some matrix techniques aimed to optimize working parameters [5] have been recently published.
However typical topics are specifically analyzed. For example it is important [6] to consider all the admissible static configurations in order to optimize the working conditions. At the same time it is fundamental to detail [7] the dynamic analysis of motion of articulated mechanisms and to estabilish numerical strategies [8-10] to determine their elastodynamic properties and capabilities of optimal control of the arm [11]. In this sense using composites requires specific investigations [12-17] also for the optimization of the structure [18-20].

2 CONSIDERATIONS ON KINEMATIC PARAMETERS

We need to express the relationships among speed, acceleration and tool replacement times, by searching the reciprocal influences with reference to the examined robot system. There is a dependence on the successive replacements of the tools in the racks performed by operating in "masqued time" in order to reduce the influence of the replacing times on the total one of the whole cycle as much as possible. Masqued time indicates the time lag during which the replacement operations are carried out simultaneously with others concerning the production cycle. Moreover the above mentioned parameters contribute to determine the size of the structural members of the robot.

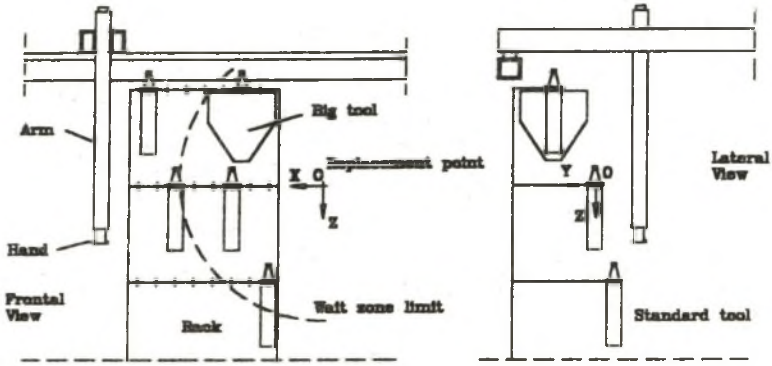

Fig. 1

We refer to a cartesian robot and a storage with modular racks (Fig. 1) where both N_s standard tools (that need only one location) and N_b big tools (that need two or three locations) take place. Furthermore the latter tools are located in predefined areas of the racks that contain shelves with either a different pitch or a topological definition in order to allow an optimum storage. In such a manner the total number of tools $N_s + N_b$ will require a number N of locations with $N \geq N_s + N_b$.

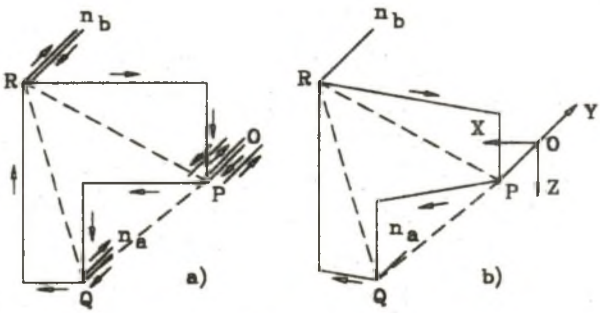

Fig. 2

In such a robot we take in account trajectories obtained by displacement laws along three coordinate axes (X,Y,Z) characterized by the velocity vector $\mathbf{v} = [v_x, v_y, v_z]^T$ and the acceleration vector $\mathbf{a} = [a_x, a_y, a_z]^T$. In Fig. 2a we indicate the replacement point O from which we take the used tool A to put it in the place coded with n_a substituting it with the other B located at the same time in the position of code n_b.

Neglecting the time lags, such as waiting, clamping or similar ones, the total replacement time is

$$T_{cu} = \sum_i T_i \qquad (1)$$

where : T_1=approaching time to O; T_2=drawing out time from O; T_3=transfer time towards n_a; T_4=setting time of the tool in n_a; T_5=disengagement time from n_a; T_6=movement time towards n_b; T_7=hooking time of the tool in n_b; T_8=drawing out time from n_b; T_9=transfer time towards O; T_{10}=setting time of t' e tools in O; T_{11}=disengagement time of the arm.

We point out that in :eality we may have the composition only of the movements in X and Y directions because the one in the Y direction is not simultaneous. Indicating with P,Q,R respectively the projections of O, n_a and n_b on the particular (X,Z) plane, Fig. 2a shows the limit path with dashed lines corresponding to successive fundamental movements while Fig. 2b refers to a possible path characterized by composed movements along the X,Z axis with assigned constant velocities and by neglecting transients.

Actually we also consider transients and then for the evaluation of the time necessary to run the defined path (P, O, P, Q, n_a, Q, R, n_b, R, P, O, P), we take in account the influence of initial and final constant acceleration for each part of it. Each time T_3, T_6, T_9 must be chosen as the greater one among those spent by the single fundamental motion. Such choices depend on the particular vectors v and a and only at this point using eq.1 we may obtain the definitive law $T_{cu} = T_{cu}(\mathbf{v}, \mathbf{a})$.

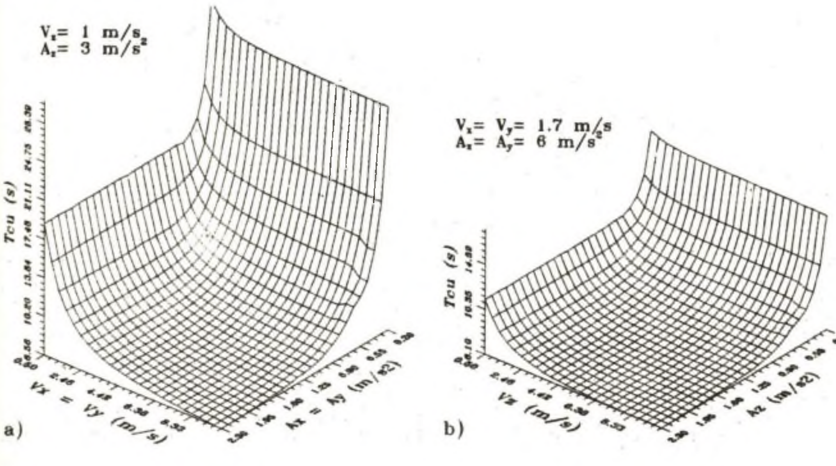

Fig. 3

Obviously if we assign strokes of the single motion and the speed v, a minimum value of the acceleration $a_{min} = v^2/s$ derives, while if with the same stroke initial and final transients have constant acceleration a, then we may consider velocities only up to the maximum value $v_{max} = \sqrt{as}$.

TAB. 1

	O	n_a	n_b	P	Q	R
X	0.0	937.5	625.0	0.0	937.5	625.0
Y	0.0	-125.0	-125.0	-600.0	-600.0	-600.0
Z	0.0	650.0	-650.0	0.0	650.0	-650.0

With reference to the coordinate cartesian system shown in Fig. 2, whose origin is the tool replacement point O and establishing the locations of Tab. 1 it is possible to obtain graphs of the above mentioned type as those shown in Fig. 3, relative to the kinematic assumptions there reported. In Fig. 3a with

$v_z = 1m/s$ and $a_z=3m/s^2$, T_m depends on the common kinematic imposed values of horizontal motions ($v_x=v_y$ and $a_x=a_y$) while in Fig. 3b , with $v_x=v_y=1.7m/s$ and $a_x=a_y=6m/s^2$, it depends on both vertical velocity v_z and acceleration a_z. It is important to note that beyond some values there is no advantage in using larger velocities or accelerations, not only because of the mentioned limits of such parameters, or because of the fact that approaching such limits their relative gains of them become smaller, but mainly for the fact that the orthogonal motion determines the result.

3 STRUCTURAL ANALYSIS

Let us consider the composed space frame of Fig. 4, where the beams (EF, GI) have a very large torsional stiffness, the corners (E, F, G, I) of the correspondent rectangular frame are simply supported, the points (A, B, C, D) transfer only translational forces to the continous beams EG and FI, deriving from the connected body that may slide along Y and support the arm HK, sliding in the Z direction.

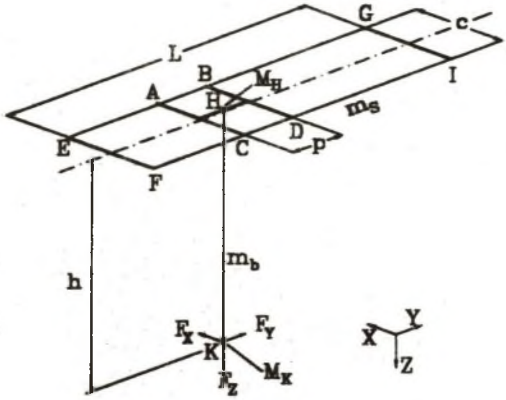

Fig. 4

The loading conditions are F_x, F_y, F_z concentrated in K and body forces caused by accelerations (a_x for all the members, a_y for the two sliding bodies, a_z for the vertical arm), then tied to both concentrated masses (M_k in K, M_s in H) and distributed ones, that are m_b for the arm and m_s for (EG, FI) element.
With respect to the (YZ) plane such loading conditions can be divided either in symmetric or antisymmetric ones. The study of the rectangular frame may thus be limited to a simply end-supported beam for the symmetric case or to an end-closed beam for the antisymmetric one, relatively to EG.
Then it is easy to determine elastic coefficients, successively named u_{ij} and w_{ij} (i=displacement point and j=load point) which correspond to unit values of either concentrated or body forces, while displacements in H (translational u or w and rotational f), as dependent of those in A and B, are

$$\mathbf{u}_H = \begin{bmatrix} u_H \\ w_H \\ f_{Hx} \\ f_{Hy} \end{bmatrix} = \begin{bmatrix} 1/2 & 0 & 1/2 & 0 \\ 0 & 1/2 & 0 & 1/2 \\ 0 & -1/p & 0 & 1/p \\ 0 & -1/c & 0 & -1/c \end{bmatrix} \begin{bmatrix} u_A \\ w_A \\ u_B \\ w_B \end{bmatrix} \qquad (2)$$

If we consider the generalized resultant forces in H (P_x, P_z, M_x, M_y), equilibrium conditions give in A and B the following actions

$$\begin{bmatrix} P_{xA} \\ P_{xB} \\ P_{zA} \\ P_{zB} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 & 0 & 0 \\ 1/4 & 0 & 0 & 0 \\ 0 & 1/4 & -1/2p & -1/2c \\ 0 & 1/4 & 1/2p & -1/2c \end{bmatrix} \begin{bmatrix} P_x \\ P_z \\ M_x \\ M_y \end{bmatrix} \qquad (3)$$

By posing $P = [\, P_x \;\; P_z \;\; M_x \;\; M_y \;\; a_z \,]^T$ and by considering eqs. (2) and (3) it is possible to obtain for the horizontal frame

$$u_H = W\,P$$

where

$$W = \begin{bmatrix} \dfrac{u_{AA}+2u_{AB}+u_{BB}}{8} & 0 & 0 & 0 & \dfrac{u_{AL}+u_{BL}}{2} \\ 0 & \dfrac{w_{AA}+2w_{AB}+w_{BB}}{8} & \dfrac{w_{AA}-w_{BB}}{-4p} & \dfrac{w_{AA}+2w_{AB}+w_{BB}}{-4c} & 0 \\ 0 & \dfrac{w_{AA}-w_{BB}}{-4p} & \dfrac{w_{AA}-2w_{AB}+w_{BB}}{2p^2} & \dfrac{w_{AA}-w_{BB}}{2pc} & 0 \\ 0 & \dfrac{w_{AA}+2w_{AB}+w_{BB}}{-4c} & \dfrac{w_{AA}-w_{BB}}{2pc} & \dfrac{w_{AA}+2w_{AB}+w_{BB}}{2c^2} & 0 \end{bmatrix}$$

Equilibrium conditions of the vertical arm give, with $F = [\, F_x \;\; F_y \;\; F_z \;\; a_y \;\; a_z \,]^T$,

$$P = H\,F$$

in which

$$F = \begin{bmatrix} 1 & 0 & 0 & M_x+m_t h & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & M_x+m_t h \\ 0 & -h & 0 & 0 & -M_x h-m_t\dfrac{h^3}{2} & 0 \\ h & 0 & 0 & M_x+m_t\dfrac{h^2}{2} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \qquad (4)$$

while the rigid body kinematics for translational displacements in K transform u_H by the matrix

$$\mathbf{S} = \begin{bmatrix} 1 & 0 & 0 & h \\ 0 & 0 & -h & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{5}$$

Taking in account the flexibility matrix of the vertical arm

$$\mathbf{d} = \begin{bmatrix} \frac{h^3}{3E_bI_{by}} & 0 & 0 & \frac{M_gh^3}{3E_bI_{by}}+\frac{m_bh^4}{8E_bI_{by}} & 0 & 0 \\ 0 & \frac{h^3}{3E_bI_{bx}} & 0 & 0 & \frac{M_gh^3}{3E_bI_{bx}}+\frac{m_bh^4}{8E_bI_{bx}} & 0 \\ 0 & 0 & \frac{h}{E_bA_b} & 0 & 0 & \frac{2M_gh+m_bh^2}{2E_bA_b} \end{bmatrix} \tag{6}$$

it is possible by means of eqs. (4), (5) and (6) to obtain the direct law for K

$$\mathbf{u}_K = (\mathbf{d} + \mathbf{S\,A\,H})\,\mathbf{F} = \mathbf{D\,F} \tag{7}$$

In eq.(7) matrix **D** depends on values of stiffnes and masses while **F** lists forces applied in K and accelerations of the system.

On the basis of the previously expressed kinematic considerations and with reference to a specific and realistic structural sketch, the problem was to define the sizes apt to give the same displacements of the centroid of the end effector, assumed as control point. The displacements were limited by allowable error value for such systems and the evaluations were made for some different materials. It is basically to this aim that the previously indicated equations were employed.

Also it is useful to remember that the knowledge of the displacements of loaded points of the beams make it possible to determine the stress state.

Steel. aluminum and laminates in graphite-epoxy were considered. The problem, obviously non linear, was solved by using an iterative procedure that gives sizes of cross sections of the arm and of the cross beams. and also by considering the presence of driving systems [21,22]. For steel and aluminum structures commercial beams were used while for graphite-epoxy some symmetrical lay-ups were considered. Some masses (motors, heading boxes, driving systems etc.) are prefixed and have the same total value of 164 kg in all cases.

TAB. 2

	STRUCT.MASS RATIO %	GAIN IN STRUCT. MASS %	GAIN IN TOTAL MASS %
STEEL	43	-	-
ALUMINUM	20	54	16
COMPOSITE	14	68	20

As a result of the calculations for each of the three cases the first column of Tab. 2 gives the percentage ratio between the structural and the total mass, the second column the gain in structural mass with reference to the solution with steel and the third column the gain in total mass with the same reference.

CONCLUSIONS

Kinematic and structural problems were considered for a cartesian robot for tool replacement. In the kinematic field succession of phases was analyzed and limit values of both accelerations and velocities for the component motions were pointed out, on the basis of transients with constant acceleration.
The solution of the two above mentioned problems were devoted to determine the effect of using different materials as in particular steel, aluminum and graphite-epoxy. The comparisons were carried out satisfying an imposed allowable position error for the end effector.
When comparing structural masses a good and growing gain pertains to aluminum and then to graphite-epoxy structures with respect to those constructed with steel, but a similar characteristic is quite inferior referring to the total mass.

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KONSTRUKTIONANALYSEN EINES ROBOTIESIERTEN WERKZEUGWECHSELSYSTEMES MIT REGALBEDIENGERAT

Zusammenfassung

In Bezug auf einen Werkzeugsspeicher mit robotisierten Werkzeugwechselgetriebe werden typische Stellungen der Hand dargestellt, damit die vorgegebenen Trajektorien mit den kinematischen Parametern in Bezieung gestellt werden und die folgerichtige totale Zeit erhalten wird. Die Grenzen solcher Parametern werden klargestellt. Ausserdem, werden die Gleichungen der Strukturanalyse geschrieben, um die Strukturen, die vor allem am Baumaterial verschieden sind, zu bemessen. Die Vorteile der verschiedenen Losungen werden dargestellt.

ANALIZA PROJEKTOWANIA ROBOTA WYMIENIAJĄCEGO NARZĘDZIA

Streszczenie

Badając robota w systemie wymiany narzędzi wskazaliśmy na typowe położenie końcówki roboczej by powiązać wcześniej opisaną ścieżkę z parametrami kinematycznymi i uzyskać w rezultacie czas całkowity.Położono nacisk na wartości brzegowe tych parametrów. Napisano również równania strukturalne w celu określenia wielkości kilku struktur, które rozróżnia się w zależności od przyjętych materiałów chwytaka. Pokazano korzyści jakie wynikają z zastosowania różnych materiałów.

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