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PROBLEMS OF THE BALANCING OF INDUSTRIAL ROBOTS' MANIPULATORS

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Abstract

The paper deals with certain problems of balancing that occur in manipulators, i.e. kinematic units of industrial robots constituting open kinematic chains of many degrees of freedom. Publications in this field testify to the need of research on the balancing of such mechanisms.

1. Introduction

In the case of the balancing of industrial robots' manipulators having the structure of open spatial kinematics' chains, some problems refer to spatial mechanisms in general, while others only to industrial robots' manipulators.

The problem of static balancing of mechanisms of the open spatial chain structure is sufficiently understood theoretically and mastered technologically. On the other hand, there are difficulties in the case of static and dynamic balancing of some types of manipulators that have the structure of open kinematic chains of many degrees of freedom.

When balancing industrial robots' manipulators, among other things, the following have to be taken into consideration: variable loads of the mass links with inertial forces, load of the kinematic pairs caused by propulsion motors of rotational or translational motion, variable masses of tools or objects manipulated, clearances or resistance in the kinematic pairs as well as the flexibility of the links.

The dynamics of a system of manipulators is also affected by a change in the position of its center of mass in the space depending on the operation cycle.

Some manipulator types contain numerous rotating elements of propulsion and control systems, e.g. planetary gears. The state of static and dynamic balancing of manipulators has an effect on their positioning, thereby on their operation in service conditions.

2. Static Balancing of Manipulators

As is well-known, the concept of static balancing of mechanisms, including manipulators, is understood as the balancing of the main vector of inertial forces, which can be achieved by balancing the static moments of gravity forces of the links and the object of manipulation. For technological reasons, static balancing of manipulators can be carried out using springs, additional masses so called counterweights or by using appropriate drives. Balancing by means of springs is frequently used in different constructions of industrial robots' manipulators, mainly in hoisting gear, despite the fact that this method does not ensure the complete balancing of the mechanism [3]. Examples of such balancing can be found in: a TUR.10 universal robot, an MP-4 robot with an electromagnetic hoist, made in the USSR or a Swedish RETAB robot [2]. Balancing spring systems which allow for rectilinear motion of the link can be divided into two groups. The first group includes such balancing systems in which the spring acts directly on the link, as shown in fig. 1.

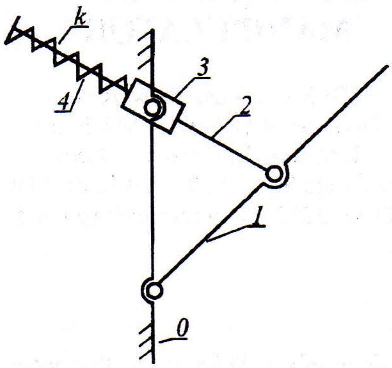

Fig.1 An example of a direct action of a spring on a link

The other comprises systems in which the action of the spring is indirect, for example, through a cam having a profile of a spiral of Archimedes. For example, in the first group, the balancing of the force **P** of a vertical direction, and directed in agreement with the path of motion of a link of constant mass is shown in fig.2a, while in the second group in fig. 2b.

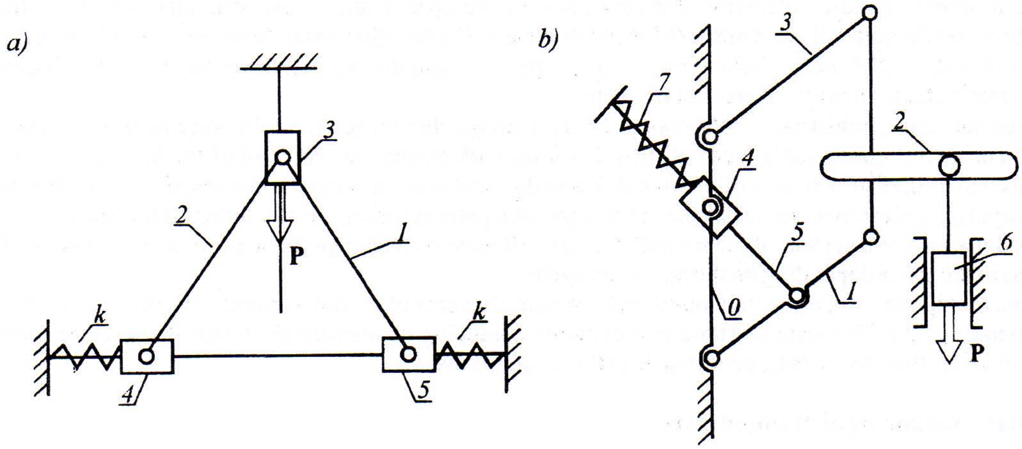

Fig.2 The manner of balancing of force P:
a) two springs of direct action b) a spring of indirect action

The above examples do not need any explanation, apart from stating that such a method allows a system of translational motion to be balanced only in a vertical direction.
It must be remembered, however, that such balancing systems can change their characteristics when small displacements occur. To counteract this phenomenon, additional elements, such as pulleys or additional links, are required.
In the case of manipulators with rotational pairs of parallel axes, as in the one shown in fig3a, balancing can be sufficiently effective after a system of links has been added, as in fig. 3b.

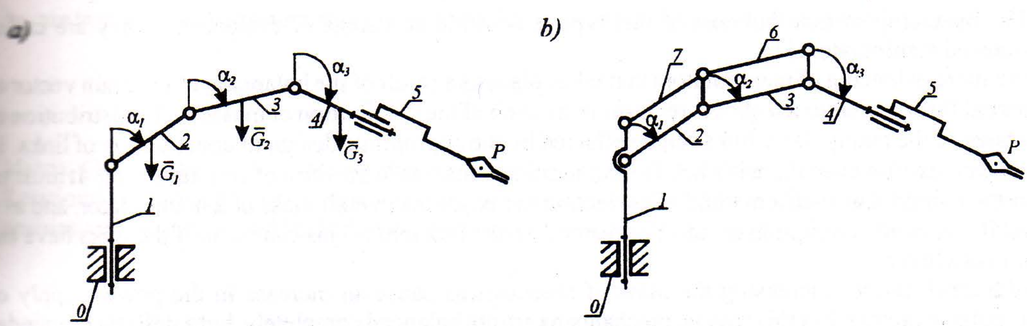

Fig.3 A manipulator of five degrees of freedom:
a) before the balancing of the masses of links; b) after applying a system of balancing links

In this case, to balance gravity forces it is also possible to introduce an additional system of springs, as shown in fig. 4.

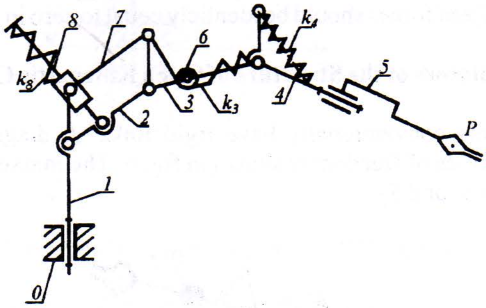

Fig.4 An example of use of a system of balancing links and springs

In some constructions of manipulators, springs can be replaced with pneumatic or hydraulic devices. A separate group of manipulators includes: hoist manipulators designed for transporting various elements of machines and devices, or materials such as ceramic tiles, paper web rollers, extension arm manipulators intended for the grinding or cutting of metal or sorting such elements as pipes, packages and the like. These manipulators can operate individually or in assembly lines. They all have a similar construction based on the principle of a pantograph, fig.5.

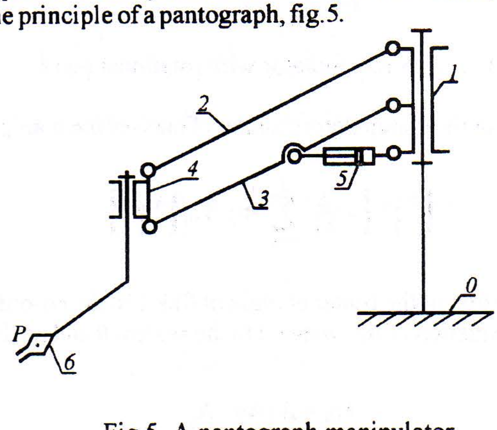

Fig.5 A pantograph manipulator

The balancing of manipulators of this type is possible at a stage of design, thus they are called balanced manipulators [1].
The static balancing of manipulators that takes place as a result of the balancing of the main vector of inertial forces, mentioned above, requires correction of the distribution of masses. The distribution of masses of the manipulator links can be effected by the appropriate design of construction of links. In many cases, however, there is a need to use additional masses in the form of counterweight. It must be borne in mind that such a method of correction increases the overall mass of a manipulator, and as a result, the counterweight mass can be greater than the link mass. This can occur if the links have the form of a lever.
Additional masses increasing the mass of mechanisms cause an increase in the power supply of propulsion motors. For this reason, mechanisms are not balanced completely, but a definite remainder unbalancing is left. Another reason for not using the complete balancing of such mechanisms is a variable mass of an object of manipulation, as well as the fact that real links are not rigid bodies. Considering a model of the manipulator mechanism in which all the links are assumed to be rigid bodies, the center of mass of the manipulator is found as a result of the balancing of masses. If the manipulator links are only affected by inertial forces, then the potential energy of the manipulator as well as generalized in a general case are functions of generalized coordinates. If the manipulator is to be balanced statically in each configuration, the potential energy cannot depend on the generalized coordinates, while generalized forces should be identicly equal to zero in all positions.

2.1. Balancing of Manipulators of the Structure of Open Kinematic Chains

Manipulator models conventionally have rigid links. A diagram of a manipulator with rotational pairs of two degrees of freedom is shown in fig. 6. The masses m_1 and m_2 of the links are concentrated in the centers S_1 and S_2.

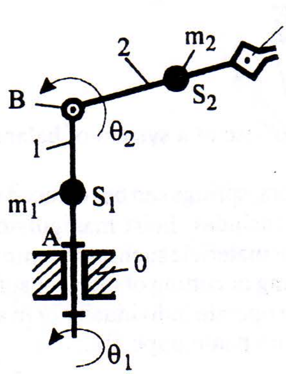

Fig. 6. A manipulator with rotational pairs

The vector radius of position of the manipulators' center of mass of the manipulator is determined by a matrix equation (1):

$$\begin{bmatrix} r_{S0} \\ 1 \end{bmatrix} = \frac{1}{M} \sum_{i=1}^{j} m_i \ T_{0i} \begin{bmatrix} r_{si} \\ 1 \end{bmatrix} \tag{1}$$

where $\mathbf{r}_{si}$ is the vector of position of the center of mass of link 1 in the co-ordinate system of this link, and $\mathbf{T}_{0i}$ is a matrix of transformation of the system *i* to the system *0* and its dimensions are 4 x 4. This matrix has the form:

$$\mathbf{T}_{0i} = \mathbf{A}_1\mathbf{A}_2 \ldots \mathbf{A}_j$$

A_i- are matrices of elementary transformations. M- is the mass of the complete kinematic chain.

$$M = \sum_{i=1}^{j} m_i$$

Matrix (1) is obtained by determining matrix $\mathbf{A}_i$ on the basis of Denavit-Hartenberdg notation. Relationships between positions of the links during one cycle of motion, formulated by directional cosines, can be established basing on instantaneous positions of the links, fig. 7.

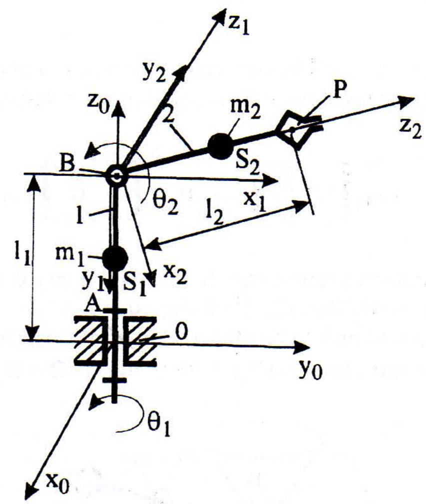

Fig. 7. A manipulator with systems of rectangular coordinates

The vector of position of point P of the manipulator's gripper, link 2 in the system of this link is determined by a transpose of the matrix

$$\mathbf{r}_{P22} = [0\ 0\ z_2]^T$$

Elementary matrices are as follows:

$$\mathbf{A}_1 = \begin{bmatrix} c\theta_1 & 0 & s\theta_1 & 0 \\ s\theta_1 & 0 & -c\theta_1 & 0 \\ 0 & 1 & 0 & z_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \mathbf{A}_2 = \begin{bmatrix} c\theta_2 & 0 & -s\theta_2 & 0 \\ s\theta_2 & 0 & c\theta_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

From matrix $\mathbf{A}_i$ (2), matrices $\mathbf{B}_1$ and $\mathbf{B}_2$ of dimensions 3x3 are isolated. After expansion matrix (1) has the following form:

$$\mathbf{r}_{S0} = \frac{1}{M} (m_1\, \mathbf{r}_{s10} + m_2\, \mathbf{r}_{s20} + m_p\, \mathbf{r}_{P20}) \tag{3}$$

where...,
$$\mathbf{r}_{s10} = \mathbf{B}_1\, [0\ \ 1/2\, y_1\ \ 0]^T$$

$$\mathbf{r}_{s20} = \mathbf{B}_1 \mathbf{B}_2\, [0\ 0\ 1/2\, z_2]^T$$

$$\mathbf{r}_{P20} = \mathbf{B}_1 \mathbf{B}_2\, \mathbf{r}_{P22}$$

while m_p is the mass of an object of manipulation, z_0, y_1, z_2 are the co-ordinates of points S_1, S_2 and P_2 in the relevant systems.
We make a preliminary assumption that the manipulator is not loaded with the mass m_p of an object of manipulation; then the vector of position of the center of mass of the mechanism is defined by the relationship:

$$\mathbf{r}_{S0} = \frac{1}{M}\ \mathbf{B}_1\left(m_1 \begin{bmatrix} 0 \\ 1/2\, y_1 \\ 0 \end{bmatrix} + m_2 \mathbf{B}_2 \begin{bmatrix} 0 \\ 0 \\ 1/2\, z_2 \end{bmatrix}\right) \tag{4}$$

The centre of mass of the manipulator will be reduced to the beginning of $Ax_0y_0z_0$ system related to the base only when the expression in brackets at $\mathbf{B}_1$ is equal to zero, that is:

$$m_1 \begin{bmatrix} 0 \\ 1/2\, y_1 \\ 0 \end{bmatrix} + m_2 \mathbf{B}_2 \begin{bmatrix} 0 \\ 0 \\ 1/2\, z_2 \end{bmatrix} = 0 \tag{5}$$

Expression (5) can be divided into two terms, the first of which, $m_1[0\ 1/2y_1\ 0]^T=0$, is equal to zero only when $y_1=0$, while the other, $m_2\mathbf{B}_2[0\ 0\ 1/2z_2]^T=0$ if $z_2=0$.
This means that the center of mass of link 1 is on the axis of rotation of the column, link 1. The center of mass of link 2 will move in the way shown in fig. 8, since matrix $\mathbf{B}_2=\mathbf{B}_2(\theta_2)$ depends on time.

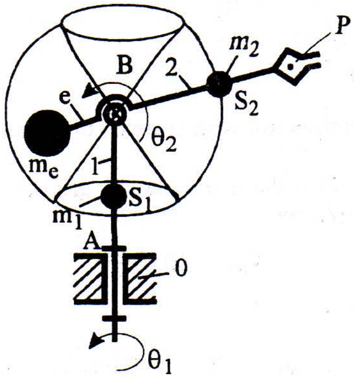

Fig. 8 A plot of motion of the centre of mass of link 2

The static moment $m_2\mathbf{B}_2\mathbf{r}_{s2,2}$ depends on θ_2, that is to say depends on time. This moment can be balanced with a counterweight of a mass me and arm e according to the relationship:

$$m_2\mathbf{r}_{s22} = m_e\, e \tag{6}$$

Following the introduction of the mass me, the total mass of link 2 will be increased according to the relationship:

$$m_{2z} = m_2 + m_e \tag{7}$$

The mass of the link will be reduced to the axis of the column, link 1.
When the gripper catches an object of manipulation, the mass of link 2 will increased by the mass m_p.
The condition of balancing can be written as the relationship:

$$(1/2m_2 + m_p)\begin{bmatrix} 0 \\ 0 \\ z_2 \end{bmatrix} = 0 \tag{8}$$

Condition (8) will be satisfied only when $z_2=0$; such a state can be achieved by increasing the mass of the counterweight from m_e to m_{ep}. This operation would require the use of a variable mass of m_{ep} within the range determined by the manipulator hoisting capacity.
An unbalanced static moment of the mass of a manipulation object will cause reactions in kinematic pairs A and B. In the manipulator type presented static balancing is practically impossible.
In the case of spatial systems, such as manipulators operating at high speeds, dynamic balancing is necessary in addition to static balancing.

3. Dynamic Balancing of Manipulators

The dynamic balancing of manipulators, which are spatial mechanisms of the structure of open kinematic chains, is a complex task and a exact solution is not always possible. Cycles of particular movements are short and in most cases are made up of starting and braking. Changes in the values of accelerations and their directions cause variable loading of the links with inertial forces.
Thus, the dynamic balancing of manipulators requires determination of the values of these forces and their position so that it is possible to select appropriate correction masses [4]. Increasing the masses of the links as a result of correction is not always possible due to an increase in power demand, and due to the possibility of limiting the operational space of a manipulator.
In this case, it is at a stage of the design that the dynamic balancing of a manipulator appears to be the most appropriate. It is then possible to select the optimal shapes of particular links. It must be assumed, however, that the elements of all the links are rigid systems.
In practice, links that are to be balanced are frequently flexible. The vibrations of manipulators caused by the drives pose another problem. The level of these vibrations affects the precision of positioning, so this level should be low. Thus, it is necessary that all the motors of rotational motion have suitable dynamic balancing intended for drive mechanisms of manipulators.
Certain possibilities of balancing are offered by devices accumulating energy at definite phases of the motion cycle to support the motion systems of a manipulator at others. These are so called energy accumulators [2].

3.1. The Principle of Dynamic Balancing

Theoretically speaking, the measure of dynamic balancing of a manipulator of relative motion of links having definite masses is an assessment made on the basis of kinetic energy of the system. Thus, it must be determined whether the coefficients at the squares of the speed or speed quotients are independent of the generalized coordinates in the expression for kinetic energy. The independence of kinetic energy of one or a number of the generalized coordinates points to the state of dynamic balancing. This needs to be explained on the basis of an example, as in fig. 6. The total kinetic energy (of both links, 1 and 2) $E=E_1+E_2$ will not depend on the generalized coordinates only when the following conditions are satisfied: $r_{s22}=0$, which has already been explained (6), and the constituents of the mass moment of inertia of link 2, B_{x2} and B_{y2} are equal to zero. Satisfying this condition will ensure the balancing of the system without taking the mass mp of an object of manipulation into consideration. The mass of an object of manipulation will affect the formation of a force of inertia. The force of inertia P, fig. 9, changes depending on the kind of object of manipulation, and will cause reactions in kinematic pairs.

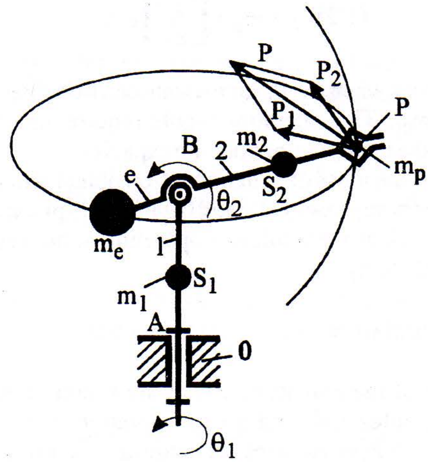

Fig.9 Manipulator with a inertia force from the mass m_p

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