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Synthesis of Robot Mechanisms of Stephenson III Type

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Abstract: *This paper is dedicated to the solution of practical problems associated with the synthesis of manipulators with basic topological structure of Stephenson III type of the die casting dosing robots. In the cases in which the target trajectory is given discretely by means of a multitude of closely situated points, the parameters of the kinematic diagram are defined by the method of the maximally contracted evolute. In the analytically given trajectory vector-matrix synthesis is used, which has certain advantages over the other methods.*

Keywords: *Mechanism of Stephenson III type, synthesis, dosing robot.*

1. Introduction

The die casting dosing robots, designed for supplying horizontal machines for high-pressure die casting with melted steel, most commonly have mechanisms of Stephenson III type. The robot mechanisms of the die casting robots manufactured by the companies “Snair” and “Buhler” have this topological structure with a higher kinematic pair, whereas the ones made by “Toshiba” and “Advance” are entirely with a lever mechanism. An exception from that is the mechanism of type Stephenson I of the die casting robots “Feedmat 1” [3] of the Bulgarian-German company “SPESIMA GmbH”. The functional typology and the structural classification of the die casting dosing robots are thoroughly described with logical consistency in this journal [6]. The dissertation of Slavkov [7] is an extensive monograph, devoted to the synthesis of mechanisms of die casting dosing robots.

The multiloop mechanisms can be synthesized by different methods [5, 4, 12, 11]. One of the most efficient ones for practical application is the generalized method for structural & dimensional synthesis [1, 2]. A part of this method for synthesis of mechanisms type Stephenson III will be used in this work. These mechanisms are fundamental for most of the widely used die casting dosing robots.

2. Structures of the fundamental mechanisms of famous die casting robots

According to the method for structural & dimensional synthesis, the structure of Stephenson III type mechanisms is developed in a specific sequence. First the structure of the main kinematic chain is defined, called *primary* [8]. By definition it is the shortest (in terms of amount of link) chain (units 0, 1, and 2), which only with lower kinematic pairs (in this case revolute) connects the end-effector (in this case the ladle) with the stand 0 (Fig. 1). Afterwards a *secondary* kinematic chain is added (units 0, 3, 4, and 2), which by definition connects two nonadjacent links (in this case 0 and 2) of the primary chain. In this way a closed five-bar chain is formed with two number of degrees of freedom (F=2). Such an outline have the observed manipulation mechanisms.

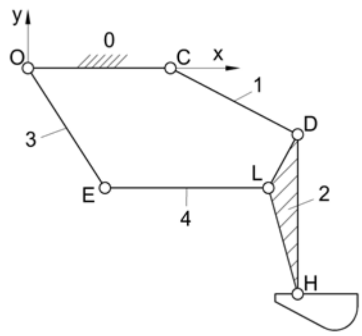

Fig. 1. Five-bar chain of a mechanism with F=2

Stephenson III structure (Fig. 2) can be obtained if the binary link 5 is added to the five-bar chain, which by means of lower kinematic pairs (in this case revolute) connects the links 0 and 4 of the secondary kinematic chain. This is the structure of the basic mechanism of the die casting robots of the firms “Toshiba” and “Advance”. Instead of being implemented with a binary link, the kinematic chain between links 0 and 4 can be realized by means of a higher kinematic pair, carried out in the form of a roller 5 in a channel on the frame 0, as it is in the die casting dosing robots of the firms “Snair” and “Buhler” (Fig. 3).

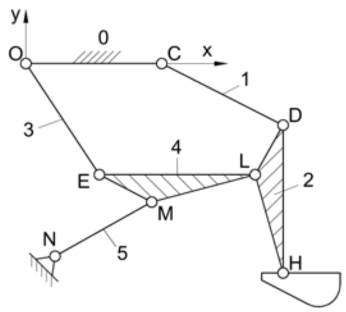

Fig. 2. Basic mechanism of die casting dosing robots of the firms “Toshiba” and “Advance”

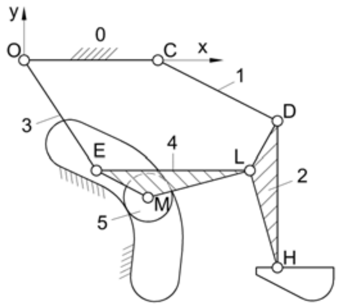

Fig. 3. Basic mechanism of die casting dosing robots of the firms "Snair" and "Buhler"

3. Mathematical models for synthesis

The synthesis of primary and secondary kinematic chains of the mechanisms is discussed in previous works [1, 2, 9], so in this work it is not considered due to the limited volume. The whole synthesis of mechanisms with structure of Stephenson III type implies determining further the centers of the revolute kinematic pairs of binary link 5, located respectively in the planes of the links 0 and 4. This task comes down to determining the trajectory and its evolute in the plane of the frame 0 on a point from link 4. For this purpose a vector-matrix method will be used (as opposed to the method of differential geometry by applying Euler's formula or the building of Bobillier) which does not require finding of the first two derivatives of the coordinates of two points on the mobile link (4), in order without differentiation the evolutes of the trajectories of a random amount of points to be determined.

When moving point $H(x, y)$ on the given target trajectory τ the number of degrees of freedom of the mechanism in Fig. 1 are reduced to F=1. If τ is given analytically with the parametric equations $x = x(t)$, $y = y(t)$, the movement of unit 4 is determined in relation to stand 0 as a result of the kinematic analysis by means of the trajectory of point L and the angle of orientation α, written down with the equations $x_L = x_L(t)$, $y_L = y_L(t)$ and $\alpha = \alpha(t)$. The coordinates (x_{L_0}, y_{L_0}) and (x_{M_0}, y_{M_0}) respectively of the points L and M determine the initial state of link 4 in relation to the frame 0. For every other state the coordinates of point $L(x_L, y_L)$ are determined in the kinematic analysis and the angle of rotation α of link 4 in relation to the frame 0, as well as their second derivatives.

The coordinates of current point M in the plane of the frame 0 are determined by the matrix equation

$$\begin{bmatrix} x_M & y_M & 1 \end{bmatrix}^{\mathrm{T}} = [U] \begin{bmatrix} x_{M_0} & y_{M_0} & 1 \end{bmatrix}^{\mathrm{T}},$$

where in the matrix for plane motion

$$[U] = \begin{bmatrix} \cos\alpha & -\sin\alpha & (x_L - x_{L_0})\cos\alpha + y_{L_0}\sin\alpha \\ \sin\alpha & \cos\alpha & (y_L - x_{L_0})\sin\alpha - y_{L_0}\cos\alpha \\ 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

the reference point is L in a current and initial state, defined by the vectors

(2) $$\vec{l} = \begin{bmatrix} x_L & y_L & 1 \end{bmatrix}^{\mathrm{T}}, \quad \vec{l}_0 = \begin{bmatrix} x_{L_0} & y_{L_0} & 1 \end{bmatrix}^{\mathrm{T}}.$$

The matrix (2) is substituted in (1) and the results are the coordinates of point M:

(3) $$\begin{aligned} x_M &= x_L + (x_{M_0} - x_{L_0})\cos\alpha - (y_{M_0} - y_{L_0})\sin\alpha, \\ y_M &= y_L + (x_{M_0} - x_{L_0})\sin\alpha + (y_{M_0} - y_{L_0})\sin\alpha. \end{aligned}$$

In infinitely close states of link 4 the result is $\vec{l} \equiv \vec{l}_0$ and $\alpha = 0$. The matrix (2) becomes single but its derivative matrices

(4) $$\begin{bmatrix} \dot{U}_0 \end{bmatrix} = \begin{bmatrix} 0 & -\dot{\alpha} & \dot{x}_L + y_L\dot{\alpha} \\ \dot{\alpha} & 0 & \dot{y}_L - x_L\dot{\alpha} \\ 0 & 0 & 1 \end{bmatrix},$$

(5) $$\begin{bmatrix} \ddot{U}_0 \end{bmatrix} = \begin{bmatrix} -\dot{\alpha}^2 & -\ddot{\alpha} & \ddot{x}_L + x_L\dot{\alpha}^2 + y_L\ddot{\alpha} \\ \ddot{\alpha} & -\dot{\alpha}^2 & \ddot{y}_L - x_L\ddot{\alpha} + y_L\dot{\alpha}^2 \\ 0 & 0 & 1 \end{bmatrix}$$

represent the momentary movement until the order of its second derivatives for every position of link 4 point M with radius-vector $\vec{m}$ passes through a normal, onto which the center of the incurvation N lies with a radius-vector $\vec{n}$. The radius of the incurvation $\rho_M = |\vec{m} - \vec{n}|$ until the order of the second derivatives is constant, due to which $(\vec{m} - \vec{n})^{\mathrm{T}}(\vec{m} - \vec{n}) = \text{const}$, and as a result after differentiation the equations for kinematic constraint are derived:

(6) $$\begin{aligned} (\dot{\vec{m}})^{\mathrm{T}}(\vec{m} - \vec{n}) &= 0, \\ (\ddot{\vec{m}})^{\mathrm{T}}(\vec{m} - \vec{n}) + (\dot{\vec{m}})^{\mathrm{T}}(\dot{\vec{m}}) &= 0. \end{aligned}$$

Because

$$\dot{\vec{m}} = \begin{bmatrix} \dot{U}_0 \end{bmatrix}\vec{m}, \; \ddot{\vec{m}} = \begin{bmatrix} \ddot{U}_0 \end{bmatrix}\vec{m}, \;\; \vec{n} = [x_N \; y_N \; 1]^{\mathrm{T}}, \; \vec{m} = [\, x_M \; y_M \; 1]^{\mathrm{T}}$$

and taking into account the matrices (5) and (6), the equations can be transformed as follows:

(7) $$a\,x_N + b\,y_N = c, \; d\,x_N + e\,y_N = f$$

with coefficients

$$
(8) \quad
\begin{aligned}
&a = \dot{\alpha}(y_M - y_L) - \dot{x}_L,\\
&b = \dot{\alpha}(x_L - x_M) - \dot{y}_L,\\
&c = \dot{\alpha}(y_M x_L - x_M y_L) - x_M \dot{x}_L,\\
&d = \dot{\alpha}^2 (x_M - x_L) + \ddot{\alpha}(x_L - x_M) - \ddot{x}_L,\\
&e = \dot{\alpha}^2 (y_M - y_L) + \ddot{\alpha}(x_L - x_M) - \ddot{y}_L,\\
&f = \ddot{\alpha} y_L (x_L - x_M) + \dot{\alpha}^2 (x_M x_L + y_M y_L - x_L^2 - y_L^2) +\\
&\quad + 2\dot{\alpha}[(x_L - x_M)\dot{y}_L + (y_M - y_L)\dot{x}_L] -\\
&\quad - \dot{x}_L^2 - \dot{y}_L^2 - x_M \ddot{x}_L - y_M \ddot{y}_L
\end{aligned}
$$

and solutions

$$
(9) \quad x_N = \frac{ce - bf}{ae - bd}, \; y_N = \frac{af - cd}{ae - bd}.
$$

There are possible two constructive solutions of the task. In the first one an appropriate position of point M_0 is chosen for center of a roller, situated in a channel with a centering incurvation, defined by equations (4). This is the constructive solution of the companies “Snair” and “Buhler”.

In the second solution the position of point M_0 can vary and appropriate are chosen in advance in the plane of link 4, while the evolute defined by equations (10) of the trajectory (4) is contracted to its maximum. Then the center of weight N^* of the evolute defines the location of the axis of the joint, connecting link 5 with the frame 0.

The method of the maximally contracted evolute can be applied in the cases, in which the trajectory τ is given discretely by means of a multitude of closely situated points H_j, which conforms the multitude of positions M_j of point M, defined by equations (4). The length of l_5 of the link 5 is defined by the extremums of the distances N^*M_j

$$
(10) \quad l_5 = 0.5[(N^* M_j)_{\max} + (N^* M_j)_{\min}].
$$

More information about the method is provided in the publication of Galabov [1, 2].

The implication of guiding link 5 is a constructive decision of the companies “Snair” and “Buhler”.

4. Conclusion

This work is dedicated to the solution of practical problems associated with the synthesis of manipulators with basic topological structure of Stephenson III type of die casting dosing robots. After synthesis and kinematic analysis of a closed five-bar chain the overall synthesis of a mechanism design is made possible with two constructive solutions: implementation in a closed five-bar chain of a roller, located in a curvilinear channel on the frame; implementation of a binary link with parameters, defined by the method of the maximally contracted evolute, in the cases in which the target trajectory is given discretely by means of a multitude of closely situated points. In the analytically given trajectory is used vector-matrix synthesis, which has certain advantages over other methods.

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Синтез роботов с механизмами типа „Stephenson III“

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(Р е з ю м е)

Настоящая работа посвящена решениям практических задач, связанных с синтезом основных манипуляционных механизмов литейных дозирующих роботов с топологической структурой типа „Stephenson III“. В случаях, в которых целевая траектория заданна дискретно, с помощью множеств близко расположенных точек, параметры кинематических схем механизмов определены методом максимально свитой эволюты. При аналитически заданной траектории, в настоящей работе использован векторно-матричный метод, имеющий определенные преимущества перед другими методами.