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DETERMINING THE ACCELERATIONS OF POINTS OF A PLANAR EIGHT-LINK THIRD-CLASS MECHANISM USING GRAPH-ANALYTICAL METHOD

С. Кошель, Г. Кошель, М. Залюбовський, О. Кошель. **Визначення прискорень точок плоского восьмиланкового механізму третього класу графоаналітичним способом**. Характерною рисою технологічних машин, що використовуються в індустрії моди є складність руху точок робочих ланок, як за геометрією так і за законами руху. Забезпечують такі технологічні рухи робочим органам складні механізми, основою яких є структурні групи ланок третього та вище класу. В багатоланкових структурних групах ланок вищого класу спостерігаються складні рухи певних точок за траєкторіями, що мають вигляд плоских шатунних кривих різної геометричної форми. Якщо в таких точках розмістити центри зовнішніх кінематичних пар іншої структурної групи, яка приєднується до попередньої групи ланок, то теоретично можна отримати будь яку траєкторію робочої точки машини з необхідними для виконання технологічної операції законами руху. При практичному застосуванні структурних груп ланок вищого класу в складі кінематичної схеми плоского механізму виникають ускладнення для його подальшого дослідження, що пояснюються необхідністю проведення досліджень з використанням спеціально розроблених методів для їх реалізації, а вразі неможливості їх застосування виникає необхідність індивідуальної розробки послідовності проведення таких досліджень в кожному конкретному випадку таких складних механізмів з урахуванням їхніх структурних особливостей. Розроблено послідовність дій та проведено кінематичний аналіз восьмиланкового механізму третього класу в графоаналітичний спосіб, виконано графічну побудову плану прискорень та розраховано величини кутових прискорень ланок механізму за величиною та напрямком. Обрання умовно іншого можливого початкового механізму дозволило восьмиланковий механізм третього класу з двома послідовно приєднаними структурними групами ланок структурно перетворити на механізм з послідовно-паралельним приєднанням груп ланок другого класу другого порядку та виконати аналіз механізму третього класу в спосіб притаманний для дослідження механізмів другого класу. Запропонований спосіб аналізу механізму вищого класу може бути корисним для проведення аналогічних досліджень.
Ключові слова: дослідження механізму, аналіз механізму, кінематичне дослідження, кінематичний аналіз, кутове прискорення, вектор лінійного прискорення, план прискорень

S. Koshel, G. Koshel, M. Zalyubovskyi, O. Koshel. **Determining the accelerations of points of a planar eight-link third-class mechanism using graph-analytical method.** A characteristic feature of technological machines used in the fashion industry is the complexity of motion of the working links, both in terms of geometry and motion laws. Such technological motions are provided by complex mechanisms, the basis of which consists of structural groups of third-class and higher-class links. In multi-link structural groups of higher classes, complex motions of certain points along trajectories resembling planar linkage curves of various geometric shapes are observed. If the centers of external kinematic pairs of another structural group, which is attached to the previous group of links, are placed at such points, theoretically, any trajectory of the working point of the machine with the necessary motion laws required for performing a technological operation can be obtained. In practical application, the use of higher-class structural groups within the kinematic scheme of a planar mechanism leads to complexities in its further investigation. This is explained by the necessity of conducting studies using specially developed methods for their implementation. In cases where these methods cannot be applied, there arises the need for individual development of a sequence for conducting such studies in each specific case of such complex mechanisms, taking into account their structural characteristics. A sequence of actions has been developed and a kinematic analysis of an eight-link third-class mechanism has been conducted using a graph-analytical method. Acceleration plan has been graphically constructed, and the magnitudes and directions of angular accelerations of the mechanism's links have been calculated. The selection of a conditionally different possible initial mechanism allowed transforming the eight-link third-class mechanism with two sequentially attached structural groups of links into a mechanism with sequentially-parallel attachment of second-order second-class link groups and performing the analysis of the third-class mechanism in a manner characteristic of the analysis of second-class mechanisms. The proposed method of analyzing higher-class mechanisms may be useful for conducting similar studies.
Keywords: research of mechanism, analysis of mechanism, kinematic investigation, kinematic analysis, angular acceleration, linear acceleration vector, acceleration plan

Introduction

Mechanical systems of solid bodies serve for that to transform the predetermined mechanical movement of one or more bodies of the system into the necessary movement of the body, in certain points of which working bodies are placed, which technologically ensure the cycle of the equipment. A characteristic feature of the technological machines used in the fashion industry is the complexity of the movement of the points of the working links, both according to the geometry and according to the

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laws of motion, in some cases with technological stops for a certain part of the movement cycle. Such technological movements of working bodies are provided by complex mechanisms, the basis of which are structural groups of links of the third and higher class. In multi-link structural groups of higher-class links, complex movements of certain points along trajectories that have the appearance of flat connecting-rod curves of various geometric shapes are observed. If the centers of the external kinematic pairs of another structural group, which joins the previous group of links, are placed at such points, then theoretically it is possible to obtain any trajectory of the working point of the machine with the laws of motion necessary for the technological operation. With the practical application of structural groups of higher-class links as part of the kinematic scheme of a flat mechanism in the future, complications may arise for its further research. The analysis of mechanisms in the structure of which complex structural groups of links of the third class and above are observed requires conducting research using specially developed methods for their implementation [1], and in case of impossibility of their application, there is a need to individually develop a sequence of conducting research in each specific case of such complex mechanisms with taking into account their structural features [2]. The result of the kinematic study of a flat mechanism using the graphoanalytical method is the graphic construction of plans of speeds and accelerations. The use of the property of articulated lever mechanisms with one driving link to the inversion of motion helps to determine the sequence of construction of such plans, provided that another possible initial mechanism is selected, which allows in the case of complex mechanisms of the fourth class and above to perform such graphic constructions, and in the case of mechanisms of the third class to significantly simplify them by the condition that when another leading link is chosen, the research of such mechanisms is carried out in a manner inherent to the mechanisms of the second class.

Analysis of basic research and publications

The number of publications devoted to the research of complex mechanisms of the third and higher classes in periodical scientific publications is significant and clearly confirms the necessity of their implementation. Thus, in the publications of recent years, in a number of works, the authors consider the issues of synthesis [3, 4], in particular, kinematic [5] and analysis [6, 7] of such mechanisms, their dynamic and force calculations are performed [8]. The authors of the works pay special attention to those issues of the section on the theory of the structure of complex flat mechanisms, in which the structural regularities of their formation are considered and the common features that structurally connect them are determined [9], in order to create software in the future that would allow automating the process of designing mechanical systems [10] for conditions of predetermined technological requirements.

The aim of the study

The purpose of the work is to develop a sequence of actions and carry out a kinematic study of an eight-link mechanism of the third class with one leading link and two sequentially connected structural groups of links and to determine the angular accelerations of all links of the mechanism in a graph analytical way (the method of building an acceleration plan). The analysis of the mechanism must be carried out taking into account the fact that mechanisms of a higher class have the property of conditionally changing their class when replacing the initial mechanism with another structurally possible one.

Presentation of the main material

The flat eight-link mechanism of the third class (Fig. 1) consists of one leading link 1, which is connected to the body 0 by a rotary kinematic pair O_1 and to the connecting rod 2 of the structural group of links of the third class of the third order (links 2 – 5), which is connected by other external it is connected to a fixed link by pairs O_2 and D and with the help of a kinematic pair E provides transmission of mechanical motion from connecting rod 3, which has the form of a complex link to the structural group of links of the second class of the second order (links 6, 7). In the mechanism of seven moving links, of which two links 1 and 5 rotate around, respectively, the centers of kinematic pairs O_1 and O_2, the other two (links 4 and 7) move forward relative to the fixed guides xx and yy, the rest of the moving links (2, 3, 6) have plane-parallel motion. Two translational pairs D, H and other rotary pairs – O_1, A, B, C, E, K, M, O_2 ensure the connection of the links of the mechanism of the third class, the structural formula of which takes the form: 1 class(links 0, 1) $\rightarrow$3 class(links 2 – 5) $\rightarrow$ 2 class (links 6, 7). In the structure of the mechanism, connecting rod 3 has the form of a complex link: four elements of the corresponding kinematic pairs are located at points B, C, E, K of the link.

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It is possible to investigate the kinematic parameters of a mechanism with a structural group of links of the third class in a graph analytical way [1] using a method in which the position of a certain "special" point is additionally determined geometrically, which conditionally belongs to a complex link (basic link) of a structural group, for which additionally a system of vector equations, which in general complicates the graphic constructions of the kinematic analysis of the mechanism.

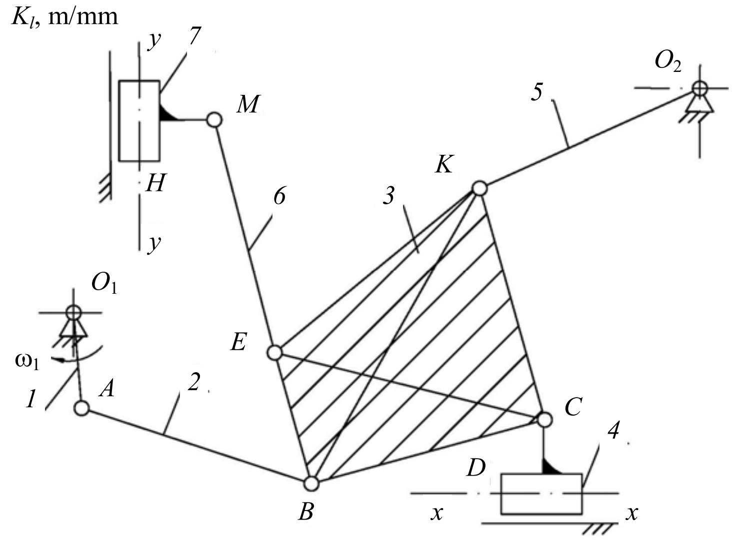

Fig. 1. Kinematic scheme of a flat eight-link mechanism of the third class

The use of another method of graphical research of the mechanism of the third class, the so-called "false provisions" method, leads to the same increase in the number of graphic constructions and also to a decrease in the accuracy of their execution in comparison with the above-mentioned method.

It should be noted that the sequence when conducting research in this way coincides with the sequence of joining structural groups of links to the initial mechanism, and therefore, when compiling systems of kinematic vector equations, problems arise with their further vector solution, due to the fact that the number of unknown parameters in vector equations is greater than the number for which they can be solved graphically.

Indeed, from the kinematic diagram of the mechanism, we can see that during kinematic research, the initial parameters are the given parameters of the movement of the crank 1, so the following equations that can be compiled refer to the point that coincides with the center of the kinematic pair *B*, which simultaneously belongs to two connecting rods 2 and 3. If for one other point *A* of link 2, the kinematic parameters are determined under the condition that it belongs to crank 1, then it is not possible to determine another second point of link 3, for which the kinematic parameters are known in magnitude and direction. Provided that points *C* and *K* belong to slider 4 and rocker arm 5, the direction of their linear velocity vectors can be determined. It is impossible to find the directions of the acceleration vectors of these two points due to the fact that the angular acceleration of connecting rod 3 is an unknown value. Taking into account the fact that the kinematic pair *E* is formed by two connecting rods 3 and 6, the movement of which is undefined, we have the fact that its kinematic parameters are unknown in terms of magnitude and direction, and therefore the point *E* cannot be used to compile a vector equation, which would be was solved in vector form to determine the acceleration of point *B*.

We propose to consider the set of links of the mechanism of the third class, as a mechanical system with the degree of mobility unit, for which the mechanical movement is given by means of another conditionally possible driving link, for example, link 5, which, like the real driving link, has a rotational movement relative to a stationary kinematic pair. Note that such "conditional actions" during the analysis of the mechanism of the third class affect only the sequence of further kinematic research and do not affect the values of the absolute and relative kinematic parameters of the points of the links of the mechanical system under investigation, and therefore do not affect the obtained results of graphic constructions in in the form of plans of speeds and accelerations, which have the same appearance regardless of the sequence in which the graphic constructions were obtained. As a result of the conditional change in the direction of transmission of mechanical motion, the system of links under study will correspond to the structural formula of the structure, in which the structural group of the second class (links 3, 4) is first joined to the initial mechanism (links 0, 5), then two more groups of links of the second class are joined in parallel class (group of links 1, 2 and 6, 7), so the mechanism of the third class is structurally transformed into the mechanism of the second class. We will perform a kinematic analysis of the mechanism using the graph analytic method, the purpose of which will be to build a plan of accelerations of a flat eight-link mechanism of the third class in a sequence determined by the conditionally chosen driving link 5. To conduct a study of the mechanism, we will consider the following kinematic parameters to be given: the angular velocity of the actual driving link 1 ($\omega_1 = 100 = \text{const}$, s^{-1}), the length scale of the kinematic scheme $K_l = 0.001$ (m/mm), the angular velocities of the mechanism links that were determined in another study($\omega_2 = 29.1$ s^{-1}, $\omega_3 = 25.0$ s^{-1}, $\omega_5 = 7.5$ s^{-1}, $\omega_6 = 20.7$ s^{-1}), geometric dimensions of links $l_{O1A} = 25$ mm, $l_{AB} = l_{BC} = l_{KC} = l_{kO2} = l_{ME} = 60$ mm, $l_{EK} = 65$ mm).

We solve the problem in a graph analytical way, while using the provisions of the theory of mechanisms and machines and theoretical mechanics courses on kinematic studies of plane mechanisms and plane-parallel motion of a rigid body.

We start construct the acceleration plan (Fig. 2) with the vector equation:

$$\vec{a}_K = \vec{a}_{K;O_2} = \vec{a}^{\,n}_{K;O_2} + \vec{a}^{\,\tau}_{K;O_2}, \tag{1}$$

where $\vec{a}^{\,n}_{K;O_2}$, $\vec{a}^{\,\tau}_{K;O_2}$ respectively, normal and tangential components of acceleration.

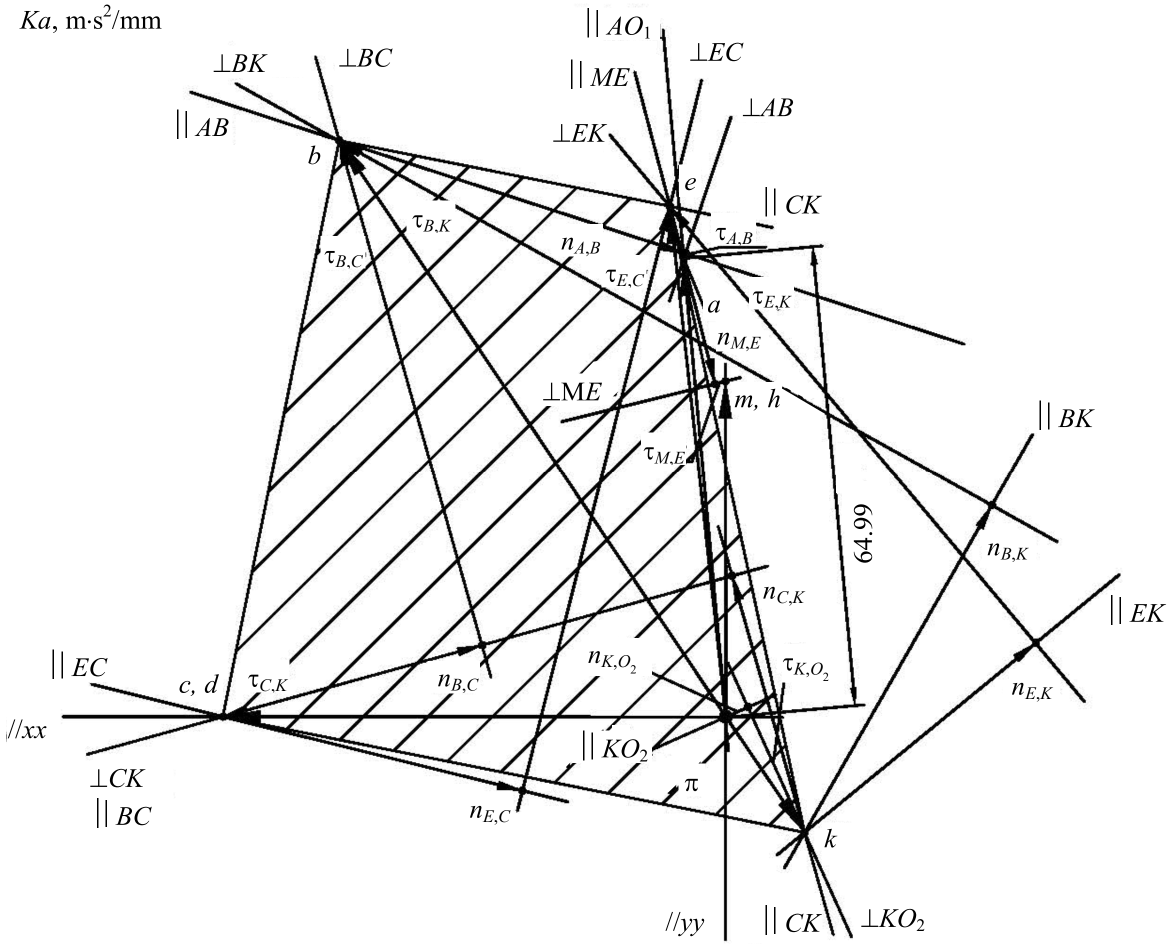

Fig. 2. Plan of accelerations of a flat eight-link mechanism of the third class

We define the length of the vector $\overrightarrow{\pi k}$ on the acceleration plane as the vector sum of the two component accelerations. The normal component is calculated from the equation:

$$a^n_{K;O_2} = \omega_5^2 \cdot l_{K;O_2} = 7.5^2 \cdot 0.06 = 3.38, \text{ m/s}^2, \tag{2}$$

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and build with a segment ($\vec{a}^{n}_{K;O_2} \parallel KO_2$) of arbitrary length (for example, $n_{K;O_2}$ =3.38 mm).

We determine the size of the construction scale:

$$Ka = \frac{a^{n}_{K;O_2}}{n_{K;O_2}} = \frac{3.38}{3.38} = 1, \frac{\text{m/s}^2}{\text{mm}}. \tag{3}$$

We set the length of the segment of the tangential component of acceleration $\vec{a}^{\tau}_{K;O_2} \perp KO_2$ on the scale Ka (in fact, we set the value of the unknown angular acceleration of link 5) in a direction that we choose arbitrarily, for example, such that determines the direction of angular acceleration of link 5 against the direction of clockwise movement. We construct the absolute acceleration vector of point *K*, which allows us to solve the following system of vector equations composed in relation to point *C* of the mechanism:

$$\left\{ \begin{aligned} &\vec{a}_C = \vec{a}_K + \vec{a}^{n}_{C;K} + \vec{a}^{\tau}_{C;K} \\ &\vec{a}_C = \vec{a}_D \end{aligned} \right\}, \tag{4}$$

where $\vec{a}_D // xx$. The magnitude of the normal component of acceleration ($\vec{a}^{n}_{C;K} \parallel CK$) is calculated from the equations:

$$a^{n}_{C;K} = \omega_3^2 \cdot l_{C;K} = 25.0^2 \cdot 0.06 = 37.5 \text{, m/s}^2\text{;} \quad n_{C;K} = \frac{a^{n}_{C;K}}{Ka} = \frac{37.5}{1} = 37.5 \text{, mm.} \tag{5}$$

We construct the absolute acceleration vector $\overrightarrow{\pi c}$ of point C on the acceleration plane, determine the vector $\vec{a}_D = \vec{a}_C$.

Points *B* and *E* belong to the complex link 3 of the mechanism, for which the acceleration of the other two points *K* and *C* is determined, so we compile systems of vector equations to plot them on the plane:

$$\left\{ \begin{aligned} &\vec{a}_B = \vec{a}_K + \vec{a}^{n}_{B;K} + \vec{a}^{\tau}_{B;K} \\ &\vec{a}_B = \vec{a}_C + \vec{a}^{n}_{B;C} + \vec{a}^{\tau}_{B;C} \end{aligned} \right\}; \quad \left\{ \begin{aligned} &\vec{a}_E = \vec{a}_K + \vec{a}^{n}_{E;K} + \vec{a}^{\tau}_{E;K} \\ &\vec{a}_E = \vec{a}_C + \vec{a}^{n}_{E;C} + \vec{a}^{\tau}_{E;C} \end{aligned} \right\}, \tag{6}$$

where are the normal components of the accelerations ($\vec{a}^{n}_{B;K} \parallel BK$, $\vec{a}^{n}_{B;C} \parallel BC$, $\vec{a}^{n}_{E;K} \parallel EK$, $\vec{a}^{n}_{E;C} \parallel EC$).

Their lengths in terms of accelerations are calculated as follows:

$$a^{n}_{B;K} = \omega_3^2 \cdot l_{B;K} = 25.0^2 \cdot 0.085 = 52.9 \text{, m/s}^2\text{;} \quad n_{B;K} = \frac{a^{n}_{B;K}}{Ka} = \frac{52.9}{1} = 52.9 \text{, mm;} \tag{7}$$

$$a^{n}_{B;C} = \omega_3^2 \cdot l_{B;C} = 25.0^2 \cdot 0.06 = 37.5 \text{, m/s}^2\text{;} \quad n_{B;C} = \frac{a^{n}_{B;C}}{Ka} = \frac{37.5}{1} = 37.5 \text{, mm;} \tag{8}$$

$$a^{n}_{E;K} = \omega_3^2 \cdot l_{E;K} = 25.0^2 \cdot 0.065 = 40.6 \text{, m/s}^2\text{;} \quad n_{E;K} = \frac{a^{n}_{E;K}}{Ka} = \frac{40.5}{1} = 40.6 \text{, mm;} \tag{9}$$

$$a^{n}_{E;C} = \omega_3^2 \cdot l_{E;C} = 25.0^2 \cdot 0.069 = 43.1 \text{, m/s}^2\text{;} \quad n_{E;C} = \frac{a^{n}_{E;C}}{Ka} = \frac{43.1}{1} = 43.1 \text{, mm.} \tag{10}$$

We take into account that the tangential components have a direction perpendicular to the corresponding normal accelerations and construct the acceleration vectors $\overrightarrow{\pi b}$ and $\overrightarrow{\pi e}$ of points *B* and *E* on the acceleration plane.

To determine the acceleration of point *M*, we compile a system of vector equations:

$$\left\{ \begin{aligned} &\vec{a}_M = \vec{a}_E + \vec{a}^{n}_{M;E} + \vec{a}^{\tau}_{M;E} \\ &\vec{a}_M = \vec{a}_H \end{aligned} \right\}, \tag{11}$$

where $\vec{a}_H // yy$.

The value of the normal component of acceleration ($\vec{a}^{n}_{M;E} \parallel ME$) is calculated from the equations:

$$a^n_{M;E} = \omega_6^2 \cdot l_{M;E} = 20.7^2 \cdot 0.06 = 25.7\text{, m/s}^2;\quad n_{M;E} = \frac{a^n_{M;E}}{Ka} = \frac{25.7}{1} = 25.7\text{, mm.} \tag{12}$$

We solve the vector system of equations (11) and construct the acceleration vector $\overrightarrow{\pi m}$ of point M on the acceleration plane.

We determine the acceleration vector $\overrightarrow{\pi a}$ of point A of the actual driving link of the third-class mechanism on the acceleration plane using vector equations:

$$\begin{cases} \vec{a}_A = \vec{a}_B + \vec{a}^n_{A;B} + \vec{a}^\tau_{A;B} \\ \vec{a}_A = \vec{a}^n_{A;O_1} + \vec{a}^\tau_{A;O_1} \end{cases}, \tag{13}$$

where $\vec{a}^n_{A;O_1} \parallel AO_1$, $\vec{a}^\tau_{A;O_1} = 0$ (ω_1 =const).

We calculate the normal component of acceleration $\vec{a}^n_{A;B}$ as follows:

$$a^n_{A;B} = \omega_2^2 \cdot l_{A;B} = 29.1^2 \cdot 0.06 = 50.8\text{, m/s}^2;\quad n_{A;B} = \frac{a^n_{A;B}}{Ka} = \frac{50.8}{1} = 50.8\text{, mm.} \tag{14}$$

We measure the length of the segment $\overrightarrow{\pi a} = n_{A;O_1} = 64.99$ mm on the plan of accelerations and determine the actual value of the scale of the plan of accelerations, which corresponds to the mechanism of the third class:

$$Ka = \frac{a_A}{\pi a} = \frac{a^n_{A;O_1}}{n_{A;O_1}} = \frac{\omega_1^2 \cdot l_{A;O_1}}{n_{A;O_1}} = \frac{100^2 \cdot 0.025}{64.99} = 3.85\,\frac{\text{m/s}^2}{\text{mm}}. \tag{15}$$

We calculate the values of the angular accelerations of the links of the mechanism:

$$\varepsilon_2 = \frac{a^\tau{}_{A:B}}{l_{A,B}} = \frac{\tau_{A;B} \cdot Ka}{l_{A,B}} = \frac{0.85 \cdot 3.85}{0.06} = +54.5,\ \text{s}^{-2}; \tag{16}$$

$$\varepsilon_3 = \frac{a^\tau{}_{C:K}}{l_{C,K}} = \frac{\tau_{C;K} \cdot Ka}{l_{C,K}} = \frac{73.7 \cdot 3.85}{0.06} = -4729.1,\ \text{s}^{-2}; \tag{17}$$

$$\varepsilon_5 = \frac{a^\tau{}_{K:O_2}}{l_{K,O_2}} = \frac{\tau_{K;O_2} \cdot Ka}{l_{K,O_2}} = \frac{19.3 \cdot 3.85}{0.06} = +1238.4,\ \text{s}^{-2}; \tag{18}$$

$$\varepsilon_6 = \frac{a^\tau{}_{M:E}}{l_{M,E}} = \frac{\tau_{M;E} \cdot Ka}{l_{M,E}} = \frac{1.57 \cdot 3.85}{0.06} = -100.7\text{, s}^{-2}, \tag{19}$$

where $\tau_{A;B}$; $\tau_{C;K}$; $\tau_{K;O_2}$; $\tau_{M;E}$, mm – corresponding lengths of segments on the plan of accelerations;

l_{AB}; l_{CK}; l_{KO_2}; l_{ME} – the length of the corresponding links, m.

The sign of the magnitude of the angular acceleration indicates its direction: "–" indicates that the direction coincides with the direction of clockwise movement, the sign "+" – the direction is opposite to the direction of clockwise movement.

Conclusions

A sequence of actions was developed and a kinematic analysis of the eight-link mechanism of the third class with one leading link was carried out in a graph analytical manner, the acceleration plan was graphically constructed and the angular accelerations of the mechanism links were calculated by magnitude and direction. Choosing a conditionally other possible initial mechanism made it possible to structurally transform an eight-link mechanism of the third class with two sequentially connected structural groups of links into a mechanism with a series-parallel connection of groups of links of the second class of the second order and to perform an analysis of the mechanism of the third class in a manner inherent in the study of mechanisms of the second class. The proposed method of analyzing the mechanism of the higher class can be useful for conducting similar studies.

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