Analytical method in the study of kinematics of process machinery mechanisms

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Abstract. Among all technological machines and equipment, the object of the study was a drainage machine. The machine operates in particularly difficult conditions. The quality of operation depends on the maintenance of process parameters. The kinematics of a working element of the drainage machine and its suspension on the base machine significantly affect the accuracy of holding the given slope of a drain trench and slot. In recent years this issue has received considerable attention. However, the existing analytical methods for kinematic studies of drainage machine mechanisms are complex and therefore not always acceptable. The geometrical methods are used more often. The developed analytical method based on the use of complex numbers conveniently combines the analytical study of the kinematics of mechanisms with geometrical representation.

1. Introduction

The developed analytical method based on the use of complex numbers conveniently combines the analytical study of the kinematics of mechanisms with the geometrical representation (1).

Each complex number \( z = x + iy \) can be represented by a point on a plane (2). The real part is placed on the horizontal line, and the imaginary part of the number \( z \) – on the vertical line [1, 2]. Let us suppose a complex number as vector \( \overrightarrow{z} \), the origin of which coincides with the origin of coordinates, and the end – with the point \( z \) on the complex plane. The vector \( \overrightarrow{z} \) is characterized by the distance \( l \) of the \( z \) point to the origin and the angle \( \phi \) with abscissa axis.

Thus,

\[
x = l \cos \phi; \quad y = l \sin \phi, \quad a
\]

\[
z = x + iy = l (\cos \phi + i \sin \phi).
\]

The vector module \( |\overrightarrow{z}| \) is based on the formula

\[
|\overrightarrow{z}| = l = (x^2 + y^2)^{1/2},
\]

and its inclination according to formulas

\[
tg \phi = \frac{y}{x}; \quad \sin \phi = y \cdot (x^2 + y^2)^{1/2}; \quad \cos \phi = x \cdot (x^2 + y^2)^{1/2}.
\]
It should be noted that formula (1) can be represented by a set of points of a curve with coordinates
\[ x = l \cos \phi; \quad y = l \sin \phi. \]  

(4)

At \( l = \text{const} \), the path described by a point is a circle with radius \( l \) when \( \phi \) is changed from 0 to \( 2\pi \). Formulas (1...4) make it possible to determine the trajectory of movement of any point of a link or a working tool at a variable \( l \) in the time function, given that \( \phi = \omega t \) (here \( \omega \) – angular velocity of a mechanism link, \( t \) – time) [3].

The speed of the link point \( \overrightarrow{V} \), its modulus, the coordinates of the velocity vector are found as follows.

By differentiating the equation (1), we get:
\[
\overrightarrow{V} = \overrightarrow{z}' = l' (\cos \phi + \sin \phi) + \phi' l i (\cos \phi + \sin \phi) = \frac{\overrightarrow{z}}{l} (l' + \phi' l),
\]

(5)

where \( \phi' = \omega \) – angular velocity of a link; \( l' \) – linear velocity of a link if its length is variable over time.

It follows from equation (5) that the vector \( \overrightarrow{z}' \) is shorter or longer than the vector \( \overrightarrow{z} \) by an amount \( \frac{l' + i \phi' l}{l} \).

Dividing the real \( R_e \) and imaginary parts \( J_m \) into equation (5), we get
\[
\overrightarrow{V} = \overrightarrow{z}' = \left( l' \cos \phi + \phi' l \sin \phi \right) + i \left( \phi' l \cos \phi + l' \sin \phi \right) = x' + iy'.
\]

(6)

The derivative \( \overrightarrow{z}' \), i.e. the speed of a link point, is depicted by the vector with the beginning at the point with the coordinates
\[
\begin{align*}
V_x &= x' = l' \cos \phi - \phi' l \sin \phi \\
V_y &= l' \sin \phi + \phi' l \cos \phi = y'.
\end{align*}
\]

(7)

The values \( x' \) and \( y' \) can also be obtained by differentiating the equations (4).

The module of the vector \( \overrightarrow{z}' \), i.e. the absolute velocity \( V \) of the point, is
\[
\left| \overrightarrow{z}' \right| = V = \left( x'^2 + y'^2 \right)^{1/2} = \left( l'^2 + l^2 \phi'^2 \right)^{1/2}.
\]

(8)

From the equation (8) we see that at \( l = \text{const} \) the velocity of the point equals \( l \phi' \).

To find the acceleration \( \overrightarrow{W} \) of a link point by differentiating \( \overrightarrow{z}' \) (see equation (5)) we get
\[
\overrightarrow{W} = \overrightarrow{z}'' = l'' \overrightarrow{z} + 2 l' \phi' i \overrightarrow{z} + l'^2 \phi'^2 \overrightarrow{z} + i l^2 y'^2 \overrightarrow{z} + l^2 \phi'^2 \overrightarrow{z},
\]

or in trigonometric form
\[
\overrightarrow{W} = \overrightarrow{z}'' = l'' (\cos \phi + i \sin \phi) + 2 l \phi' i (\cos \phi + i \sin \phi) +
+ i l^2 y'^2 (\cos \phi + i \sin \phi) + l^2 \phi'^2 i (\cos \phi + i \sin \phi)
\]

(10)

or by separating the real and imaginary parts, \( \overrightarrow{W} = \overrightarrow{z}'' = x'' + iy'' \).
The second derivative \( \dddot{z} \) corresponding to the acceleration vector is represented by a vector with the beginning at a point with coordinates

\[
W_x = x'' = l'' \cos \phi - 2l' \phi' \sin \phi - l \phi'' \cos \phi
\]
\[
W_y = y'' = l'' \sin \phi + 2l' \phi' \cos \phi - l \phi'' \sin \phi + l \phi'' \cos \phi.
\]

The module of the vector \( \dddot{z} \) equal to the full acceleration \( W \) of a link point is determined from the formula

\[
W = |\dddot{z}| = \left( x''^2 + y''^2 \right)^{1/2} = \left( l''^2 + 4l'^2 \phi'^2 + l^2 \phi''^2 + l^2 \phi''^2 \right)^{1/2}.
\] (11)

2. Results

It should be noted that regardless of the complexity of the mechanism, the determination of speeds and accelerations of link points according to the developed method is reduced to the compilation and solution of linear equations. This facilitates the task [4, 5]. For example, let us conduct a kinematic study of the suspension mechanism of the excavating attachment of the drainage machine on the base machine.

The kinematic scheme of this mechanism is shown in Figure 1, and Figure 2 illustrates an analogue in the form of vector polygons [5, 6].

In this case, the closedness equations of vector polygons should be differentiated by a generalized coordinate, and not by time, since the base machine is influenced by variable bond forces.

**Figure 1.** Kinematic diagram of an excavator – drainage machine: 1 – base machine; 2 – drive unit; 3, 4 – hydraulic drives; 5 – working element

If the frame of the base machine is stationary or in rectilinear and uniform movement, then \( \phi = t \) (\( \phi \)-radians).

**Figure 2.** Vector analogue of an excavator – drainage machine kinematic scheme
The dependence of the generalized coordinate $\varphi_1$ on $t$ is found from the dynamics equation of a drive link (2), which moves under the action of a hydraulic cylinder (3) (Figure 1), which overcomes the resistance of forces from the drive link. Angle $\varphi_1$ is chosen as the generalized coordinate.

So we get the velocity $v_A$ from the equation.

$$\vec{z}'_{OA} = v_A = -\phi_1' OA \sin \phi_1 + i\phi_1' OA \cos \phi_1. \quad (12)$$

Considering that $i^2 = -1$, and $\phi_1 = 1$, we get

$$\vec{v}_A = \vec{z}'_{OA} = iOA \left( \cos \phi_1 + i \sin \phi_1 \right) = i\vec{z}_{OA}. \quad (13)$$

From the equation we see that the vector $\vec{v}_A$ is perpendicular to the vector $\vec{z}_{OA}$, the beginning of the vector has coordinates $y'_A = OA \cos \phi_1; x'_A = -OA \sin \phi_1$, i.e. coincides with the end of the vector $\vec{z}_{OA}$.

Module $\left| \vec{z}'_{OA} \right| = v_A = \left( x'^2_A + y'^2_A \right)^{1/2} = OA$.

To find the acceleration of point $A$, let us differentiate the equation:

$$\vec{W}_A = \vec{z}'_{OA} = i^2 OA \left( \cos \phi_1 + i \sin \phi_1 \right) = i^2 \vec{z}_{OA}. \quad (14)$$

From equation (14) we see that the vector $\vec{W}_A$ is turned in relation to the vector $\vec{z}_{OA}$ by 180° and directed to the center $O$. The beginning of the vector $\vec{W}_A$ at the point with coordinates $x''_A = -OA \cos \varphi_1; y''_A = -OA \sin \varphi_1$, and the modulus

$$W_A = \left| \vec{z}'_{OA} \right| = \left( x'^2_A + y'^2_A \right)^{1/2} = OA.$$

Let us find the change in the length of a hydraulic cylinder rod (3), its inclination angle, angular velocity and angular acceleration at $\varphi_1$ change [7].

From the vector triangle $OAD$ we have (when compiling the vector closedness equation you should bypass the perimeter in the set direction, if the vector is directed against the bypass, it is taken with minus):

$$\vec{z}_{AO} = \vec{z}_{AD} - \vec{z}_{OA},$$

or, by substituting the values of the vectors, we get

$$\vec{z}_{AD} = OD \left( \cos \varphi_{OD} + i \sin \varphi_{OD} \right) - OA \left( \cos \varphi_1 + i \sin \varphi_1 \right).$$

However, given that $\varphi_{OD}=0$, we finally have

$$\vec{z}_{AD} = OD - OA \left( \cos \phi_1 + i \sin \phi_1 \right). \quad (15)$$

According to equation (15): $x''_{AD} = OD - OA \cos \varphi_1; y''_{AD} = OA \sin \varphi_1$.

The length $AD$ changes by law
The inclination of a hydraulic cylinder (3) is found from the formula
\[
\cos \phi_{AD} = \frac{x_{AD}}{\left(x_{AD}^2 + y_{AD}^2\right)^{1/2}} = \frac{OA \cos \phi_1}{\left(OD^2 - 2OD \cdot OA \cos \phi_1 + OA^2\right)^{1/2}}
\]
(16)
or
\[
tg \phi_{AD} = \frac{y_{AD}}{x_{AD}} = \frac{OA \sin \phi_1}{OD - OA \cos \phi_1}.
\]
(16a)
To find the angular velocity of the hydraulic cylinder (3), let us differentiate the equation (16a)
\[
\omega_{AD} = \dot{\phi}_{AD} = \frac{OA \cos^2 \phi_{AD} (OD \cos \phi_1 - OA)}{(OD - OA \cos \phi_1)^2}. \quad (17)
\]
By substituting the value \( \cos^2 \phi_{AD} \) from the equation (16), we finally get the angular velocity \( AD \)
\[
\omega_{AD} = \dot{\phi}_{AD} = \frac{OA(OD \cos \phi_1 - OA)(OA \cdot \cos \phi_1)^2}{(OD^2 - 2OD \cdot OA \cos \phi_1 + OA^2)(OD - OA \cdot \cos \phi_1)^2}. \quad (17')
\]
To find the angular acceleration of link \( AD \) (hydraulic cylinder (3)), it is necessary to differentiate the equation (17).

By grouping the real and imaginary parts, we have
\[
\bar{z}_{OB} = (OC \cos \phi_1 + CB \cos \phi_{CB}) + i(OC \sin \phi_1 + CB \sin \phi_{CB}). \quad (18)
\]
From the equation (18) we find the coordinates of point \( B \)
\[
x_B = OC \cos \phi_1 + CB \cos \phi_{CB};
\]
\[
y_B = OC \sin \phi_1 + CB \sin \phi_{CB}. \quad (19)
\]
After grouping, we get
\[
\bar{z}_{OB} = (OA \cos \phi_1 + AB \cos \phi_{AB}) + i(OA \sin \phi_1 + AB \sin \phi_{AB}). \quad (20)
\]
From the equation (20) we have the coordinates of point \( B \)
\[
x_B = OA \cos \phi_1 + AB \cos \phi_{AB};
\]
\[
y_B = OA \sin \phi_1 + AB \sin \phi_{AB}. \quad (21)
\]
The module of vectors \( \bar{z}_{OB} \) equals
\[
OB = |\bar{z}_{OB}| = (OA^2 + 2OA \cdot AB \cos (\phi_1 - \phi_{AB}) + AB^2)^{1/2} = . \quad (21')
\]
By equating the coordinate values of point \( B \) found from the equation (19) and (21), we get
\[
\sin \phi_{CB} = \frac{-AC \sin \phi_1 + AB \sin \phi_{AB}}{CB} \quad (21')
\]
where \(-OA+OC=AC\).
From the last equation we find $\varphi_{CB}$.

After differentiating $\varphi_{CB}$ we get the angular velocity $\omega_{CB}$ of the CB link, and after secondary differentiation – its angular acceleration $\varepsilon_{CB}$.

The velocity and acceleration of point B can be found by differentiating the vector $\vec{z}_{OB}$ (see equation (20), or equations $\vec{z}_{AB} = \vec{z}_{AC} + \vec{z}_{CB}$, or

\[
\vec{z}_{AB} = AC(\cos \phi_i + i \sin \phi_i) + CB(\cos \phi_{CB} + i \sin \phi_{CB}).
\]  

(22)

Then

\[
x'_B = AC \cos \phi_i + CB \cos \phi_{CB};
\]

\[
y'_B = AC \sin \phi_i + CB \sin \phi_{CB}
\]

– derived from the closedness equation of the $ACB$ vector triangle

\[
AB = \left( x^2 + y^2 \right)^{1/2} = \left( AC^2 + 2AC \cdot CB \cos (\phi_i - \phi_{CB}) + CB^2 \right)^{1/2}
\]

By differentiating the vector $\vec{z}_{AB}$ (according to equation (22)), we get

\[
\vec{V}_B = \vec{z}'_{AB} = \left[ AC(\cos \phi_i + i \sin \phi_i) + \phi'_{CB}CB(\cos \phi_{CB} + i \sin \phi_{CB}) \right] =
\]

\[
i \vec{z}_{AC} + i \phi'_{CB} \vec{z}_{CB}.
\]  

(23)

The inclination angle of the velocity vector $\vec{V}_B$ equals

\[
tg \phi_{\vec{V}_B} = \frac{y'_B}{x'_B} = \frac{AC \cos \phi_i + CB \phi'_{CB} \cos \phi_{CB}}{-AC \sin \phi_i - CB \phi'_{CB} \sin \phi_{CB}}.
\]  

(24)

It shall be noted that according to formulae (23) and (24), at $\varphi_{CB} =$const, i.e. while maintaining a given angle $\varphi_{CB}$, during adjustment with the help of hydraulic cylinders (3) and (4) $\phi'_{CB} = 0$, and $\phi_{CB} = \phi_i + 270' \pm \psi$, i.e. the velocity vector of point B should always be directed to the vector $\vec{z}_{OA}$ at an angle $\left(270' + \phi_i\right)$ [8, 9, 10].

After differentiating the vector $\vec{z}_{AB}$, we get the acceleration vector $\vec{W}_B$ of point B

\[
\vec{W}_B = \vec{z}'_{AB} = \left[ -AC \cos \phi_i - CB \phi^2_{CB} \cos \phi_{CB} - CB \phi'_{CB} \sin \phi_{CB} \right] -
\]

\[
i \left( AC \sin \phi_i + CB \phi^2_{CB} \sin \phi_{CB} - CB \phi'_{CB} \cos \phi_{CB} \right)
\]  

(25)
or after grouping we get
\[ \overline{W}_B = i\left[(CB\varphi_{CB}^*\cos\varphi_{CB} + iCB\varphi_{CB}^*\sin\varphi_{CB}) + i^2\left[(AC\cos\varphi_1 + iAC\sin\varphi_1) + (CB\varphi_{CB}^2\cos\varphi_{CB} + CB\varphi_{CB}^2\sin\varphi_{CB})\right]\right] = i\varphi_{CB}^* \overline{z}_{CB} + i^2\overline{z}_{AC} + i\varphi_{CB}^2 \overline{z}_{CB}. \]  
(25)

We will find the inclination angle \( \overline{W}_B \) by the formula
\[ \tan\varphi_{W_B} = \frac{\varphi_{B}^*}{x_B} = \frac{AC\sin\varphi_1 - CB\varphi_{CB}^{11}\cos\varphi_{CB} + CB\varphi_{CB}^{12}\sin\varphi_{CB}}{AC\cos\varphi_1 + CB\varphi_{CB}^{11}\sin\varphi_{CB} + CB\varphi_{CB}^{12}\cos\varphi_{CB}} \]
(\( x_B \) and \( y_B \) – defined from equation (25)).

Let us study the mechanism of suspension of the working tool shown in Figure 3 (the vector analogue of this mechanism is shown in Figure 4).

The mechanism is actuated by a hydraulic cylinder (1). The \( OA \) link is made in the form of a hydraulic cylinder (2). Additional condition is the perpendicularity of the \( AB \) link to X axis regardless of the hydraulic cylinder position (1).

Vector \( \overline{z}_{OA} \) can be written as
\[ \overline{z}_{OA} = \overline{OA}(\cos\varphi_{OA} + i\sin\varphi_{OA}), \]
(26)
where \( \overline{OA} \) – length of the \( OA \) link (variable);
\( \varphi_{OA} \) – inclination angle of the \( OA \) link to X axis.

We get
\[ \left(\ln\overline{z}_{OA}\right) = \left(\ln\overline{OA}\right)' + i\varphi_{OA} \]
\[ \ln\overline{z}_{OA} + i\varphi_{OA} \]
(27)

Next, the equation (27) can be widely used in the analysis of mechanisms, but the function \( \ln\overline{z}_{OA} \) is multi-valued, i.e. \( \ln\overline{z}_{OA} = \ln\overline{OA} + i\varphi_{OA} + 2K\pi i \), but the main value is obtained at \( K = 0 \).

Turning to the mechanism analysis (Figure 3, 4), based on the closedness of a triangle \( OAB \), we can write
\[ \overline{z}_{AB} = \overline{z}_{OA} - \overline{z}_{OB} \]
(28)
Let us differentiate the vector $\vec{z}_{AB}$ and set the result to zero.

Vector $\vec{z}_{OA}$ equals

$$\vec{z}_{OA} = \left( \ln OA \right) \vec{z}_{OA} + i \vec{z}_{OA} \varphi'_{OA}$$

(28a)

Vector $\vec{z}_{OB}$ equals

$$\vec{z}_{OB} = i \vec{z}_{OB} \varphi'_{OB}.$$  

(there is no valid part since $OB=\text{const}$).

Based on the equality of vectors $\vec{z}_{OA}$ and $\vec{z}_{OB}$ we get

$$\vec{z}_{OA} - \vec{z}_{OB} = \left( \ln OA \right) \vec{z}_{OA} + i \vec{z}_{OA} \varphi'_{OA} - i \vec{z}_{OB} \varphi'_{OB} = 0.$$  

If the vector equals zero, then $R_c=J_m=0$, i.e.

$$\left( \ln OA \right) \vec{z}_{OA} = \vec{z}_{OA} \varphi'_{OA} - \vec{z}_{OB} \varphi'_{OB}$$

(29)

(this equality can also be obtained after moving $J_m$ to the right and squaring the left and right parts).

The ratio of vectors from the equation (29) is

---
\[
\frac{\ddot{Z}_{OA}}{Z_{OB}} = -\frac{\varphi_{AB}'}{(\ln OA)' - \omega_{OA}' - \omega_{OA}},
\]

where \( \omega_{OB} \) and \( \omega_{OA} \) – angular speeds of \( OA \) and \( OB \) links.

Considering the obtained expression, the equation (28) can be written as
\[
\ddot{Z}_{AB} = \ddot{Z}_{OA} + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}}.
\]

By differentiating the equation (30) and equating the result to zero, we get
\[
\frac{\ddot{Z}_{OA}}{\omega_{OB}} + \frac{\ddot{Z}_{OA}}{\omega_{OB}} = 0.
\]

Let us put \( \ddot{Z}_{OA} \) outside the brackets and, taking into account the equation (28a), we get
\[
\left[(\ln OA)' \ddot{Z}_{OA} + i\ddot{Z}_{OA} \varphi_{OA} + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}} + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}}\right] = 0.
\]

By dividing \( R_i \) and \( J_m \) considering that \( \ddot{Z}_{OA} \), we get
\[
\left[(\ln OA)' \ddot{Z}_{OA} + i\ddot{Z}_{OA} \varphi_{OA} + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}} + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}}\right] = 0.
\]

If the vector is zero, then \( R_i = J_m = 0 \).

Therefore, we have two equations of complex trajectories of the working tool points of the drainage machine and its suspension.

3. Conclusion
The developed analytical method of analyzing the mechanisms of a drainage machine makes it possible to study their kinematics by analytical calculation, to determine quite complex movement trajectories of the mechanism points, their velocity and acceleration.

The velocity equation:
\[
\omega_{OA} \left[1 + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}}\right] = 0
\]

\[
(\ln OA)' \left[1 + \frac{(\ln OA)' - \omega_{OA}}{\omega_{OB}}\right] + \frac{1}{\omega_{OB}} = 0.
\]

Based on the first equation, we get (taking into account that \( \omega_{OA} \neq 0 \)) quite interesting kinematic relations:
\[ \omega_{OA} - \omega_{OB} = (\ln OA)'; \]
\[ \phi'_{OA} - \phi'_{OB} = (\ln OA)'; \]
\[ \phi_{OA} - \phi_{OB} = \ln OA. \]  

(31)

As a result, \( \omega'_{OA} - \omega'_{OB} = (\ln OA)' \), where \( \omega_{OA} \) and \( \omega_{OB} \) – angular velocities of \( OA \) and \( OB \) links.

The second equation gives more complex dependencies, which should be solved in relation to \( (\ln OA)' \) taking into account the equations (31).

After transformations, it is equated to following

\[ y''B + y'(A + y'B) + C = 0, \]

where

\[ y = \ln OA; \quad A = \left( \omega_{OB}^2 - \omega_{OB} \cdot \omega_{OA} - \varepsilon_{OB} \right); \]
\[ B = \omega_{OB}; \quad C = \left( -\omega_{OB} \varepsilon_{OA} + \omega_{OA} \varepsilon_{OB} \right); \]

\( \varepsilon_{OB} \) and \( \varepsilon_{OA} \) – angular accelerations of links \( OB \) and \( OA \).

After solution, we get \( OA = f(\omega_{OB}) \).

This makes it possible to improve the accuracy and quality of laying drainage trench shelters in especially harsh operating conditions of process machines and equipment.

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