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50. Internationales Wissenschaftliches Kolloquium
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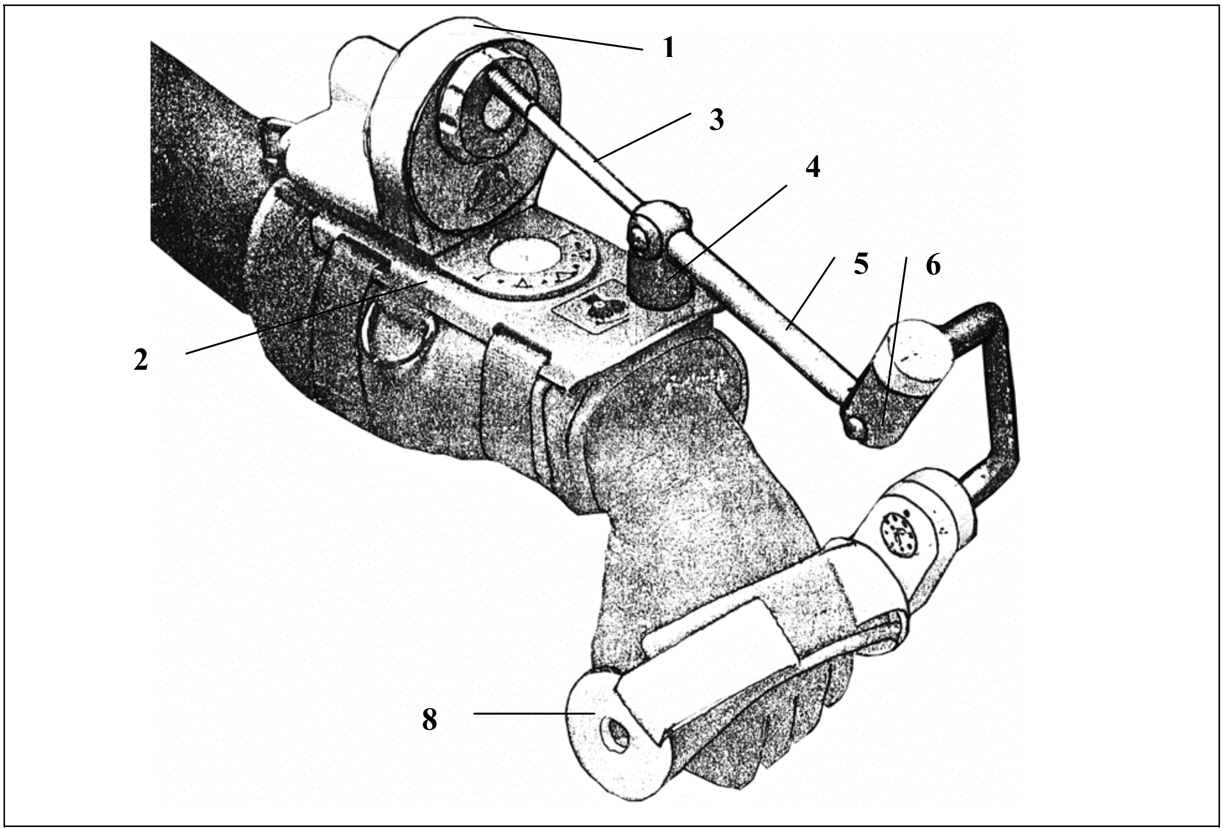
ANALYSIS OF THE BIOMECHANICAL SYSTEM OF THE ARM-REHABILITATION DEVICE

ABSTRACT

This paper describes the construction of portable device for the restoration of the functions of human extremities' joints and muscles, which has a possibility to regulate the speed of the movements and the amplitudes of the hand turning angles in two planes. The kinematic and dynamic models of the biomechanical system and the research methods of their parameters are elaborated. The computer modeling is implemented and the kinematic and power parameters are derived, particularly the turning angles, reactions and the turning moment of the drive.

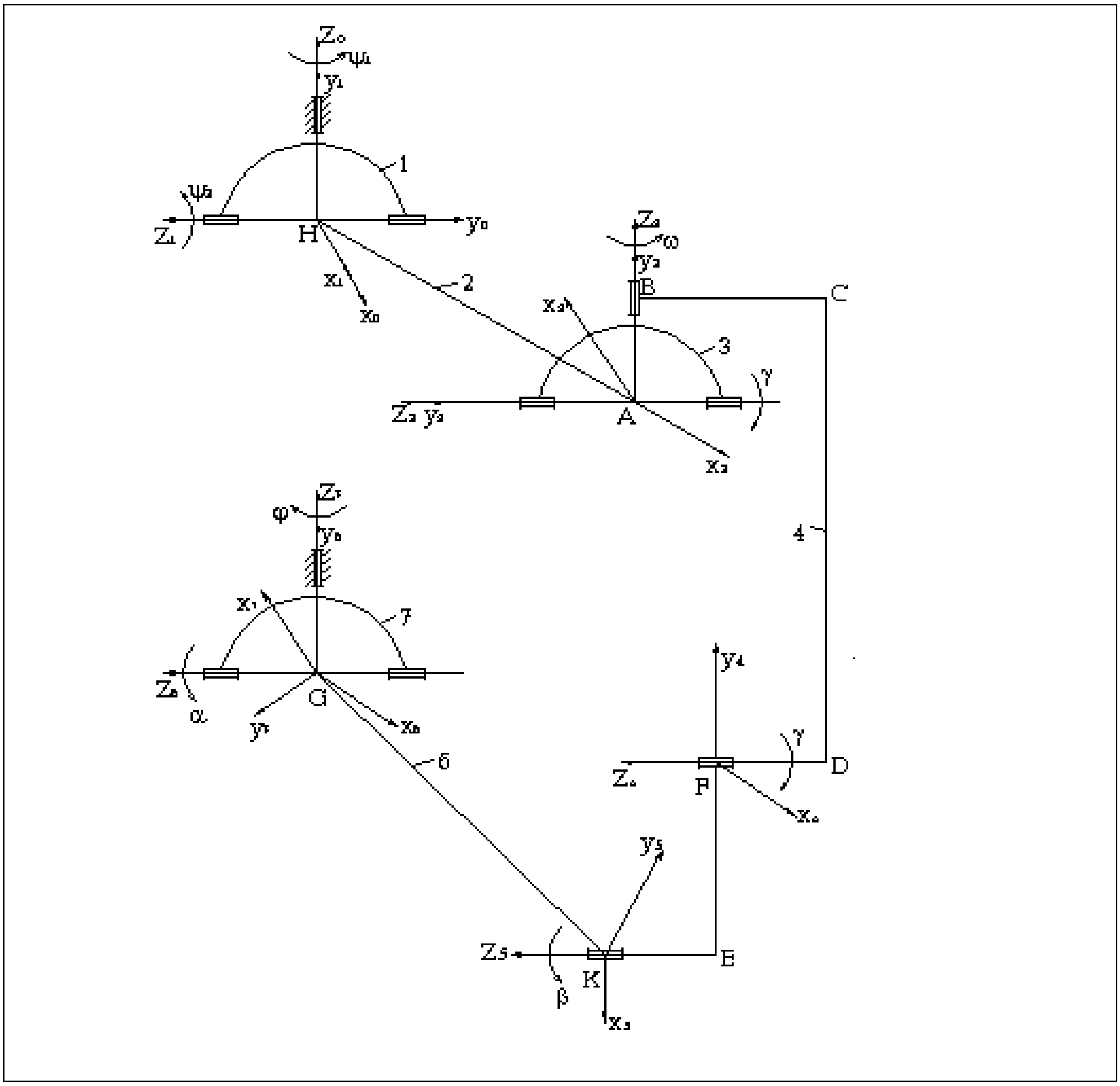
ANALYSIS OF SYSTEM

The rehabilitation devices operate by either mechanical or electro-mechanical principles. However, the portability of the device, as well as simplicity of its setup and maintenance, are important factors for its application. The analysis and description of such a portable electro-mechanical rehabilitation device are presented in this paper (for the general view of the device see Picture 1).



Picture 1.

The rehabilitation device serves for the restoration of the functions of the joints and muscles of the hand. The device consists of 1 drive with self-contained power supply, 2 supports on which the drive and executing lever motion are placed. The latter consists of telescopic shafts (which is connected to the drive by flexible shafts (5) and is placed on the support (4)), shafts (5, 6 and 7) and handle (8). The support is fixed to the arm by the elastic belts. The handle is placed on the arm also by the elastic belt. The amplitude of the rotating movements in the joint are regulated by the rotations of dial, which changes the position of the flexible shaft compared to the axis of the rotor, and by the rotation of drive related to the support axis. The prototype of the investigated device is the “Mobilimb” Canadian device. Based on this device it was elaborated the optimization structure and rehabilitation device with descriptions. Below are presented the investigation and projection methodology. The kinematics model of the biomechanical system, arm-rehabilitation device, was elaborated in the form of closed kinematics chain of rotating pairs (Picture 2).



Picture 2

Here the preshoulder of the arm and the support are unmovable and the global coordinating system is attached to them. The local coordinating systems are placed in the chains of the joints and are connected with the links 1,2, …., 7. The angels between the telescopic shaft and the horizontal and vertical planes passing through the rotating axis of the drive rotor are determined.

$$tg\psi_1 = \frac{R \cdot sin\,\theta}{L}, \quad tg\psi_2 = \frac{R \cdot cos\,\theta}{L}, \tag{1}$$

Where θ is the angle of rotor rotation, R- the deviation of the flexible shaft from the rotor rotation axis, L- the length of the telescopic shaft. The coordinates of A joint are determined.

$$\begin{aligned} x_A &= -x_H + HA \cdot cos\,\psi_2 \cdot cos\,\psi_1, \\ y_A &= -y_H + HA \cdot cos\,\psi_2 \cdot sin\,\psi_1, \\ z_A &= -z_H + HA \cdot sin\,\psi_2, \end{aligned} \tag{2}$$

where x_H, y_H, z_H are the coordinates of H point connected in the coordinating system with the G point of the joints of the hand, BC; KE; FD; CD; BA; HA; GE; FE – the lengths of the levers.

The angle of rotation φ of the hand in the horizontal plane is determined.

$$\varphi = 2arctg(\frac{x_A \pm \sqrt{x_A^2 + y_A^2 - (BC - KE - FD)^2}}{BC - KE - FD - y_A}) \tag{3}$$

The coordinates $x_7 = -x_A \cdot cos\,\varphi - y_A \cdot sin\,\varphi$ are determined

$$x_7 = -x_A \cdot cos\,\varphi - y_A \cdot sin\,\varphi,$$

$$z_7 = z_A - CD + BA, \qquad GD = \sqrt{x_7^2 + z_7^2}: \tag{4}$$

The angle of rotation α of the hand in vertical plane is determined:

$$\alpha_1 = arccos(\frac{GD^2 + GE^2 - FE^2}{2 \cdot GD \cdot GE}), \tag{5}$$

$\alpha_2 = arctg(|z_7|/|x_7|)$, if $x_7<0,\ z_7>0$, $\alpha_2 = -arctg(|z_7|/|x_7|)$, if $x_7<0,\ z_7<0$,

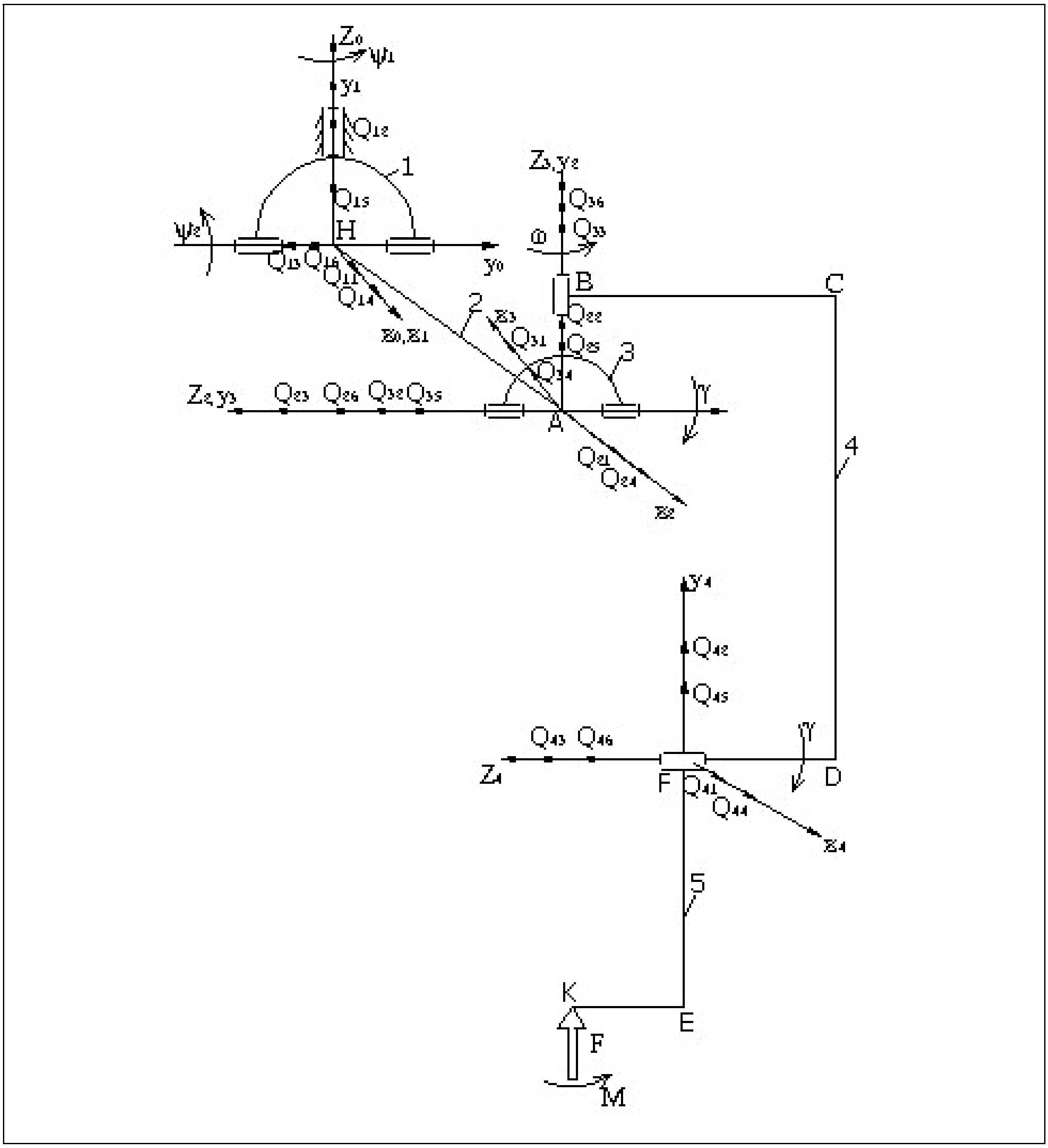
$\alpha_2 = \pi - arctg(|z_7|/|x_7|)$, if $x_7>0,\ z_7>0$, $\alpha_2 = \pi + arctg(|z_7|/|x_7|)$, if $x_7>0,\ z_7<0$,

$\alpha = \alpha_2 - \alpha_1:$

The angle of rotation in the K joint is determined

$$\beta_1 = arccos(\frac{FE^2 + GE^2 - GD^2}{2 \cdot FE \cdot GE}), \ \beta = \pi - \beta_1 + \alpha, \ \gamma = \frac{\pi}{2}, \ \omega = \frac{\pi}{2} - \psi: \tag{6}$$

For the dynamic analysis of the biomechanical system its dynamic model in the form of an open kinematics chain was formed. It is loaded by the $(\vec{F}, \vec{M})$ systems from the hand side (Picture 3).



Picture 3

The reactions in the kinematics pairs are presented in the expressions of the generalized forces. $$Q_i = tr\{\lambda_i \cdot B_i^T\} = tr\{\lambda_i \cdot A_i \cdot \Theta^T \cdot T_{i-1}^T\} \qquad (7)$$

For the determination of the generalized forces there are formed matrixes 4x4 for the external forces and moments: Φ_i **:** $i = 1, 2, \ldots\ldots, N,$, then the equations of the λ_i recurrent ratios are solved by sequential numbers : $i = N, N-1, \ldots\ldots., 2, 1$

$$\lambda_i = \lambda_{i+1} \cdot A_{i+1}^T + \hat{O}_i,\ \ i = 1, 2, \ldots\ldots, N-1 \textbf{:} \qquad (8)$$

for the observed model N= 5 and we derive the following:

$$\lambda_{i+1} = \lambda_5 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & F \\ 0 & 0 & 0 & 0 \end{bmatrix}, \ \lambda_4 = \lambda_5 \cdot A_5^T, \ \ \lambda_3 = \lambda_4 \cdot A_4^T, \ \ \lambda_2 = \lambda_3 \cdot A_3^T, \ \ \lambda_1 = \lambda_{25} \cdot A_2^T, \quad (9)$$

The matrix, which connects T_i and T_{i-1} is the following

$$A_i = \begin{vmatrix} \cos\theta_i & -\sin\theta_i \cdot \cos\alpha_i & \sin\theta_i \cdot \sin\alpha_i & a_i \cdot \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cdot \cos\alpha_i & -\cos\theta_i \cdot \sin\alpha_i & a_i \cdot \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & s_i \\ 0 & 0 & 0 & 1 \end{vmatrix}, \quad (10)$$

where a_i, s_i and α_i - are constant for the any position of the model and are determined by the structures of the links, θ_i - variable (i- 1) and i is the comparable angle of the link rotation. The matrixes $A_1, A_2, ...A_5$ are formed

$1)\, a_1 = 0; s_1 = 0; \alpha_1 = \pi/2; \theta_1 = \psi_1$ $\quad$ $2)\, a_2 = HA; s_2 = 0; \alpha_2 = 0;\ \theta_2 = \psi_2$

$$A_1 = \begin{vmatrix} \cos\psi_1 & 0 & \sin\psi_1 & 0 \\ \sin\psi_1 & 0 & -\cos\psi_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \ A_2 = \begin{vmatrix} \cos\psi_2 & -\sin\psi_2 & 0 & HA \cdot \cos\psi_2 \\ \sin\psi_2 & \cos\psi_2 & 0 & HA \cdot \sin\psi_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix},$$

$3)\, a_3 = 0; s_3 = 0; \alpha_3 = \pi/2; \theta_3 = \pi/2 + \omega$

$$A_3 = \begin{vmatrix} \cos(\frac{\pi}{2} + \omega) & 0 & \sin(\frac{\pi}{2} + \omega) & 0 \\ \sin(\frac{\pi}{2} + \omega) & 0 & -\cos(\frac{\pi}{2} + \omega) & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \quad (11)$$

$4)\, \mathrm{a}_4 = 0; \mathrm{s}_4 = \mathrm{BC} - \mathrm{CD}; \alpha_3 = \pi/2; \theta_4 = \pi + \varphi - \psi$

$$\mathrm{A}_4 = \begin{vmatrix} \cos(\pi + \varphi - \psi_1) & 0 & \sin(\pi + \varphi - \psi_1) & 0 \\ \sin(\pi + \varphi - \psi_1) & 0 & -\cos(\pi + \varphi - \psi_1) & 0 \\ 0 & 1 & 0 & (\mathrm{BA} - \mathrm{CD}) \\ 0 & 0 & 0 & 1 \end{vmatrix},$$

$5)\, \mathrm{a}_5 = \mathrm{EF}; \mathrm{s}_5 = \mathrm{KE}; \alpha_5 = 0; \theta_5 = \beta + \pi$

$$\mathrm{A}_5 = \begin{vmatrix} \cos(\beta + \pi) & -\sin(\beta + \pi) & 0 & \mathrm{EF} \cdot \cos(\beta + \pi) \\ \sin(\beta + \pi) & \cos(\beta + \pi) & 0 & \mathrm{EF} \cdot \sin(\beta + \pi) \\ 0 & 0 & 1 & \mathrm{KE} \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

The projective matrixes are imported (input), which are necessary both for kinematics and dynamic modeling

$$T_i = T_{i-1} \cdot A_i \qquad T_0 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$
$$i = 1,2,\dots,N.$$

$$\Theta_1 = \begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \quad \Theta_2 = \begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \quad \Theta_3 = \begin{vmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \tag{12}$$

$$\Theta_4 = \begin{vmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \quad \Theta_5 = \begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}, \quad \Theta_6 = \begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{vmatrix}:$$

For example in $q = 0;\ \psi_1 = 0^0;\ \psi_2 = 35{,}5^0;\ \beta = 335{,}9^0;\ \varphi = -136{,}5^0;\ \omega = 54{,}4^0$ case we derive

$$A_1 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \quad A_2 = \begin{vmatrix} 0.81 & -0.58 & 0 & 81 \\ 0.58 & 0.81 & 0 & 58 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \quad A_3 = \begin{vmatrix} -0.81 & 0 & 0.58 & 0 \\ 0.58 & 0 & 0.81 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix},$$

$$A_4 = \begin{vmatrix} 0.72 & 0 & -0.69 & 0 \\ -0.69 & 0 & -0.72 & 0 \\ 0 & 1 & 0 & -23 \\ 0 & 0 & 0 & 1 \end{vmatrix}, \quad A_5 = \begin{vmatrix} -0.91 & -0.41 & 0 & -40.14 \\ 0.41 & -0.91 & 0 & 18 \\ 0 & 0 & 1 & 51 \\ 0 & 0 & 0 & 1 \end{vmatrix}:$$

The results of the kinematics and dynamic modeling.

The kinematics input parameters

AB=38 mm, BC=42 mm, CD=61 mm, EF=44 mm, EG=90 mm, HA=100 mm,

KE=51 mm, FD=47 mm, x_H=0, y_H=0, z_H=-40 mm.

The kinematics output parameters

	ψ_1	ψ_2	β_1	β_2	φ_1	φ_2	ω
$\theta_1=0^0$	0	35.6	335.9	146.7	-136.5	-43.5	54.5
$\theta_2=40^0$	24.7	28.7	315.2	110.3	-115.6	-14.9	61.3
$\theta_3=80^0$	35.2	7.1	293.5	50	-110.5	-0.83	82.9
$\theta_4=120^0$	31.8	-19.9	461.5	177.7	-111.7	-4.7	109.7
$\theta_5=160^0$	13.8	-33.9	456.3	150.8	-123.8	-28.3	123.9
$\theta_6=200^0$	-13.8	-33.9	456.3	150.8	-151.3	-56.2	123.9
$\theta_7=240^0$	-31.8	-19.7	461.5	177.7	-175.3	-68.3	109.7

$\theta_8 = 280^0$	-35.2	7.1	293.5	50	179.2	-69.5	82.9
$\theta_9 = 320^0$	-24.7	28.7	315.2	110.3	-165.0	-64.4	61.3
$\theta_{10} = 360^0$	-3.6	35.6	335.9	145.8	-140.1	-47.0	54.5

Here φ_1, φ_2 and β_1, β_2 – are the angles of hand rotation.

The output parameters of the dynamic modeling, when the reactions in kinematics pairs F= 100N.

$q=0^0$	$Q_{11}=0.91$	$Q_{12}=-14.4$	$Q_{13}=0$	$Q_{14}=0$	$Q_{15}=0$	$Q_{16}=100$
	$Q_{21}=0.91$	$Q_{22}=0$	$Q_{23}=14.4$	$Q_{24}=0$	$Q_{25}=100$	$Q_{26}=0$
	$Q_{31}=0.74$	$Q_{32}=-0.53$	$Q_{33}=6.3$	$Q_{34}=58$	$Q_{35}=81$	$Q_{36}=0$
	$Q_{41}=-0.9$	$Q_{42}=6.3$	$Q_{43}=0$	$Q_{44}=0$	$Q_{45}=0$	$Q_{46}=993$
	$Q_{51}=-5.1$	$Q_{52}=0$	$Q_{53}=-3.9$	$Q_{54}=0$	$Q_{55}=993$	$Q_{56}=0$

$q=90^0$	$Q_{11}=8.88$	$Q_{12}=-3.83$	$Q_{13}=0$	$Q_{14}=0$	$Q_{15}=0$	$Q_{16}=100$
	$Q_{21}=5.08$	$Q_{22}=0$	$Q_{23}=8.2$	$Q_{24}=0$	$Q_{25}=100$	$Q_{26}=0$
	$Q_{31}=5.07$	$Q_{32}=-0.26$	$Q_{33}=-1.7$	$Q_{34}=5.2$	$Q_{35}=99.9$	$Q_{36}=0$
	$Q_{41}=-5.08$	$Q_{42}=-1.75$	$Q_{43}=0.09$	$Q_{44}=1.8$	$Q_{45}=0$	$Q_{46}=100$
	$Q_{51}=-5.14$	$Q_{52}=0.09$	$Q_{53}=-1.5$	$Q_{54}=1.5$	$Q_{55}=100$	$Q_{56}=1$

$q=180^0$	$Q_{11}=3.65$	$Q_{12}=-4.05$	$Q_{13}=0$	$Q_{14}=0$	$Q_{15}=0$	$Q_{16}=100$
	$Q_{21}=3.39$	$Q_{22}=0$	$Q_{23}=4.27$	$Q_{24}=0$	$Q_{25}=100$	$Q_{26}=0$
	$Q_{31}=2.75$	$Q_{32}=1.97$	$Q_{33}=-3.8$	$Q_{34}=-58$	$Q_{35}=81$	$Q_{36}=0$
	$Q_{41}=-3.38$	$Q_{42}=-3.82$	$Q_{43}=6.79$	$Q_{44}=0.2$	$Q_{45}=0$	$Q_{46}=99.6$
	$Q_{51}=-5.08$	$Q_{52}=0.004$	$Q_{53}=0.4$	$Q_{54}=0.1$	$Q_{55}=99.6$	$Q_{56}=0.1$

$q=270^0$	$Q_{11}=5.9$	$Q_{12}=-7.9$	$Q_{13}=0$	$Q_{14}=0$	$Q_{15}=0$	$Q_{16}=100$
	$Q_{21}=6.4$	$Q_{22}=0$	$Q_{23}=7.5$	$Q_{24}=0$	$Q_{25}=100$	$Q_{26}=0$
	$Q_{31}=5.2$	$Q_{32}=-3.7$	$Q_{33}=-0.6$	$Q_{34}=58$	$Q_{35}=81.4$	$Q_{36}=0$
	$Q_{41}=-6.4$	$Q_{42}=-0.6$	$Q_{43}=0$	$Q_{44}=0$	$Q_{45}=0$	$Q_{46}=99.9$
	$Q_{51}=4.6$	$Q_{52}=2.1$	$Q_{53}=2.8$	$Q_{54}=41.6$	$Q_{55}=-90$	$Q_{56}=0$

Computer modeling is implemented and kinematics and power parameters are derived: the angles of rotations, reactions and the moment of drive rotation, which are changed within the following ranges:

$$\alpha \in \left[-\mathbf{35^0};\mathbf{35^0}\right] \quad \text{and} \quad \beta \in \left[-\mathbf{35^0};\mathbf{35^0}\right]$$

$$\mathbf{Q_1} \in \left[\mathbf{0.7,...,8.8}\right]\text{N}\cdot\text{mm} \quad \mathbf{Q_2} \in \left[\mathbf{0,...,14.4}\right]\text{N}\cdot\text{mm} \quad \mathbf{Q_3} \in \left[\mathbf{0,...,14.4}\right]\text{N}\cdot\text{mm}$$

$$\mathbf{Q_4} \in \left[\mathbf{0,...,58}\right]\text{N} \qquad \mathbf{Q_5} \in \left[\mathbf{0,...,100}\right]\text{N} \qquad \mathbf{Q_6} \in \left[\mathbf{0,...,100}\right]\text{N}$$

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