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GEARBOX LUBRICATION SYSTEM OPTIMIZATION

Silvia Maláková
Technical University of Kosice, Faculty of Mechanical Engineering, Letná 9, Kosice, Slovak Republic, EU, silvia.malakova@tuke.sk (corresponding author)
Samuel Sivák
Technical University of Kosice, Faculty of Mechanical Engineering, Letná 9, Kosice, Slovak Republic, EU, samuel.sivak@tuke.sk
Jozef Krajňák
Technical University of Kosice, Faculty of Mechanical Engineering, Letná 9, Kosice, Slovak Republic, EU, jozef.krajnak@tuke.sk

Keywords: spur gear, bevel gear, lubrication, optimization
Abstract: The aim of gearbox lubrication is to reduce wear on the sides of the teeth, increase of the efficiency by reducing friction as well as dissipating the heat generated by friction. Lubrication of gearboxes is a discontinuous process, that means, during the meshing every meshed pair of teeth needs to have a new lubrication film created on the surfaces. The geometric shape of the sides of the teeth is conditioned by rolling and sliding movement, therefore gears often work under a mixed friction condition. This is confirmed by damage to gearboxes and by measured power losses. This contribution is devoted to the issue of innovation of the original lubrication of the first stage of the bevel helical gearbox used for the drive of the rope drum.

1 Introduction

The most common gearbox lubrication system is wading lubrication, which currently solves the lubrication of a given bevel helical gearbox. The oil creates the filling of the gearbox and the gear wheels that are waded in the oil moves the oil into the meshing [1-3]. This lubrication system is used for circumferential speeds of $v \leq 12\ m.s^{-1}$. It is recommended that, for high-speed gear wheels, the immersion depth does not exceed double the value of the gearing module and should not be less than 10 mm. Because the oil level decreases during operation, the immersion depth of the high-speed wheels tends to be up to four times the gearing module at rest [4,5]. At small circumferential speeds up to $1.5\ m.s^{-1}$, the immersion depth can be up to 1/6 of the gear wheel pitch diameter.

Another possible way is to lubricate with forced circulation - with central circulation lubrication, in which the oil that is fed to the lubrication areas is drained back into the tank, which makes the oil to circulate [6-8]. Requirements for circulatory lubrication include the reliability of the whole lubrication system as well as its parts, the possibility of choice or control of lubrication areas, the possibility of automation of the operation and reliable control and operation of the control elements [9].

2 Characteristics of the original gearbox lubrication

It is a three-speed bevel gearbox with a gear ratio of 19.706, power of 500 kW. The original lubrication is designed by spraying the wading wheel in an oil filling with a volume of 800 l. This method of lubrication is unsatisfactory at very low speeds (max. input speed approx. 200 rpm, most often speeds from 0 - 100 rpm), as evidenced by the fact that the first gear of the bevel gearbox shows a considerable degree of wear [10,11]. Over the last 10 years, the input side pinion with the counterpart has been changed three times and, in addition, the input side pinion alone, was changed two times more. Drawings of spare parts for these gears as well as for the entire gearbox are not available [12-15].

3 Design of circulating lubrication and description of its activity

On a base of central circulating lubrication of the bearings for the first template and bevel gearing, the circulation system shown in Fig.1 has been proposed.

The description of the operation is as follows. Before putting the device into operation (in case of prolonged shutdown), it is necessary to actuated a thermostat that detects the temperature of the lubricating medium. If the temperature is below the required working value, the lubricating medium must be heated by means of a heating element (spiral) up to the desired temperature. After reaching the desired temperature of the lubricating oil, its heating process is ceased and the device (gearbox) is ready to start. Also during operation of the device, the working temperature of the lubricating medium is monitored and in case of drop below the specified temperature, the heating is switched on and carried out by a heating element.

When the device is put into operation, i.e. when the desired lubrication medium working temperature is reached, central circulatory lubrication can be started by switching on the pump unit. The pump unit consists of a gear monoblock low pressure pump, the speed of which is 960 min^{-1}, the flow pressure of the pump 0.5 MPa (5 bar), max. viscosity of pumped oil 228 $mm^2.s^{-1}$ and flow rate is Q = 0,22 $l.s^{-1}$ (13,2 $l.min^{-1}$).

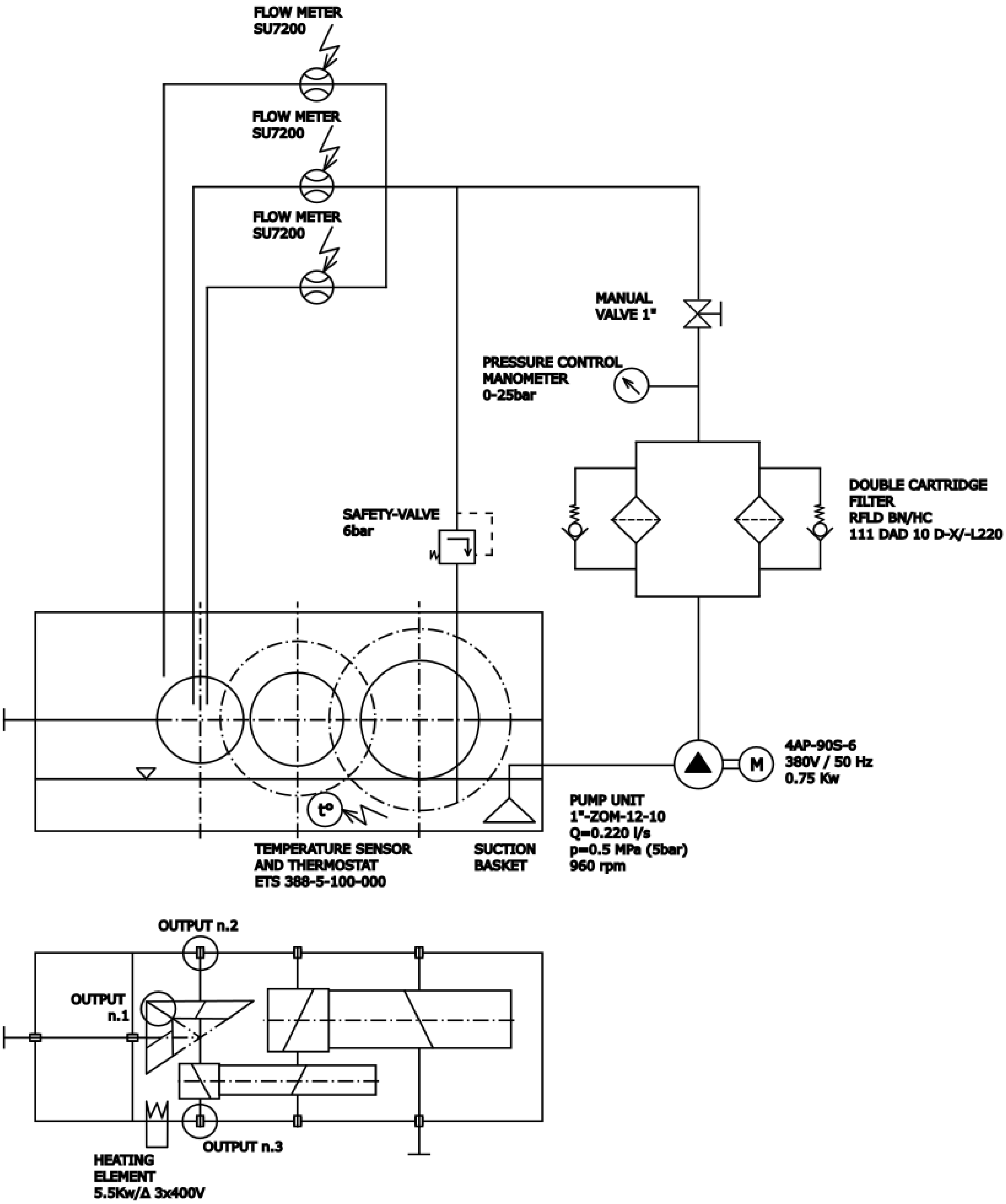

Figure 1 Central circulation lubrication scheme

The pump is powered by an electric motor (which is part of the pump unit) 4AP – 90S – 6 with a power of 0.75 kW (standard three phases asynchronous motor with shortcircuit armature for direct connection to the grid,

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closed version with its own surface cooling for a voltage of 380V, 50Hz). This pump unit draws the lubricating medium from the gearbox oil bath through the suction basket, the function of which is to prevent coarse impurities from entering the circulatory lubrication system and drives the lubricating medium into the filter.

The filter (Fig.2) is mounted on the outlet of the pump unit, it is a double cartridge, switchable with optical-electric indicator of the filter insert clogging (version with a voltage of 220 V). The filter ensures that the flow is at its outlet. The filter must be flexibly connected, not firmly set to the floor, designed for hydraulic systems that operate non-stop. When the filter insert is clogged, it is necessary to replace it. The filter consists of two parts and thanks to this, one part can be cleaned during operation and oil can be filtered with the other one. Another element in the central lubrication system is a pressure control manometer of 0 to 25 bar. This is followed by a manual throttle valve, a safety valve at 1.2 times the pressure in the system, i.e., up to 6 bar. This is followed by a flow divider (from one to three, with the same flow rate equal to one third of the total flow rate in each branch) mounted on the outlet pipe and three lubricating medium flow sensors.

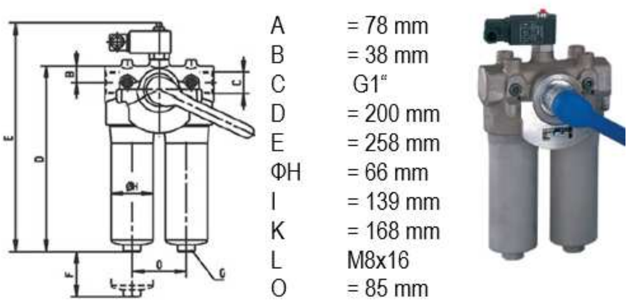

Figure 2 Filter

Flow sensors (Fig. 3) with ultrasonic sensor and programmable two switching outlets. The first outlet is a flow control of the lubricating medium with a display of the amount of flow in l.min^{-1} and a signalization at insufficient (zero) flow rate. The second outlet can be used to measure the temperature of the lubricating medium in °C.

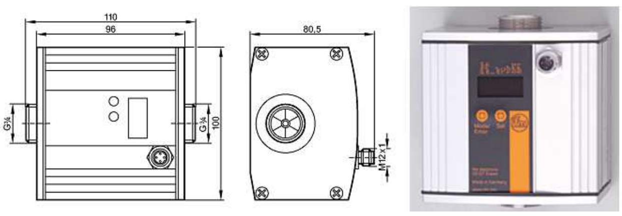

Figure 3 Flow sensor

The final element on each branch is the spraying nozzle. For the supply of lubricating medium to the bearings, it is recommended to use nozzles with a ring shape of spraying and for the supply of lubricating medium to the meshing of a bevel gearing, nozzle with a fan-shaped oil spraying. The oil returns to the gearbox, back into circulation.

The design of the amount of lubricating medium, i.e., the flow rate for lubrication of bearings by the central circulatory system, was based on the outer diameter of the bearing used on the first template (340 mm diameter). Based on reference [3], a lubricating medium flow rate between 0,1 l.min^{-1} and 10 l.min^{-1} is required for this case, noted that higher flow rates are used if the lubricating medium also serves as a cooling medium necessary for heat dissipation. Based on this requirement, a pump unit with flow rate Q = 0.22 l.s^{-1} (13,2 l.min $^{-1}$) has been selected. The flow rate by which the lubrication areas (bevel gearing meshing and bearings) are equal to a third of the pumping unit flow rate, i.e. the flow rate of 4,4 l.min $^{-1}$, which corresponds to the required range of oil needed to lubricate the bearings and at the same time meets the requirement of the necessary amount of lubricating medium for lubrication of the bevel gearing during meshing. Due to hydraulic resistances in the branches of circulating lubrication, the resulting flow rate will be even slightly lower, since the flow rate is inversely proportional to the resistance to movement. It is important to fine-tune the lubrication system during operation.

4 Conclusions

Perfect gearing lubrication ensures great durability, small mechanical losses, partially dampens noise and lead away heat. Gearboxes are usually lubricated with oil or plastic lubricant. Oil lubrication is often preferred for better heat dissipation. Lubrication with plastic lubricants is usually limited to the casings of gearboxes that cannot be sealed or can only be sealed at high design costs.

The original lubrication of the bevel helical gearbox was solved by wading the wheels in the oil filling, which was unsatisfactory, and the gearing was damaged. Based on the request, central circulatory lubrication of the bearings of the first template and the first degree of the gearbox consisting of a bevel gearing was designed. The task of lubrication systems is to bring and distribute the lubricant from one central source to all places of the machine where unwanted friction occurs, in an exactly specified quantity and time. Dripping oil flows back into the oil tub. With this method of lubrication, the oil can be filtered and cooled to separate the impurity particles and to dissipate heat.

In order to solve the issue of lubrication by designed central circulatory lubrication, it is necessary to implement a modification in the body of the gearbox.

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KINEMATIC ANALYSIS OF THE INDUSTRIAL ROBOT EFFECTOR

Ingrid Delyová
Department of Mechatronics, Faculty of Mechanical Engineering, Technical University of Košice, Park Komenského 8, 042 00 Košice, Slovakia, EU, ingrid.delyova@tuke.sk (corresponding author)
Darina Hroncová
Department of Mechatronics, Faculty of Mechanical Engineering, Technical University of Košice, Park Komenského 8, 042 00 Košice, Slovakia, EU, darina.hroncova@tuke.sk
Peter Frankovský
Department of Mechatronics, Faculty of Mechanical Engineering, Technical University of Košice, Park Komenského 8, 042 00 Košice, Slovakia, EU, peter.frankovsky@tuke.sk

Keywords: kinematic analysis, transformation matrix, joint, arm of robot, effector
Abstract: The technical level of industrial robots and manipulators is rapidly increasing, thus supporting the expansion of their application space. The requirements of the industry are various special manipulations with objects, guiding the end effector of the robot along the prescribed trajectory at a given speed while maintaining the angular position and orientation of the object. The paper presents a survey of a robot with a kinematic scheme formed by an open kinematic chain with revolute joints.

1 Introduction

The development of robots and manipulators belongs to the complex development process of entire mechanical engineering, electrical engineering and many other fields as their inseparable parts. Extending the handling capabilities requires the development of new types of kinematic structures, not only of individual types of manipulators but also of entire handling systems [1-3].

Assessing industrial robots and manipulators requires distinguishing between the mechanical part and the part formed by the control system. A characteristic feature of the mechanical part is the kinematic structure, which significantly affects the basic properties of robots and manipulators, especially the size and shape of the handling and working space.

1.1 Kinematic investigation of mechanisms

In the kinematic investigation of mechanisms, we encounter two types of tasks:

- Kinematic analysis of mechanisms
- Kinematic synthesis of mechanisms

Kinematic analysis of mechanisms of given dimensions investigates the relationship between position, speed and acceleration of driven and driving members. If we investigate only the trajectories of individual members of the mechanism and their points corresponding to the given movement of the driving members, we speak of forwarding kinematics of trajectories [1,3].

Kinematic synthesis of mechanisms is to design mechanisms that meet various technological and functional requirements for their operation in machines, devices and their parts. Finding the position of individual members of an industrial robot at known coordinates of individual kinematic pairs is a relatively simple task. A more difficult task is the inverse position problem, where the position and orientation of the gripper are given, and we look for the coordinates of individual kinematic pairs [4-6].

1.2 The forward kinematics

Various objects, obstacles, tools, etc., can be placed in the robot's handling space. Their position can be easily described with respect to the base space. The forward kinematics is used to determine the relative position of the arm with respect to the objects located in the manipulation space of the robot for the given articulated coordinates. The relationship between generalized articulated coordinates and coordinates of the base space is nonlinear (1), (2):

$$q_j = q_j(r_i), \tag{1}$$

or

$$q_j = q_j(x_i, y_i, z_i), \tag{2}$$

where q_j are generalized coordinates, $j = 1,2,, \dots, n$,
j is the number of degrees of freedom,
i is the number of members $i = 1,2, \dots, m$.

A change in the joint coordinates means that, in general, neither the trajectory of the effector point is straight nor the orientation of the effector is linear. This nonlinearity is based on the fact that the functions between the articulated and external (global) coordinates consist of expressions containing trigonometric functions. The solution is in the creation of a kinematic model of the robot. There are several methods for building such a model. The most common method is the Denavit-Hartenberg kinematic modelling convention. It connects the local coordinate

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system with each member. The method of connection depends on the homogeneous transformation matrix [1-2].

1.2.1 Denavit-Hartenbergová convention

Let's consider an open kinematic chain with n members and a coordinate system to which we assign the respective kinematic parameters [5-7]. Each member of the chain is characterized by two dimensions, a common normal distance b_j along a common normal between the axes of the joints i and i-1 and the other dimension is the angle of rotation β_j between these axes in a plane perpendicular to b_j.

We assign a coordinate system O_i, x_i, y_i, z_i to each member and a generalized coordinate q_i to each joint, which is defined in the axis of rotation. The axis z_i is oriented in the direction of the *(i+1)-th* axial joint. The axis x_i is normal to the z_{i-1} and z_i and is oriented from joint i to joint i+1. The axis y_i complements the rectangular, right-handed coordinate system.

1.2.2 Homogeneous transformation matrix

Homogeneous transformation matrices contain information about the rotation between two coordinate systems and information about the distance between their origins. The purpose of introducing these matrices is to allow a more compact notation of position vectors expressed in different coordinate systems. The position vector ${}^{i-1}\mathbf{r}_A$ of point A with respect to the system i-1 can be expressed by the relation (3)

$$ {}^{i-1}r_A = {}^{i-1}A_i \cdot {}^{i}r_{i-1,i}, \tag{3}$$

where

${}^{i}\mathbf{r}_A$ is the position vector of point A with respect to the system i,

${}^{i}\mathbf{r}_{i-1,i}$ is the vector of the distance between the origin of the system i with respect to the system i-1,

${}^{i-1}\mathbf{A}_A$ is the rotation matrix between the system i and i-1.

The homogeneous transformation matrix is expressed by the relation (4), (5)

$$ {}^{i-1}T_i = \begin{pmatrix} {}^{i-1}A_i & {}^{i}r_{i-1,i} \\ 0 \quad 0 \quad 0 & 1 \end{pmatrix}. \tag{4}$$

We then write the position vector

$$ {}^{i-1}r_A = {}^{i-1}T_i \cdot {}^{i}r_A. \tag{5}$$

2 Kinematic structure of the robot

The kinematic structure of the robot is represented by an open kinematic chain with six degrees of freedom of movement [8-9]. The chain consists of two basic parts. The first part comprises members 1, 2, 3, has three degrees of freedom of movement and serves to position the manipulated object, fig. 1. The second part serves for the orientation of the gripper and thus the manipulated object in space, it comprises members 4, 5, 6 and also has three degrees of freedom of movement. Member 1 is the stand rotatably mounted to the base plate, Fig. 1. An arm is connected to the stand with a shoulder joint 2. There is another arm connected to this arm with elbow joint 3. Each joint has a limited range of rotation. The investigated mechanism consists of rotating kinematic pairs only. One of the members of the robot is a gripper, which represents a multi-member mechanism. It has an associated coordinate system that defines its orientation in space.

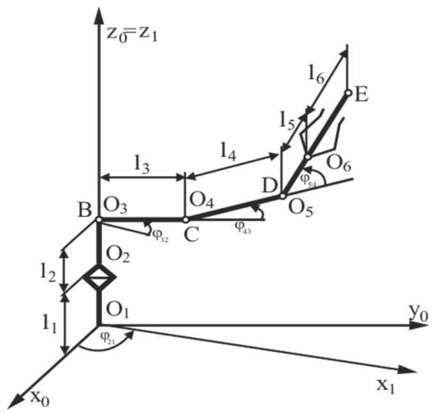

Figure 1 Robot diagram (B - shoulder joint, C - elbow joint, D - wrist joint, E - effector endpoint

Homogeneous transformation matrices have a relatively complex expression, so we introduce an abbreviated notation of a function (6), (7).

$$ c_i = \cos q_i, \qquad s_i = \sin q_i, \tag{6}$$

$$ c_{ijk} = \cos(q_i + q_j + q_k), \; s_{ijk} = \sin(q_i + q_j + q_k), \tag{7}$$

The transformation matrix T_{17} of the whole robot's kinematic chain is obtained as a product of the individual transformation matrices (8), (9).

$$ T_{17} = T_{12} \cdot T_{23} \cdot T_{34} \cdot T_{45} \cdot T_{56} \cdot T_{67} \tag{8}$$

$$ T_{17} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{9}$$

We used following parameters for members of the robot:

Table 1 The four parameters of robot of DH convention

i	β_i [°]	b_i [mm]	θ_i [°]	d_i [mm]
1	$\frac{\pi}{2}$	0	q_1	l_1
2	0	l_2	q_2	0
3	0	l_3	q_3	0
4	$\frac{-\pi}{2}$	0	q_4	l_4
5	$\frac{\pi}{2}$	0	q_5	l_5
6	0	0	q_6	l_6

The position of point E with respect to the reference coordinate system is given by the equation (10), (11).

$$ {}^{1}r_E = T_{17} \cdot {}^{7}r_E \tag{10} $$

$$ \begin{pmatrix} {}^{1}\mathbf{r}_{Ex} \\ {}^{1}\mathbf{r}_{Ey} \\ {}^{1}\mathbf{r}_{Ez} \\ 1 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} {}^{7}\mathbf{r}_{Ex} \\ {}^{7}\mathbf{r}_{Ey} \\ {}^{7}\mathbf{r}_{Ez} \\ 1 \end{pmatrix} \tag{11} $$

Simultaneous start-up in individual kinematic pairs with constant angular acceleration $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4$

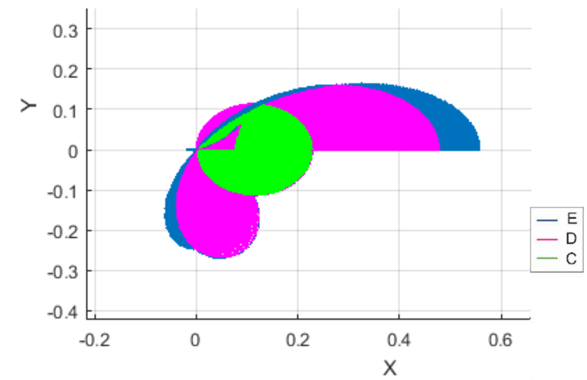

Figure 2 The trajectories of individual members

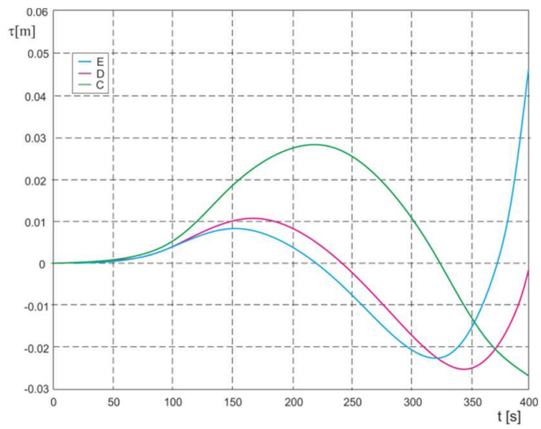

Figure 3 Radius of torsion of joint trajectory

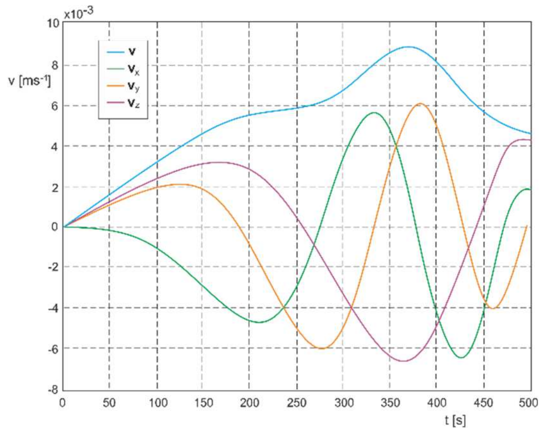

Figure 4 Joint E velocity at constant angular accelerations

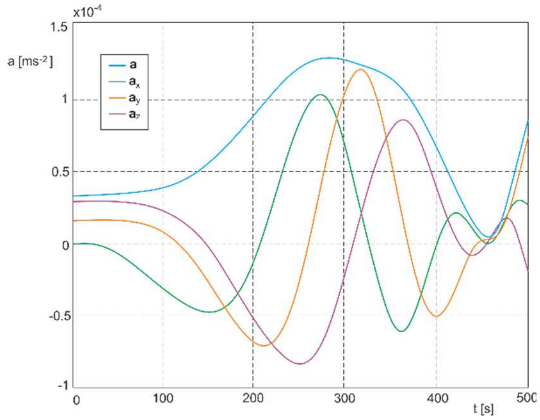

Figure 5 Joint E acceleration at constant angular accelerations

Figure 6 shows the acceleration of joint E at constant angular accelerations for which it applies $\alpha_1 > \alpha_2 > \alpha_3 > \alpha_4$. Figure 7 shows the acceleration of the joint E at angular accelerations $\alpha_1 = 0$, $\alpha_2 > \alpha_3 > \alpha_4$.

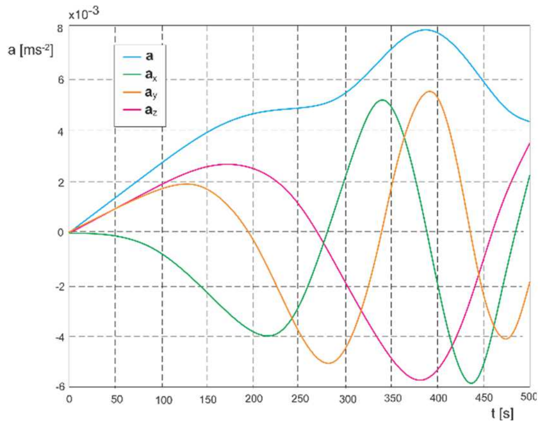

Figure 6 Joint E acceleration

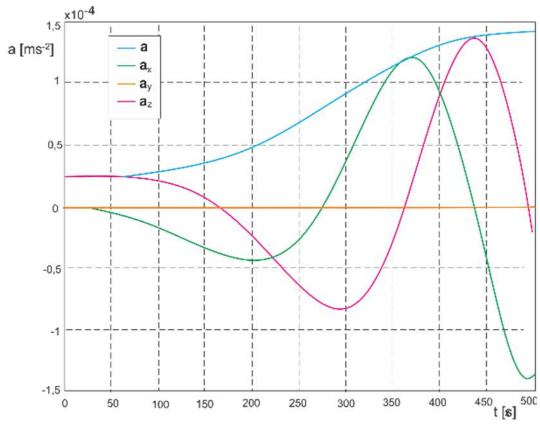

Figure 7 Joint E acceleration

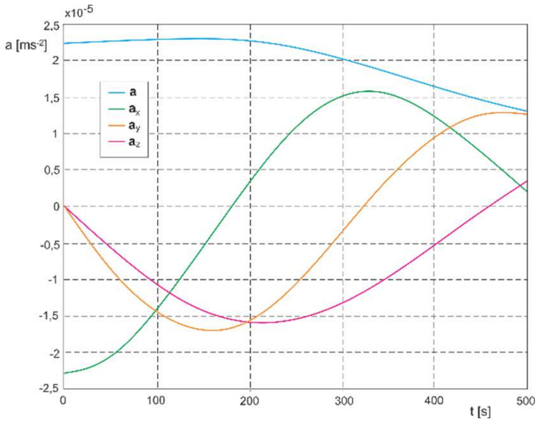

Figure 8 Joint E acceleration at constant angular velocity

Figure 8 and Figure 9 show the acceleration of the joint E with simultaneous starts of individual kinematic pairs with constant angular velocities. The acceleration for $\omega_1 = \omega_2 = \omega_3 = \omega_4$ is in Fig. 8, for $\omega_1 > \omega_2 > \omega_3 > \omega_4$ is in Fig. 9

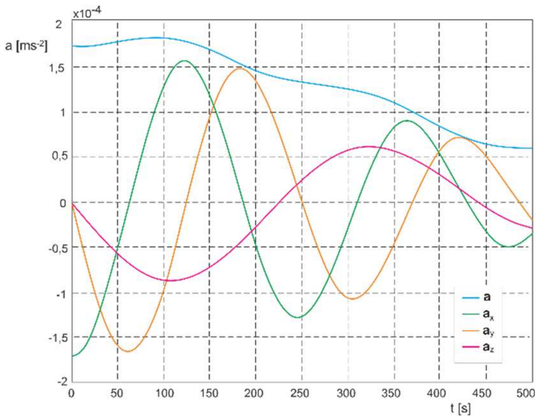

Figure 9 Joint E acceleration at $\omega_1 > \omega_2 > \omega_3 > \omega_4$

3 Conclusion

The paper deals with the issue of kinematic analysis of an industrial robot. The kinematic structure of the robot is represented by an open kinematic chain. The matrix method was used to solve the problem. The solution procedure consists of construction of the transformation matrices of coordinate systems and graphical representation of the manipulation space of the end-effector. The analysis also includes graphical representations of some kinematic quantities and also the evaluation of the influence of the parameters of the mechanism, which influence their values.

Acknowledgements
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