An Increase in Accuracy of Robotic Milling

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An increase in accuracy of robotic milling

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Abstract

The results of the theoretical research and computer simulation, aimed at increase in accuracy of robotic milling, are presented in the article. An analysis of the mathematical models of the system «technological robot – milling process» is conducted. The prospects of the usage of precision dual motor servo drives and trajectory-impedance control systems are underlined. The facts that such drives and systems allow us significantly increasing dynamic stiffness of technological robots and promote increasing accuracy and performance of robotic milling are also testified.

Introduction

At present time application of technological robots for milling is of great interest [1, 2]. Robotic milling has its advantages if parts have complex shapes of surface and large sizes. In this case, a crucial role is played by the ability of technological robot to implement complex spatial movements of its tool in large workspace, while the quantity of metal in robot is less than in machine tool. However, robots, which are widespread in industry and which have an open kinematic chain and also drives with closed position control loops of their motor shafts, have relatively low stiffness. Therefore, cutting forces cause large deviations of the actual tool position from its desired position, set by a control program. This fact often leads to inadmissible decrease in accuracy of machined part. The reduction of feed velocity promotes rise in accuracy, however it results in drop of performance, which is not always acceptable.

Manipulators with closed kinematic chain possess significantly larger accuracy and they are also applied in milling tasks [3, 4]. However, they have limited workspace. Such a problem of increasing accuracy of milling at the usage of robots with open kinematic chain is suggested to be solved by using computer control methods, a new type of drives [5, 6], closed by position control loops of manipulator links, and impedance control [7, 8].

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Accuracy and performance requirements of robotic milling

It is feasible to aspire to achievement of the highest productivity of robotic milling while the requirements to accuracy of the machined part are observed. Accuracy depends on several factors. The most significant among them are the forces, applied to manipulator tool during the milling process. They lead to a deviation δ_T of the instrument normal to the desired trajectory of its movement and they change size and shape of the workpiece surface. The greater the removal rate of workpiece material is, the higher is performance of robotic milling, which is calculated by the formula

$$Q = BhS, \tag{1}$$

where h – cutting depth; B – width of the removed layer; S – velocity of longitudinal feed of the tool (path velocity). Cutting force F_C is often calculated by empirical formulas. For instance, in case of milling with end mill the following relation can be used

$$F_C = k_F B^{n1} h^{n2} S^{n3}, \tag{2}$$

where k_F – proportional coefficient, which takes into account material properties of the machined workpiece and tool, diameter D, number of teeth z and rotation frequency n; $n1, n5, n3$ – exponent indexes. From (1) and (2) it goes that accuracy and performance of robotic milling are interrelated. Therefore, increase in performance is possible until the accuracy requirement of milling is satisfied

$$|\delta_T| \leq \delta_{T.ADM}, \tag{3}$$

where $\delta_{T.ADM}$ – admissible deviation of the tool. We note that the deviation δ_T decreases when the cutting force is reduced. This fact can be achieved by a reduction of path velocity S. However, at the same time the performance decreases too. The most attractive way here we see in raising accuracy and performance of robotic milling by increasing stiffness of the dynamic system «technological robot – milling process».

The increase in accuracy of technological robots built on precision dual motor drives on the basis of impedance control

In order to increase accuracy and performance of robotic milling we propose using robots, built on precision drives, closed by position control loops of manipulator links. The research results [3, 4] allow us recommending dual motor servo drives with two position control loops and two position sensors in this case. In such servo drives one of the motors is a part of the primary servo system, closed by a position control loop of manipulator link. The other motor is a part of a torque drive – a loader, which is an active controlled backlash eliminating devise. The main feature of the suggested type of servo drives is in fact that there is an integral controller in the outer position control loop of manipulator link. It controls the inner subsystem, which represents a drive, closed by a position control loop of its motor shaft. The loader allows us eliminating self-oscillations in the primary servo system. Due to the primary feedback position control loop of manipulator link, robots with such servo drives possess considerably higher dynamic stiffness than robots built on servo drives with traditional structure of control means.

The usage of the precision drives described above in combination with impedance computer control gives a possibility to realize the highest performance when the accuracy requirements of actuated movements are met. It is also important to note that the positive effect is achieved at a constant structural elasticity of gears. Impedance control is implemented as a result of introducing corrective velocity control loops of manipulator links, which changes impedance of the system «technological robot – milling process» in a desired way and which damps resonant oscillations of manipulator links. It allows us obtaining the highest possible stiffness in a direction normal to the desired trajectory of movement, the highest controlled stiffness for movements along the trajectory and a sufficient damping level.

Increase in accuracy of robotic milling can be revealed as a result of analysis of linearized mathematical model of the system «technological robot – milling process» (Fig. 1). There are 3 impacts applied to the drive system: a vector of reference impact Δq_{REF}, a vector of moments M_{FH}, applied to the manipulator link and caused by nominal cutting force, and a vector of deviations Δh_0 of the height of the workpiece surface which is defined along the normal direction to the machined surface. The equation, which links an error vector δ of the servo drive to the above-mentioned impact vectors, is the following:

$$\delta = C_{Eq}^{-1}(q,p)[Q(q,p)\Delta q_{REF} - M_{FH} - G(q)\Delta h_0], \qquad (4)$$

where $C_{Eq}(q,p)$ – transfer matrix of the equivalent dynamic stiffness of virtual spatial spring, which characterizes elastic and damping properties of the system «technological robot – milling process»; $Q(q,p)$ – stiffness matrix, which characterizes an influence of the vector Δq_{REF} on the vector of the resulting moments of forces, acting on the manipulator links; $G(q)$ – column matrix of coefficients of influence of the deviation Δh_0 on the moments M_F, acting on the manipulator links; p – differential operator.

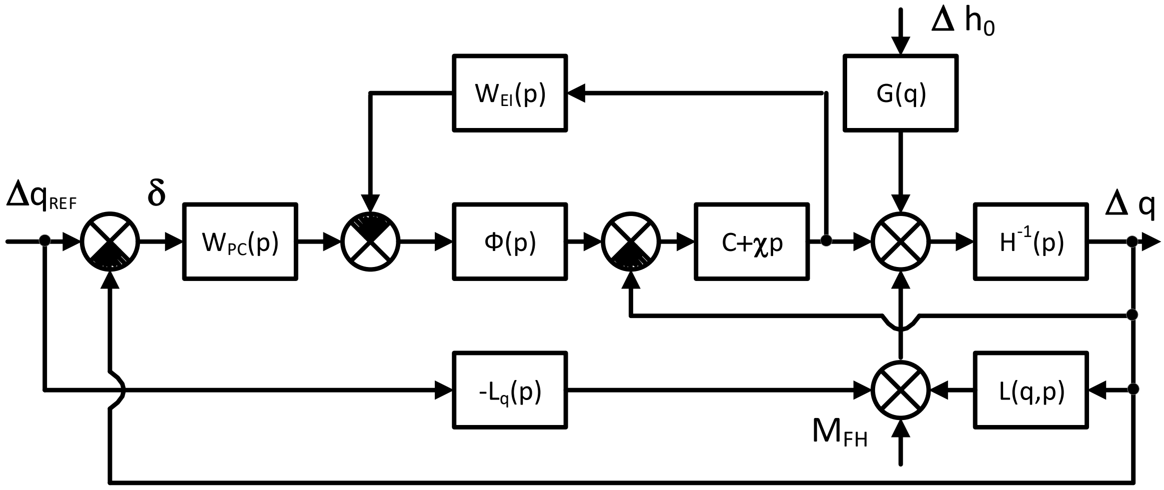

Fig. 1. The system «technological robot – milling process».

The matrix $C_{Eq}(q,p)$ is defined in the following way:

$$C_{Eq}(q,p) = \{H(p) - L(q,p) + [I + (C+\chi p)\Phi(p)W_{El}(p)]^{-1}(C+\chi p)[I + W_{PC}(p)\Phi(p)]\}, \qquad (5)$$

where I – unity matrix; $\Phi(p)$ – diagonal transfer matrix of the internal subsystem of the servo drives, closed by position control loops of their actuating motor shafts; C, χ – stiffness matrix and internal viscous friction matrix of mechanical transmission; $W_{El}(p)$ – diagonal transfer matrix of natural feedback loops, conditioned by reactions of elastic mechanical transmissions applied to the motor shafts; $W_{PC}(p)$ – diagonal transfer matrix of outer position controllers of the system of servo drives; $H(p)$ – operator matrix of the linearized dynamic model of the manipulation mechanism, which has the form

$$H(p) = \left[A_M(q_0)p^2 + B_M(q_0, \dot{q}_0)p + C_M(q_0, \dot{q}_0, \ddot{q}_0) \right], \qquad (6)$$

where A_M, B_M, C_M – matrices of coefficients, which depend on values of components of generalized coordinates vectors $q_0, \dot{q}_0, \ddot{q}_0$, velocities and accelerations of manipulator at the supporting point of trajectory, respectively. $L(q,p)$ – equivalent dynamic stiffness of the spatial "technological spring" of the system «technological robot – milling process», which depends on the Jacobian matrix $J_R(q)$ and the vector q of generalized coordinates of the manipulator. The connections caused by the spatial “technological spring”, possess dynamic nature and occur only during the tool movement in contact with the machined object.

The matrix $Q(q,p)$ can be calculated by an equation

$$Q(q,p) = \{\ H(p) - L(q,p) + L_q(q) + \left[E + (C+\chi p)\Phi(p)W_{El}(p)\right]^{-1}(C+\chi p)\ \}, \tag{7}$$

where $L_q(q)$ – matrix of coefficients of the influence of reference impacts Δq_{REF} variations on the moments M_F. This matrix depends on the Jacobian matrix $J_R(q)$. In (4) – (7) the column matrix has dimension (6×1), the rest matrices have dimension (6×6).

The form of matrix of controllers $W_{PC}(p)$ significantly affects the matrix of the dynamic stiffness of the system $C_{Eq}(q,p)$. In a steady-state regime the following relations $W_{El}(0)=0$, $L(q,0)=L_q(q)$, $H(0)=C_M$, $\Phi(0)=I$, $Q(q,0)=C+C_M$ take place. Therefore, on the basis of (5) we have

$$C_{Eq}(q,0) = C\left[E + W_{PC}(0)\right] + C_M - L_q(q). \tag{8}$$

The form of formula (8) testifies the fact that increase in stiffness of the system can be achieved as a result of selection of matrix $W_{PC}(p)$ of the form

$$W_{PC}(p) = N_{PC}^{-1}(p), \tag{9}$$

with components $N_{PCii}(p) = T_{ii}p$, where T_{ii} – time constant of integral position controller of the *i*-th manipulator link; $i = 1,..., N$, while N – number of degrees of freedom (DOF) of the manipulator. We note, that at $p = j\omega \to 0$ components of the matrix $|W_{PC}(j\omega)|$ tend to infinity. Therefore $C_{Eq}^{-1}(q,p)=0$. So, in a steady-state regime of movement the vector of errors $\delta \to 0$. This statement also testifies the fact that $\delta_T \to 0$. At variable impacts on the tool the smaller the error is, the smaller is the value of the time constant T_{ii}. Rise in potential accuracy can be used in order to increase the permissible feed velocity of the tool, which leads to increase in machining performance.

The results of computing experiments.

In order to clarify the possibilities of the two previously discussed approaches of building robotic milling systems a computer research has been carried out. The tool movement accuracy during the robotic milling process depending on path velocity of milling cutter and rated value of the cutting depth has been defined. The first approach is based on the usage of traditional servo drives with one motor, closed by position control loops of their motor shafts. The second approach contains precision dual motor drives, closed by position control loops of manipulator links, and controlled torque loaders. A process of cylindrical up-milling of the lateral surface of the workpiece, which is a rectangular plate of aluminum alloy D16T (AlCu4Mg1), has been considered. The milling cutter has 5 teeth and diameter 6 mm. The length of the working part of the cutter is 12 mm, the angle of the helical chip grooves is 20°, frequency of rotation of the tool – 10000 rpm. The robot moves the cutter along a linear path. The width of the removed layer is 12 mm, the trajectory length is 200 mm.

The robot manipulator, considered in the actual research, has four DOF (Fig. 2). Three of them are provided by planar mechanism of the angular type with 3 DOF. One more degree of freedom is implemented by the rotation of the column around the vertical axis. The masses of the «shoulder» and the «elbow» links equal to 38 and 35 kg respectively, and their lengths are the same and they equal to 0.68 m. There is an assumption that the links of manipulator mechanism are absolutely rigid. The milling process occurs when the configuration of the manipulator, characterized by the angle between the «shoulder» and «elbow» links, is approximately equal to 45°.

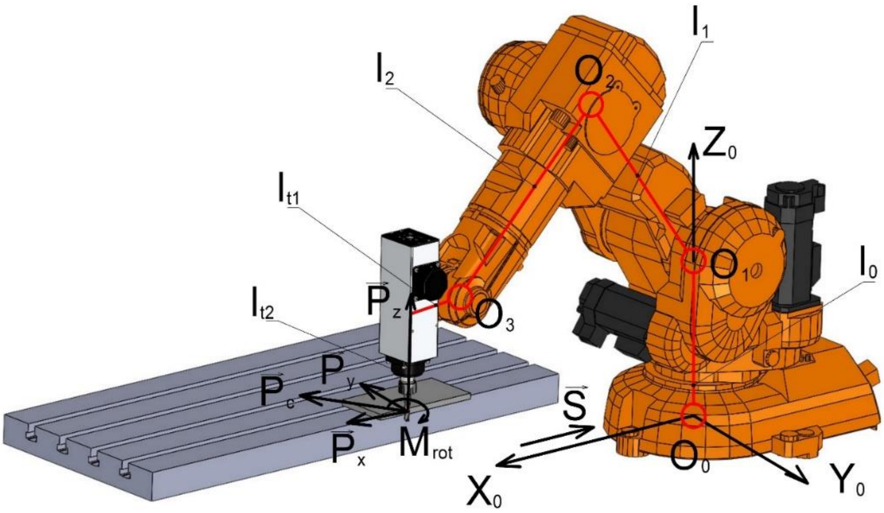

Fig. 2. Schema of the simulated robot

As a basis for creating mathematical models of drives of the manipulators column and «shoulder» link motors model 44.SM.203-34B5 by KEB and gears model HFUC-50-2A-GR by Harmonic Drive have been selected. The gears ratio is 120. Rated power of such drive is 2,67 kW, rated torque – 8.5 Nm, rated rotation frequency – 3000 rpm. Stiffness coefficient of gear is 400000 Nm/rad, backlash equals about 1 arc. min. The similar motors and gears are used for the primary drive and the loader. For the «elbow» link drive motors model 42.SM.203-34B5 by KEB and gears model HFUC-40-2A-GR by Harmonic Drive have been selected. The gears ratio is 120. Rated power of the drive is 1,44 kW, rated torque – 4.6 Nm, rated rotation frequency – 3000 rpm. Stiffness coefficient of gear is 130000 Nm/rad, backlash equals about 1 arc. min. The PWM frequency of the frequency converter, used for vector control of the drives, is 16 kHz. A resolver with resolution of 2047 discrete per revolution is used in closed position control loop of the motor shaft. The closed position control loop of the manipulator link is realized by means of the encoder with resolution 250000 discrete per revolution.

During the simulation process the tool has been moved along X axis in the direction to the robot base. In order to measure movements accuracy during the computer simulation a deviation of the tool normal to the desired trajectory of its movement, which has been along Y axis, has been being defined. The average value of the absolute value of the deviation of the tool from trajectory d, measured along Y axis, and the maximal value of deviation $\Delta d_{\max}$ from d along Y axis, have been considered as indicators of movements. The values d and $\Delta d_{\max}$ have been defined by the following formulas:

$$d = \frac{1}{T}\int_{0}^{T} \left|\delta_T(t)\right| dt, \tag{10}$$

$$\Delta d_{\max} = \max\left|\left(\left|\delta_T(t)\right| - d\right)\right|, \tag{11}$$

where T – total time of tool movement during milling process of the workpiece.

The dependencies, presented in Fig. 3, of the indicator d on path velocity S at different rated values of cutting depth h_0, obtained for the manipulators built on traditional drives with one motor, show large deviations of the milling cutter from the desired trajectory. The values of this indicator lie in the range between 156 and 425 μm while the velocity varies from 2 to 7 mm/s and the rated cutting depth varies from 0.5 to 1.5 mm. If we rise S and h_0, the deviations rise too. At the same conditions the values of indicator $\Delta d_{\max}$ lie in the range from 23 to 100 μm. In many practical applications such deviations are often inadmissible. The reasons of such deviations are in a cutting force component, acting along Y axis and which values lie in the range of 16 … 151 N, and also in insufficient stiffness of the manipulator, which lies in the range from 100000 to 356000 N/m, depending on the values of S и h_0.

Due to closed position control loops of manipulator links stiffness of the manipulator with the suggested dual motor drives increases significantly. As a result of the computing experiments the obtained values of the manipulator stiffness along Y axis lie between $6{,}8 \cdot 10^8$ to $2{,}16 \cdot 10^9$ N/m. When there is a cutting force component along Y axis, which values lie in the range of 11 … 114 N, this fact gives us considerably higher accuracy of robotic milling. The dependencies of the indicator d on S and h_0 (Fig. 4) show that at variations of S from 2 to 7 mm/s and h_0 from 0,5 to 1,5 mm the values of d lie in the range of 0,0052…0,168 μm. At the similar conditions the value of $\Delta d_{\max}$ lie within the range of 0,01 … 0,048 μm.

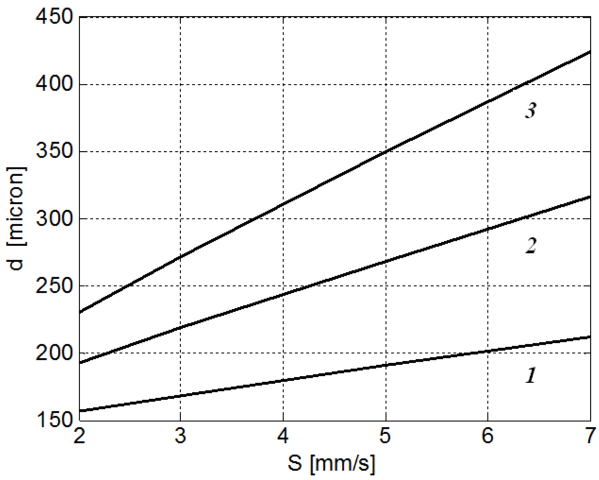

Fig. 3. The dependence of the deviation *d* on the path velocity S at h_0 = 0,5 mm (1), 1 mm (2), 1,5 mm (3) for the manipulator, built on geared drives with traditional structure.

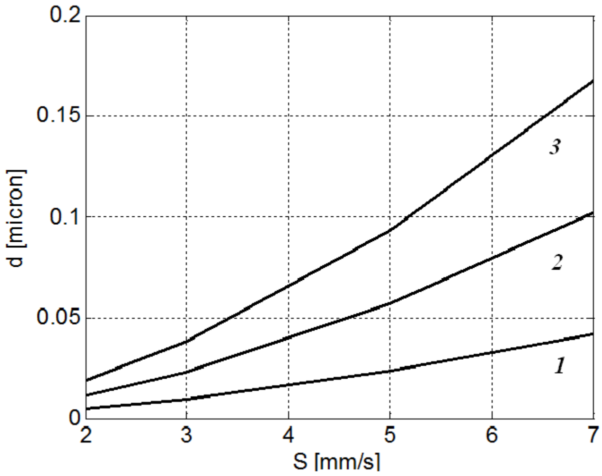

Fig. 4. The dependence of the deviation *d* on the path velocity S at h_0 = 0,5 mm (1), 1 mm (2), 1,5 mm (3) for the manipulator, built on precision dual motor drives.

The increase in accuracy of the milling cutter movements opens more opportunities for the growth of robotic milling performance. For example, if we restrict the permissible deviation from the desired trajectory at 180 μm then by means of the traditional approach we cannot exceed the values of S = 2 mm/s and h_0 = 0,5 mm. The new approach based on dual motor drives allows us implementing milling at S = 7 mm/s and h_0 = 1,5 mm and having a large accuracy margin at that. The performance gain is not less than 10,5. We make a conclusion that the usage of technological robots with the suggested dual motor drives promotes significant increasing in accuracy of the tool movements and allows us speaking about possibility of implementation of high precision and high performance robotic milling.

Conclusion

1. In order to increase accuracy and performance of robotic milling the usage of the technological robots, built on precision dual motor servo drives, closed by position control loops of manipulator links, is proposed.

2. In order to improve the dynamic properties of such robots it is feasible to apply impedance control, which can be realized by introducing corrective control loops of manipulator links velocity.

3. The suggested solution allows us significantly increasing static and dynamic stiffness of the robot by control means without significant changes in mechanical robot components. This fact gives a possibility to reduce the influence of cutting forces on the deviation of tool from its desired trajectory and to increase performance of the robotic milling process on this basis.

4. The results of computing experiments have shown a considerable increment in the accuracy and tenfold gain in the performance of the suggested solution in comparison with the robot with traditional structure of servo drives, closed by position control loops of their motor shafts.

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