Control of accuracy of turning treatment of parts of machines based on fuzzy logic algorithms

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Abstract. The paper considers the possibility of using fuzzy logic algorithms in the development of automatic control systems for precision machining of cylindrical surfaces. For the theoretical justification of the use of these algorithms, a mathematical model of the turning process and a mathematical model of the fuzzy-controller were developed. When developing the fuzzy-controller mathematical model, its input and output linguistic variables were determined, their fuzzification was carried out. The base of fuzzy linguistic rules that formed the algorithm for controlling the processing accuracy was developed. The defuzzification method was chosen, which allows determining the value of the control value depending on the value of the mismatch of the controlled value. The value of the error of the dynamic adjustment of the processing process was considered as an input linguistic variable fuzzy-regulator was considered, and the value of the correction made to the value of the longitudinal feed - as its output linguistic variable. The results of the comparative theoretical analysis of the processing accuracy in the process system without control were studied along with the control of the classic proportional regulator and proportional fuzzy-controller using the fuzzy inference algorithm Mamdani. Based on the results of the comparative analysis, it is concluded that the use of fuzzy logic algorithms is promising in the development of automatic control systems for precision turning of machine parts.

1. Introduction

Ensuring the required accuracy of machine parts will always be an urgent task of mechanical engineering. One of the possible ways to solve this task is the use of automatic control systems of processing accuracy (ACS PA). As you know [1], the logic of the functioning of any ACS PA is mostly determined by the presence of a priori information about external and internal relations in the control object. In the design of ACS PA, this information is used to develop a mathematical model of the control object, reflecting the pattern of changes in the controlled value when applied to the object of control and disturbing effects.

A large number of external and internal factors that determine the regularity of the processes of machining, and insufficient study of the relationships between these factors in some cases leads either to the impossibility of creating an adequate mathematical model of the control object, or to its significant complication, which impedes considerably the development of ACS PA. The presence of the above problems necessitates the use of new methods in the design of ACS PA, allowing taking into account
the incompleteness and inaccuracy of a priori data about the control object. One of these is a method based on the use of fuzzy logic, the basic concepts of which were presented in [2 - 6].

2. Problem statement and research methods

The paper considers the possibility of using fuzzy logic regulators in the creation of ACS PA of machine parts on metal-cutting machines and provides a comparative analysis quality of the control processes using classical and fuzzy logic proportional regulators. The analysis of quality of control processes was carried out on the basis of comparison of results of their computer modeling received at the same values of initial data.

As an object of control, controlled parameter and control action, respectively, were considered:

- the process of orthogonal turning of the outer cylindrical surfaces of axisymmetric parts;
- the size of the dynamic adjustment formed on the workpiece during its processing;
- the amount of correction $\Delta S$ made to the longitudinal feed value in order to minimize the mismatch between the set value of the dynamic adjustment size $A_d^f$ and its actual value $A_d^i$, i.e. to minimize the dynamic adjustment error.

The general functional scheme of ACS PA with the use of the fuzzy regulator is shown in figure 1.

![Diagram](image_url)

**Figure 1.** The general functional scheme of ACS PA with the use of the fuzzy regulator

3. A mathematical model of the process of turning

A mathematical model of the turning process was developed for computer simulation of machining accuracy control under the following assumptions:

- the size of the dynamic adjustment is formed as a result of elastic deformation of the cutter, deformation of the remaining elements of the technological system is not taken into account;
- elastic system of the cutter-oscillatory system with concentrated mass, reduced to the top of the tool;
- oscillation of the elastic system of the cutter due to the fluctuation in the radial component of the cutting force;
- fluctuations in the radial component of the cutting force due to the variability of the cutting depth.

The calculation scheme for the system of equations of the mathematical model of the turning process is presented in figure 2.
Figure 2. The calculation scheme for the system of equations of the mathematical model of the turning process

In accordance with the calculation scheme, the linearized mathematical model of the turning process was developed which has the following form:

\begin{align}
M \frac{d^2 \Delta y}{dt^2} + h \frac{d \Delta y}{dt} + j \Delta y &= \Delta P_y \\
\Delta P_y &= \Delta P^R_y + \Delta P^S_y \\
T_1 \frac{d \Delta P^R_y}{dt} + \Delta P^R_y &= K_x \Delta t_y \\
T_2 \frac{d \Delta P^S_y}{dt} + \Delta P^S_y &= K_{AS} \Delta S \\
\Delta t_y &= \Delta t_o - \Delta y
\end{align}

where \( M \), \( h \), and \( j \) - the reduced mass, the ratio of the drag force and the stiffness of the elastic system of the cutter, respectively; \( \Delta y \) - the offset of the cutter from the equilibrium position numerically equal to the error of dynamic setting; \( \Delta P_y \) - the increment of radial component of cutting force; \( \Delta P^R_y \) - part of the increment of the radial component of the cutting force due to changes in the depth of the cut; \( \Delta P^S_y \) - part of the increment of the radial component of the cutting force due to changes in feed; \( T_1 \) and \( T_2 \) - constant; \( \Delta S \) - the increment of feed; \( \Delta t_o \) - the deviation of the actual depth of the cut due to the variability of the size of the original workpiece.

In the system of equations (1), the coefficients \( K_x \) and \( K_{AS} \) were determined by linearization of the nonlinear dependence for the cutting force according to the formulas:

\begin{align}
K_x &= C_r \cdot t_o \cdot \frac{v_o}{S_o} \cdot S_{vo} \cdot V_{o}^{\nu} \\
K_{AS} &= C_r \cdot t_o \cdot \frac{v_o}{S_o} \cdot S_{vo} \cdot V_{o}^{\nu} 
\end{align}

where \( t_o \), \( S_o \), \( V_o \) - nominal values of cutting depth, feed and cutting speed, respectively, \( C_r \), \( x_p \), \( y_p \), \( n_p \) - coefficients specific for special processing conditions.

The values of constants in equations (1,2) were determined for conditions corresponding to the rough turning of a smooth shaft made of steel 1020, 100 mm in diameter and 200 mm in length, from rolled steel, 105 mm in diameter under nominal cutting conditions \( V_o = 1.67 \) m/s, \( S_o = 0.6 \) mm/Rev, \( t_o = 2.5 \times 10^{-3} \) m and coefficient values \( C_r = 2430 \), \( x_p = 0.9 \), \( y_p = 0.6 \), \( n_p = -0.3 \). The reduced mass, the coefficient of resistance and stiffness of the elastic system of the cutter, as well as the time constants
$T_1$ and $T_2$ were taken equal to: $M = 5 \cdot 10^3 \text{ H} \cdot \text{s}^2 / \text{m}$, $h = 9 \cdot 10^3 \text{ H} \cdot \text{s} / \text{m}$; $j = 10.75 \cdot 10^6 \text{ H} / \text{m}$; $T_1 = 0.04 \text{ s}$ and $T_2 = 0.05 \text{ s}$.

When modeling the turning process, a normally distributed value of the cutting depth with the parameters was taken as a random disturbance:

$$
\Delta t = 0; \quad \sigma_{\Delta t} = T_c / 6,
$$

where $\Delta t$ - average value, $\Delta t_c$; $T_c$ - the tolerance of the workpiece size.

Figure 3 shows the numerical solution of the system of equations (1) with respect to the value $\Delta y = \Delta A_y$, obtained by using the Control System Toolbox package of Matlab R2014 with the excluded fourth equation of the system (in the absence of control of processing accuracy). To find the solution, the Dorman-Prince method was used with a fixed integration step of 0.01 s.

![Figure 3](image_url)

**Figure 3.** The calculated values of the value $\Delta A_y$ in the absence of control processing accuracy.

To assess the possibility of using fuzzy logic algorithms, the quality of the dynamic adjustment error control process was analyzed by a fuzzy logic regulator using the Mamdani fuzzy inference algorithm [7, 8]. A mathematical model of the fuzzy logic regulator was developed for calculations, namely its input and output linguistic variables were determined; fuzzification of linguistic variables was carried out. The base of fuzzy linguistic rules forming the control algorithm is determined; the method of defuzzification is chosen, which allows determining the value of the control parameter depending on the value of the mismatch of the controlled parameter. The value $\Delta y = \Delta A_y$ was considered as the input linguistic variable fuzzy logic regulator, and as its output linguistic variable of the value $\Delta S$. Characterizing the value of the longitudinal feed during processing was made. The sets of values of the above variables, as well as their membership functions, were chosen on the basis of a survey of practitioners.

The set of the variable was taken in the following form: $T_{y1} = \{\text{positive big (PB)}; \text{ positive medium (PM)}; \text{ positive small (PS)}; \text{ positive, close to zero (PZ)}; \text{ zero (Z)}; \text{ negative, close to zero (PZ)}; \text{ negative small (NS)}, \text{ negative medium (NM)}, \text{ negative big (NB)}\}$. For the variable $\Delta S$ the set of its values was generated as follows: $T_{S1} = \{\text{positive big (PB)}; \text{ positive medium (PM)}; \text{ positive small (PS)}; \text{ positive, close to zero (PZ)}; \text{ zero (Z)} \text{ negative, near zero (NZ)}; \text{ negative small (NS)}, \text{ negative medium (NM)}, \text{ negative big (NB)}\}$. 
For the values of the sets of variables $T_\alpha$ and $T_{\Delta y}$, Gaussian membership functions were taken, having the following form:

$$\mu(x,c,\sigma) = \exp\left(\frac{- (x-c)^2}{2\sigma^2}\right)$$

(4)

where $x$ - the numerical value of a certain term from the corresponding set; $c$ and $\sigma$ - the numerical parameters characterizing, respectively, the mean and the standard deviation of the considered term. The specific type of membership functions of values of term-sets of variables due to the limited volume of the article is not given.

The base of fuzzy linguistic rules of dynamic tuning error control was formed as follows: $B_{\Delta y,\Delta S} =$

- if $\Delta y = PB$, then $\Delta S = NB$;
- if $\Delta y = PM$, then $\Delta S = NM$;
- if $\Delta y = PS$, then $\Delta S = NS$;
- if $\Delta y = PZ$, then $\Delta S = NZ$;
- if $\Delta y = Z$, then $\Delta S = Z$;
- if $\Delta y = NZ$, then $\Delta S = PZ$;
- if $\Delta y = NS$, then $\Delta S = PS$;
- if $\Delta y = NM$, then $\Delta S = PM$;
- if $\Delta y = NB$, then $\Delta S = PB$.

The center of gravity method was adopted as a defuzzification method. The calculation of the control action $\Delta S$ in accordance with this method was carried out by the formula:

$$\Delta S = \int_{\text{Min}}^{\text{Max}} z \cdot \mu(z) \, dz / \int_{\text{Min}}^{\text{Max}} \mu(z) \, dz,$$

(5)

where $z$ - fuzzy output variable of the regulator, obtained after the accumulation stage; $\mu(z)$ - function of belonging of the output variable of the regulator after the accumulation stage; $\text{Min}$ and $\text{Max}$ - left and right points of the carrier interval of the fuzzy set of the output variable $z$.

The procedure for determining the value $z$ and function of its membership $\mu(z)$ depends on the adopted fuzzy inference algorithm. In particular, the algorithm of Mamdani’s fuzzy inference is considered in detail in [4, 5] and due to the limited volume of the article it is not given here. In general:

$$z = F_1^* (\Delta y, T_\alpha, B_{\Delta y,\Delta S}); \mu(z) = F_2^* (\Delta y, T_\alpha, B_{\Delta y,\Delta S}, z),$$

(6)

where $F_1^*$ and $F_2^*$ - fuzzy functions that determine the relationship between the input and output variables of the fuzzy logic regulator, as well as the base of fuzzy linguistic control rules.

A complete mathematical model of the ACS PA uses the fuzzy logic regulator as a system of equations (1) with attached fuzzy control equations (5, 6). The numerical solution of the system of equations (1-3, 5, 6) for the value $\Delta y = \Delta A_c$ provided the package of Control System Toolbox system and the package of Fuzzy-logic systems Matlab R2014, shown in figure 4. To find the solution, as before, the Dorman-Prince method was used with a fixed integration step of 0.01 s. For comparison, figure 5 shows the solution of the system of equations (1-3) with the attached equation of the classical proportional regulator:

$$\Delta S = K_a \cdot \Delta y,$$

(7)

where $K_a$ gain P-regulator, determined as a result of its settings. Settings of the P-regulator was carried out using the Control System Toolbox package of Matlab R2014 system on the basis of minimizing the error square integral in response to the Heaviside function. As a result of the settings, the gain value of the P-regulator was obtained $K_a \approx 0.6$.

Based on the simulation results, the values of the mean square deviations and the scattering fields of the dynamic adjustment error presented in table 1 were calculated.
Table 1. Mean square deviation and scattering field of dynamic adjustment error for different control methods.

| Technological system          | The standard deviation of the error dynamic settings $\sigma_{y\Delta}$, $10^{-3}$ m | Dynamic adjustment error scattering field $6\sigma_{y\Delta}$, $10^{-3}$ m |
|-------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Without regulation            | 0.025                                                                             | 0.15                                                                    |
| With the P-regulator           | 0.052                                                                             | 0.312                                                                   |
| With fuzzy regulator           | 0.014                                                                             | 0.084                                                                   |

Figure 4. Calculated values $\Delta A_y$ when using a fuzzy logic regulator.

Figure 5. Calculated values $\Delta A_y$ when using the P-regulator.
The analysis of the data presented in table 1 allows us to conclude that fuzzy control provides a decrease in the scattering field error of dynamic adjustment of about 1.8 times, compared with the technological system in which there is no control. Moreover, at the accepted values of the initial data, fuzzy control is the only possible way to reduce the error of dynamic adjustment, since the control using a classical regulator is unacceptable as it leads to an increase in the error of dynamic adjustment by more than 2 times compared to the technological system in which there is no regulation.

4. Conclusion
As a result of the studies conducted in this paper, the following conclusions can be drawn:

- theoretical studies have been carried out to prove the possibility of using fuzzy-logic algorithms in the design of automatic control systems of machine parts;
- studies conducted on the theoretical model of the turning process showed that when controlling the dynamic adjustment error, the fuzzy-logic regulator allowed reducing its scattering field about 1.8 times compared to the technological system in which there is no regulation. The use of the classical proportional regulator for the conditions of the considered model is unacceptable, since it leads to an increase in the scattering field of the dynamic adjustment error;
- the obtained theoretical results show that the use of fuzzy-logic regulators is a promising direction in the development of ACS PA, since they allow providing the greatest reduction in the error of dynamic adjustment compared to the classical regulators.

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