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Using fuzzy models in machining control system and assessment of sustainability

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Abstract. Description of the complex relationship of the optimum velocity with the temperature-strength state in the cutting zone for machining a fuzzy model is proposed. The fuzzy-logical conclusion allows determining the processing speed, which ensures effective, from the point of view of ensuring the quality of the surface layer, the temperature in the cutting zone and the maximum allowable cutting force. A scheme for stabilizing the temperature-strength state in the cutting zone using a nonlinear fuzzy PD−controller is proposed. The stability of the nonlinear system is estimated with the help of grapho−analytical realization of the method of harmonic balance and by modeling in MatLab.

1. Introduction
The cutting speed for different machining methods ambiguously affects the temperature in the cutting zone and the strength characteristics of the process. The optimal state of the surface layer should be ensured by the selection of certain treatment regimes depending on the temperature-strength state of the cutting process. The algorithm and fuzzy model of the choice of cutting speed based on the measurement of two parameters (strength and temperature) makes it possible to reduce the disturbing effect of the uncertainty factor of parameters of such complex process as chip formation and to improve the accuracy of cutting control systems. The construction of a governing law based on fuzzy rules largely takes into account the uncertainty of the connection between the cutting force and temperature [1]. The use of the base of fuzzy rules allows one to avoid the computational functional process. The problems of estimating the stability of such systems can be solved on the basis of classical methods of nonlinear dynamics and using simulation data.

2. Research methodology
Conditions for developing a fuzzy model for determining the cutting speed based on the requirements for the technological process and the requirements for the quality of the product are formulated. The developed fuzzy output block should ensure the selection of the optimum cutting speed in accordance to the following conditions [2]:

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$$T(v) \to \max \\ \begin{cases} \left|\overline{F}_{summ}\right| \le F_{\lim}; \\ v_{st\min} \le v \le v_{stm\max}, \end{cases} \quad (1)$$

where T – temperature in the cutting zone; $\overline{F}_{summ}$ – total component of cutting force; $v_{st\,min}$, $v_{st\,max}$ – minimum and maximum speeds provided by machine tools; $F_{\lim}$ – allowable value

The selection of the supported temperature for conditions (1) can be carried out by the criterion of ensuring the optimum temperature regime in the cutting zone or with the aim of reducing the adhesive and diffusion wear of the cutting edge of the tool [3,4].

Fuzzy output model. The development of a mathematical model for selecting the cutting speed included the following standard steps [5, 6]:

1. Fuzzification of input and output variables: $T = \{< T, \mu(T) >\}$, $F = \{< F, \mu(F) >\}$, $V = \{< V, \mu(V) >\}$, where $\mu(T) \to [0,1]$, $\mu(F) \to [0,1]$, $\mu(V) \to [0,1]$ – degree of belonging of temperature, T; a radial component of cutting force F and cutting speed V respectively.
2. Determination of membership functions for term-sets of input and output variables in the form of triangular and sigmoidal functions.
3. Development of the production model of the knowledge base in the form of fuzzy control rules, implementing a fuzzy system in which the temperature will be kept as high as possible, and the cutting force should not exceed the preset value assigned based on the appropriate quality criterion.
4. Composition of truth degrees and definition of truncated values in terms of output functions of velocity membership.
5. Combining all degrees of truth of the conclusion of fuzzy control rules to obtain the output membership function:
6. Defuzzification of the output velocity value produced on the basis of the center of gravity method.

In a generalized form, the mathematical model of the fuzzy-logic output of cutting speed V_{FL} as a function of current values F and T can be represented as follows:

$$V_{FL} \to \left\{ \begin{array}{lll} T = [T_1] + [T_2] + [T_3]; & F = [F_1] + [F_2] + \ldots [F_5]; & V = [V_1] + [V_2] + \ldots [V_7]; \\ T' = (T_1', T_2', T_3'); & F' = (F_1', F_2', \ldots, F_5'); & V' = (V_1', V_2', \ldots, V_7'); \\ b_1'' = b_{15}'; & b_2'' = \max(b_{14}', b_{10}'); & b_3'' = b_9'; \\ b_4'' = b_5'; & b_5'' = \max(b_4', b_7'); & b_6'' = \max(b_1', b_3', b_6', b_{12}'); \\ b_7'' = b_1'; & \upsilon_1' = \mu(\upsilon)_1; & \upsilon_2' = \mu(\upsilon)_2; \\ \upsilon_3' = \mu(\upsilon)_3; & \upsilon_4' = \mu(\upsilon)_4; & \upsilon_5' = \mu(\upsilon)_5; \\ \upsilon_6' = \mu(\upsilon)_6; & \upsilon_7' = \mu(\upsilon)_7; & \upsilon'' = \bigvee_{i=1}^{n} \upsilon_i'; \upsilon_{real} = \sum_{i=1}^{n} \upsilon_i' \cdot b_i'' \Big/ \sum_{i=1}^{n} b_i'' \end{array} \right\}. \quad (2)$$

The dependence of the control signal of the fuzzy system on the two values fed to its input is shown in Figure 1. The control surface displays a nonlinear control law formulated on the basis of the rules for fuzzy inference of the cutting speed as a function of the temperature-force state of the cutting zone [7].

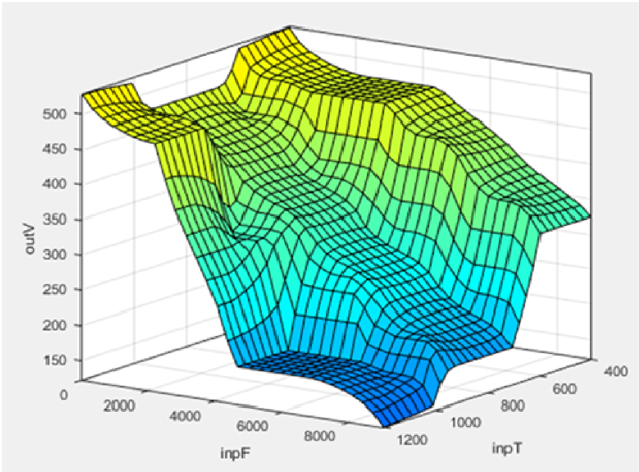

Figure 1. The surface response of the output variable of the mathematical model of fuzzy control

Fuzzy proportional-differentiating (PD) regulation of temperature in the cutting zone. The modeling of the operation of the fuzzy selection system of cutting speed has shown satisfactory results and the required quality of regulation, in comparison, for example, with the classical laws of regulation. The developed fuzzy model of choice of cutting speed is used in the automatic system of temperature stabilization (Fig. 2) in the block of fuzzy logic.

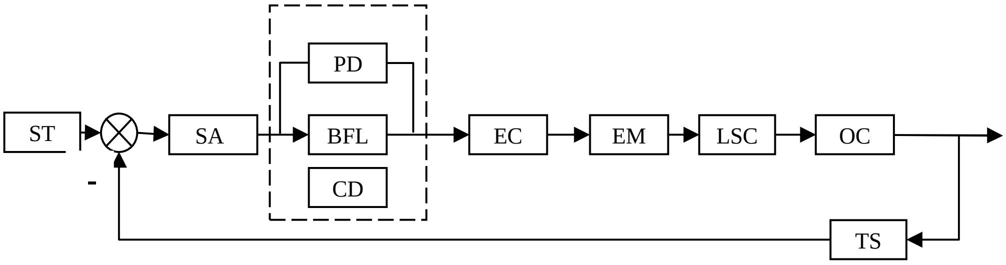

Figure 2. A functional scheme of temperature state control in the cutting zone: ST – setter; SA – signal amplifier; PD – controller; BFL – fuzzy logic block; CD – correcting device; EC – electrical converter; LSC – linear speed converter; EM – electric motor; OC – object of control; TS – temperature sensor

The output signal of the control object is read by the comparison element and the error with the setter signal is calculated. This system by the principle of action is observational. The set temperature is controlled in response to changes in the voltage at the entrance to the system. The output voltage is compared with the voltage at the setter, and the difference is applied to a correcting device containing a fuzzy and a PD−part [8, 9]. To design a fuzzy PD−controller, it is necessary to determine the relationship between the components of regulation, the number and composition of the base of fuzzy rules (Figure 3). Here let us consider the implementation of a P−control with two rule bases for each input of the PD−controller or their combinations.

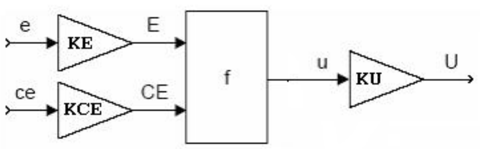

Figure 3. A connection scheme of a fuzzy and PD-regulator

The order for designing a fuzzy PD controller with the transition from a linear law to a nonlinear one consisted in: entering and setting a precise PD controller; choosing coefficients of proportional gain K_p and constant differentiation T_d ; transferring the parameters of the PD–controller to a fuzzy controller. Further, by changing the membership functions in the linear regulator, a nonlinear control surface was determined (Figure 4).

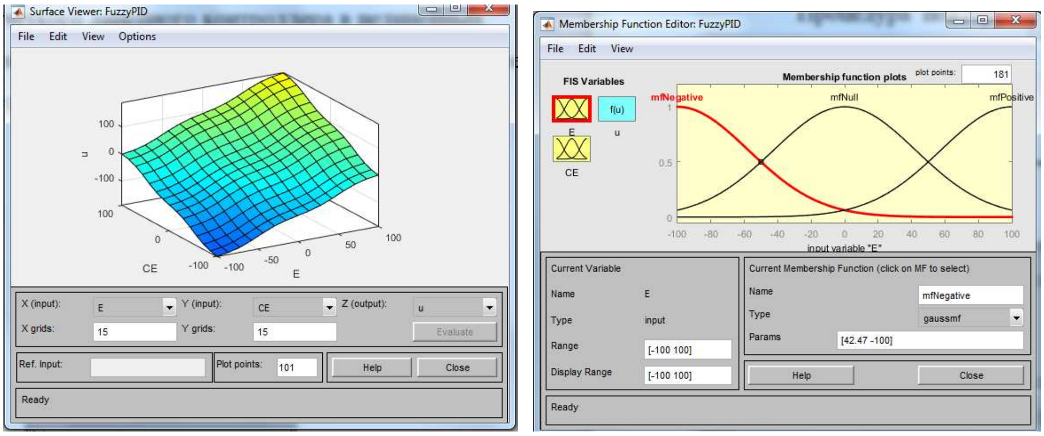

Figure 4. The control surface of a nonlinear fuzzy PD controller and the membership function of input variables

Estimation of the stability of a nonlinear fuzzy control system for the temperature-force state. The harmonic balance method is used to construct a system with an equivalent nonlinear element and a linear part for determining the possibility of an autooscillatory regime in a nonlinear system [10]. The scheme for estimation the stability of a nonlinear system with an equivalent nonlinear regulator (Figure 5) includes a linearized W_{ne} element consisting of a PD-controller and its fuzzy part and a linear part of system W_{lp} consisting of the transfer ratios of the incoming elements determined from the reference literature and experimentally (see Fig. 5).

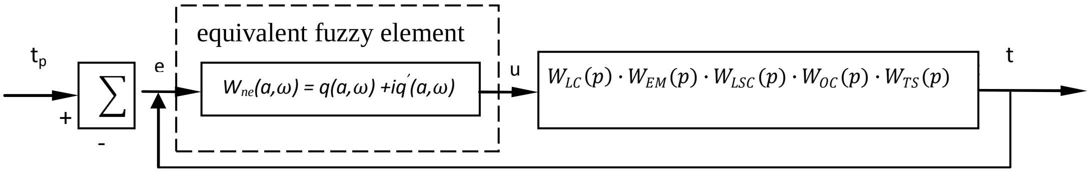

Figure 5. An automatic control system with an equivalent nonlinear element

For the stabilization of the considered system, the transfer function of the linear part of system $W_{lp}(j\omega)$ after multiplying the transfer functions of the elements of the system, expanding in a polynomial and eliminating terms with the highest degrees and small coefficients has the form:

$$W_{lp}(j\omega) = \frac{3.47}{0.003(j\omega)^4 + 0.0596(j\omega)^3 + 0.227(j\omega)^3 + 0.384(j\omega)^2 + 0.69(j\omega)}. \quad (3)$$

The harmonic balance condition for the nonlinear and linear parts of the system has the form:

$$W_{ne}(a)W_{lp}(j\omega) = W_{lp}(a, j\omega) = -1. \quad (4)$$

Expression (4) represents a necessary condition for the existence of self-oscillations in the system and is called a harmonic balance condition, that is, for $\omega = \omega_n$, $a = a_n$ the linear part of the system and the nonlinear one can have common frequencies and amplitudes and intersect.

For the graphical solution, it is convenient to express (4) in the form:

$$W_{lp}(j\omega) = -\frac{1}{W_{ne}(a)} = -M_{ne}(a), \tag{5}$$

where $-M_{ne}(a)$ – reversed coefficient of transmission of linear link:

$$-M_{ne}(a) = -\frac{1}{q(a) + jq'(a)}. \tag{6}$$

To solve equation (6), the hodograph of the linear part of system $W_{lp}(j\omega)$ and the hodograph of the complex transmission coefficient of the nonlinear link $(-M_{ne}(a)$ are defined graphically. The hodograph module of nonlinear part $\frac{1}{A_n}$ is related to the amplitude of the input and output signals:

$$\frac{1}{A_n} = \frac{a}{x_{2m}}, \tag{7}$$

where a – amplitude of input signal; x_{2m} – amplitude of output signal.

The data are necessary for drawing the hodograph of the nonlinear part (half-period of oscillations of output signal $\frac{Tc}{2}$, sec; phase shift γ, sec; amplitude of output signal x_{2m}, were obtained by simulating a control system with a fuzzy PD-controller in the MatLab Simulink) for the harmonic signal passing through a nonlinear PD-controller with given by frequency ω = 1 and in the range of amplitudes a = 2 ... 10.

Based on the calculated values of expressions (6) - (7), which determines the phase shift of signal φ_0, phase shift angle ψ_m, the hodograph of the nonlinear equivalent part of system M_{ne} is constructed, and the frequency characteristic of the linear part of system $W_{lp}(j\omega)$ is shown in Figure. 6.

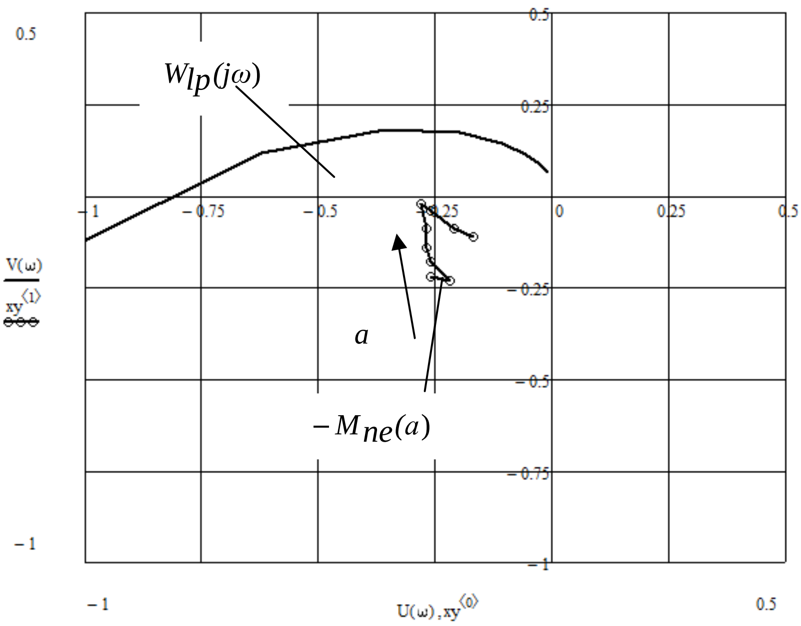

Figure 6. The hodographs of the linear part of the system and the nonlinear element

The hodograph of a nonlinear link is outside of the hodograph zone of the linear part, they do not intersect, that is, there are no common frequencies and amplitudes, hence the system is stable and the oscillations in it are damped.

3. Conclusion

Based on the data of numerical simulation of the chip formation process, synthesis of fuzzy logic control algorithms for the control system for the force and temperature of cutting was performed, during which the functions of the input and output parameters were determined, and the foundation of fuzzy control rules was created. A graphical-analytical evaluation of the stability of a nonlinear control system using the harmonic balance method is carried out.

The results of the study can be used in control systems having uncertainties in the mathematical description of the control object, such as the temperature-force state in the cutting zone during machining.

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