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Design and Simulation of Fuzzy Temperature Controller for Machine Tool

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Abstract

The pursuit of more productive machining regularly requires a review of spindle technology. The performance of the machine tool spindle unit directly decides the efficiency of the machining process. The present paper elaborates about the design and simulation study of Fuzzy Temperature Controller for machine tool spindle to aiming at minimize the thermal deformation error.

Keywords: Fuzzy controller, machine tool, spindle, thermal deformation.

Introduction

In highly competitive market, machine tool manufacturers must build high precision machines, while at the same time keeping prices as low as possible. Machine tool history is irrevocably integrated to machine tool precision and consequently to the precision of parts to be produced by them. The improvement in machine tool precision has greatly helped to increase the quality of manufactured parts, decreasing the adjusting and finishing operations. When machining tolerances are reduced, the systems are more economical, reliable and less manual adjusting operations are required for the final assembly. High-speed spindle is a very important component, whose precision may affect the overall performance of machine tool [1]. The source of certain machining errors has been observed to be closely associated with the spindle temperature of machine tool [2, 3]. The present system adopts the active compensation technique using thermoelectric cooling to maintain the standard working temperature of machine tool within acceptable limits.

Mathematical Model of the Process Under Control

Mathematical model of the process consists of heating effect of the main spindle, spindle thermal deformation in particular axis and cooling effect of the cooler unit. Measuring the temperature rise at the spindle and controlling it by force cooling is required right at the spindle. This performs in minimizing the thermal deformation to an extent and aids to enhance process stability in the manufacturing process. Hong Yong et.al. (2003) modeled the dynamic behaviors of temperature field and thermal deformation of machine tool structures [4]. The transfer function for the heating effect (Temperature of spindle per unit time) of main spindle is given by Equation 1 [4].The step response of machine tool spindle is shown in Figure 1.

$$\frac{1}{1000s+1}e^{-1500s} \qquad (1)$$

The transfer functions for thermal deformation in Y-axis and Z-axis is given by the Equation 2. Thermal deformation in X-direction is negligible [5]. The step response of machine tool for

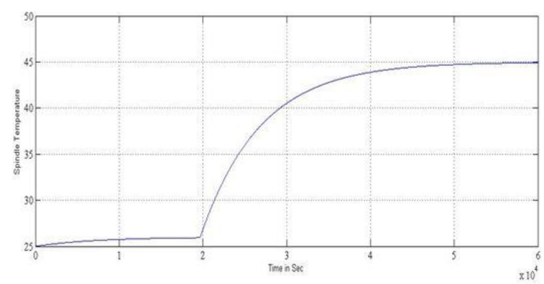

Figure 1:Thermal step response of the machine tool spindle

thermal deformation is shown in Figure 2.

$$\frac{E_{z\_heat}}{\Delta T} \qquad (2)$$

Where

$$E_{z\_heat} = \frac{K_1 + K_2 s + K_3 s^2}{T_1 + T_2 s + T_{D1} s^2}$$

The transfer function parameters are as follows
K_1=0.0162 m.k^{-1}, K_2=10.74 m.s. K^{-1}, K_3=5.368 m.s^2. K^{-1}, T_1=0.002098, T_2 =3.379s, T_{D1}=1s^2

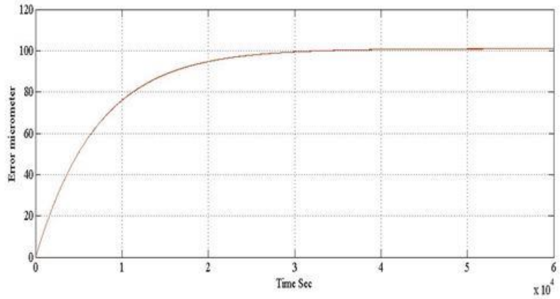

Figure 2: Thermal deformation response of the spindle

To cool machine tool spindle and enclosures, the present work uses thermoelectric technology that offers a number of significant advantages over "conventional" cooling methods like vapor-compression refrigeration and water-cooled systems such as air-to-water heat exchangers [7, 8]. The transfer function of output cold side temperature to input current of a TEC, modeled from an experiment by [9, 10] is given by Equation 3.

$$G(t) = \frac{\text{Temperature}}{\text{Current}} = (-6.4061)\frac{0.646s + 0.00854}{s^2 + 0.5964s + 0.00855}$$

(3)

Figure 3 shows the step response of thermoelectric cooler obtained from Equation 3.

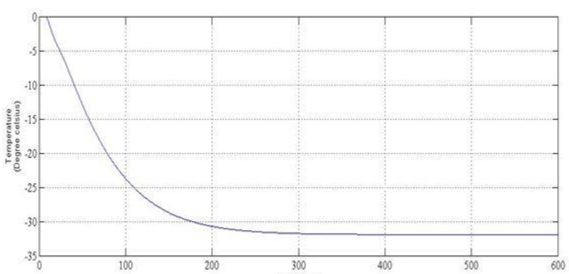

Figure 3: Step response of thermoelectric cooler

Design Ethics of Fuzzy Logic Temperature Control System for Machine Tool

Thermal deformation is highly dependent on the machine tool internal heat sources (drives, friction on nuts, etc.) and temperature variations of the working room. Thermal errors have a complex, non-linear nature that makes them difficult to handle with conventional control technique. Fuzzy logic is suitable here to handle the non-linear nature of thermal error. A generalized block diagram of the fuzzy control system is shown in the Figure 4.

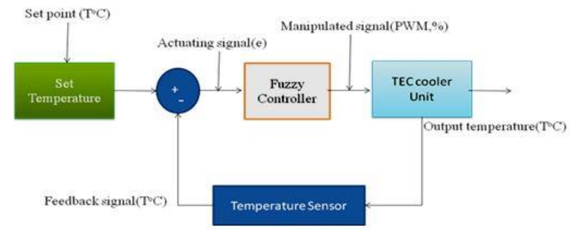

Figure 4: Temperature feedback control of thermoelectric cooler (TEC)

Design and Matlab Simulation for Fuzzy Temperature Control System

The Single Input Single Output (SISO) fuzzy temperature control system have been designed and simulated but this paper discusses only **design** of Multi-Input-Single-Output (MISO). MISO fuzzy logic controller consists two input namely *Error (E)* signal which is the difference between present temperature (T_p) and standard reference temperature of the machine tool spindle (T_{set}) and 'control signal' as an output signal. '*change in error'* as shown in the Figure 5. Change in error is the difference between the previous error and present error.

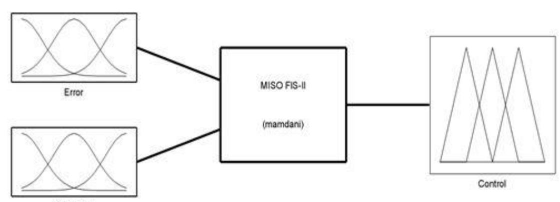

Figure 5. Block diagram of MISO Fuzzy Logic Controller

The tabular representation and relative range of the linguistic terms '*Error'* and '*Change'* are shown in Table 1.

The fuzzy set of second input consist of five linguistic variable as
NM= 'Negative Medium'. NS= 'Negative Small', Z= 'Zero', PS= 'Positive Small', PM= 'Positive Medium'.

Table 1: The tabular representation of linguistic terms

Sr. No	Fuzzy Variable label	Crisp Input Range of *'Error'*	Crisp Input Range of *'change'*
1	NM	[-40 -40 -20 -10]	[-3 -2 -1]
2	NS	[-0.08 0 0.08]	[-2 -1 0]
3	Z	[-20 -8 0]	[-1 0 1]
4	PS	[0 8 20]	[0 1 2]
5	PM	[10 20 40 40]	[1 2 3]

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The rule base of fuzzy control is shown in Table 2. This rule base is composed of 25 rules. The rules are defined such that the decision output resembles the human expert operator's selection process as an expert.

Table 2: Fuzzy control rules for FIS-II

Control		Change in Error (*Change*)				
		NM	NS	Z	PS	PM
Error	NM	PM	PM	PM	PS	Z
	NS	PM	PM	PS	Z	NS
	Z	PM	PS	Z	NS	NM
	PS	PS	Z	NS	NM	NM
	PM	Z	NS	NM	NM	NM

The standard reference temperature for testing the geometric accuracy of machine tools is 20ºC [11-13]. Linear positioning accuracy of the machine tool is set at the factory, in an ambient temperature of 68 F (20ºC) [14]. Hence, 20ºC set point is chosen for simulation study. The Simulink model of MISO Fuzzy System is shown in Figure 6.

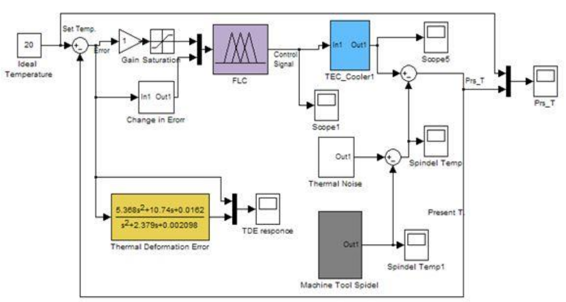
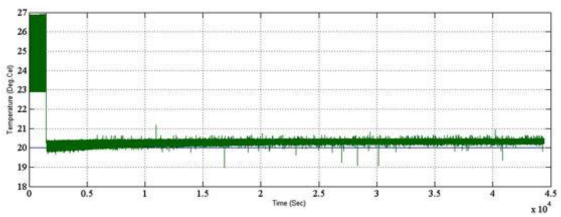


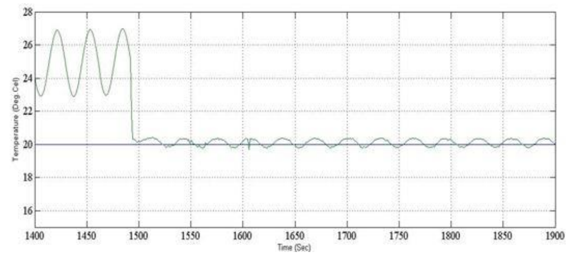
Figure 6: Simulink model of MISO Fuzzy Logic Controller

Simulation Results

The temperature response of the MISO Fuzzy Controller with possible noise at feedback for set point of 20ºC is shown in the Figure 7. Figure 7(b) shows the closer view of the process temperature. The process temperature is kept at 20⁰C with minor deviation of ± 0.2ºC. The corresponding thermal deformation error of spindle lies below ± 0.5 micrometers in the MISO Fuzzy System as shown in Figure 8.

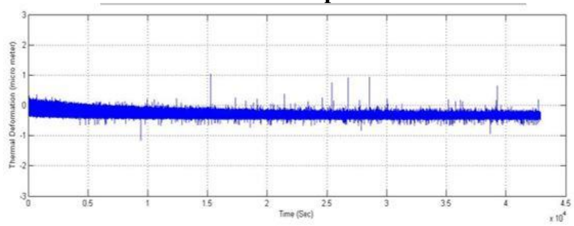


(a): Wide view

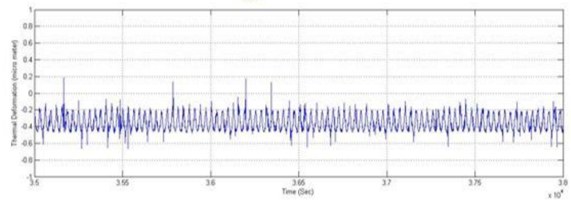


(b): Closer View

Figure 7: MISO Fuzzy Logic Controller- Response vs. Set point



(a): Wide view



(b): Closer view

Figure 8: Thermal deformation error of spindle

Conclusion

Fuzzy Logic Controller for high-speed machine tool spindle temperature control is designed and simulated successfully. From the simulation result, it is observed that the present system is able to maintain the ideal working temperature for machine tool spindle specified by the ISO230-7 standard. This minimizes the thermal deformation error in the machine tool spindle and consequently improves the spindle accuracy.

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