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A Novel Control Scheme for Temperature Control of Machine Tool Coolers

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Abstract: A novel Proportional-Integral-Derivative (PID) control method is proposed for the oil cooler of machine tools to achieve better set-point tracking and disturbance rejection performance. The simple PID controller based on Smith predictive method is adopted as the basic controller. To deal with the nonlinear time varying and time delay characteristic of the system, the PWM (pulse width modulation) technique is then chosen as an auxiliary duty ratio control to modulate the bypass solenoid valve to provide precise oil temperature control. Both simulation results using MATLAB and on-site experimental results are presented and compared extensively for demonstrating the effectiveness of the proposed control scheme. The control scheme not only improves the performance of PID controllers cost-effectively but also maintains permanent temperature control specific for machine tool coolers.

Key words: Machine tool coolers, Smith predictor, PID controller, PWM

INTRODUCTION

Due to the highly generated heat from cutting, milling and drilling of high speed machining, the machine tool cooler is widely adopted for heat rejection to keep the precise control of oil temperature. The machine tool coolers are also the best managers of oil (or water) temperature in avoiding the deviation of spindle centerline for machine tools. However, most of the machine tool coolers are simply equipped with a simple ON/OFF temperature controller. The temperature can merely be controlled within the range of ±3°C. For high-speed machine tool, such temperature fluctuations will degrade the manufacturing performance significantly and cause many side effects such as tool deformation, poor manufacturing precision and reduction of lifetime for the machine tool. In addition, an ON/OFF controlled compressor basically consumes much more energy due to the frequent starting losses (Huang, 2001; Huang and Tsai, 2002). In view of these shortcomings, an improved type of oil-cooling machine equipped with a variable-frequency compressor together with a high performance controller has been proposed to control the oil coolant with steady state accuracy up to ±0.3°C.

PID controllers are still applied extensively in industrial application. A simple approach to obtain parameters of a PID controller for closed loop system has been simulated and analyzed comprehensively (Kaya *et al*., 2003). Besides, PID design method and future direction were presented thoroughly by computerized and simulation-based approach (Li *et al*., 2006). The differences between academic research and industrial practice in PID controller have been discussed to motivate new research directions. Moreover, a new design and tuning procedure for PID feedforward controller is proposed to achieve a predefined process output transition time (Visioli, 2004). The proposed method represented better performance for inverse model-based approach from simulation and experimental results. Furthermore, a tuning algorithm for the PID controller utilizing fuzzy theory was conducted by simulation (Hwang *et al*., 1999). The fuzzy auto tuning algorithm for PID controller reduced the overshoot and rise time significantly. Besides, the experiment of an intelligent refrigeration system utilizing an inverter has been proposed to demonstrate the reducing of energy consumption in comparison with the traditional on-off system under the same operating condition (Buzelin *et al*., 2005). To control the refrigeration system capacity, the fuzzy control of the compressor speed was applied to evaluate the energy saving potential. A significant energy saving on an average about 13% has been obtained using the compressor speed control algorithm based on the fuzzy logic in comparison with the thermostatic control (Aprea *et al*., 2004).

For the improved oil cooler, the motor speed can be continuously varied to eliminate the frequent starting losses and the temperature tracking control accuracy can

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be improved as well. However, since the oil-cooling process is a rather nonlinear and time-varying dynamic behavior. Although many existing control schemes such as PID control (Wang *et al.*, 1999) predictive control (Maciejowski, 2002) adaptive predictive control have been proposed in literature, it is still a research topic to pursuit a more practical, high performing and energy saving temperature controller. In this study, a new PID control method is proposed for controlling the temperature of an oil cooler system. The traditional PID control based on the smith predictive method (Astrom *et al.*, 1994) is adopted as a basic controller of the cooler system. To deal with the nonlinear time varying and time delay characteristic of the cooler system, the PWM (pulse width modulation) technique is then chosen as an auxiliary control to modulate the hot-gas by-pass solenoid valve with duty ratio to provide the oil precise control of temperature. Not only simulation but also experimental results are also given for demonstrating the effectiveness of the proposed control scheme. The control scheme not only improves the performance of PID controllers cost-effectively but also maintains a permanent temperature control specific for machine tool coolers.

CONFIGURATION OF THE CONTROL SYSTEM

The basic configuration of the investigated oil cooler system is shown in Fig. 1. There are two subsystems demonstrated in Fig. 1. The first subsystem mainly involves the circulating loop of the cooling oil circulating system. Through a fixed frequency induction motor controlled pump, the oil is forced to circulate around the loop containing the oil tank, pump, heat exchanger and the tool machine. Another subsystem involves the circulating of the refrigerant system which a variable frequency induction motor controlled compressor is installed. The refrigerant of the cooler system circulates around the loop containing compressor, condenser, refrigerant control valve and the heat exchanger to remove away the heat from the machine tool.

As shown in Fig. 1, this system is controlled simply through a variable Voltage Variable Frequency (VVVF) inverter to control the induction motor speed, which could provide the precise control of oil temperature at the outlet of the heat exchanger. This induction motor is three-phase, 60 Hz, 114 V, 1.5 HP 4-pole squirrel cage type. Besides, the inverter provides a three phase variable frequency and variable voltage with a fixed voltage to frequency ratio to keep the air gap flux of the induction motor constant. The input command of the inverter can be varied from 0 V to 10 V corresponding to 0 rpm to 1800 rpm for the induction motor speed. Furthermore, the proposed controller, based on the input signal of the oil temperature at the outlet of the heat-exchanger, generates the desired output signal as the inverter command signal.

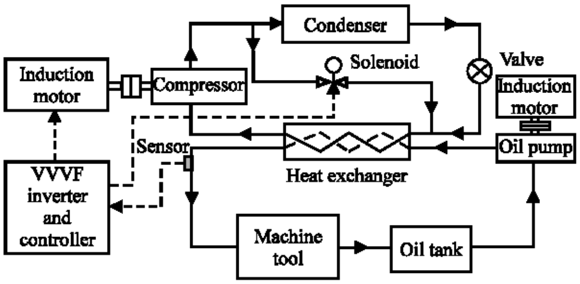

Fig. 1: Basic configuration of the oil cooler system for machine tool

PROPOSED NEW PID CONTROL SCHEME

Figure 2 represents the block diagram of the proposed controller. The proposed controller basically consists of three parts. They are PID controller, differential auxiliary circuit and PWM circuit, respectively. The familiar PID controller based on the Smith method is adopted as a basic controller of the system as shown in Fig. 3. However, utilization of this single controller is not sufficient to achieve the desired performance specification. In fact, due to complicated nonlinear and time varying characteristic of the cooler system, it is quite challenging to provide precise temperature control if the controller is not well tuned. To stabilize the complicated system, a Smith predictive control scheme is added. The PWM technique is then chosen as an auxiliary duty ratio control to modulate the by-pass solenoid value to keep the oil temperature as constant as possible.

Since the time constant of the controlled system is rather long, traditional PID controller is not good at controlling the systems with large delay time. It is quite easy to cause the temperature fluctuations for the cooler system. In the larger delay systems, the pure delay segment $e^{-\tau s}$ is the source term which leads to the confusion of the control information. The control information can approach the controller only after a long period of time because of the delay term ($e^{-\tau s}$). Even worse, the controller will not work appropriately when the delay term becomes too large. It is quite essential and critical to adjust the control information to improve the controller's performance of controller.

Thereafter, the Smith compensate arithmetic algorithm with Smith controller which was specially designed for large delay system was used to solve the problem mentioned previously. The first order delayed

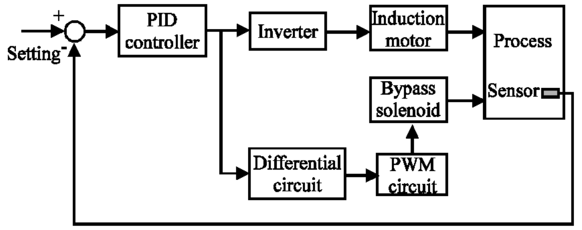

Fig. 2: Block diagram for the proposed controller

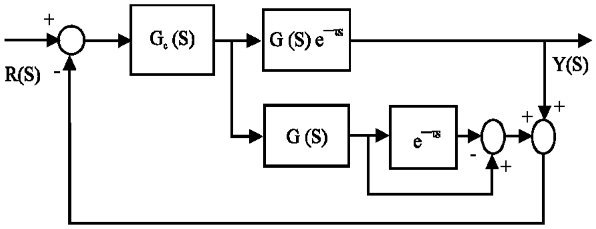

Fig. 3: Block diagram of the Smith predictor

model transfer function from literature (Mudi and Pal, 1999) was adopted and can be expressed as:

$$\frac{K}{TS+1}\varepsilon^{-\tau s} \tag{1}$$

Where:

T = Time constant

K = System gain

τ = Delay time

The transfer function of system is G(s) $e^{-\tau s}$, so the Smith compensation is G(s) (1-$e^{-\tau s}$). The equivalent diagram of the Smith predictor is showed in Fig. 4. The control section of Smith predictor was shown in Fig. 4. The transfer function of the enclosed dash line area is G_{PID}. The PID controller was conducted by exploiting the system identification model of Eq. 1 and match with the simple formula derived as:

$$G_{PID}(S) = \frac{T/_{T'K}}{1+\tau/_{T'}}\left(1+\frac{1}{TS}\right) = K_p\left(1+\frac{1}{T_i S}+T_d S\right) \tag{2}$$

where, T, T', K and τ represent time constant, expectative time constant, gain and delay time of system model, respectively, whereas K_p is proportional constant, T_i is integral time constant, T_d is the derivative time constant and

$$K_p\left(1+\frac{1}{T_i S}+T_d S\right)$$

is the transfer function of PID controller based on $e^{-\tau s}$ equal to (1-τs) approximately. Under the appropriate design of the controller, we can fulfill the accuracy of control system merely by a simple commercial available PID controller.

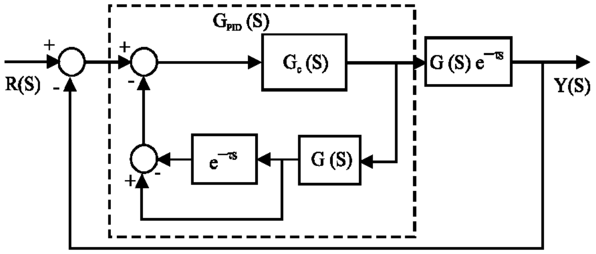

Fig. 4: Equivalent diagram of the Smith predictor

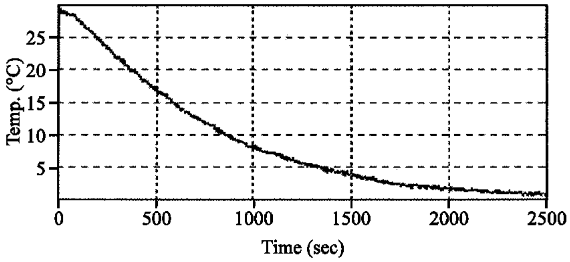

Fig. 5: Measured oil temperature for system identification using a step input to the controlled system under open loop condition

In this study, the step input (10 V) of signal is applied to the inverter. The oil temperature at the outlet of the exchanger is measured and represented in Fig. 5. The on-site measurement data can be used to conduct system identification and to estimate the coefficients of G(s). In other words, the model G(s) is chosen according to system identification based on measurement data and can be expressed as the following:

$$G(S) = \frac{2.6}{550S+1}\varepsilon^{-50S} \tag{3}$$

RESULTS AND DISCUSSION

To demonstrate the effectiveness of temperature control for the proposed control scheme, both simulation and experimental results are presented. The traditional PID controller based on the Ziegler-Nichols method is first determined for comparison. For the measured system after system identification, the corresponding parameters of the traditional PID controller have been determined as $K_p = 4$, $T_i = 100$, $T_d = 28.5$. The oil temperature at the outlet of the heat exchanger was kept at 24°C in the initial stage (t = 0 sec). The set points were chosen to be 22°C under constant loading of 1000 W.

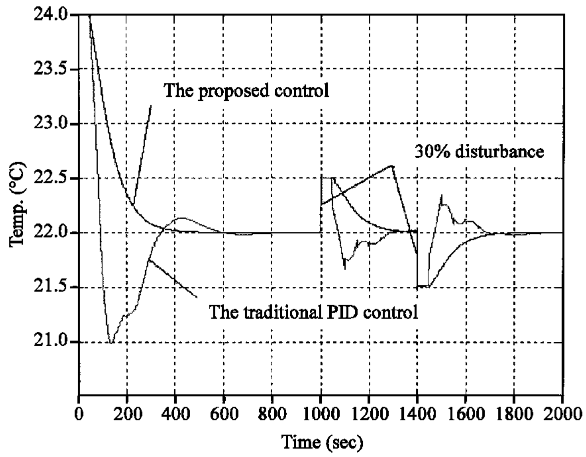

Fig. 6: Comparison of the traditional PID controller and the proposed method

Comparison for the simulation results of the traditional PID control and the proposed control are shown in Fig. 6. The temperature fluctuation of traditional PID controller is much lager than that of proposed method. The control performance parameters such as maximum overshoot, rise time, setting time and steady state error are far from the proposed control scheme. It also reveals that application of traditional PID controller still exist some problems in dealing with the nonlinear time varying and time delay characteristic of the cooler system for high speed machining (Fig. 6). The performance of traditional PID controller is obviously not good enough for our goal. As shown in Fig. 6, the control accuracy of the proposed control scheme is better than that of traditional PID controller and can achieve the precise temperature control within ±0.3°C for the steady state. Furthermore, the proposed control scheme can provide satisfactory result even under the effect of abrupt load disturbance. Therefore the controller developed by our study is pretty simple and cost-effective, also can be easily adopted by industry application.

As shown in Fig. 7, one can see that the temperature fluctuation is much lager than that of Fig. 8. The performance of the traditional PID control is obviously not good enough. However, for the proposed control schemes (Fig. 8), the steady state error is within ±0.3°C. The experimental results reveal that the satisfactory control accuracy of temperature in spite of the nonlinear time varying characteristic of the plant.

From Eq. 2, the proportional constant K_p can be obtained from the coefficient of time constant (T), expectative time constant (T'), gain (K) and delay time (τ) of system model. Actually the integral time constant (T_i) is equal to the coefficient of time constant (T), the corresponding parameters of the proposed controller are K_p = 1.5, T_i =550, T_d = 0. Therefore, we can fulfill the accuracy of control system merely by a simple commercial available PID controller under the precise system identification and appropriate design of the controller. In industry application, the controller is often handled with PC-based and DSP-based to obtain high accuracy and high performance control. However, it got some drawbacks such as high cost, complicated operation and difficult to maintain. Therefore, the proposed Smith predictor controller can fulfill high accuracy only by using commercial available PID controllers. The proposed PID control method has the advantage of simple construction, low cost and easy regulation. It could meet the industrial application demand extremely.

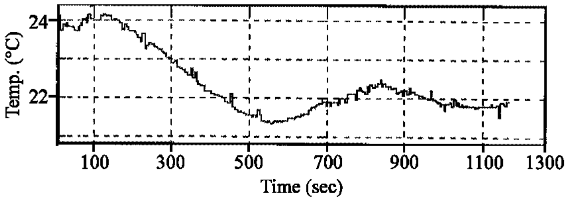

Fig. 7: The experimental results of the traditional PID controller under constant loading of 1000W

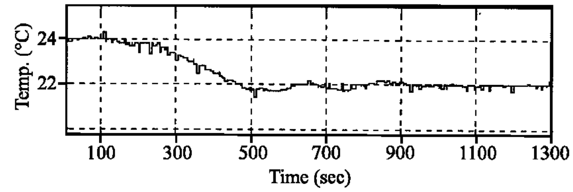

Fig. 8: The experimental results of the proposed controller under constant loading of 1000W

The experimental results of the temperature response under step load change abruptly for the traditional PID control and the proposed control are shown in Fig. 9 and 10, respectively. From the comparison of temperature response, we can observe the experimental results roughly resemble the simulation results in spite of the nonlinear time varying characteristic of the cooler systems (Fig. 9). The control accuracy of the proposed control scheme is better than that of traditional PID controller and can achieve the precise temperature control within ±0.3°C at the steady state. Besides, to observe the effect of load disturbance, the same PID controller is compared with the proposed controller when the loading is altered from 1000 W to 700 W abruptly at t = 1000 sec. The loading of 1000 W were added to at t = 1400 sec thereafter. From the results shown in Fig. 10, the proposed PID control scheme still can achieve satisfactory control accuracy of

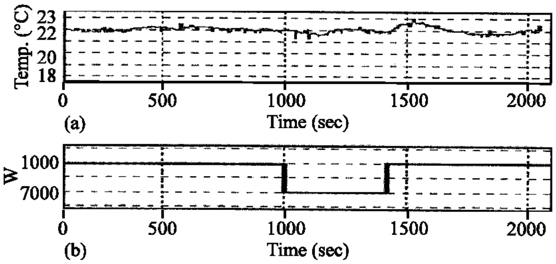

Fig. 9: Temperature response for the traditional PID controller under step load altered abruptly

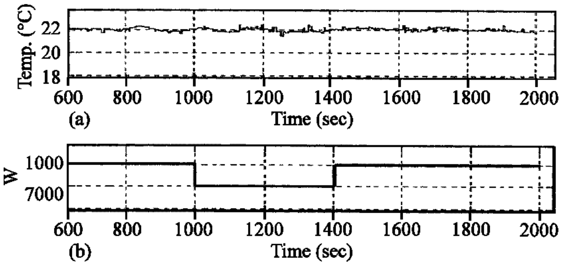

Fig. 10: Temperature response for the proposed controller under step load altered abruptly

temperature for the system at the steady state. However, during the step load change period, the temperature variation becomes too large to be acceptable for traditional PID controller.

CONCLUSION

The machine tool coolers are also the best managers of coolant temperature in avoiding the deviation of spindle centerline for high speed machining. However, there exists the problem of the nonlinear time varying and time delay characteristic of the cooler system for high speed machining. In this study, a new PID scheme for method temperature control is proposed specific for machine tool cooler. The satisfactory set-point tracking and disturbance rejection performance has been achieved by the proposed control scheme. A simple commercial available PID controller based on the Smith predictive method is adopted as a basic controller. Besides, to deal with the nonlinear time varying and time delay characteristic of the plant, the PWM technique is then chosen as an auxiliary duty ratio control to modulate the hot-gas by-pass solenoid valve to provide precise oil temperature control. Some simulation and experimental results are also given and compared extensively for demonstrating the effectiveness of the proposed control scheme. The control scheme not only improves the performance of PID controllers cost-effectively but also maintains a permanent temperature control specific for machine tool coolers.

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