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Optimized Digital Proportional Integral Derivative Controller for Heating and Cooling Injection Molding System

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Abstract – Proportional integral derivative (PID) control is one of the conventional control strategies. Industrial PID control has many options, tools, and parameters for dealing with the wide spectrum of difficulties and opportunities in manufacturing plants. It has a simple control structure that is easy to understand and relatively easy to tune. Injection mold is warming up to the idea of cycling the tool surface temperature during the molding cycle rather than keeping it constant. This “heating and cooling” process has rapidly gained popularity abroad. However, it has discovered that raising the mold wall temperature above the resin’s glass-transition or crystalline melting temperature during the filling stage is followed by rapid cooling and improved product performance in applications from automotive to packaging to optics. In previous studies, optimization methods were mainly selected on the basis of the subjective experience. Appropriate techniques are necessary to optimize the cooling channels for the injection mold. In this study, a digital signal processor (DSP)-based PID control system is applied to injection molding machines. The main aim of this study is to optimize the control of the proposed structure, including a digital PID control method with a DSP chip in the injection molding machine.

Keywords: PID controller, Heating and cooling injection mold system

1. Introduction

Injection molding is one of the widely used forming methods in the plastic industry which is an im portant manufacturing sector. [1] The plastic injection molding (PIM) process is generally carried out by heating the plastic, transporting the polymer into the mold, cooling the mold, and finally ejecting the product. [2] The closed and empty mold is prepared for melting the plastic charged in the injection unit. The melted polymer is injected through the mold cavities with the screw, and then the injection pressure is kept constant to prevent changes in dimensions of the piece. The cooling of the piece continues until the injection pressure is removed. Then, the mold is opened to eject the piece. This process cycle is universally used for plastic transformation because of its high production levels for complex geometries at low costs. [3, 4] In the injection molding control, product quality is affected by some important parameters such as position, velocity, and temperature. [5] Therefore, there is a need to improve the injection cycle, temperature control algorithm, and digital implementation. [6-8]

Proportional integral derivative (PID) control is the most conventional, the most common, and the most sophisticated control method in automatic control. [9] With advances in the industry, control objects have become increasingly complex, and many of these objects have time-varying, nonlinear, and real-time parameters. [10-12] Thus, PID controllers are the most common industrial system controllers. In modern digital control systems, it is required to digitize the PID algorithm with stronger and faster calculation components. [13, 14]

An optimal implementation scheme and digital PID controller design is described in detail in this study. Although the implementation of PID controllers with microprocessors and DSP chips is generally used, very few studies on the implementation of PID controllers using DSP chip for the injection mold temperature control are reported in the literature. Thermal control of an injection molding system is the key issue in the development of high-efficiency injection molds. For an effective thermal management system, this investigation provides a strategy to identify the thermal dynamic model for designing a controller. [15-17]

2. System Configuration

2.1. Digital PID control system

The PID algorithm comprises three basic modes, such as the proportional (P), integral (I) and derivative (D) modes. When the PID algorithm is utilized, it is important to determine the modes to be used and to specify the parameters for each mode. Three basic algorithms are generally used by P, PI, and PID. In the digital PID control

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process, it is necessary to control many variables. This increases the complexity of the DSP control architecture along with the computational load because the parameters have to be controlled in parallel. [2] A different situation occurs when the set-point temperature is different from the balanced temperature. [17] The further the set-point temperature is from the balanced temperature, the further the PID constants are from their optimum values. The difference depends on the gap between the balanced temperature and the set-point below / above the current temperature. Fig. 1 shows the closed loop control system with a PID function controller. As shown in the Fig. 1, the PID controller calculates an actuating value from proportional, integral and derivative components.

When the conventional controllers are used, non-linearities in the process cause errors because of its adaptability problems. The PID control algorithm is given by the following equation:

$$u(t) = k_p(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}) \qquad (1)$$

In a DSP chip, it is important to minimize system complexity by dividing the control processes to accommodate the processing units. The PID constants depend on the time constant and the gain of the controlled system. [17] If they are selected appropriately, they will cancel the poles of the controlled system transfer function. Different rates of the heating and cooling processes affect the optimum values of the PID constants, which makes the estimation very difficult as shown in the following equation:

$$u_k = u_{k-1} + (1+\frac{T_d}{T})e_k + k_p(-1+\frac{T}{T_i}-2\frac{T_d}{T})e_{(k-1)} + k_p\frac{T_d}{T}e_{(k-2)} \qquad (2)$$

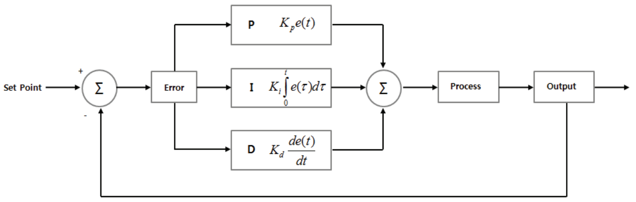

Fig. 1. Closed loop control system with a PID function controller.

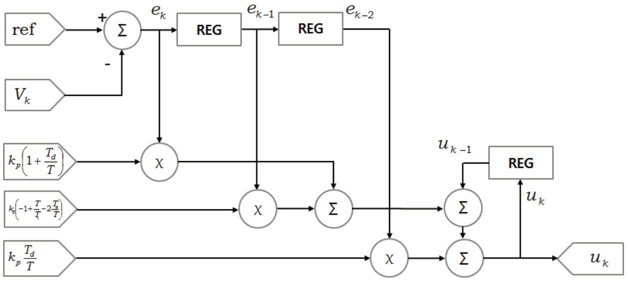

Fig. 2. PID structure for DSP controller.

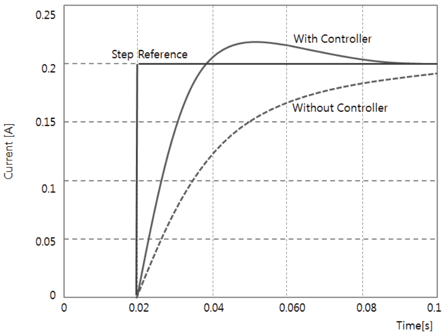

Fig. 3. Step response characteristics of the current with and without the PID controller.

, where K_p, T_i, and T_d are the PID parameters for tuning, and T is the sampling period in seconds. In order to improve the speed and minimize the cost while achieving a good performance, the adopted structure included three combinational logic multipliers, one subtractor, three adders, and three registers. Fig. 2 shows the adopted architecture, which requires all computation operators in each phase.

The step responses of the current with or without the controller are presented in Fig. 3. Simulation results show an overshoot of approximately 11%, and the settling time does not exceeding 80 ms. Fig. 3 shows the characteristics of the closed loop with optimized PID controllers for the DSP system, as well as the good settling time without a notable overshoot and steady-state error. [18]

The PID controller is implemented in a high-performance 32-bit DSP chip (TI Co., TMS320F2812). For the storage of real numbers, the fixed or floating point formats used by all modern computers can be used; however, this requires considerable computational capacity. The objective function should be defined in the PID controller design based on the constraints under the input testing signal for the desired specifications. A performance index refers the design of the objective function to the entire closed loop responses in order to tune the PID controller. Typical output specifications in the time domain are peak overshooting, rise time, settling time, and steady-state error.

2.2. Heating and cooling injection molding system

PIM involves many parameters such as position, velocity, temperature, pressure, and some discrete input/output (I/O) events. [2, 5] These parameters that determine the final product quality in most cases are correlated with one another, and therefore, this correlation makes it difficult to control them accurately.

Heating and cooling processes have been important in the area of injection molding. The optimum temperature profile is decided by many parameters, including screw/mold/part design, machine-capacity-ratio to shot size, and cycle time. The barrel temperature controller is a PID type controller that settles the material-melting gradually with coolness and hotness in the rear and front zones, respectively, as shown in Fig. 4.

Injection molding experiments were performed for an optical Fresnel lens with a plastic lens mold, as shown in Fig. 5. The heating and cooling system geometry is considerably important because it affects not only the heating/cooling efficiency but also temperature uniformity.

A K-type thermocouple was placed 10 mm away from the cavity surface to examine the mold temperature profile during the molding cycle.

The proposed hardware of the PID control system comprises the devices incorporated on the application board including the following: transducer, signal conditioner, anti-alias filter, analog-to-digital converter, digital-to-analog converter, four-quadrant pulse-width-modulator (PWM), and one optic isolation stage for the PWM. On the other hand, the PID control system also contains digital processors to measure and control the signal to the actuator.

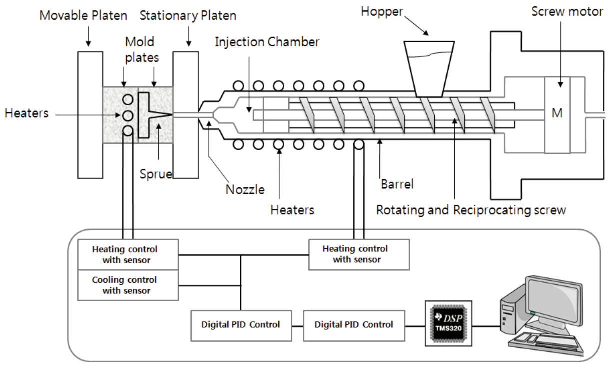

Fig. 4. Schematic diagram of the proposed overall control system for the PIM machine.

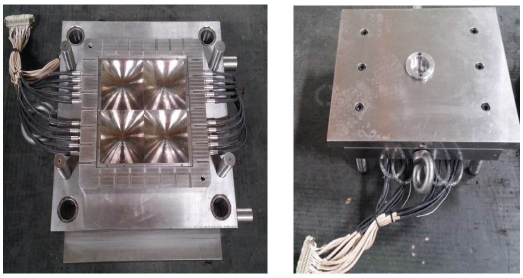

Fig. 5. Photographs of the application to plastic lens mold for the experiment

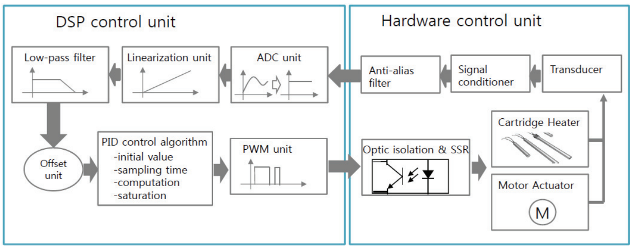

Fig. 6. Block diagram of the proposed control processor with the DSP control unit and hardware control unit.

Fig. 7. Photograph of the DSP control unit and hardware control unit.

This proposed PID control method was implemented in a DSP that was carrying out an indirect self-tuning under the parameter variations and load disturbances. Fig. 6 shows the proposed control processor, which consists of the DSP control unit and hardware control unit shown in Fig. 7.

3. Experimental Results and Discussion

Owing to the importance of the PIM process, experiments were configured and performed to regulate the position, pressure, and temperature with a digitalized PID controller using the DSP module in the precision optical lens mold machine. In the temperature-control section, several different heating zones are analyzed. Dynamic mold-temperature cycling was used for flat parts, complex shapes, and large / small parts with some different variants. The thermal monitoring gave information about the attained uniform temperature on the mold wall surface at the end of the heating phase. Furthermore hot and cold spots can be safely detected. Depending on the cooling channel layout, it is also possible to obtain the temperature profile during the cooling phase profile and the efficiency of the mold cooling process. These investigations guaranteed that the cycle times could not increase unnecessarily because the layout of the inductors and the mold cooling are adjusted to the optimum level of the cooling and heating phases. Fig. 8 shows the temperature distribution on the mold wall surface at the end of the heating time. It was possible to heat the mold surface efficiently over a short period without spreading the heat on the entire mold. The curves in Fig. 8 present the temperature profile over

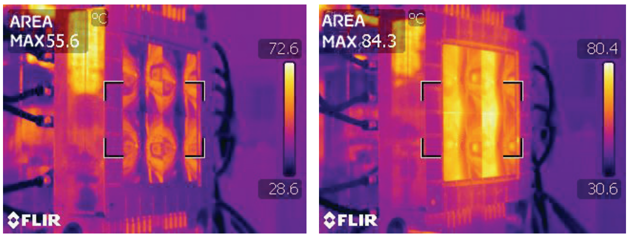

Fig. 8. Temperature variations with PID mold system controller in (a) cooling and (b) heating phases.

the time. The temperature is higher in the middle area than that in the lower area. The temperature controller specified the system input on the basis of the mold surface temperature of 130°C obtained with the preceding tests.

There are two fundamental concepts that should be stressed regarding the closed loop control. First, it is important to note that the process control of precision injection molding is dependent not on the response time of the controller but on the response time of the system. As a simple example, consider the task of increasing the temperature of a 100 kg steel barrel by 10°C, which requires 473,000 J theoretically. If four 1-kW-heaters are utilized, then the minimum theoretical response time is approximately 120 s. However, the response time would be three to ten times longer than the theoretical minimum, depending on whether the system is over or under damped, and how much error is tolerable. A reduction in the response time of the control system may be less important than an improvement in the control law, controller tuning, heater design, and barrel design for improving the performance of the precision molding process. Second, it is important to understand heating and cooling fundamentals regarding the observability and controllability of the precision injection molding process. Fig. 9 shows digital signal control output voltage and current waveforms. Fig. 10 shows the heat- and cool-mode voltage and current controls and the current waveform for heating. This waveform is clearly sinusoidal with several high-frequency ripples.

Fig. 11 shows input power voltage to the cartridge heater set. Fig. 12 presents digital PID control turn-on and turn-off signals in two channels, and the current waveform for heating is shown in Fig. 13. In precision injection molding, the term of *optimum* implies "much more robust". First, the process should produce the maximum percentage of the acceptable molded products. Second, the process should operate efficiently with minimum cycle time, energy consumption, and material waste. Whereas the first condition strongly encourages robustness, the second criterion provides a practical limit on the desirability of

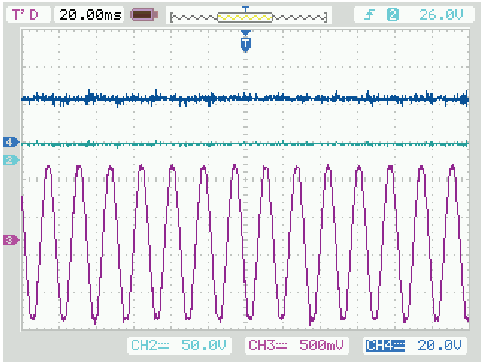

Fig. 11. Input power voltage to cartridge heater set.

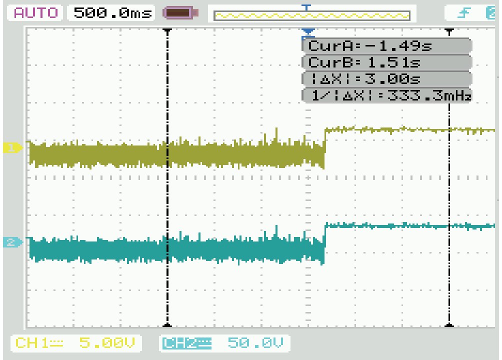

Fig. 9. Digital signal control output voltage and current waveforms.

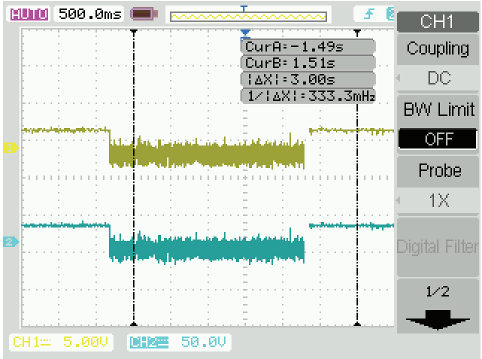

Fig. 12. Digital PID control turn-on and turn-off signals in two channels.

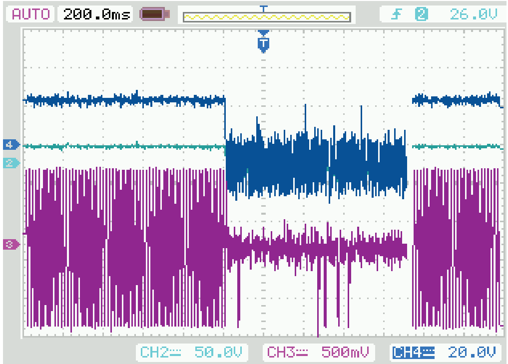

Fig. 10. Heat- and cool-mode voltage and current controls.

Fig. 13. Current waveform for heating.

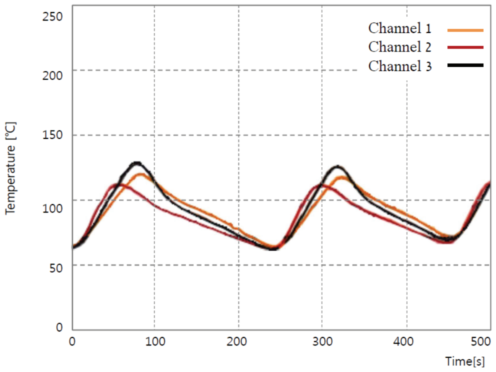

Fig. 14. Target temperature profiles on each zone for heat- and cool-modes.

that robustness. It is desirable to minimize the total system cost. This is a function of (1) the marginal processing cost of the materials, labor, and machine, (2) the processing yield of acceptable parts, and (3) the marginal cost of molding defective product. Fig. 14 shows an experimental temperature profile of the mold wall over time. The temperature is raised above the melt temperature of the polymer and lowered to an ambient temperature in approximately 230 s. When the heating process finished, the target temperature was attained at the cavity surface for filling and packing the melted polymer. The cooling process began with the switching of the valve control to allow the cold water to flow into the channels. The double cooling channel system was adapted to achieve the perfect cooling process. Fig. 14 shows the target temperature profile on each zone for heat- and cool-modes. The coupling effect was minimized by this control while the cooling and heating controller were individually applied to each 1-3 zone. Although the 4 zones were also employed to the same actuator, each zone showed different dynamic behaviors owing to the coupling effect. It is very difficult for thick metals such as mold to control the temperature in the heating process. The proposed PID control method performed the synchronization over 75% and 96% in heating and cooling zone, respectively. Although the coupling effect was still present when the metal heating system with the sheath heater was used, the individual PID control could improve the transient phenomena.

4. Conclusion

This study presented a DSP-based PID controller applied to injection molding machines. An optimization method was developed to determine the temperature distribution on a cooling line to obtain a uniform temperature field in the part that leads to the smallest gradient and the minimum cooling time. The PID controller was tuned to satisfy the good steady-state regulation and transient step response performance. Controller gains were easily changed by using the real time emulation feature while the DSP was running. A thermoelectric cooler system was successfully implemented by using a TI DSP. In addition, the system was driven by the digital control with the exception of the instrumentation circuit for reading the thermistor. This offers an advantage in noisy environments over traditional analog component plastic molding systems. In this study, a novel robust PID based controller was proposed and demonstrated for DSP implementation. The efficient implementation of a dynamic system is achieved with high precision, better performance, good stability, and low cost as compared to the conventional analog counterpart.

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