Design Method of PID Compensator by Internal Model Control

Atsushi IEKI

Mass Flow Controllers (MFC) with thermal flow sensors are widely accepted in the semiconductor industry for the control of process gas flow. New semiconductor manufacturing technologies require MFCs to improve fast process gas flow response capability and response reproducibility to improve throughput and yield. The design of control systems for MFCs is critical for speeding up the flow response, as well as maintaining constant responsiveness during the manufacture of MFCs. This paper proposes a method for designing a control system using Internal Model Control and shows the availability of the proposed method based on the experiment results.

Introduction

In a semiconductor manufacturing process, the fluid control performance of the process gas is an important technical element that determines the quality of the semiconductor. In recent years, in order to miniaturize semiconductor devices or improve the throughput in their production, there is a need for a rapid switching of the process gas. Furthermore, in order to reduce a system-to-system difference among semiconductor manufacturing systems, it is necessary to reduce a difference in flow response between systems. As a flow control performance required for a Mass Flow Controller (hereafter "MFC"), an important technical element is to reduce an individual difference in the fast response to flow rate and settling time between controllers.

In order to control flow rate, a controller for a MFC uses PID compensation,[1] which is a typical method of feedback control and widely used. A desired flow control can be obtained by optimizing a proportional gain, integral gain, and differential gain, to reduce an individual difference in the fast response to flow rate and settling time between controllers. In this paper, we apply the design method of Internal Model Control (hereafter "IMC")[2] to theoretically design a controller and show the results of verification.

MFC Structure and Control Object

MFC Structure and Transient Response Characteristics

Figure 1 shows the main structure of a MFC.

This figure shows a MFC equipped with a corrosive resistant and high-pressure-resistant mass flow sensor, characterized by having a structure where the sensing part, called a thermal flow sensor, is not in direct contact with the process gas. The structure of the MFC comprises a thermal flow sensor, laminar flow element/resistive element (hereafter "Bypass"), flow control valve, and circuit section. The process gas is introduced from the

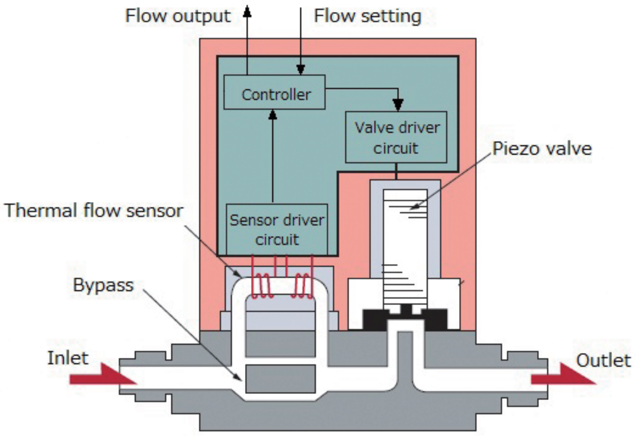


Figure 1 MFC internal structure.

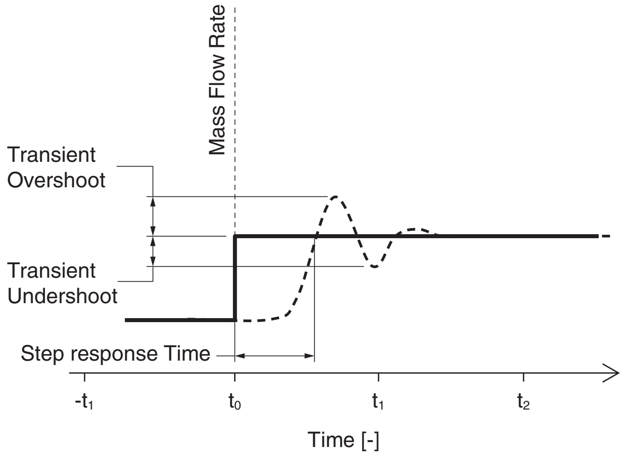


Figure 2 Step response conditions for MFC.

Inlet side, and the gas flow rate is measured by the thermal flow sensor. The Bypass has a characteristic of diverting the flow rate of gas flowing into the thermal flow sensor at a certain rate. The flow rate is controlled by operating an opening position of the flow control valve to make the steady-state deviation zero relative to the reference flow rate. The circuit section converts the output of the PID compensator to a voltage to be applied as an operation amount to the flow control valve to control the opening position. The control object is the thermal flow sensor and flow control valve.

In a semiconductor manufacturing process, in order to improve the productivity, a MFC is required to have a fast response that enables an instant supply at a desired flow rate of the process gas to the process chamber. Figure 2 shows an example of the transient response characteristics of a MFC. The characteristics are evaluated by the step response time and the amount of transient overshoot or undershoot.

Model of Thermal Flow Sensors

Thermal flow sensors measure mass flow rate by measuring the amount of change in the temperature distribution in a fluid flowing in a stainless steel or other capillary with a heat element wrapped around it. The sensors use a Bypass to measure mass flow rate of the process gas diverted by the Bypass at a given rate. Since a conversion factor to convert each gas to N_2 gas is identified, adjustment by substitute gas (N_2 gas) is possible, which is one of the widely adopted methods.

The characteristics between the input and output of thermal flow sensors can be expressed by a transfer function*1 $P_{sen}(s)$ of first-order system[1] shown in Equation 1, where the sensor sensitivity is K_{sen} and the time constant of the response is T_{sen}.

$$P_{sen}(s) = \frac{K_{sen}}{T_{sen}s + 1} \quad \cdots\cdots (1)$$

Model of Flow Control Valves

Flow control valve systems include a piezo actuator valve. A displacement of the piezoelectric element, caused by the voltage applied to the piezo stack, is used to actuate the valve. The characteristics between the input and output of flow control valves can be expressed by a transfer function $P_{val}(s)$ of first-order system shown in Equation 2, where the gain is K_{val} and the time constant of the response of the valve is T_{val}.

$$P_{val}(s) = \frac{K_{val}}{T_{val}s + 1} \quad \cdots\cdots (2)$$

Model of Control Object

The control object of a MFC is the thermal flow sensor and flow control valve. The transfer function $G_p(s)$ of the control object is expressed by using Equation 1 and Equation 2.

$$G_p(s) = \left(\frac{K_{sen}}{T_{sen}s + 1}\right)\left(\frac{K_{val}}{T_{val}s + 1}\right) \quad \cdots\cdots (3)$$

Control System Design

Internal Model Control Structure

In the design of a control system to ensure the controlled variable $y(s)$ follows the reference flow rate $r(s)$, the feedforward control is useful. When the transfer function $G_p(s)$ of the control object of the MFC shown in Equation 3 is given in Figure 3 the controlled variable $y(s)$ matches the reference value by applying the reciprocal

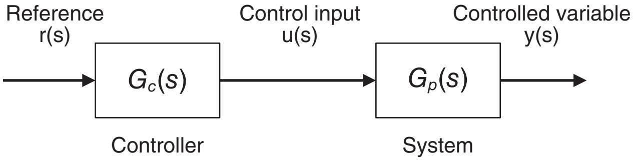


Figure 3 Feedfoward control system.

---

*1: Transfer function: A mathematical model to represent the characteristics of the control object, which is given by the ratio of the Laplace transform of the output to the Laplace transform of the input, as described in Equation 4, when all initial values are 0.[1]

$$\text{Transfer function} = \frac{\text{Laplace transform of the output}}{\text{Laplace transform of the input}} \quad \cdots\cdots (4)$$

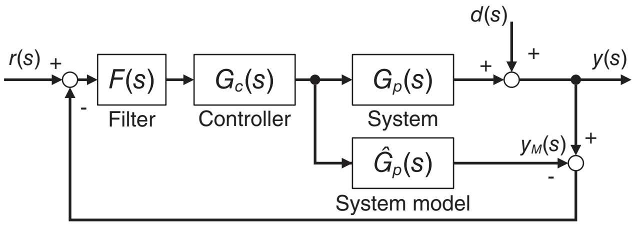


Figure 4 Internal model control system.

of the transfer function of the control object as shown in Equation 5 to the transfer function $G_c(s)$ of the controller, and desirable response characteristics are obtained.

$$G_c(s) = G_p(s)^{-1} \quad \cdots\cdots\cdots\cdots \tag{5}$$

However, modeling errors associated with a system-to-system difference or time deterioration and external disturbances cannot be dealt with by the feed-forward control only.[3] In order to deal with these issues, a control system using the IMC method is designed as shown in Figure 4, where the external disturbances are $d(s)$ and the transfer function of the control object model is $\hat{G}_p(s)$.

In Figure 4, by comparing the output $y(s)$ of the control object $G_p(s)$ of the MFC with the output $y_M(s)$ of the control object model $\hat{G}_p(s)$, modelling errors and external disturbances $d(s)$ are compensated by feedback. Furthermore, in order to minimize the effects of modeling errors and improve the robustness, $G_{IMC}(s)$ shown in Equation 7, in which the controller $G_c(s)$ is connected in series with a filter $F(s)$ as shown in Equation 6, is used for the controller.[4]

$$F(s) = \frac{1}{(T_I s + 1)^n} \quad \cdots\cdots\cdots\cdots \tag{6}$$

$$G_{IMC}(s) = F(s)\, G_c(s) \quad \cdots\cdots\cdots\cdots \tag{7}$$

In the above equation, where T_I is the time constant of the filter, n is selected to ensure a proper $G_{IMC}(s)$ for the controller of the control system.

The output $y(s)$ of the control system of Figure 4 is as described in Equation 8.

$$y(s) = \frac{F(s)\, G_c(s)\, G_p(s)}{1 + [G_p(s) - \hat{G}_p(s)]\, F(s)\, G_c(s)}\, r(s) + \frac{[1 - F(s)\, G_c(s)\, \hat{G}_p(s)]}{1 + [G_p(s) - \hat{G}_p(s)]\, F(s)\, G_c(s)}\, d(s) \quad \cdots\cdots\cdots\cdots \tag{8}$$

In Equation 8, if the control object model $\hat{G}_p(s)$ is close enough to the control object $G_p(s)$ in terms of the characteristics, the right-hand side denominator of Equation 8 approaches 1. Thus, if Equation 5 is established, then the output $y(s)$ can be expressed by Equation 9.

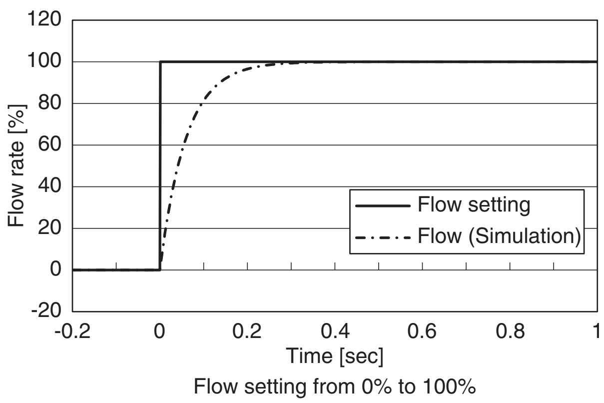


Figure 5 Simulation result of step-up response.

$$y(s) = F(s)\, r(s) + [1 - F(s)]\, d(s) \quad \cdots\cdots\cdots\cdots \tag{9}$$

The first term on the right hand side of Equation 9 represents the reference tracking performance, and the second term represents the characteristics of external disturbance rejection.

Control System Response Simulation

The control object of a MFC are expressed by a transfer function of second-order system[1] as shown in Equation 3, the control object model $\hat{G}_p(s)$ is given by Equation 10.

$$\hat{G}_p(s) = \left[\frac{\hat{K}_{sen}}{\hat{T}_{sen}s + 1}\right]\left[\frac{\hat{K}_{val}}{\hat{T}_{val}s + 1}\right] \quad \cdots\cdots\cdots\cdots \tag{10}$$

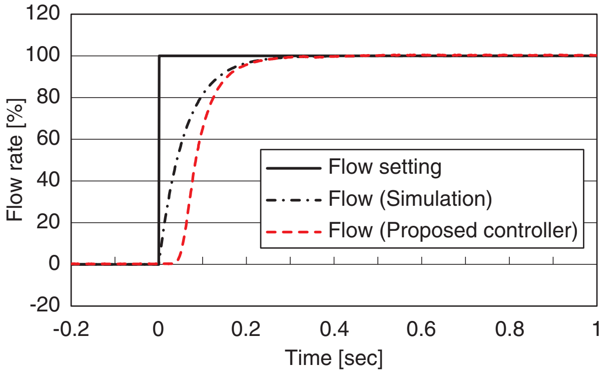
When the simulation is designed using $n = 1$ in Equation 6, if the control object model $\hat{G}_p(s)$ is close enough to the control object $G_p(s)$ in terms of the characteristics, Equation 9 can be expressed by Equation 11.

$$y(s) = \frac{1}{(T_I s + 1)}\, r(s) + \frac{T_I s}{(T_I s + 1)}\, d(s) \cdots\cdots \tag{11}$$

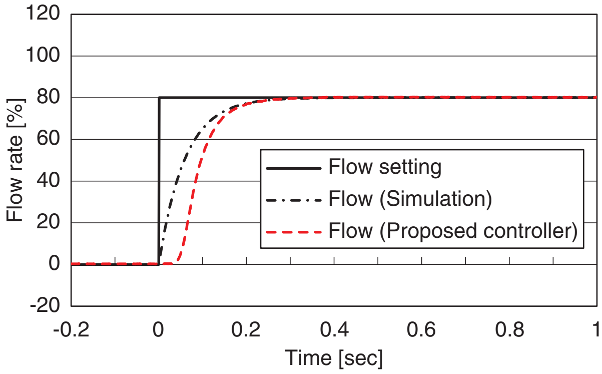
Figure 5 shows the simulation result of Equation 11. This $y(s)$ relative to $r(s)$ is the response of a first-order system with the time constant[1] T_1.

Experimental Verification

This section presents the result of comparison between measurement and simulation of the flow response in the control system using the proposed method. The horizontal axis represents time, and the result is normalized at the time when the flow rates of the simulation reached 98%.



(a) Flow setting from 0% to 100%



(b) Flow setting from 0% to 80%

Figure 6 Step-up response comparison between simulation and experimental result.

Figure 6 shows the result of the set-up response comparison. A similar settling time result was obtained from the simulation and the proposed method, and the overshoot was limited to 1% or less as compared to the reference flow rate. In the actual control object, the dead time not considered in the model was observed, but a similar settling time to the simulation was obtained, reflecting the robustness of the proposed method.

Conclusion

This paper proposes the application of a design method of PID compensator using control engineering as an approach to a theoretical design of a controller. In the control system applying the proposed method, the effectiveness is demonstrated by simulation and real system experiment. By taking into consideration further modeling errors in the design, more accurate controllers can be designed in the future.

References

[1] SUGIE, FUJITA, Introduction to Feedback Control, CORONA PUBLISHING Co., Ltd. (1999)
[2] M. MORARI and E. ZAFIRIOU, Robust Process Control, Prentice-Hall International, Inc. (1989)
[3] Kenji SAWADA, "Servo System and Internal Model Principle", *SYSTEMS, CONTROL AND INFORMATION*, **56-4**, 188 (2012)
[4] Ming T. THAM, Internal Model Control, http://www.lorien.ncl.ac.uk/ming/robust/imc.pdf (ref. Sept 12. 2014)

Atsushi IEKI
Development Design Dept.1
Research & Development Division
HORIBA STEC, Co., Ltd.