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Self-Tuning Type-2 PID control system and its application

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Abstract:
This study proposes an adaptive control method of a weigh feeder. A weigh feeder dispenses material into a process at a precise rate, and it has been employed in industries, e.g., process control, cement manufacturing plants, food industry equipment, and so on. To introduce advanced control into industries, self-tuning controllers are designed for controlling a weigh feeder. Three difference controllers are designed; one degree-of-freedom (1DOF) PID, 1DOF PD, and two degree-of-freedom (2DOF) PD controllers, and these control methods are compared through experimental results. Because discharged mass is measured by employing loss-in-weight method, a reference input followed by a plant output is ramp-type, and a type-2 control system has to be designed. Since the controlled object includes an integrator, a type-2 control system can be obtained by using 1DOF PID controller. In design of 2DOF PD control, a pre-compensator is designed to eliminate steady-state velocity error. Further, to be compared with 1DOF PID and 2DOF PD control, a 1DOF PD controller is designed. In this paper, PID and PD controllers are designed on the basis of generalized minimum variance control (GMVC) to obtain useful control methods adopted in industries. In design of the proposed control methods, GMVC can be replaced precisely with a simple PID or PD controller, and advanced control performance can be obtained. Experimental results are shown and compared, and the effectiveness of the proposed design method is shown.

Keywords: PID control, minimum variance control, self-tuning control, integral compensator, control application, mechanical system

1. INTRODUCTION

This paper discusses the design method of a controller for a weigh feeder shown in Fig. 1. A weigh feeder dispenses material into a process at a precise rate (Hopkins (2006); Sato and Kameoka (2007)), and it has been employed widely in industries, e.g., process control (Heinrici (2000)), cement manufacturing plants (Haefner (1996)) and food industry equipment (Vermylen (1985)) because of its functional capability. Weigh feeders used in industries are controlled mainly by using PID control. To obtain high control performance, the authors have proposed a weigh feeder system with generalized minimum variance control (GMVC) (Clarke and Gawthrop (1979); Yamamoto et al. (1990)), and sufficient control result has been achieved. However, its plant parameters are assumed to be known, and a control system has been designed. Hence, this paper proposes a self-tuning control method for a weigh feeder in case of unknown plant parameters. Further, engineers on work-site prefer PID control rather than advanced control because their experience can be used. Hence, a PID controller is designed so that GMVC is approximated by PID control. Therefore, this paper proposes a self-tuning GMVC-based PID controller for controlling a weigh feeder. As a result, the high performance of advanced control can be achieved by employing easy-to-use PID control methods.

The purpose of a weigh feeder is to dispense material constantly at a specified rate. However, the feed rate of discharged material cannot be measured directly, and a measurable output signal is discharged mass. Then, a reference input to be followed by the output signal is ramp-type, and a type-2 control system has to be designed (Usui (1992); Sato and Kameoka (2007)). It follows from internal model principle that a type-2 control system can be obtained easily by employing PID control because of an integrator included in a weigh feeder. Further, in this paper, a new self-tuning type-2 control system without an integrator is proposed, that is, a self-tuning 2DOF PD controller is proposed on the basis of GMVC with a pre-compensator which compensates steady-state velocity error. To be compared with the 1DOF PID and 2DOF PD controllers, a self-tuning 1DOF PD controller is designed on the basis of GMVC without an integrator. It is expected that steady-state velocity can be eliminated by using the 1DOF PID and 2DOF PD controllers and that reference response at the initial stage can be improved by 2DOF PD control. To confirm of the effectiveness of the proposed design methods, experimental results are shown.

This paper is organized as follows. Sec. 2 gives a weigh feeder which is the controlled object in this study and controllers to be designed for the weigh feeder. Next, the controllers are designed in Sec. 3. Sec. 4 gives the design method of self-tuning controllers in the case of unknown plant parameters. In Sec. 5 the designed controllers are applied to a weigh feeder, and experimental results are

Fig. 1. weigh feeder

shown. Finally, Sec. 6 gives concluding remarks and future works.

2. PROBLEM STATEMENT

A model of a weigh feeder, which is the control object in this study, is given in this section. A nominal model of the transfer function from a control input to measured discharged mass is assumed to be described by the following transfer function (Sato and Kameoka (2007)).

$$P(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\frac{1}{s}K_d K_g \frac{K_m}{1+Ts}K_i \tag{1}$$

where, K_i is the gain of an inverter, K_m and T are the gain and the time-constant of a motor, K_g is the gain of a reduction gear, and K_d is the feed rate of a disk in a weigh feeder. A loadcell to be employed to measure discharged mass is assumed to be a second-order system, and ω_n and ζ are a natural angular frequency and damping ratio, respectively. Since discharged mass is measured by employing loss-in-weight method, it is obtained by measuring the decreased amount of material which is stored in a hopper deployed above the feeder.

A plant model to be used to design controllers is derived without the dynamics of a loadcell because of a low-pass filter to be employed to remove the effect of noise included in a measured signal. Hence, the model of a controlled object is a first-order plus integrator system, and the discrete-time model is given by the following.

$$A[z^{-1}]y[k] = z^{-1}B[z^{-1}]u[k] + \xi[k] \tag{2}$$

$$A[z^{-1}] = 1 + a_1 z^{-1} + a_2 z^{-2} \tag{3}$$

$$B[z^{-1}] = b_0 \tag{4}$$

where $y[k]$ is discharged mass and is called an output signal or a plant output, and $u[k]$ and $\xi[k]$ are a control input and noise, respectively. z^{-1} denotes the backward shift operator. Due to the specification of an inverter in a weigh feeder, the control input is limited as Eq. (5) (Sato and Kameoka (2007)).

$$0 \leq u[k] \leq 9.82 \tag{5}$$

In control of the weigh feeder, using a loadcell, discharged mass is measured but feed rate is not measured directly. Hence, a reference input to be followed by a plant output is a ramp signal, and a type-2 control system has to be designed in this paper to make a plant output follow a ramp signal without steady-state velocity error.

Digital form 1DOF PID, 1DOF PD and 2DOF PD controllers for controlling the weigh feeder are designed. A 1DOF PID is given as Eq. (6), and 1DOF and 2DOF PD controllers are described as Eqs. (9) and (11), respectively.

$$\Delta u[k] = C_i[z^{-1}](w[k] - y[k]) \tag{6}$$

$$C_i[z^{-1}] = k_c\left\{\Delta + \frac{T_s}{T_I} + \frac{T_D}{T_s}\Delta^2\right\} \tag{7}$$

$$\Delta = 1 - z^{-1} \tag{8}$$

$$u[k] = C_1[z^{-1}](w[k] - y[k]) \tag{9}$$

$$C_1[z^{-1}] = k_{c1}\left\{1 + \frac{T_{D1}}{T_s}\Delta\right\} \tag{10}$$

$$u[k] = C_2[z^{-1}]w[k] - C_1[z^{-1}]y[k] \tag{11}$$

$$C_2[z^{-1}] = k_{c2}\left\{1 + \frac{T_{D2}}{T_s}\Delta\right\} \tag{12}$$

where, k_c, T_I and T_D are proportional gain, integral time and derivative time, respectively, k_{c1} and k_{c2} are proportional gain, and T_{D1} and T_{D2} are derivative time. $w[k]$ is a reference input to be followed by a plant output, and T_s denotes a sampling interval.

Under the condition that the plant parameters are unknown, the controller parameters have to be designed to satisfy both the stability of a closed-loop system and the reference response of a ramp input. In this paper, self-tuning PID controllers are designed based on GMVC, and the weigh feeder is controlled by using the proposed PID controllers.

3. DESIGN OF CONTROLLERS

To control the discharged mass of the weigh feeder, three different versions of a PID controller are designed in 3.1, 3.2 and 3.3.

3.1 1DOF GMVC-Based PID Controller

A GMVC law with an integrator is derived, and the PID parameters of the 1DOF PID controller are designed based on the derived GMVC law.

Control law of GMVC with an integrator The design objective of GMVC, which includes an integrator explicitly, is to minimize the following cost function.

$$J_i = E[\Phi_i[k+1]^2] \tag{13}$$

$$\Phi_i[k+1] = P_i[z^{-1}]y[k+1] + Q_i[z^{-1}]\Delta u[k] - R_i[z^{-1}]w[k] \tag{14}$$

where, $E[\cdot]$ denotes the expectation, and polynomials $P_i[z^{-1}]$, $Q_i[z^{-1}]$ and $R_i[z^{-1}]$ are the design parameters of GMVC. $y[k+1]$ is the dead-time forward predictive output at step k.

To obtain the control law of GMVC, the following Diophantine equation is solved

$$P_i[z^{-1}] = \Delta A[z^{-1}]E_i[z^{-1}] + z^{-1}F_i[z^{-1}] \tag{15}$$

$$E_i[z^{-1}] = e_{i,0} \tag{16}$$

$$F_i[z^{-1}] = f_{i,0} + f_{i,1}z^{-1} + f_{i,2}z^{-2}, \tag{17}$$

and then a control law is derived as follows.

$$G_i[z^{-1}]\Delta u[k] = R_i[z^{-1}]w[k] - F_i[z^{-1}]y[k] \tag{18}$$

$$G_i[z^{-1}] = E_i[z^{-1}]B[z^{-1}] + Q_i[z^{-1}] \tag{19}$$

where, the order of $P_i[z^{-1}]$ is assumed to be set less than or equal to 3 because the dead-time of the weigh feeder system is 1.

Substituting the derived control law into the plant model, a closed-loop system is obtained by the following equations.

$$y[k] = \frac{z^{-1}B[z^{-1}]R_i[z^{-1}]}{T_i[z^{-1}]}w[k] + \frac{G_i[z^{-1}]\Delta}{T_i[z^{-1}]}\xi[k] \quad (20)$$

$$T_i[z^{-1}] = P_i[z^{-1}]B[z^{-1}] + \Delta Q_i[z^{-1}]A_i[z^{-1}] \quad (21)$$

It follows from Eq. (20) that the stability of the closed-loop system can be achieved by designing $P_i[z^{-1}]$ and $Q_i[z^{-1}]$.

Calculation of PID parameters The PID parameters of the 1DOF PID controller are designed based on GMVC. Comparing the 1DOF controller (6) with the derived GMVC law (18), the following relations have to be satisfied (Yamamoto et al. (1999)).

$$C_i[z^{-1}] = \frac{F_i[z^{-1}]}{G_i[z^{-1}]} \quad (22)$$

$$R_i[z^{-1}] = F_i[z^{-1}] \quad (23)$$

Generally, since $G_i[z^{-1}]$ is a polynomial, Eq. (22) cannot satisfied straightforwardly. However, $Q_i[z^{-1}]$ is assumed to be $Q_i[z^{-1}] = q_{i,0}$ (constant), and then $G_i[z^{-1}]$ is a constant because of $E_i[z^{-1}] = e_{i,0}$. In that case, $G_i[z^{-1}]$ is expressed as follows.

$$G_i[z^{-1}] = g_{i,0} = e_{i,0}b_0 + q_{i,0}. \quad (24)$$

Consequently, Eq. (22) is satisfied reasonably. It follows from Eqs. (22) and (24) that the PID parameters based on GMVC with an integrator are derived as follows.

$$k_c = -\frac{1}{g_{i,0}}(f_{i,1} + 2f_{i,2}) \quad (25)$$

$$T_I = -\frac{f_{i,1} + 2f_{i,2}}{f_{i,0} + f_{i,1} + f_{i,2}}T_s \quad (26)$$

$$T_D = -\frac{f_{i,2}}{f_{i,1} + 2f_{i,2}}T_s \quad (27)$$

Because the controller (6) includes an integrator, the plant output in Eq. (2) can be made to follow a ramp-type reference input without steady-state velocity error by employing the controller (6) in the case that a closed-loop system is stabilized.

3.2 1DOF GMVC-Based PD Controller

The PD parameters of the 1DOF PD controller are designed based on 1DOF GMVC without an integrator.

Control law of 1DOF GMVC GMVC derives a control law minimizing the following cost function.

$$J_1 = E[\Phi_1[k+1]^2] \quad (28)$$

$$\Phi_1[k+1] = P_1[z^{-1}]y[k+1] + Q_1[z^{-1}]u[k] - R_1[z^{-1}]w[k] \quad (29)$$

where, the order (n_{p1}) of $P_1[z^{-1}]$ is assumed as

$$n_{p1} \le 2 \quad (30)$$

A GMVC law is given by the following.

$$G_1[z^{-1}]u[k] = R_1[z^{-1}]w[k] - F_1[z^{-1}]y[k] \quad (31)$$

$$G_1[z^{-1}] = E_1[z^{-1}]B[z^{-1}] + Q_1[z^{-1}] \quad (32)$$

where,

$$P_1[z^{-1}] = A[z^{-1}]E_1[z^{-1}] + z^{-1}F_1[z^{-1}] \quad (33)$$

$$E_1[z^{-1}] = e_{1,0} \quad (34)$$

$$F_1[z^{-1}] = f_{1,0} + f_{1,1}z^{-1}. \quad (35)$$

Using the derived control law, a closed-loop system is given by the following.

$$y[k] = \frac{z^{-1}B[z^{-1}]R_1[z^{-1}]}{T_1[z^{-1}]}w[k] + \frac{G_1[z^{-1}]}{T_1[z^{-1}]}\xi[k] \quad (36)$$

$$T_1[z^{-1}] = P_1[z^{-1}]B[z^{-1}] + Q_1[z^{-1}]A[z^{-1}] \quad (37)$$

Comparing Eqs. (21) with (37), a major difference between these equations is Δ ($= 1 - z^{-1}$) which is caused by an integrator.

Calculation of PD parameters The following relations are derived in a similar way to the design of the 1DOF PID controller in 3.1.2.

$$C_1[z^{-1}] = \frac{F_1[z^{-1}]}{G_1[z^{-1}]} \quad (38)$$

$$R_1[z^{-1}] = F_1[z^{-1}] \quad (39)$$

Further, the use of $Q_1[z^{-1}] = q_{1,0}$ gives Eq. (40) because of $E_1[z^{-1}] = e_{1,0}$.

$$G_1[z^{-1}] = g_{1,0} = e_{1,0}b_0 + q_{1,0}. \quad (40)$$

Hence, the PD parameters of $C_1[z^{-1}]$ are calculated as follows.

$$k_{c1} = \frac{1}{g_{1,0}}(f_{1,0} + f_{1,1}) \quad (41)$$

$$T_{D1} = -\frac{f_{1,1}}{f_{1,0} + f_{1,1}}T_s \quad (42)$$

By using the obtained 1DOF GMVC-based PD controller, feed rate can be made constant, but steady-state velocity error remains. Therefore, the 1DOF GMVC-based PD controller is extended into a 2DOF controller in 3.3.

3.3 2DOF GMVC-Based PD Controller

To design of the PD parameters of the 2DOF PD controller, a GMVC law with a pre-compensator is derived first. Next, the PD parameters are designed based on the derived GMVC law.

Control law of 2DOF GMVC (Yamamoto et al. (1990)) A 2DOF GMVC law that a pre-compensator $\frac{1}{S[z^{-1}]}$ is appended to the 1DOF GMVC law (31) is given as follows.

$$G_1[z^{-1}]u[k] = \frac{R_2[z^{-1}]}{S[z^{-1}]}w[k] - F_1[z^{-1}]y[k] \quad (43)$$

where, $R_2[z^{-1}]$ is a design polynomial employed instead of $R_1[z^{-1}]$, and $S[z^{-1}]$ is a design polynomial and has to be stable. Then, the cost function (28) and (29) to be minimized is rewritten as follows.

$$J_2 = E[\Phi_2[k+1]^2] \quad (44)$$

$$\Phi_2[k+1] = P_1[z^{-1}]S[z^{-1}]y[k+1] + Q_1[z^{-1}]S[z^{-1}]u[k] - R_2[z^{-1}]w[k] \quad (45)$$

The use of the 2DOF GMVC law (43) gives the following closed-loop system.

$$y[k] = \frac{z^{-1}B[z^{-1}]R_2[z^{-1}]}{T_1[z^{-1}]S[z^{-1}]}w[k] + \frac{G_1[z^{-1}]}{T_1[z^{-1}]}\xi[k] \quad (46)$$

It follows from (46) that the reference response can be redesigned independently to the disturbance response by designing $R_2[z^{-1}]$ and $S[z^{-1}]$.

Design of $R_2[z^{-1}]$ and $S[z^{-1}]$ Using the 2DOF GMVC law, steady-state velocity error e_∞ from a ramp-type reference input to a plant output is given as follows (Sato and Kameoka (2007)).

$$e_\infty = \lim_{z\to 1} \frac{T_1[z^{-1}]S[z^{-1}] - z^{-1}B[z^{-1}]R_2[z^{-1}]}{T_1[z^{-1}]S[z^{-1}](1-z^{-1})} r \tag{47}$$

where, r is the gradient of a ramp-type reference input.

In this paper, $R_2[z^{-1}]$ and $S[z^{-1}]$ are designed so that the numerator of the right-hand side in Eq. (47) is to be $(1-z^{-1})^2$. Then, $R_2[z^{-1}]$ and $S[z^{-1}]$ are given as follows.

$$R_2[z^{-1}] = r_{2,0} + r_{2,1}z^{-1} \tag{48}$$

$$S[z^{-1}] = s_0, \tag{49}$$

and the coefficient parameters are calculated as follows.

$$r_{2,0} = \frac{1}{b_0}\left\{2 + \frac{p_{1,1}b_0 + q_{1,0}a_1}{p_{1,0}b_0 + q_{1,0}}\right\} \tag{50}$$

$$r_{2,1} = \frac{1}{b_0}\left\{\frac{p_{1,2}b_0 + q_{1,0}a_2}{p_{1,0}b_0 + q_{1,0}} - 1\right\} \tag{51}$$

$$s_0 = \frac{1}{p_{1,0}b_0 + q_{1,0}} \tag{52}$$

where, $P_1[z^{-1}] = p_{1,0} + p_{1,1}z^{-1} + p_{1,2}z^{-2}$.

Calculation of PD parameters In the case that $C_1[z^{-1}]$ is designed as Eq. (38), comparing Eq. (11) with Eq. (43), $C_2[z^{-1}]$ in the 2DOF PD controller is designed based on the 2DOF GMVC law by satisfying the following equation.

$$C_2[z^{-1}] = \frac{R_2[z^{-1}]}{S[z^{-1}]G_1[z^{-1}]} \tag{53}$$

Because the order of $S[z^{-1}]$ is 0 from Eq. (49), the PD parameters of $C_2[z^{-1}]$ are calculated as follows.

$$k_{c2} = \frac{r_{2,0} + r_{2,1}}{g_{1,0}s_0} \tag{54}$$

$$T_{D2} = -\frac{r_{2,1}}{r_{2,0} + r_{2,1}}T_s \tag{55}$$

Using the obtained 2DOF system, the stability of a closed-loop system is ensured by $C_1[z^{-1}]$, and the property of a reference input is improved by $C_2[z^{-1}]$ independently to the closed-loop stability. Especially, steady-state velocity error is eliminated by employing $C_2[z^{-1}]$.

4. SELF-TUNING CONTROLLER

In the case that plant parameters are unknown, using the following recursive least square identification law, the plant parameters are identified

$$\hat{\theta}[k] = \hat{\theta}[k-1] + \frac{\Gamma[k-1]\psi[k-1]}{1+\psi^T[k-1]\Gamma[k-1]\psi[k-1]}\varepsilon[k] \tag{56}$$

$$\Gamma[k] = \Gamma[k-1] + \frac{\lambda\Gamma[k-1]\psi[k-1]\psi^T[k-1]\Gamma[k-1]}{1+\lambda\psi^T[k-1]\Gamma[k-1]\psi[k-1]} \tag{57}$$

$$\varepsilon[k] = \Delta y[k] - \hat{\theta}^T[k-1]\psi[k-1] \tag{58}$$

$$\hat{\theta}[k] = [\hat{a}_1[k],\ \hat{a}_2[k],\ \hat{b}_0[k]]^T \tag{59}$$

$$\psi[k-1] = [-y_f[k-1],\ -y_f[k-2],\ u_f[k-1]]^T \tag{60}$$

$$\Gamma[0] = \alpha I \quad (0 < \alpha < \infty), \tag{61}$$

and control parameters are derived by employing the identified parameters $\hat{a}_1[k]$, $\hat{a}_2[k]$, $\hat{b}_0[k]$ instead of $a_1,\ a_2,\ b_0$. λ is a forgetting factor $(0 < \lambda < 2)$, $\Gamma[k]$ is an estimated covariance matrix, and $y_f[k]$ and $u_f[k]$ are the filtered signals of $y[k]$ and $u[k]$ using a low pass filter.

5. EXPERIMENTAL RESULTS

To confirm the effectiveness of the designed control systems, experiments that a specific amount of flour is fed have been conducted.

Since the system parameters are unknown, controller parameters are calculated by using identified parameters updated at every sampling step. The initial values of identified parameters are set as follows.

$$\hat{a}_1[0] = -1.9967,\ \hat{a}_2[0] = 0.9967,\ \hat{b}_0[0] = 0.7000 \times 10^{-7} \tag{62}$$

where, the forgetting factor and the initial value of an estimated covariance matrix are set as 0.9999 and $10^3 I$, respectively.

The conditions of experiments are as follows; a sampling interval 0.01[s], the gradient of a ramp-type reference input 0.01, and design polynomials $P[z^{-1}] = 1 - 0.1z^{-1}$, $Q[z^{-1}] = 0.25 \times 10^{-2}$. $\hat{R}_i[k : z^{-1}]$ and $\hat{R}_1[k : z^{-1}]$ in the 1DOF PID and PD control systems are decided by $\hat{F}_i[k : z^{-1}]$ and $\hat{F}_1[k : z^{-1}]$ respectively calculated by using identified parameters at sampling step k. $\hat{R}_2[k : z^{-1}]$ and $\hat{S}[k : z^{-1}]$ are also decided by Eqs. (50) $\sim$ (52) calculated by using identified parameters. Further, noise on a measured signal was rejected by using a 10th Butterworth filter with a cut-off frequency 10[Hz] and a 10th auto-regressive moving average filter.

The weigh feeder is controlled under the conditions abovementioned. The experimental results are shown in Fig. 2 $\sim$ Fig. 10. The control result obtained by using the self-tuning 1DOF PD controller is shown in Fig. 2 and Fig. 3. The result shows that the weigh feeder could be controlled stably, and Fig. 3 shows that a control input was not saturated. However, a plant output could not follow the reference input, and steady-state velocity error could not be eliminated. On the other hand, from Fig. 4 and Fig. 5, a plant output could follow the reference input without steady-state velocity error by using the self-tuning 2DOF PD controller although overshoot appeared at the initial stage of experiment. It follows from these experimental results that the feed rate in the 1DOF PD control could be controlled the same as the 2DOF PD control although steady state could not be eliminated. The obtained proportional gain k_{c1}, k_{c2} and derivative time T_{D1}, T_{D2} of the self-tuning 2DOF PD controller are shown in Fig. 6 $\sim$ Fig. 8.

The control result obtained by using the self-tuning PID controller is shown in Fig. 9 and Fig. 10. It follows from the experimental result that a plant output followed the reference input virtually, but it oscillated due to the saturation of a control input. It is inferred from this result that too much control input is needed in the case that the weigh feeder is controlled by using a self-tuning PID controller but the oscillation of a plant output arose due to the constraint of a control input. Hence, the design parameters have to be tuned carefully in the case that a self-tuning PID controller is designed.

Finally, the plant output errors are illustrated in Fig. 11. The error in the 1DOF PID control oscillated, and steady state error could not be eliminated by employing 1DOF PD control. On the other hand, The error obtained by using the 2DOF PD controller oscillated at the initial stage but converged to 0 gradually. Hence, it can be seen that the proposed 2DOF PD control is effective to reduce the steady-state velocity error.

6. CONCLUSION

This paper has proposed new design methods of a weigh feeder system. To make a plant output follow a reference input even if plant parameters are unknown, self-tuning controllers are designed for controlling the weigh feeder. To obtain a feasible control system, this study have proposed three control methods; 1DOF PID, 1DOF PD

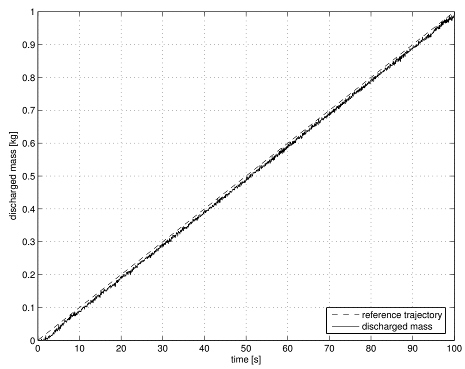

Fig. 2. Plant output: 1DOF PD control

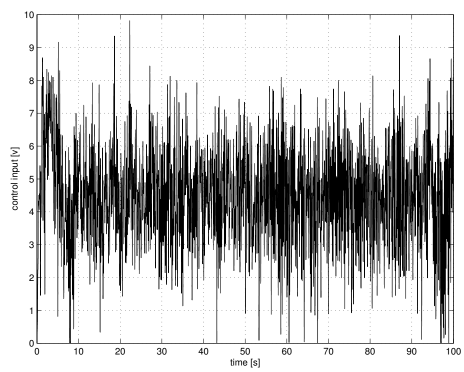

Fig. 3. Control input: 1DOF PD control

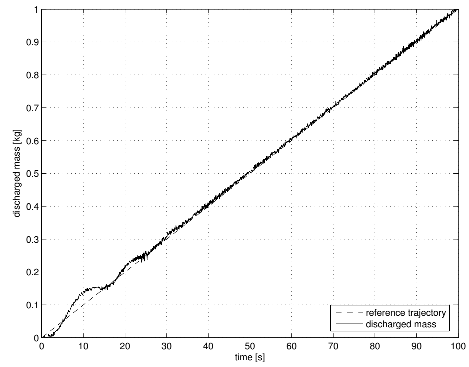

Fig. 4. Plant output: 2DOF PD control

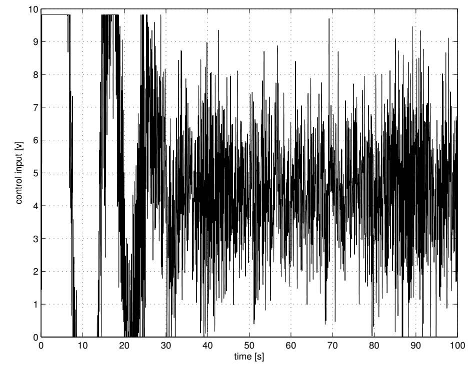

Fig. 5. Control input: 2DOF PD control

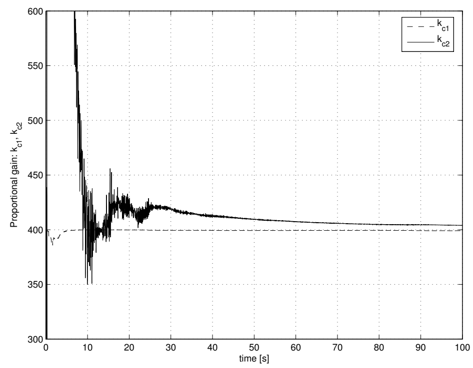

Fig. 6. Proportional gain k_{c1}, k_{c2}: 2DOF PD control

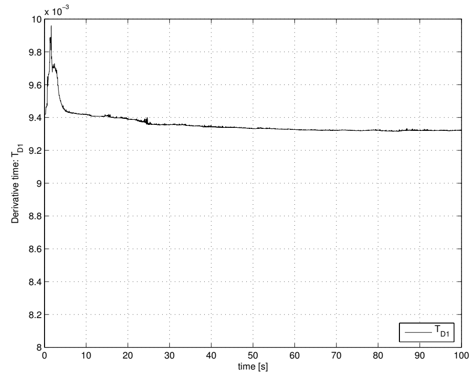

Fig. 7. Derivative time T_{D1}: 2DOF PD control

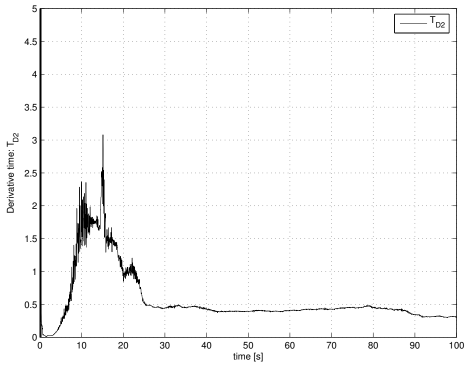

Fig. 8. Derivative time T_{D2}: 2DOF PD control

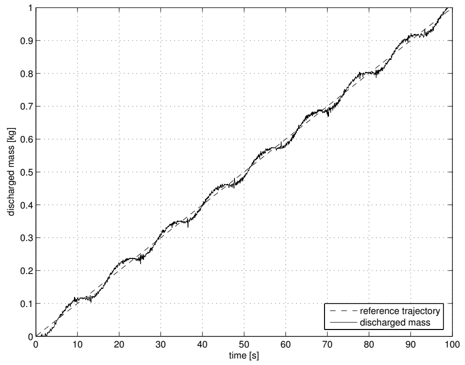

Fig. 9. Plant output: 1DOF PID control

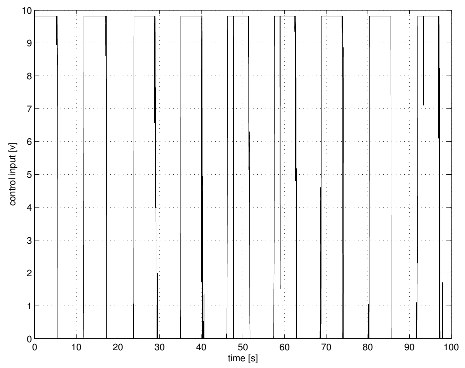

Fig. 10. Control input: 1DOF PID control

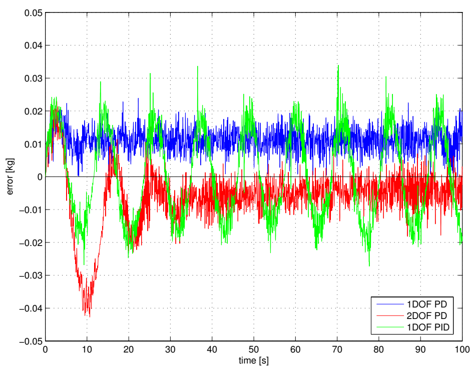

Fig. 11. Output error

and 2DOF PD control, and these control parameters are designed on the basis of generalized minimum variance control (GMVC). Further, these control methods have been compared through experiments.

Since, a reference input to be followed by a plant output is ramp-type, a type-2 control system has to be designed. Using a PID controller, the type-2 control system can be obtained easily, but an output result oscillated due to the saturation of a control input. Hence, the weigh feeder system has to be designed taking into account anti-reset windup to design a control system considering the constraint of a control input. On the other hand, an output result obtained by using a 2DOF PD controller converged to the reference input without steady-state velocity error. In control of 1DOF PD control, a plant output could be controlled stably although steady-state velocity error could not be eliminated. In this paper, the pre-compensator of the 2DOF PD controller has been designed to compensate steady-state velocity error, but it should be designed to improve transient response.

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