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Design Method of Fault Detector for Injection Unit

Kiyoshi Ochi [**, *] **Masami Saeki** [**]

[*] *The Japan Steel Works, LTD. HIROSHIMA PLANT, Hiroshima 736-8602 Japan (Tel:81-82-822-3186; E-mail: kiyoshi_ochi@hiro.jsw.co.jp).*
[**] *Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima 739-8527 Japan (E-mail: saeki@hiroshima-u.ac.jp)*

Abstract:
An injection unit is considered as a speed control system utilizing a reaction-force sensor. Our purpose is to design a fault detector that detects and isolates actuator and sensor faults given that the system is disturbed by a reaction force. First described is the fault detector's general structure. In this system, a disturbance observer that estimates the reaction force is designed for the speed control system in order to obtain the residual signals, and then post-filters that separate the specific frequency elements from the residual signals are applied in order to generate the decision signals. Next, we describe a fault detector designed specifically for a model of the injection unit. It is shown that the disturbance imposed on the decision variables can be made significantly small by appropriate adjustments to the observer bandwidth, and that most of the sensor faults and actuator faults can be detected and some of them can be isolated in the frequency domain by setting the frequency characteristics of the post-filters appropriately. Our result is verified by experiments for an actual injection unit.

1. INTRODUCTION

In consideration of the global environment, in recent years efforts have been made to create industrial machines which are more energy-efficient. One of the technological innovations in injection molding machines is the adoption of an electric servo motor instead of the traditional hydraulic pressure system for the drive system. This technical innovation allowed the development of a high performance closed-loop control system while also creating a more energy-efficient device. Higher reliability and stability have come to be demanded from injection molding machines. Various plastic products are manufactured by injection molding machines which are operated continuously for 24 hours. In the injection process, melted resin is injected to the metal mold quickly, demanding control of the injection pressure and the injection speed. These feedback modes are very important processes in realizing the reproducibility of plastic products, thus forcing pressure sensors to play crucial roles. Generally, reaction force rather than injection pressure is measured by a reaction-force sensor such as a load cell. In the case of sensor faults, critical problems such as a breakdown of the metal mold or damage to the injection screw may occur. Thus, the detection of sensor faults is a vital issue. Such sensor faults include signal wire breakdown of the sensor, zero-point drift, gain variance, etc. It is especially difficult to distinguish between a sensor fault and an actuator fault, i.e., a so called system gain fault. Thus, a method of FDI (Fault Detection and Isolation) is required.

Many studies have addressed fault detection and isolation (Pertew et al. [2005], Chen et al. [2006], Liu et al. [1997]). For example, in (Pertew et al. [2005]), a method of the dynamic observer for the multi-sensor fault isolation has been proposed which utilized the frequency band of the residual signal, and in which the observer was designed as a kind of filter. Disturbance and model uncertainty are important factors to be considered in the FDI system design. A fault estimation method which is insensitive to the process disturbance is given in Gao et al. [2007]. Approaches using an adaptive observer or a sliding mode observer are studied (Ding et al. [1992], Wang et al. [1996], Yang et al. [1995], Akhenak et al. [2003], Inoue et al. [2006]). The injection unit can be represented by a linear time-invariant model quite well where the reaction force is a large disturbance to the unit. Therefore, disturbance should be considered rather than model uncertainty, and a time-invariant observer may be sufficient. By the way, our problem has such a particularity that the disturbance affects the sensor output instantaneously. Because of this, the method of Gao et al. [2007] cannot be applied to our problem. As far as we know, there is no method applicable to our problem.

In this paper, we consider a FDI system for a speed control device equipped with a reaction-force sensor. The system is analyzed as a general FDI system, and the transfer characteristics from the fault disturbance to the residual signals are analyzed. We construct a fault detector using a full-order disturbance observer and post filters, with their parameters being determined from the viewpoint of fault detectability. Moreover, the fault isolatability for the system including the process disturbance by using the residual signals and the frequency characteristic of the system is shown. We apply this method to the injection unit, and the actual construction of the FDI system is shown. The

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validity of our method is shown by experiments for an actual injection unit.

2. MODELING AND PROBLEM DEFINITION

2.1 Model of injection unit

Figure 1 shows a diagram of an injection unit. A servo motor is used as the driving source, and a ball screw converts the driving torque of the servo motor to the thrust working in a straight line. A timing belt and pulleys are used to obtain the deceleration ratio. Thrust is applied to the slide plate connected to the injection screw, and it generates injection pressure on the resin injected into the metal mold. This injection pressure is detected as a reaction force that the slide plate receives, and this force is measured by the load cell. Here we consider the basic characteristics of FDI, so the injection unit is simply modeled as a one-mass damper system as

$$\dot{x}_1 = \frac{1}{J}(\tau - \tau_L - Dx_1), \tag{1}$$

where τ, x_1, J, and D are the motor torque, the rotational speed of the motor, the total inertia, and the viscosity constant of the drive system, respectively. The reaction force is considered as the disturbance torque τ_L of the system.

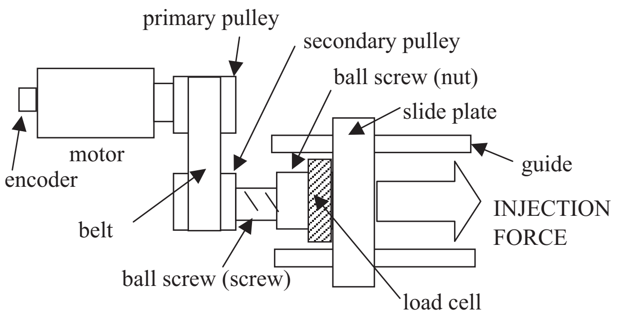

Fig. 1. Injection unit

2.2 Problem definition

Figure 2 shows a block diagram of the speed control system with the reaction-force sensor. P(s) is the transfer function of the injection unit. It is described by $P(s) = 1/(Js + D)$ from equation (1), where the input of $P(s)$ is τ and the output is x_1. y_1 is the detected value of x_1, and y_1^* is the set value of y_1. u is the control input to the plant $P(s)$, namely τ. $G_c(s)$ is the speed controller. w is the disturbance that corresponds to the reaction force of the injection unit, y_2 is the value of the reaction force measured by the reaction-force sensor, and d_1 and d_2 are the equivalent disturbances which correspond to the actuator fault and the sensor fault, respectively.

From Figure 2, the system is described by the following equations :

$$\dot{x}_1 = Ax_1 + Bu + Bw + Bd_1 \tag{2}$$

$$y_1 = Cx_1 \tag{3}$$

$$y_2 = w + d_2, \tag{4}$$

where $P(s) = C(sI - A)^{-1}B$. As noted in Introduction, the equation (4) has a disturbance d_2, which makes the application of the previous methods impossible to our problem. Our problem is to design a fault detector that detects and isolates d_1 and d_2 from the information of u, y_1, and y_2.

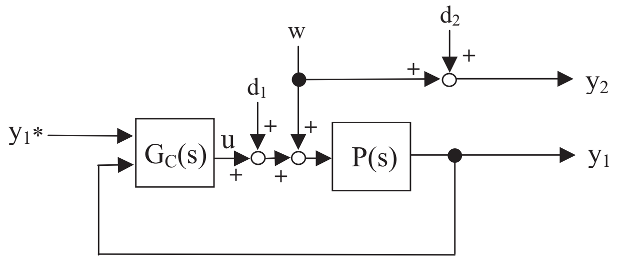

Fig. 2. Block diagram of speed control system with reaction-force sensor

3. CONSTRUCTION OF FAULT DETECTOR

3.1 Basic approach

We consider a fault detector utilizing an observer as shown in Figure 3 in order to detect the faults of the control system shown in Figure 2. The full-order observer denoted by 'OBS' in Figure 3 outputs $\hat{y}_1$ and $\hat{y}_2$, the estimates of y_1 and y_2. The residuals e_1 and e_2 are calculated from the difference between $\hat{y}_1$ and y_1 or between $\hat{y}_2$ and y_2, respectively. The fault signals r_1 and r_2 are separated from e_1 and e_2 by the post filters $Q_1(s)$ and $Q_2(s)$.

3.2 Design of disturbance observer

In this section, we construct the disturbance observer. If we assume that w is the step disturbance then the equation $\dot{x}_2 = 0$ is obtained where $x_2 = w$. By setting $d_1 = 0$ and $d_2 = 0$ in the equations (2) and (4), we obtain the following state equation :

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u. \tag{5}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{6}$$

The full-order observer for the equations (5) and (6) is described by

$$\begin{bmatrix} \dot{\hat{x}}_1 \\ \dot{\hat{x}}_2 \end{bmatrix} = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u - \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} (\hat{y}_1 - y_1). \tag{7}$$

$$\begin{bmatrix} \hat{y}_1 \\ \hat{y}_2 \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} \tag{8}$$

The characteristic equation of the observer is described by

$$det(s^2 I + (F_1 C - A)s + BF_2 C) = 0, \tag{9}$$

and the observer gain $F = [F_1 \;\; F_2]^T$ is determined so that the poles of the observer may be placed appropriately. As shown in Figure 3, the residual signals which are utilized for fault detection are given by

$$e_1 = y_1 - \hat{y}_1 = C(x_1 - \hat{x}_1) \tag{10}$$

$$e_2 = -\hat{y}_2 + d_2 + w. \tag{11}$$

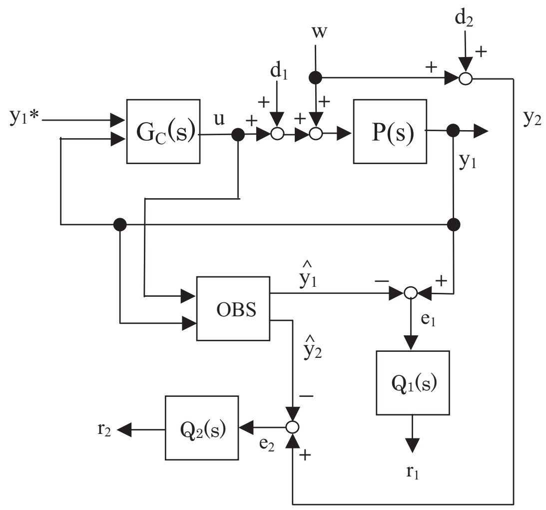

Fig. 3. Block diagram of fault detector utilizing observer and post filters

3.3 Analysis of transfer characteristics

Our purpose is to observe the disturbance d_1 and d_2 by utilizing the information of e_1 and e_2. However, the influence of the disturbance w also appears in e_1 and e_2. Therefore, we analyze the transfer characteristics from the disturbances w, d_1, d_2 to the residuals e_1, e_2. From (7) and (8),

$$\dot{\hat{x}}_1 = A\hat{x}_1 + B\hat{x}_2 + Bu - F_1C(\hat{x}_1 - x_1) \tag{12}$$
$$\dot{\hat{x}}_2 = -F_2C(\hat{x}_1 - x_1). \tag{13}$$

And from (2)−(12), we obtain

$$\begin{aligned} &\dot{x}_1 - \dot{\hat{x}}_1 \\ &= A(x_1 - \hat{x}_1) - B\hat{x}_2 + Bw + Bd_1 + F_1C(\hat{x}_1 - x_1) \\ &= (A - F_1C)(x_1 - \hat{x}_1) - B\hat{x}_2 + Bw + Bd_1. \end{aligned} \tag{14}$$

From (13) and (14),

$$\dot{\xi}_1 = (A - F_1C)\xi_1 - B\hat{x}_2 + Bw + Bd_1 \tag{15}$$
$$\dot{\hat{x}}_2 = F_2C\xi_1, \tag{16}$$

where $\xi_1 = x_1 - \hat{x}_1$.

Moreover, (10) and (11) are described by

$$e_1 = C\xi_1 \tag{17}$$
$$e_2 = -\hat{x}_2 + d_2 + w. \tag{18}$$

Thus, the error system is obtained as

$$\begin{bmatrix} \dot{\xi}_1 \\ \dot{\hat{x}}_2 \end{bmatrix} = \begin{bmatrix} A - F_1C & -B \\ F_2C & 0 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \hat{x}_2 \end{bmatrix} + \begin{bmatrix} B & B & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} w \\ d_1 \\ d_2 \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & -I \end{bmatrix} \begin{bmatrix} \xi_1 \\ \hat{x}_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ I & 0 & I \end{bmatrix} \begin{bmatrix} w \\ d_1 \\ d_2 \end{bmatrix}, \tag{20}$$

and the transfer function matrix is given by

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} sC\Phi(s)B & sC\Phi(s)B & 0 \\ I - F_2C\Phi(s)B & -F_2C\Phi(s)B & I \end{bmatrix} \begin{bmatrix} w \\ d_1 \\ d_2 \end{bmatrix}, \tag{21}$$

where $\Phi(s) = (s^2I - (A - F_1C)s + BF_2C)^{-1}$.

4. APPLICATION TO INJECTION UNIT

4.1 Analysis of transfer characteristics for injection unit

Let us concretely examine the frequency characteristics for the injection unit, based on the analysis of the previous section. The injection unit is described by

$$\dot{x}_1 = \frac{1}{J}(u + w - Dx_1 + d_1). \tag{22}$$
$$y_1 = x_1 \tag{23}$$

This equation corresponds to equations (2) and (3) with $A = -D/J, B = 1/J, C = 1$. If we denote the observer gain as $[F_1, F_2] = [g_1, g_2]$, then

$$\Phi(s) = \frac{1}{(s^2 + (D/J + g_1)s + g_2/J)}, \tag{24}$$

and equation (21) becomes

$$e_1 = \frac{s\Phi(s)}{J}(w + d_1) \tag{25}$$
$$e_2 = (1 - \frac{g_2\Phi(s)}{J})w - \frac{g_2\Phi(s)}{J}d_1 + d_2. \tag{26}$$

The characteristic equation (9) becomes

$$s^2 + (\frac{D}{J} + g_1)s + \frac{g_2}{J} = 0. \tag{27}$$

We give the observer gain as

$$g_1 = \frac{2\zeta\omega_n J - D}{J}, \tag{28}$$
$$g_2 = J\omega_n^2 \tag{29}$$

so that (27) has the roots of the 2nd order standard form given by

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0. \tag{30}$$

Substitution of the observer gain into (25) and (26) gives

$$e_1 = G_1(s)(w + d_1) \tag{31}$$
$$e_2 = G_2(s)w - G_3(s)d_1 + d_2, \tag{32}$$

where

$$G_1(s) = \frac{s}{J(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{33}$$
$$G_2(s) = \frac{(s^2 + 2\zeta\omega_n s)}{(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{34}$$
$$G_3(s) = \frac{\omega_n^2}{(s^2 + 2\zeta\omega_n s + \omega_n^2)}. \tag{35}$$

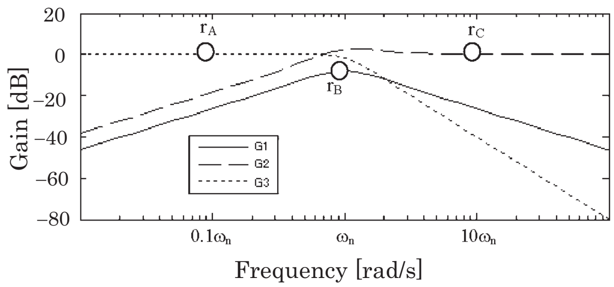

Fig. 4. Relation between $G_1(s)$,$G_2(s)$, and $G_3(s)$

4.2 Construction of fault detector

In this section, we construct the fault detector for the injection unit considering the following basic approach.

(a) The fault signals will be obtained by utilizing the frequency characteristics of the transfer functions $G_1(s)$,$G_2(s)$,$G_3(s)$.
(b) The frequency characteristics of the fault signals should be considered for fault isolation.

The gain characteristics of (33),(34),(35) are drawn in Figure 4. We can grasp that $G_1(s)$ has a band pass characteristic, $G_2(s)$ has a high pass characteristic, and $G_3(s)$ has a low pass characteristic, where ω_n is the natural frequency or the cut-off frequency. We choose three characteristic points shown by circles r_A, r_B, and r_C in Figure 4. We introduce the low pass filter $Q_A(s)$ to separate the signal of r_A, the band pass filter $Q_B(s)$ to separate the signal of r_B, and the high pass filter $Q_C(s)$ to separate the signal of r_C. Namely,

$$\begin{aligned} r_A &= Q_A(s)e_2 \\ &= Q_A(s)\{G_2(s)w - G_3(s)d_1 + d_2\} \end{aligned} \tag{36}$$

$$\begin{aligned} r_B &= Q_B(s)e_1 \\ &= Q_B(s)G_1(s)(w + d_1) \end{aligned} \tag{37}$$

$$\begin{aligned} r_C &= Q_C(s)e_2 \\ &= Q_C(s)\{G_2(s)w - G_3(s)d_1 + d_2\}. \end{aligned} \tag{38}$$

Since $Q_A(s)$ is low-pass and $G_2(s)$ is high-pass, the term $Q_A(s)G_2(s)w$ can be ignored, and (36) is approximated as

$$r_A \simeq Q_A(s)\{-G_3(s)d_1 + d_2\} \tag{39}$$

Similarly, since $Q_C(s)$ is high-pass and $G_3(s)$ is low-pass, the term $Q_C(s)G_3(s)d_1$ can be ignored, and (38) is approximated as

$$r_C \simeq Q_C(s)\{G_2(s)w + d_2\}. \tag{40}$$

Considering the above, we construct the fault detector shown in Figure 5. The upper part of the block diagram above the dotted line is the speed control system, and the lower part is the fault detector.

The occurrence of the fault is decided using the fault signals r_A,r_B,r_c, but the fault decision signals should be the logical outputs. So we set the threshold levels c_* to convert the continuous values to the logical values F_{r*} :

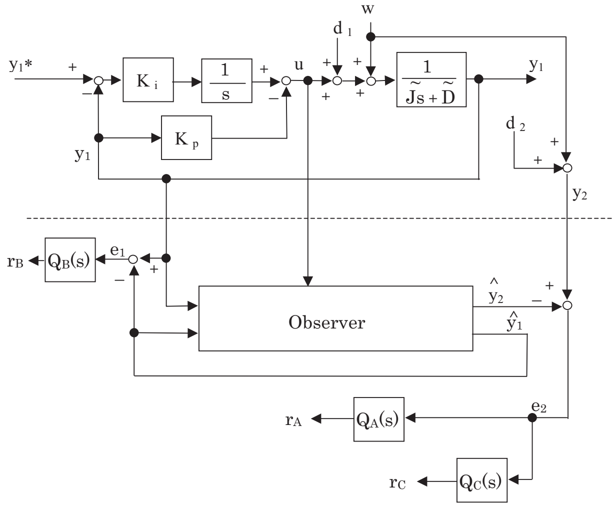

Fig. 5. Block diagram of fault detection system for injection unit

$$F_{r*} = \begin{cases} 1, |r_*| \geq c_* \\ 0, |r_*| < c_* \end{cases} \quad (* = A, B \ or \ C). \tag{41}$$

From (39),(37), and (40), when the signals d_1,d_2 and w are given to the system, the output of F_{rA},F_{r_B},F_{rC} will react as seen in Table 1. The notation 'Normal' means the normal process $d_1 = d_2 = w = 0$, and '-' means no reaction.

Table 1. Fault detection table

	F_{rA}	F_{rB}	F_{rC}
d_1	ON/OFF	ON/OFF	−
d_2	ON/OFF	−	ON/OFF
w	−	ON/OFF	ON/OFF
Normal	−	−	−

4.3 Fault detectability and isolatability

Detectability is the ability of discovering the occurrence of the faults d_1 or d_2 in cases in which it is not necessary to determine which faults occurred. Isolatability is the ability to distinguish the faults. From Table 1, if F_{rA} becomes ON, we know that the faults d_1 or d_2 occurred. Since F_{rA} is the output of the low-pass filter $Q_A(s)$, it has information only in the low frequency range. In other words, if d_1 and d_2 are small in the low frequency range, d_1 and d_2 cannot be detected from the fault decision signal F_{rA}. Thus, the faults d_1 and d_2 in the lower frequency range can be detected by F_{rA}, but cannot be isolated.

In the cases of F_{rB} and F_{rC}, the situation is different from that of F_{rA}. From Table 1, if F_{rB} becomes ON, we know that the fault d_1 or w occurred. However, we cannot know the fault occurred because w affects F_{rB}. The same problem is found in the case of F_{rC}. Therefore, in order to detect faults by F_{rB} and F_{rC}, the magnitude of w in the middle and the high frequencies must be negligibly small, respectively.

The disturbance w represents the reaction force, and the frequency band is usually less than 30 rad/s. On the other hand, the band of the speed control system is much higher than 30 rad/s in order to attenuate the disturbance effectively. The natural frequency of the speed control system, ω_v is usually 100 $\sim$ 200 rad/s, and hence the middle frequency range of d_1 caused by actuator faults will be observed at the point of ω_v. Therefore, the appropriate bandwidth of the observer is given by setting $\omega_n = \omega_v$ in the design of the observer. When the middle frequency range is ω_v, the magnitude of w is negligibly small in the middle and high frequencies.

We may conclude that in our case, F_{rA} and F_{rB} are not sensitive to w. Namely, $r_B \approx Q_B(s)G_1(s)d_1$ and $r_C \approx Q_C(s)d_2$. Thus, the fault d_1 in the middle frequency range can be detected and isolated by F_{rB}, and the fault d_2 in the high frequency range can be detected and isolated by F_{rC}.

4.4 Detectability of injection unit failures

From the previous section, we know that detectability depends on the main frequency range of d_1 and d_2. Here we discuss the failures of the injection unit from this viewpoint.

(1) The miss-alignment of the driving shaft, the torque constant fluctuation and the pulsation of the motor torque are represented by d_1 and they are large in the range from low to middle frequency. Therefore, these failures can be detected by F_{rA} and F_{rB}.
(2) The sensor gain fluctuation is proportional to the response of the reaction force, so it is large in the low frequency range. Therefore, this failure is detected by F_{rA}.
(3) The actuator failures and the sensor failures are both detected by F_{rA}, we cannot isolate these failures in the low-frequency band.
(4) The wire breakdown of the sensor causes the rapid change of the sensor output, so it is large in the high frequency range. Therefore, this failure is detected and isolated by F_{rC}.

These results are summarized in Table 2.

Table 2. Failure specification

Band	Failure Mode	Detector
Low	Sensor Gain Fluctuation	F_{rA}
Low $\sim$ Middle Freq.	Miss-alignment of Driving Shaft Pulsation of Motor Torque Torque Constant Fluctuation	F_{rA} and F_{rB}
High Freq.	Sensor Wire Breakdown	F_{rC}

5. VERIFICATION BY EXPERIMENT

In this section, we verify the validity of the proposed method by using experimental data of the actual injection unit. First, we design the FDI system. The plant parameters are $J = 0.0206$ kgf·m^2, $D = 0.0962$ N.m·s/rad. We set the natural frequencies of the speed control system and the observer as the same value $\omega_n = 123$ rad/s, and the damping ratios as the same value $\zeta = 0.68$. The post filters are $Q_A(s) = 10/(s + 10)$, $Q_B(s) = 184.5s/(s^2 + 184.5s + 15129)$, and $Q_C(s) = s/(s + 1000)$, whose gain characteristics are shown in Figure 6. The injection unit with

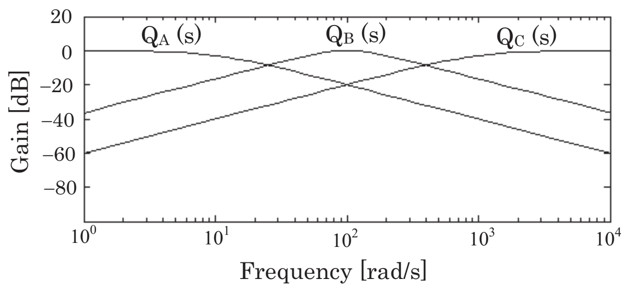

Fig. 6. Characteristics of post filters $Q_A(s)$,$Q_B(s)$,$Q_C(s)$

the speed control system is equipped with the disturbance observer, and the residuals e_1 and e_2 are obtained. The fault detection is executed to the residual data off-line.

Figure 7 shows the responses in the normal operation without fault where the injection unit injects the resin for the constant stroke. The four graphs show the set value y_1^* of the rotational speed of the motor, the rotational speed y_1 and its estimate $\hat{y}_1$, the motor torque τ, and the reaction-force sensor output y_2 and its estimate $\hat{y_2}$, respectively, where the dashed lines show the estimates. The response of the reaction force is much slower than that of the rotational speed. Actually, the frequency band of the reaction force is found to be lower than 30 rad/s by FFT analysis, and hence the condition on w for isolatability is satisfied.

Figure 8 shows the responses in the case of the torque constant fluctuation where the torque constant is 70 percent of the normal value. The machine operation is the same as that of the normal case. The fourth graph shows that the estimation error of the reaction force becomes considerably large. This suggests the occurrence of the sensor fault of the reaction force or actuator fault, but it is difficult to distinguish them from the graph. Let us apply our method.

Figure 9 shows the residual signals e_1 and e_2, and Figure 10 shows the fault signals and fault decision signals obtained from the residual signals, where the threshold levels are $c_A = 8, c_B = 5, c_C = 10$ in consideration for the fault signal levels in the normal case. The fault signals r_A and r_B are beyond threshold levels shown by dashed lines, and therefore, the fault decision signals F_{rA} and F_{rB} react as shown in the fourth and fifth graphs and F_{rC} does not react. This pattern of the decision signals corresponds to the first row of Table 1, which implies that the actuator fault d_1 has occurred. We have also tested the sensor fault, and the fault was detected successfully.

6. CONCLUSION

We have constructed a fault detector for an injection unit. This newly developed system allows the detection of actuator faults and sensor faults as well as the isolation of some of them as summarized in Table 2. The main frequency band of each fault is utilized to isolate the faults. The detector is composed of a disturbance observer in order to obtain residual signals, post filters to separate the specified frequency band of the residual signals, and threshold levels to obtain the decision variables. The injection unit has been improved and is becoming a more complex system much like a multi-axis drive system. In

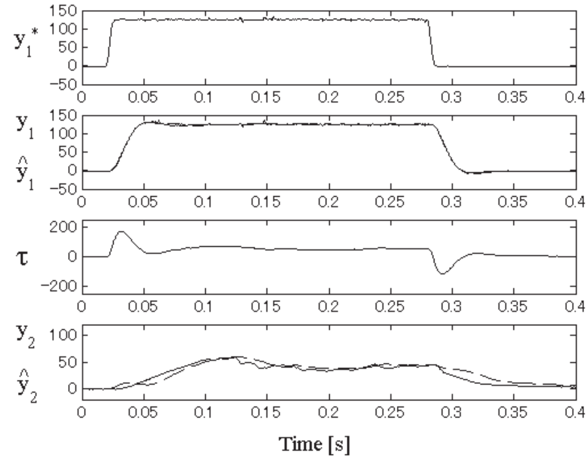

Fig. 7. Normal operation without fault

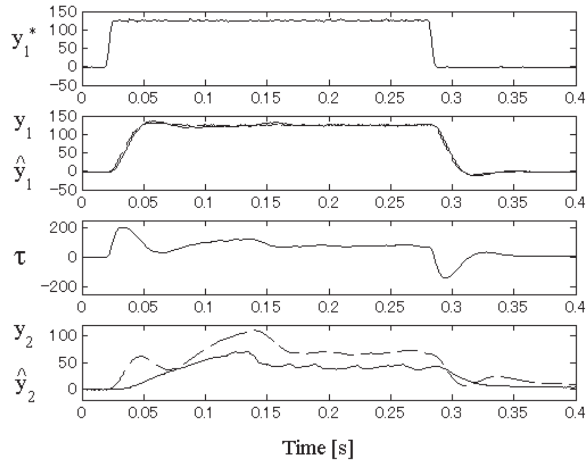

Fig. 8. Torque constant fluctuation

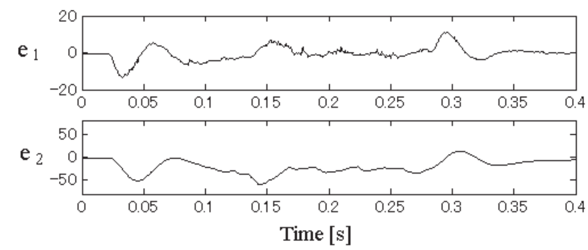

Fig. 9. e_1 and e_2 in the case of torque constant fluctuation

future study, we would like to apply our method to more complicated systems.

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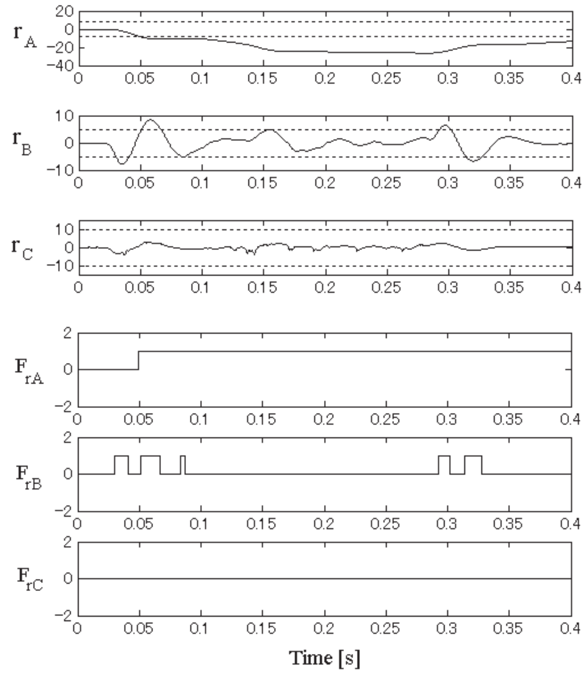

Fig. 10. Fault detection for torque constant fluctuation

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