Fault-tolerant Control System of Flexible Arm for Sensor Fault by Using Reaction Force Observer

Yu Izumikawa, Kazuhiro Yubai, and Junji Hirai
Department of Electrical and Electronic Eng.
Mie University
Email:izumi@ems.elec.mie-u.ac.jp, yubai@elec.mie-u.ac.jp, hirai@elec.mie-u.ac.jp

***Abstract*— In recent years, control system reliability has received much attention with increase of situations where computer-controlled systems such as robot control systems are used. In order to improve reliability, control systems need to have abilities to detect a fault (fault detection) and to maintain stability and control performance (fault tolerance). In this paper, we address the vibration suppression control of a one-link flexible arm robot. Vibration suppression is realized by an additional feedback of a strain gauge sensor attached to the arm besides motor position. However, a sensor fault (*e.g., disconnection*) may degrade the control performance and make the control system unstable at its worst. In this paper, we propose a fault tolerant control system for strain gauge sensor fault. The proposed control system has a strain gauge sensor signal observer based on the reaction force observer and detects the fault by monitoring the estimation error. After fault detection, the proposed control system exchanges the faulty sensor signal for the estimated one and switches to a fault mode controller so as to maintain the stability and the control performance. We apply the proposed control system to the vibration suppression control system of a one-link flexible arm robot and confirm the effectiveness of the proposed control system by some experiments.**

I. Introduction

In recent years, control system reliability has received much attention with increase of situations where robots are used. In order to improve reliability, control systems need to have abilities to detect a fault (fault detection) and to maintain stability and control performance (fault tolerance). In this paper, we address the vibration suppression control of a one-link flexible arm robot. In our control system, vibration suppression is realized by an additional feedback of a strain gauge sensor attached to the arm besides motor angle. However, a sensor fault (e.g., disconnection) may degrade the control performance and make the control system unstable at its worst. To avoid these situations, the control system needs to have abilities to detect faults as fast as possible and to execute appropriate action.

In this paper, we propose a fault tolerant control system for a disconnection fault of a strain gauge sensor. The proposed control system has a sensor signal observer to estimate the strain gauge sensor signal from only a motor angle in addition to disturbance observer for the tip position control and the vibration suppression. The reaction force observer is used to estimate the strain gauge sensor signal and to detect a fault from the estimation error. After fault detection, the proposed control system exchanges the faulty sensor signal for the estimated one and switches to a fault mode controller so as to maintain the stability and the control performance. The effectiveness of the proposed control system is confirmed by some experiments.

II. Mathematical Model of Flexible Arm Robot and Vibration Suppression Control Configuration

Bernoulli-Euler beam theory and some simplifications give the mathematical model from an input torque τ^{ref} to motor angle θ and to bending moment M_x written as eqs.(1) and (2), respectively. In these equations, higher order vibration modes more than the second one are neglected for simplicity of the controller design.

$$\frac{\theta(s)}{\tau^{ref}(s)} = \frac{1}{J_t}\left\{\frac{1}{s^2} + \frac{(\phi'(0))^2}{s^2+2\zeta\omega s+\omega^2}\right\} \quad (1)$$

$$\frac{M_x(s)}{\tau^{ref}(s)} = \frac{EI}{J_t}\left\{\frac{\phi'(0)\phi''(x)}{s^2+2\zeta\omega s+\omega^2}\right\} \quad (2)$$

x	:	distance from the root of arm
J_t	:	total moment of inertia
E	:	Young's modulus of arm
I	:	second moment of rectangular cross section
ζ	:	damping factor of arm
ω	:	resonant frequency of arm
ϕ	:	mode function

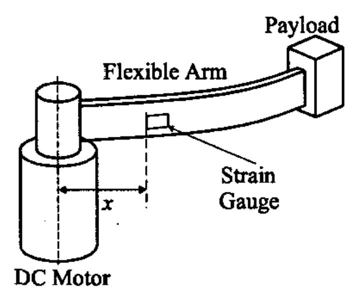

Fig. 1. Configuration of the one-link flexible arm

The strain gauge sensor is placed at the node of the second order vibration mode so that the strain gauge sensor mainly detects the first order vibration mode. The configuration of the one-link flexible arm is depicted in Fig.1. Vibration suppression control and position control are realized by feedbacking distortion of the arm M_x/EI and motor angle θ through an appropriate stabilizing controller C as shown in Fig.2[1],[2]. Disturbance observer is added to the flexible arm to compensate any disturbances and model uncertainties from the nominal system $1/J_t s^2$.

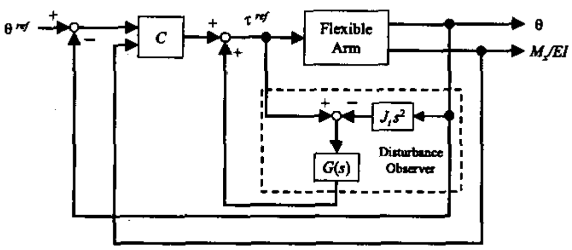

Fig. 2. Configuration of the vibration suppression control system

Since this control system has no alternate for encoder or actuator, the control system has to stop the operation immediately after fault is detected in encoder or actuator. However, strain gauge sensor is additional one to suppress the vibration, it is possible to reduce the degradation of the control performance by estimating a strain gauge sensor signal and controlling with the estimated one. The estimation of the strain gauge sensor signal M_x/EI from the motor angle θ is based on the reaction force observer, which is explained in the succeeding section.

III. Sensor Signal Observer

A faulty sensor signal cannot be used for the control since there is a big difference between the observed signal through the faulty sensor and the actual signal. However if the actual signal can be estimated by other signals obtained in the control system, stability and control performance may be maintained. In the proposed control system, we estimate the strain gauge sensor signal M_x/EI from only the motor angle θ by a sensor signal observer. This observer is composed of a reaction force observer and an adaptive gain. We explain the configuration of the sensor signal observer in this section.

A. Reaction Force Observer

We assume the disturbance torque τ^{dis} that acts on the motor is decomposed as follows:

$$\tau^{dis} = D\dot{\theta} + \tau^{fric} + \tau^{reac} \tag{3}$$

where D, τ^{fric}, and τ^{reac} are motor viscosity, friction torque, and reaction force, respectively. The reaction force is estimated by using the estimated disturbance torque $\hat{\tau}^{dis}$ as follows:

$$\hat{\tau}^{reac} = \hat{\tau}^{dis} - D\dot{\theta} - \tau^{fric} \tag{4}$$

where D and τ^{fric} are identified in advance[3]. The configuration of the reaction force observer is shown in Fig.3[4],[5]. τ^{reac} is estimated through a band pass filter.

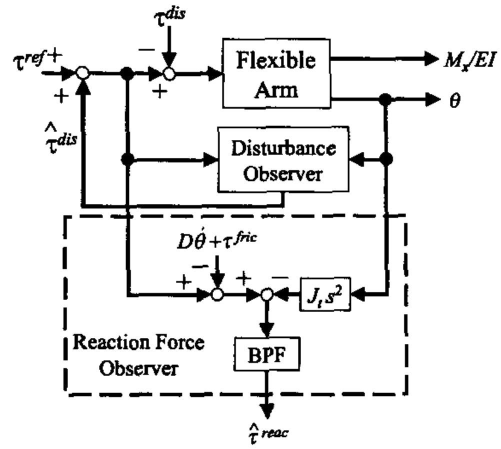

Fig. 3. Reaction force observer

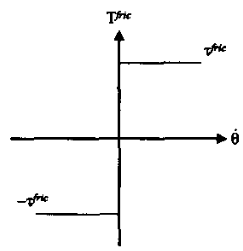

Fig. 4. Friction model I

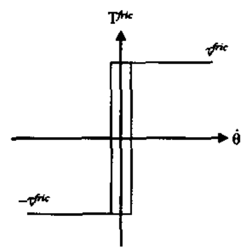

Fig. 5. Friction model II

This band pass filter is determined so as to pass around the resonant frequency of the controlled plant. Therefore this observer is able to estimate mainly the resonant component. τ^{fric} is determined by using the friction model shown in Fig.4. However, in the case of using friction model I, the estimated $\hat{\tau}^{reac}$ and control performance after fault detection may degrade because the sign of τ^{fric} changes rapidly by a sensor noise around $\dot{\theta} = 0$. In this paper, we adopt the relay model shown in Fig.5 as the friction model so as to avoid the effect of the sensor noise around $\dot{\theta} = 0$.

B. Adaptive Gain K

Assuming that the estimation speed of τ^{reac} is sufficiently fast and the damping factor ζ is 0 in eqs.(1) and (2). The transfer functions from τ^{ref} to $\hat{\tau}^{reac}$ and M_x/EI are written as eqs.(5) and (6).

$$G_{\hat{\tau}^{reac}} = -\frac{\phi'(0)^2 s^2}{\{1+\phi'(0)^2\}s^2 + \omega^2} \tag{5}$$

$$G_{M_x/EI} = \frac{\phi'(0)\phi''(x)/J_t}{\{1+\phi'(0)^2\}s^2 + \omega^2} \tag{6}$$

It is clear that $G_{\hat{\tau}^{reac}}$ and $G_{M_x/EI}$ have the same resonant frequency $\omega/\sqrt{1+\phi'(0)^2}$, and that $\hat{\tau}^{reac}$ and M_x/EI are dominated by the same frequency component. Therefore, M_x/EI can be approximated by multiplying an appropriate gain K to $\hat{\tau}^{reac}$. The gain K is calculated at the resonant

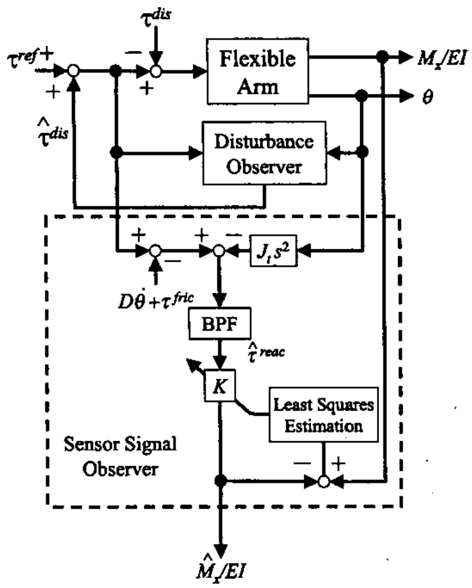

Fig. 6. Sensor signal observer

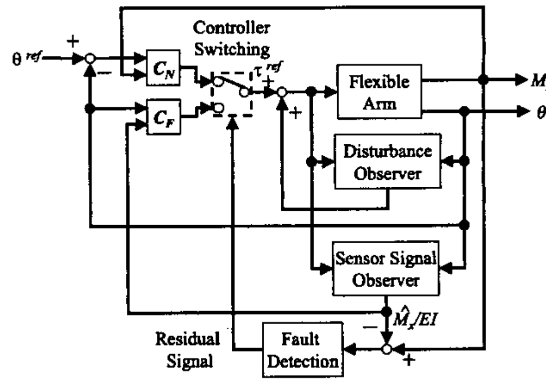

Fig. 7. Proposed fault tolerant control system

frequency $\omega/\sqrt{1+\phi'(0)^2}$ as shown in eq.(7).

$$K = \frac{\phi''(x)\{1+\phi'(0)^2\}}{J_t\omega^2\phi'(0)^2} \quad (7)$$

Since K includes plant parameters such as J_t and ϕ, the plant deviation cause to poor estimation of M_x/EI. Hence we introduce the adaptation of K, and adopt least squares estimation as the adaptation algorithm of K shown in eqs.(8) and (9)

$$K(k+1) = K(k) + l(k+1)\{M_x/EI - \hat{M}_x/EI\} \quad (8)$$

$$l(k+1) = \frac{\rho\tau^{reac}(k)}{1+\rho(\tau^{reac}(k))^2} \quad (9)$$

where ρ is adaptive gain. The configuration of the sensor signal observer is shown in Fig.6. In this observer, K is updated only while there is no fault because the wrong information is obtained after the sensor fault occurs.

IV. Fault Tolerant Control System for Strain Gauge Sensor Fault

A. Fault Detection and Fault Tolerant Control Scheme

It is necessary to set up the residual signal, which is the index of fault detection, to detect the sensor fault. In this paper, we assume the faulty sensor signal deviates largely from the normal one at disconnection fault. Therefore, we adopt an estimation error between the sensor signal M_x/EI and the estimated value $\hat{M}_x/EI$ as the residual signal. Fault detection based on residual signal has been developed in many literatures[6],[7],[8],[9],[10]. The residual signal should be nearly zero during fault-free, and take nonzero under faulty situation. The fault is detected when the residual signal exceeds the prespecified threshold.

After sensor fault occurs, the faulty sensor signal must be interrupted because the wrong information is obtained through the faulty sensor. This interruption leads to severe degradation of the control performance, especially of the vibration suppression performance. To maintain the control performance after fault detection, the control system exchanges the faulty sensor signal for the estimated one[11], and switches from the normal mode controller C_N to the fault mode controller C_F. The configuration of the proposed fault tolerant control system is shown in Fig.7.

B. Controller Design

Loop Shaping Design Procedure (LSDP) is adopted to design C_N and C_F. LSDP is based on shaping of open-loop characteristics and has the advantage that frequency weighting functions are determined easily in comparison with H_∞ control. Moreover, since both input and output sensitivity can be considered simultaneously, LSDP is suitable for the controlled plant that has the bad condition number. The design procedure is shown as below:

1) Shape the open-loop characteristics to be the desired one by using a precompensator W_{pre} and a post-compensator $W_{post} = [W_2^T,\ W_3^T]^T$.
2) Synthesize the stabilizing controller C_∞ for the augmented plant $G_s = W_{post}PW_{pre}$, whose state space matrix is (A,B,C,D), by solving the Riccati equations shown in eqs.(10) and (11)

$$X(A-BR^{-1}D^TC)+(A-BR^{-1}D^TC)^TX - XBR^{-1}B^TX + C^T\tilde{R}^{-1}C = 0 \quad (10)$$

$$(A-BD^T\tilde{R}^{-1}C)Y + Y(A-BD^T\tilde{R}^{-1}C)^T - YC^T\tilde{R}^{-1}CY + BR^{-1}B^T = 0 \quad (11)$$

where

$$R = I + D^TD \quad \tilde{R} = I + DD^T. \quad (12)$$

3) Construct the overall feedback controller as

$$C = W_{pre}C_\infty W_{post}. \quad (13)$$

Please refer to [12] for details of this procedure. The configuration of the augmented plant G_s is shown in Fig.8. P_M and P_S indicate transfer functions from τ^{ref} to θ and M_x/EI, respectively. Assuming that the estimation speed

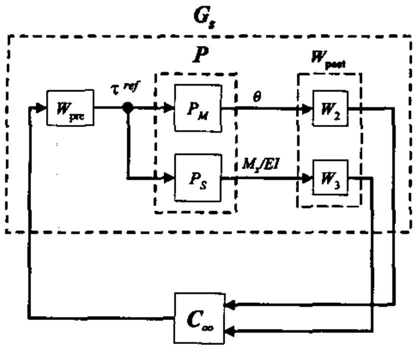

Fig. 8. Augmented plant G_s

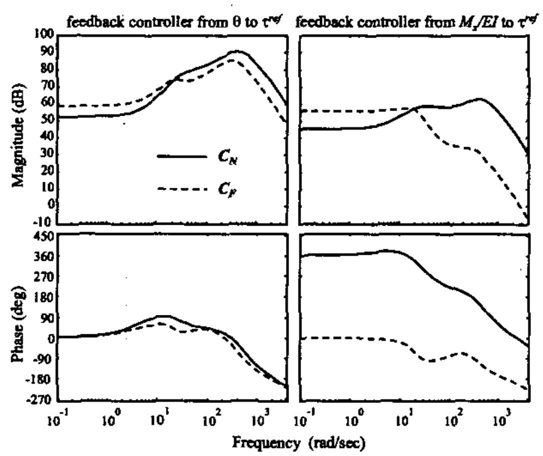

Fig. 9. Bode diagram of C_N and C_F

of the disturbance observer is sufficiently fast, the transfer functions P_M and P_S can be regarded as shown in eq.(14).

$$P_M = \frac{1}{J_t s^2}, \quad P_S = \frac{1}{J_t} \frac{\phi'(0)\phi''(x)}{\{1+\phi'(0)^2\}s^2 + \omega^2} \tag{14}$$

W_{pre} is specified as the low pass filter to suppress the effect of sensor noise and W_2 and W_3 are specified as the phase lead compensators to extend the control band. By regarding the estimation error between M_x/EI and $\hat{M}_x/EI$ as the sensor noise, we design C_N and C_F based on the same controlled plant P and on the different postcompensator W_{3N} and W_{3F}, respectively. W_{pre}, W_2, W_{3N} and W_{3F} are specified as follows:

$$W_{pre} = \frac{300}{s+300}, \quad W_2 = \frac{31870s + 176598}{s+300},$$
$$W_{3N} = \frac{-3199s + 114069}{s+300}, W_{3F} = 200$$

W_{3F} is determined as a constant weighting which is lower than the DC-gain of W_{3N} since $\hat{M}_x/EI$ is contaminated by sensor noise. The bode diagram of C_N and C_F are shown in Fig.9. We confirmed that C_F has lower gain, especially from M_x/EI to τ^{ref}, than C_N in high frequencies.

C. Controller Switching

In our proposed control system, the feedback controller is switched after fault detection in order to maintain the control performance. It is desirable to keep continuity of τ^{ref} at the switching time because a discontinuous input signal (a bump) may cause to degradation of control performance. Therefore, an initial state of C_F should be set to appropriate value so that output of C_F coincides with that of C_N [13],[14].

The discrete time state space representation of C_F is written as eq.(15)

$$\begin{aligned} x_{C_F}(k+1) &= A_{C_F} x_{C_F}(k) + B_{C_F} y(k) \\ u_{C_F}(k) &= C_{C_F} x_{C_F}(k) + D_{C_F} y(k) \end{aligned} \tag{15}$$

where $x_{C_F} \in \Re^n$, $u_{C_F} \in \Re^m$ and y are controller states and output of C_F and the plant output. The initial states $x_{C_{F_0}}(t_c)$ at the switching time t_c are determined by using eq.(16).

$$x_{C_{F_0}}(t_c) = C_\nu^T (C_\nu C_\nu^T)^{-1} U_\nu \qquad (0 \le m\nu \le n) \tag{16}$$

where

$$U_\nu = \begin{bmatrix} u_{C_N}(t_c) - D_{C_F} y(t_c) \\ u_{C_N}(t_c) - 1) - D_{C_F} y(t_c - 1) \\ \quad + C_{C_F} A_{C_F}{}^{-1} B_{C_F} y(t_c - 1) \\ \vdots \\ u_{C_N}(t_c - \nu) - D_{C_F} y(t_c - \nu) \\ \quad + \sum_{\tau=1}^{\nu} C_{C_F} A_{C_F}{}^{\tau-\nu-1} B_{C_F} y(t_c - \tau) \end{bmatrix} \tag{17}$$

$$C_\nu = \begin{bmatrix} C_{C_F} \\ C_{C_F} A_{C_F}{}^{-1} \\ \vdots \\ C_{C_F} A_{C_F}{}^{-\nu} \end{bmatrix} \tag{18}$$

Such $x_{C_{F_0}}(t_c)$ enables u_{C_F} to coincide with u_{C_N}, which represents the output of C_N, from ν-step before. Generally, it is well-known that smooth switching can be achieved if ν is enough large. However, large ν causes to large computational effort, we specifies $\nu = 3$ for the 6th order controller considering both the computational effort and smooth switching.

TABLE I
PLANT PARAMETERS

J_t	0.8733	[kg·m^2]
E	7.03×10^{10}	[N/m^2]
I	2.667×10^{-10}	[m^4]
ω	22.93	[rad/s]
D	9.7654	[Nm/rad/s]
τ^{fric}	9.1130	[Nm]
$\phi'(0)$	0.8446	
$\phi''(x)$	-8.8846	
ζ	0.0129	

V. Experimental Results

In order to verify the effectiveness of the proposed control system, we have performed some experiments. Plant parameters are listed in Table I.

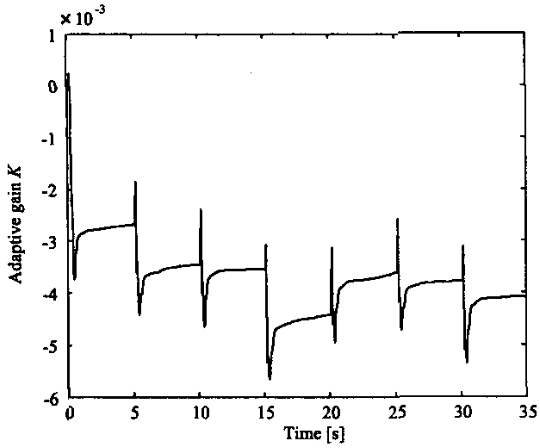

Fig. 10. Transition of K

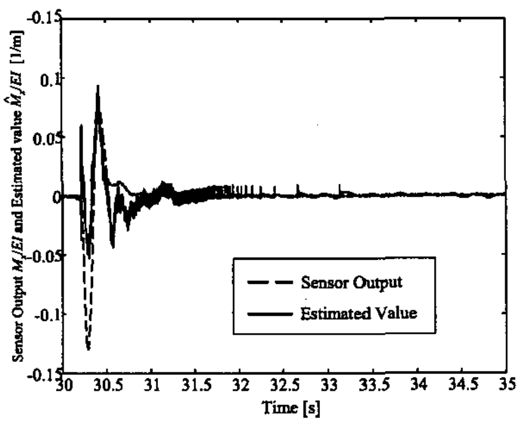

Fig. 11. Estimation of strain gauge sensor signal M_x/EI

A. Sensor Signal Estimation Result

Firstly, we have performed the strain gauge sensor signal estimation by the sensor signal observer. The initial value of K is set to 0. The transition of K and the result of the sensor signal estimation after convergence of K are depicted in Figs.10 and 11, respectively. From these results, the gain K converges to the steady value K_0 with a little variation, and the strain gauge sensor signal is estimated well by the sensor signal observer after convergence of K.

B. Fault detection and fault tolerant control result

Secondly, we have simulated disconnection fault of the strain gauge sensor during control. The reference θ^{ref} is filtered step input. In this experiment, disconnection fault occurs virtually at 10.35[s]. The faulty sensor indicates 1.0[1/m] after the disconnection fault occurrence. The threshold is set to ± 0.2[1/m] for the disconnection fault. Initial value of adaptive gain K is set to the value that is obtained in the previous experiment.

Experimental results are depicted in Figs.12, 13, 14 and 15. Figure 12 shows the residual signal. The residual signal is nearly equal to zero when there is no fault. After fault occurs, the residual exceeds the threshold, and it is confirmed that the sensor fault detection can be achieved.

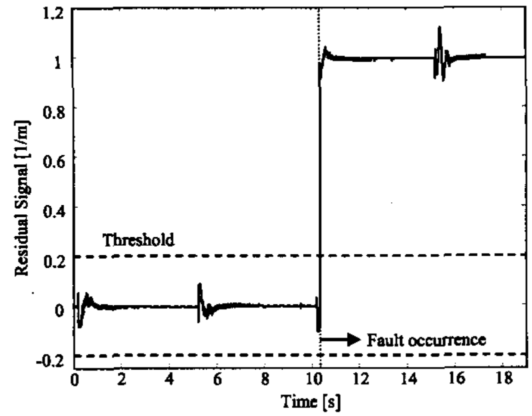

Fig. 12. Residual signal

Torque reference τ^{ref} around the fault occurrence is shown in Fig.13. In Fig.13, the small bump is observed at the switching time. However, if $x_{C_{F_0}}$ is not set (i.e. $x_{C_{F_0}} = 0$), the control system stops the operation since τ^{ref} exceeds torque limiter (about 1.1[Nm]).

Figures 14 and 15 represent motor angle θ and the distortion of arm M_x/EI, respectively. In Figs.14 and 15, no-switching case and the case using friction model I in the sensor signal observer are included together with the proposed case for comparison. In no-switching case, only the interruption of the faulty sensor signal is performed. The tracking performance associated with motor angle θ has little degradation but the vibration suppression performance much degrade in no-switching case. In the case of using friction model I, though the vibration suppression performance is maintained after fault occurrence, the vibration is observed after 17[s]. This vibration is caused by the estimation error of τ^{fric}. The rapid change of the sign of the estimated τ^{fric} by friction model I is observed, and it causes to the vibration after 17[s]. On the other hand, the vibration suppression performance is improved in the proposed case by using the friction model II. These results show that the proposed control system maintains the overall performance and is not affected by the sensor noise.

VI. Conclusion

In this paper, we proposed the fault tolerant control system against the strain gauge sensor fault. In the vibration suppression control system of the one-link flexible arm, we designed the sensor signal observer based on the reaction force observer in order to estimate the strain gauge sensor signal and detect the strain gauge sensor fault. In this observer, we adopt the relay type friction model to suppress the effect of the sensor noise. By exchanging the faulty sensor signal for the estimated one and switching to the fault mode controller, the stability and the vibration suppression performance were maintained. The effectiveness of the proposed control system was confirmed by some experiments.

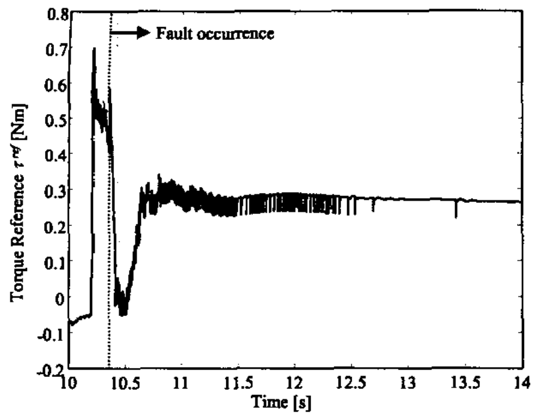

Fig. 13. Torque reference τ^{ref}

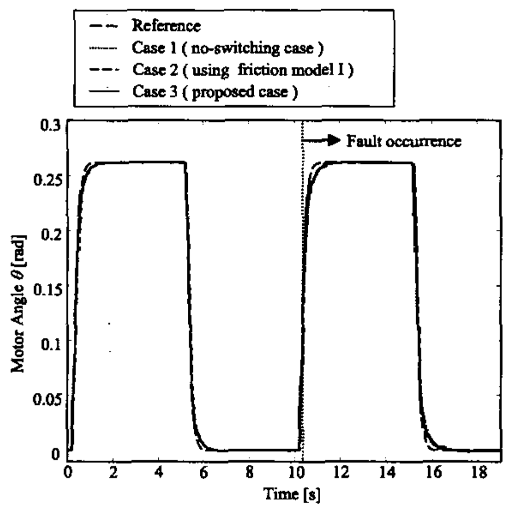

Fig. 14. Motor angle θ

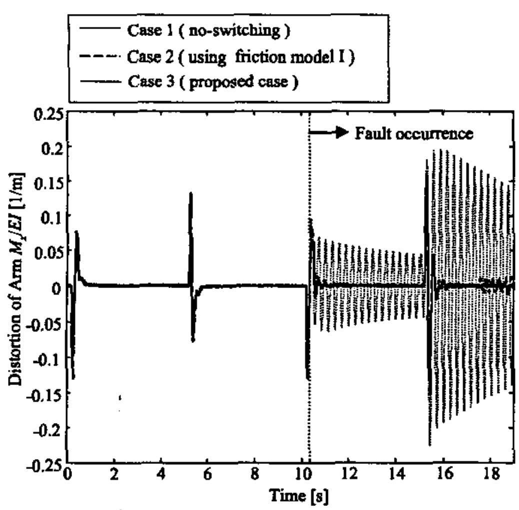

Fig. 15. Distortion of arm M_x/EI

REFERENCES

[1] Atsushi Inoue, Satoshi Komada, and Takamasa Hori, "Control of Flexible Arms by Bending Moment Considering Second Mode Vibration", national convention record IEEJ -industry applications society-, vol.1, no.128, pp.403-404, 1999. (in Japanese)

[2] Satoshi Komada, Kenji Ohta, Muneaki Ishida, and Takamasa Hori, "Trajectory Control of Flexible Arms Using Vibration Suppression Control by First Order Lag Strain Signal Feedback", Proceedings of the 2nd Asian Control Conference, July 22-25, 1997, Seoul, pp.185-188.

[3] Ichiro Awaya, Yoshiki Kato, Yuzi Ohta, Iwao Miyake, and Masami Ito, "Parameter Identification Method for Motion Systems with Unknown Coulomb Friction", The Japan Society of Mechanical Engineers Journal Series C, vol.59, no.11, pp.108-114, 1993. (in Japanese)

[4] Kazuaki Yuki, Toshiyuki Murakami, and Kouhei Ohnishi, "Vibration Control of a 2 Mass Resonant System by the Resonance Ratio Control", IEEJ Transactions on Industry Applications, vol.113-D, no.10, pp.1162-1169, 1993. (in Japanese)

[5] Masaru Kino, Noboru Morita, Toshiyuki Murakami, and Kouhei Ohnishi, "A Vibration Suppression Control of Flexible Manipulator by Estimated Reaction Torque and Multiple Acceleration Feedback", IEEJ Transactions on Industry Applications, vol.119-D, no.12, pp.1477-1484, 1999. (in Japanese)

[6] Xianchun DING and Paul M. FRANK,"Fault detection via factorization approach", Systems and Control Letters, 14, pp.431-436, 1990.

[7] Hiroyuki Yamaguchi, Masataka Osawa, Norio Iwama, and Masaki Yamamoto,"The Estimation of Ambiguous Change in 4WS Control System Using Failure Detection Filter", The Japan Society of Mechanical Engineers Journal Series C, vol.62, no.4, pp.121-128, 1996. (in Japanese)

[8] H. Noura, T. Bastogne, V. Dardinier-Maron, "A General Fault-Tolerant Control Approach: Application to a Winding Machine", in Proc. IEEE Int. Conf. Decision and Control, pp.3575-3580, 1999

[9] Arun T. Vemuri,"Sensor Bias Fault Diagnosis in a Class of Nonlinear Systems", IEEE Transactions on Automatic Control, vol.46, no.6, June, 2001, pp.949-954.

[10] Xiaodong Zhang, Marios M. Polycarpou, and Thomas Parisini,"A Robust Detection and Isolation Scheme for Abrupt and Incipient Faults in Nonlinear Systems", IEEE Transactions on Automatic Control, vol.47, no.4, April, 2002, pp.576-593.

[11] Rolf Isermann, Ralf Schwarz, and Stefan Stölzl, "Fault-Tolerant Drive-by-Wire Systems", IEEE Control Systems Magazine, vol.22, no.5, 2002, pp.64-81.

[12] Duncan McFarlane, and Keith Glover, "A Loop Shaping Design Procedure Using H_∞ Synthesis", IEEE Transactions on Automatic Control, vol.37, no.6, June, 1992, pp.759-769.

[13] Alan B. Arehart, and William A. Wolovich, "Bumpless Switching in Hybrid Systems", Hybrid systems, pp.1-17, 1996.

[14] Hayato Komatsu, Tadanao Zanma, Tatsuya Suzuki, and Shigeru Okuma,"Switching of H_∞ Controllers under Constraints and Decision of Controller State at Instance of the Controller Switching", IEEJ Transactions on Electronics, Information and Systems Society, vol.121-C, no.12, pp.1897-1904, 2001. (in Japanese)