Interaction between a Fault-tolerant Flight Control System using Simple Adaptive Control and Pilot's Pitch Control

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***Abstract*— This paper deals with a fault-tolerant flight control system where the aircraft is manually controlled by pilots. Our previous research demonstrated that Simple Adaptive Control (SAC) with a PID compensator could automatically control an aircraft even after the dynamic characteristics change due to aircraft damage only under predetermined desired value. Now we focus on the interaction between the pilot's input and the adaptive controller. In this paper, we installed the adaptive controller in the flight simulator in order to check the basic performance of the developed system and the interaction in landing phases between the pilot's control input and the adaptive controller.**

***Index Terms*— Simple Adaptive Control, Fault-tolerant Flight Control , Human Pilot, Manual Control**

I. INTRODUCTION

Nowadays, air transportation achieves economic growth and development with the increasing demand expected over the next several decades. However, the accident rate of air transportation has remained flat for the last few decades. Therefore, the more departures and flight hours increase, the more the number of aircraft accidents increases [1]. Thus, many researchers have proposed fault-tolerant control systems in order to make air transportation safer and more reliable [2]–[4].

A basic fault-tolerant control system consists of failure detection, failure identification and reconfiguration of controller [5]. While this basic approach is easy to understand, it remains difficult to actually deal with unexpected failures. In order to cope with this difficulty, adaptive controllers have been investigated. The authors' group has developed Simple Adaptive Controllers with a PID compensator. This method is easy to apply as a complement to existing PID flight control systems and tuning of its parameters is not complicated. Our previous research demonstrated that Simple Adaptive Control (SAC) with a PID compensator could automatically control an aircraft even after the dynamic characteristics change due to aircraft damage.

In spite of the advances in autopilot systems, pilot's manual control is still required. Especially, at the landing phase pilot usually control manually since automatic landing systems impose strict requirements on the aircraft, airport, weather and crew [6]. Even in the manual control phase, a fault-tolerant control system is required when the dynamic characteristics change due to faults. In this case, interaction between the adaptive controller and the human pilot's desired maneuver must be investigated since the adaptive system changes the system dynamics during the flight. In this paper, a fault-tolerant system for supporting pilots during landing phase is proposed by using SAC with a PID compensator (PID-SAC). The remainder of this paper is organized as follows. Section II describes the outline of fault-tolerant system for pilots. Section III describes the control design of SAC. Section IV shows the simulation result, and Section V concludes this paper.

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II. FAULT-TOLERANT SYSTEM FOR PILOTS

A. Outline of simple adaptive control

Let us consider the following linear system:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (1)$$

$$y(t) = Cx(t) \quad (2)$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control input, and $y(t) \in \mathbb{R}^m$ is the measurement output. In addition, Eqs. (1) and (2) are supposed to satisfy the Almost Strictly Positive Real (ASPR) condition.

In this paper, we define the following linear system as the reference model.

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t) \quad (3)$$

$$y_m(t) = C_m x_m(t) \quad (4)$$

where $x_m(t) \in \mathbb{R}^{n_m}$, $u_m(t) \in \mathbb{R}^m$, and $y_m(t) \in \mathbb{R}^m$, and we assume $n_m \leq n$. Even if the parameters of the system in Eqs. (1) and (2) are unknown, we can find a control input $u(t)$ which drives the plant output $y(t)$ to the reference model output $y_m(t)$, only when the ASPR condition is satisfied [7]. In this case, the control input is given by

$$u(t) = K(t)z(t) \quad (5)$$

$$z(t) = [e(t)^T \quad x_m(t)^T \quad u_m(t)^T]^T \quad (6)$$

$$K(t) = [k_e(t)^T \quad k_{xm}(t)^T \quad k_{um}(t)^T]^T \quad (7)$$

$$e(t) = y(t) - y_m(t) \quad (8)$$

and shown in the block diagram in Fig. 1. Since the typical aircraft dynamics equations are not ASPR, a parallel feed-forward compensator (PFC) is added. Details can be found in [7].

We use the integral adjustment rule for adapting the control gains.

$$\dot{K}(t) = -e(t)z(t)^T \Gamma_I - \sigma K(t) \quad (9)$$

where σ is a constant in order to avoid the burst phenomena, and $\Gamma_I \in \mathbb{R}^{(n_m+2m)\times(n_m+2m)}$ is an adaptation rate.

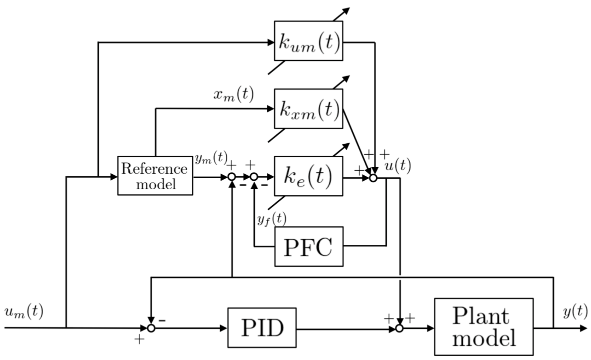
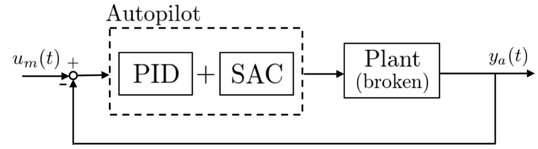
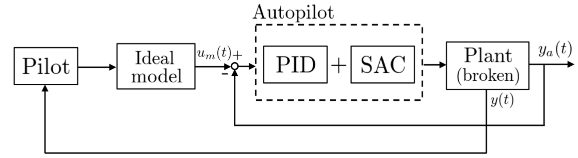


Fig. 1. The structure of SAC system with PID compensator.



(a) Basic fault-tolerant system [3], [4].



(b) Proposed system.

Fig. 2. The structure of SAC system with Pilots.

B. Fault-tolerant system with pilots

Figure 2 shows the structure of the fault-tolerant system with pilots. This proposed system has two merits, compared to the conventional system.

- Pilots can determine the desired value $u_m(t)$ in flight, which may enable us to use the proposed system in landing phases.
- By adjusting the ideal model appropriately, pilots can feel comfortable to control the aircraft, even after faults occur on the aircraft.

In this paper, we use the following linearized longitudinal equation of motion as the ideal model.

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) \tag{10}$$

$$A_i = \begin{bmatrix} X_u + X_{\dot{w}} Z_w & X_w + X_{\dot{w}} Z_w & -g(\cos\theta_0 + X_{\dot{w}} \sin\theta_0) & -W_0 + X_q + X_{\dot{w}}(U_0 + Z_q) \\ Z_u & Z_w & -g\sin\theta_0 & U_0 + Z_q \\ 0 & 0 & 0 & 1 \\ M_u + M_{\dot{w}} + Z_u & M_w + M_{\dot{w}} Z_w & -g M_{\dot{w}} \sin\theta_0 & M_q + M_{\dot{w}}(U_0 + Z_q) \end{bmatrix}$$

$$B_i = \begin{bmatrix} X_{\delta_e} + X_{\dot{w}} Z_{\delta_e} \\ Z_{\delta_e} \\ 0 \\ M_{\delta_e} + M_{\dot{w}} Z_{\delta_e} \end{bmatrix}$$

where symbols g, θ_0, U_0 and W_0 are the acceleration due to gravity, steady equilibrium pitch angle, steady equilibrium velocities in X- and Z-directions, respectively. The state vector $x_i(t)$ and the input vector $u_i(t)$ are given by

$$x_i(t) = [u(t) \;\; w(t) \;\; \theta(t) \;\; q(t)]^T \tag{11}$$
$$u_i(t) = \delta_e(t) \tag{12}$$

where $u(t)$, $w(t)$, $\theta(t)$, $q(t)$, and $\delta_e(t)$ are the velocities in X-and Z-direction, pitch angle, pitch rate, and elevator deflection. Note that these parameters are deviations from the trim (steady-state) condition.

By using this model, the ideal aircraft states are calculated from the pilot's control inputs. These ideal states are then used as reference values, to be tracked as closely as possible by the damaged aircraft using the PID-SAC system. This way, pilots will feel as if they are controlling the ordinary (undamaged) aircraft.

III. DESIGN OF SAC WITH A PID COMPENSATOR

A. Parallel feed-forward compensator

Since the typical aircraft dynamics equations are not ASPR, the PFC is designed to ensure that the augmented plant including PFC is ASPR. The augmented plant is defined as follows.

$$\dot{x}_a(t) = A_a x_a(t) + B_a u(t) \tag{13}$$
$$y_a(t) = y(t) + y_f(t) = C_a x_a(t) + D_a u(t) \tag{14}$$

$$A_a = \begin{bmatrix} A & 0 \\ 0 & A_f \end{bmatrix}, \quad B_a = \begin{bmatrix} B \\ B_f \end{bmatrix}$$

$$C_a = \begin{bmatrix} C & C_f \end{bmatrix}, \quad D_a = D_f$$

where the extended state vector is given by

$$x_a(t) = \begin{bmatrix} x(t) \\ x_f(t) \end{bmatrix}. \tag{15}$$

The transfer function of the augmented plant is given as follows.

$$G_a(s) = C_a(sI - A_a)^{-1} B_a + D_a \tag{16}$$

In order to use SAC, a PFC has to be designed to ensure that the transfer function $G_a(s)$ becomes ASPR. In this study, the transfer function of PFC $G_f(s)$ is defined as follows.

$$G_f(s) = \frac{0.01}{s+1} \tag{17}$$

B. Reference model and adjustment parameters

The reference model is selected to be

$$0.05 \cdot \dot{x}_m(t) = -x_m(t) + u_m(t) \tag{18}$$
$$y_m(t) = x_m(t) \tag{19}$$
$$G_m(s) = \frac{1}{0.05s + 1} \tag{20}$$

where $x_m(t) \in \mathbb{R}$, $u_m(t) \in \mathbb{R}$, and $G_m(s)$ is the transfer function of the reference model.

The adjustment parameters were set as follows.

$$\Gamma_I = \mathrm{diag}(3, 0.8, 0.8) \tag{21}$$
$$\sigma = 0.01 \tag{22}$$

C. PID compensator

The PID compensator $C_{PID}(s)$ is described as

$$C_{PID}(s) = 5.0 + 6.0\frac{1}{s} + 2.0s \tag{23}$$

where the parameters of the PID compensator were set so as to have high target tracking performance before the fault occurs.

IV. SIMULATION

A. Simulation under predetermined desired value

In order to verify the performance of the proposed system, we installed the adaptive controller in the flight simulator as shown in Fig. 3. At the first step of our study, we have done the simulation under predetermined desired value in order to check the target tracking performance and the convergence of the adaptive gains, since it directly leads to feeling of controlling an aircraft for pilots in the proposed fault-tolerant system.

The aircraft dynamics model is JAXA's Multi-Purpose Aviation Laboratory (Mupal-α), modified Do228-200. We assume the fault case where the elevator effectiveness reduces to 10% of its ordinary state at 80s. The reduction in elevator effectiveness is emulated by reducing the control gain in the flight simulator.

As with the previous research [3], [4], we compare the PID control, which is mainly used in the autopilot systems, with the PID-SAC. Figures 4 and 5 show the pitch angle response under the predetermined desired value. The dashed line shows the desired value, the solid line in Fig. 4 is the behavior of the PID only, and the solid line in Fig. 5 is the SAC with PID compensator. With the PID-only control, the overshoot of the pitch angle is too large after the reduction in elevator effectiveness. On the other hand, the PID-SAC improved control performance by adjusting the control gains to fault aircraft dynamics as shown in Figs. 5 and 6. The convergence of the adaptive gains was verified by running a 400s simulation under the same conditions (Fig. 7).

B. Simulation with a human pilot in the loop

The simulation environment is the same as in section IV-A, but this time the elevator control input is determined by a retired airline pilot, who is trying to track a reference pitch angle displayed on the cockpit instruments ("Flight Director").

Figure 8 shows the pitch angle response for the manual control, and Fig. 9 shows the response with the proposed fault-tolerant system. In Fig. 9, the solid line shows the response of the actual aircraft, the dashed line shows the pilot's desired pitch angle calculated from his elevator input using the ideal aircraft model, and the dash-dotted line shows the reference pitch angle indicated by the Flight Director. The difference between the desired value calculated from his elevator input and the reference pitch angle is due to the

Fig. 3. Flight simulator.

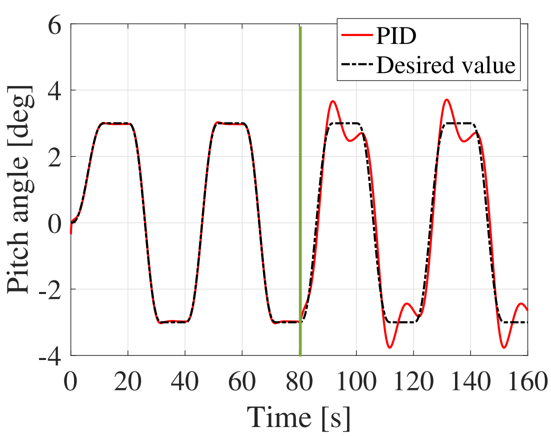


Fig. 4. Response of pitch angle.

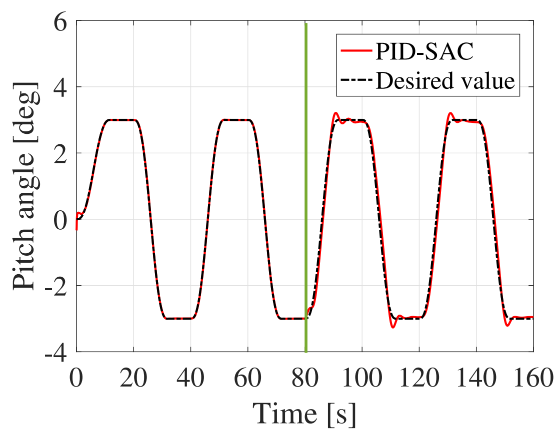


Fig. 5. Response of pitch angle.

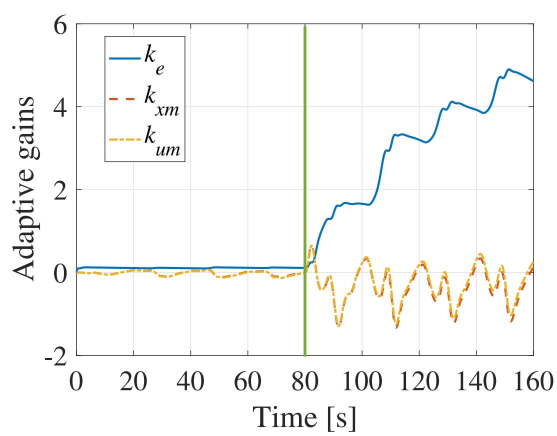


Fig. 6. Time history of adaptive control gains.

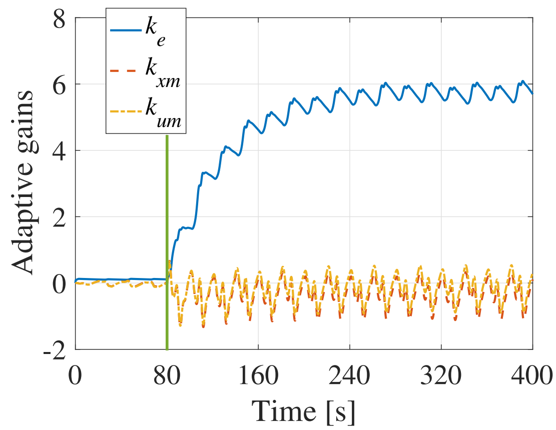


Fig. 7. Time history of adaptive control gains.

pilot's skill, and the difference between the desired value calculated from his elevator input and the response of the actual aircraft is due to the control performance of the PID-SAC (and the accuracy of the ideal model compared to the simulated model). In the unassisted manual control as shown in Fig. 8, the response of the aircraft is slower and the target following performance is worse due to the fault. However, the proposed system enables the pilot to track the reference value even after the fault (Fig. 9) . In addition, the behavior with the proposed fault-tolerant system after the fault is very similar to the behavior before the fault and also to the normal aircraft from Figs. 8 and 9.

Figure 10 shows the time history of pilot inputs. After the aircraft is stabilized by the pilot in about the first 20s, the behaviors of the pilot inputs are almost the same in both cases until the failure occurs. However, some differences are seen after the fault. In the manual control, pilot inputs are larger after the fault occurs, which means that the pilot dealt with the dynamic characteristic changes due to faults. In the simulation, the pilot noticed something different from usual flight and felt the trim condition changed. On the other hand, in the proposed method, pilot inputs almost don't change when the fault occurs. In the simulation, the pilot felt a slight change but did not mind. Therefore, by adapting the control gains to match with the fault aircraft dynamics in Fig. 11, the pilot feels as if he controls the undamaged aircraft after the fault occurs.

C. Simulation in landing phases

The final approach to landing can be divided into two phases (Fig. 12). In the first phase the pilot makes control adjustments to keep the aircraft on a constant descent path which is generally about 3 degrees. This phase will be referred to as the 'glide'. In the second phase the pilot makes the aircraft pitch up before touchdown in order to decrease the sink rate and land softly on the main gear. This maneuver

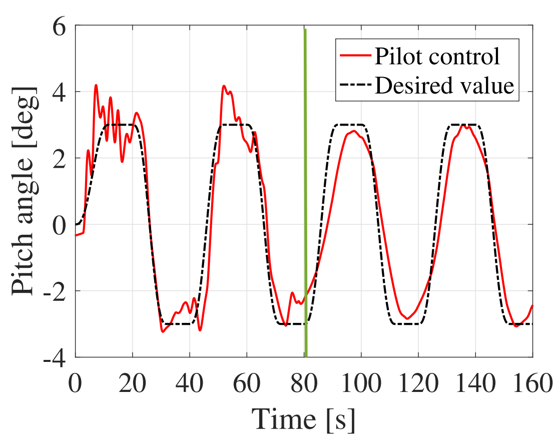


Fig. 8. Response of pitch angle.

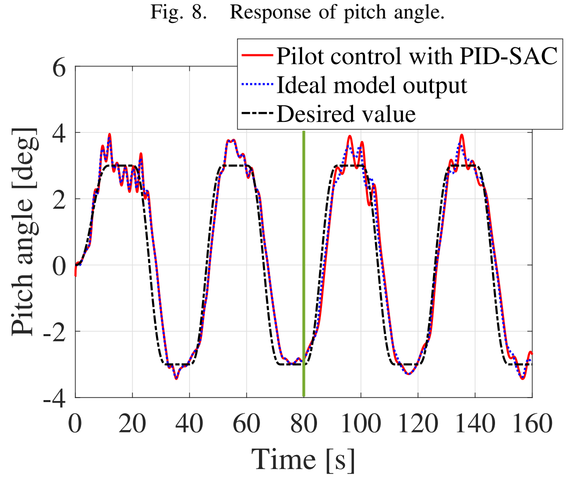


Fig. 9. Response of pitch angle.

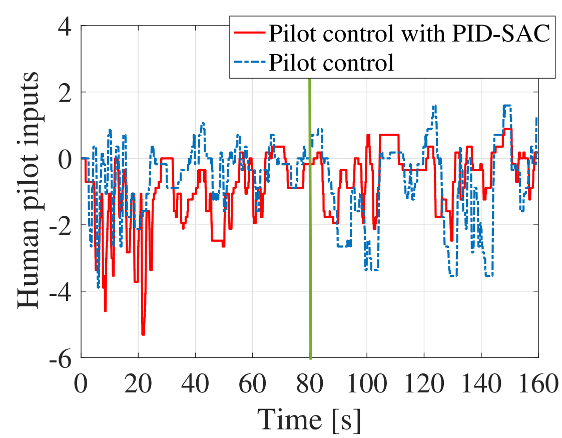


Fig. 10. Time history of pilot inputs.

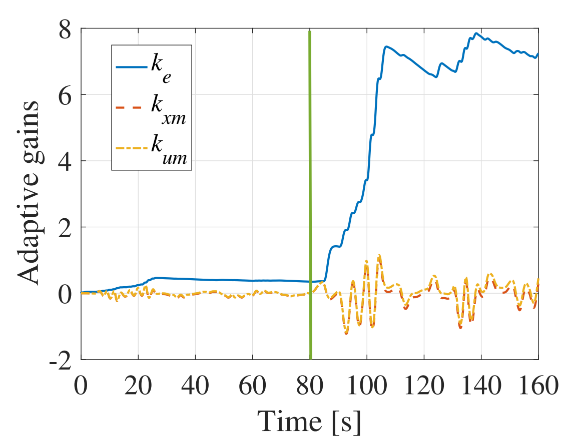


Fig. 11. Time history of adaptive control gains.

is called the 'flare'. The flare is important since a too late or too soft flare will result in a hard landing, which is bad for the landing gear and for passenger comfort, or even a crash. Thus, we assume the fault case where the elevator effectiveness reduces to 25% of its ordinary state shortly before the flare is performed. In the simulation, the fault occurs after 20s, the flare is performed at about 40s, and the throttle (engine power) of the aircraft is automatically controlled.

Figures 13 and 14 show the the pitch angle responses and the pilot inputs of the final approach to the landing. The solid line shows the pitch angle response for the manual control with the proposed fault-tolerant system, the dashed line shows the response for the unsupported manual control case, and the dash-dotted line shows the response of the ordinary landings without faults. As can be seen from Fig. 13, in the manual control case, the pitch angle at landing is 0.102 degrees, that is, the pilot couldn't make the aircraft pitch up to the ordinary pitch angle, which means the safety became worse since a negative pitch angle at landing may cause damage to the nose gear. From Fig. 14, we can see that the pilot inputs are different from the ordinary landing after the faults. In a real flight, the pilot wouldn't make such input in the flare being afraid to over-control, which may also lead to an accident. However, in the manual control with the PID-SAC, the behavior of the pilot inputs is almost not different from the ordinary landings after the faults by the PID-SAC system tracking the ideal model output (Figs. 15 and 16).

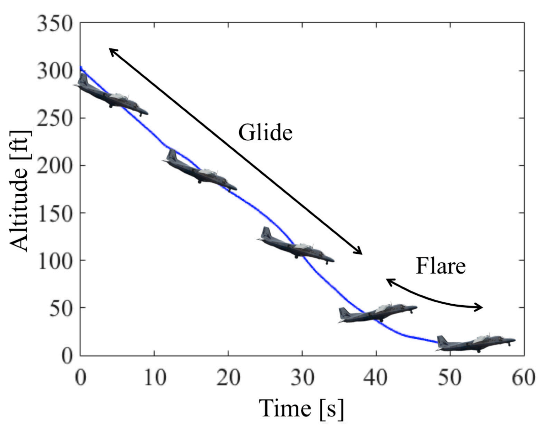


Fig. 12. In the final approach to landing, the pilot pitches up to arrest sink rate and land softly on the gear. This maneuver is called the flare.

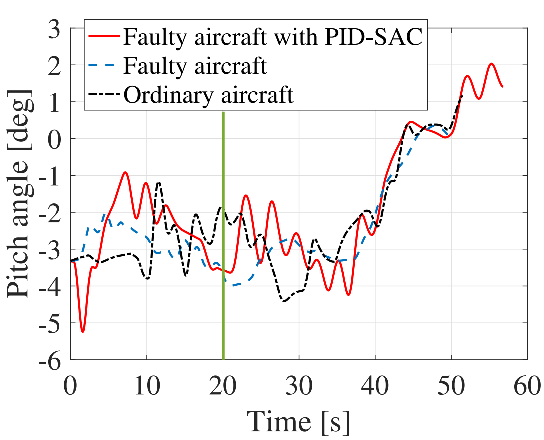


Fig. 13. Response of pitch angle.

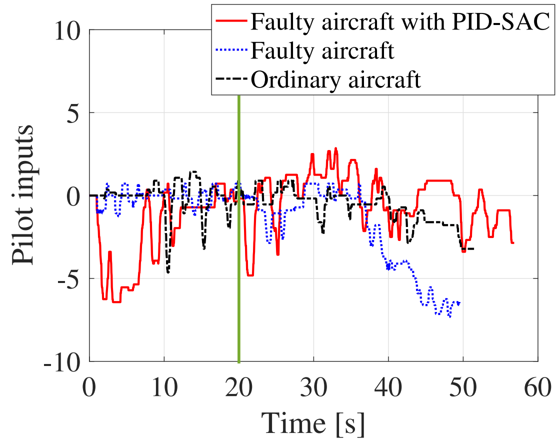


Fig. 14. Time history of pilot inputs.

At the beginning of the simulation, the response of the proposed method and the pilot inputs are different from those of the ordinary aircraft. This is considered to be due to the difference between the ideal model and the actual model. In this study, we use the linearized model under the steady level flight trim condition as the ideal model, so the adaptive system or the pilot have to adjust to the difference of the trim condition at the beginning of the simulation.

V. CONCLUSION

In this paper, we proposed a fault-tolerant flight control system using SAC with a PID compensator and analyzed the interaction between the adaptive control system and the pilot's pitch control. Once the system adapts to the faulty aircraft and the pilot inputs, the behavior of the faulty aircraft with the fault-tolerant system is very similar to the behavior of the ordinary aircraft by the PID-SAC tracking the ideal model output. This result suggests that the pilot feels as if he is controlling the ordinary aircraft even after the faults occur.

The key points to make the proposed fault-tolerant system more effective and reliable, are matching the ideal model

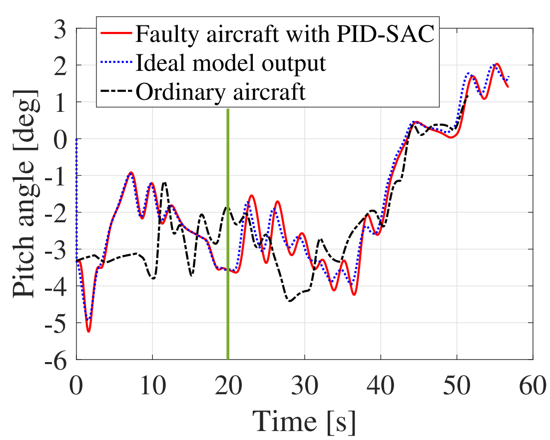


Fig. 15. Response of pitch angle.

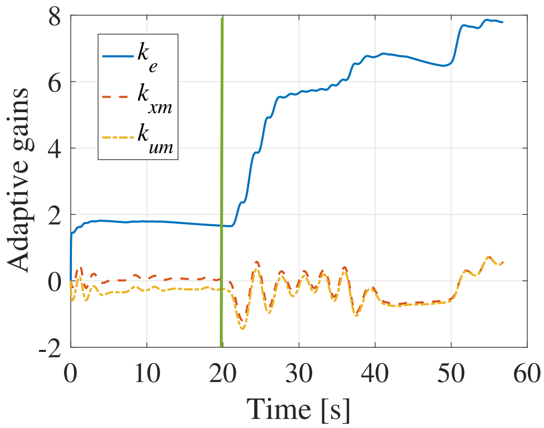


Fig. 16. Time history of adaptive gains.

and the actual aircraft dynamics accurately and setting the appropriate adaptation rate. Of course a large adaptation rate enable us to deal with the aircraft fault quickly. However, we wouldn't set a too large adaptation rate since it may lead the vibrational response of the aircraft, which means that the pilot can't control the aircraft comfortably by using the proposed system. Therefore, future works are considering an appropriate ideal model in order to obtain the comfortable aircraft control for the pilot even with a large adaptation rate.

VI. ACKNOWLEDGEMENT

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REFERENCES

[1] Boeing Commercial Airplane, "Statistical summary of commercial jet airplane accidents," Worldwide operations 1959-2013, 2013

[2] A. Belkharraz, and K. Sobel, "Simple adaptive control for aircraft control surface failures," IEEE transactions on aerospace and electronic systems, Vol.43, No. 2, pp. 600-611, 2007

[3] Y. Omori, and S. Suzuki, "Flight Test of Fault-Tolerant Flight Control System using Simple Adaptive Control with PID Compensator," Guidance, Navigation, and Control and Co-located Conference, AIAA, 2013

[4] T. Nishiyama, S. Suzuki, M. Sato, and K. Masui, "Simple Adaptive Control with PID for MIMO Fault Tolerant Flight Control Design," AIAA SciTech Forum, 2016

[5] C. Edwards, T. Lombaerts, and H. Smaili, "Fault Tolerant Flight Control," Springer, Apr 18, 2010

[6] K. Wien. "Plane Answers: When Do Pilots Use the Autopilot?," Online, May 2008. URL `http://gadling.com/2008/05/02/plane-answers-when-do-pilots-use-the-autopilot/`

[7] I. Barkana, "Simple Adaptive Control - A Stable Direct Model Reference Adaptive Control Methodology - Brief Survey," IFAC, 2007