31st Congress of the International Council
of the Aeronautical Sciences

Belo Horizonte, Brazil; September 09-14, 2018

FAULT-TOLERANT FLIGHT CONTROL SYSTEM WITH SIMPLE ADAPTIVE CONTROL CONSIDERING PILOT INPUT

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Keywords: *Simple Adaptive Control, Fault-Tolerant Flight Control, Human Pilot, Manual Control.*

Abstract

A piloted simulator evaluation is an important step for making a Fault-Tolerant Flight Control (FTFC) system more practical and reliable. Especially, in the case of an adaptive technique, conformance of the adaptive controller to the human pilot's intended maneuver must be investigated carefully since the overall control performance will be changed by the additional loop closed by the pilot. In this paper, we present a pilot in the loop simulation of Simple Adaptive Control (SAC) with a PID compensator. By SAC adjusting to the faulty aircraft dynamics, the proposed FTFC system reduces the pilot workload in emergency situations.

1 Introduction

A Fault-Tolerant Flight Control (FTFC) system is a backup technique for aircraft faults and damage, and recent researches on FTFC systems have improved the survivability of faulty aircraft [1, 2, 3, 4, 5]. A basic fault-tolerant control system consists of failure detection, failure identification, and reconfiguration of the controller [6]. 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 as a fault-tolerant flight controller.

The authors' group has developed Simple Adaptive Controllers with a PID compensator. This method is easy to apply to existing PID flight control systems and adjustment of tuning parameters is not complicated. In addition, this adaptive technique, in principle, does not need information from a Fault Detection and Isolation (FDI) scheme, which means that the controller can be reconfigured without knowledge of the faults and damage to the aircraft. Our previous simulations and flight experiments demonstrated that Simple Adaptive Control (SAC) with a PID compensator could automatically keep a faulty aircraft at a predetermined desired attitude.

The next task of our study is investigating the performance of the proposed FTFC system throughout not a predetermined desired attitude but various piloted flight maneuvers. This evaluation is an important task in order to make a FTFC system more practical and reliable. Especially, in the case of adaptive techniques, nominal control performance of a flight system will be changed by an external disturbance and an outer loop closed by a human pilot. This continuous change may impose additional workload on pilots even without faults. For these difficulties of adaptive techniques, flight control systems with an adaptive controller (such as SAC) have been mainly investigated in full-autopilot situations, not a pilot in the loop simulation [3, 4, 5, 7].

In this paper, we present a pilot in the loop simulation of SAC with a PID compensator (PID-SAC). In Ref. [8], we applied the proposed system to the aircraft longitudinal motion and piloted simulations were carried out in level flight

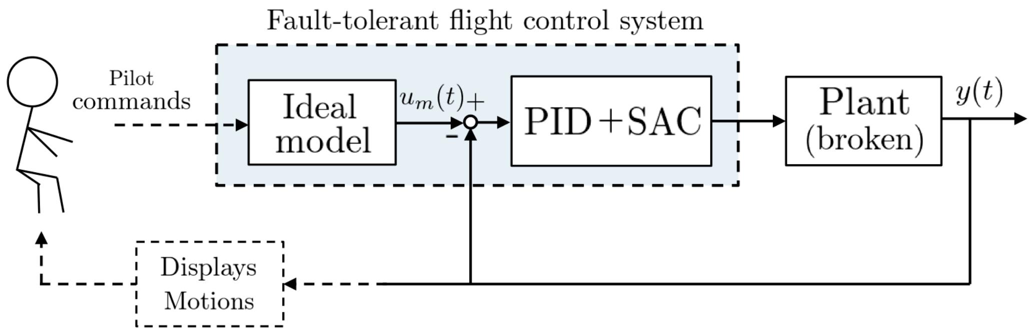


Fig. 1 The integrated FTFC system with an outer loop closed by the human pilot.

and the final approach to landing. On the other hand, this paper deals with the piloted evaluation of lateral motion, which is a more challenging task than the previous study since aircraft lateral motion is a MIMO system. In addition, the simulation is carried out even under disturbance by wind gusts. The results of this paper will show that the PID-SAC can cope with faults and assist manual control once the system adapts to the fault and pilot inputs.

The rest of this paper is organized as follows. Section 2 describes the FTFC system considering pilot inputs. Section 3 describes the piloted simulation results, and Section 4 concludes this paper.

2 Fault-Tolerant Flight Control system

2.1 Integrated FTFC system with pilot inputs

In modern aircraft, pilots control aircraft with the help of the electrical 'fly-by-wire' system. Based on the pilot control inputs and available measured signals, the flight computer calculates the required surface deflections and gives the appropriate electronic commands to all actuators. With the advances of computer performance, such computer-based (software-based) flight control systems provide multiple backups or redundancies to deal with aircraft faults and damage. However, in spite of the advances in autopilot systems, pilot's manual control is still required and particularly so in non-normal operations. Therefore, the interaction between pilot commands and the flight system's actions must be addressed carefully in the design of controllers since the integrated system is influenced by an additional closed loop including the human pilot.

Figure 1 shows the proposed FTFC system which is integrated with the pilot input. In the case of manual control, an outer loop is needed since pilots determine the desired aircraft state from the cockpit displays or motions of aircraft. In this paper, we propose a nominal model following SAC with PID controller. In order to support pilot manual control, we would like to know the pilot's intention without faults (even if the actual aircraft is damaged by faults). By using this ideal 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.

2.2 Ideal model

In this paper, we use the following linearized model as the ideal model.

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) \tag{1}$$

$$A_i = \begin{bmatrix} Y_v & W_0 + Y_p & -U_0 + Y_r & g\cos\theta_0 \\ L_v & L_p & L_r & 0 \\ N_v & N_p & N_r & 0 \\ 0 & 1 & \tan\theta_0 & 0 \end{bmatrix}$$

$$B_i = \begin{bmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \end{bmatrix}$$

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

$$x_i(t) = [v(t),\ p(t),\ r(t),\ \phi(t)]^T \quad (2)$$
$$u_i(t) = [\delta_a(t),\ \delta_r(t)]^T \quad (3)$$

where $v(t)$, $p(t)$, $r(t)$, $\phi(t)$, $\delta_a(t)$, and $\delta_r(t)$ are the velocities in Y-direction, roll rate, yaw rate, roll angle, aileron deflection and rudder deflection, respectively. Note that these parameters are deviations from the trim (steady-state) condition. The relation between coefficients $[\ \bullet\ ]_\beta$ and $[\ \bullet\ ]_v$ is given by $[\ \bullet\ ]_\beta = [\ \bullet\ ]_v/U_0$, where $\beta(t)$ is the sideslip angle.

Although nonlinear aircraft dynamics (e.g. the same dynamics of a flight simulator) may be the candidates for the ideal model, we select the linearized model for simplicity. In order to ensure satisfactory aircraft responses to the pilot inputs, some proportional gains have been added in the input and output channel of the ideal aircraft model.

In this study, the roll and sideslip angle, which are the outputs of the ideal model, are selected as the reference value to be tracked by the PID-SAC. Details of the reason and application to flight control are described in Section 2.4.

2.3 Outline of Simple Adaptive Control

Let us consider the following linear system:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (4)$$
$$y(t) = Cx(t) \quad (5)$$

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. (4) and (5) are supposed to satisfy the Almost Strictly Positive Real (ASPR) condition.

In this paper, we define the following linear system as the so called 'reference model' $G_m(s)$:

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t) \quad (6)$$
$$y_m(t) = C_m x_m(t) \quad (7)$$

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. (4) and (5) 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 [9]. In this case, the control input is given by

$$u(t) = K(t)z(t) \quad (8)$$
$$z(t) = [e(t)^T\ \ x_m(t)^T\ \ u_m(t)^T]^T \quad (9)$$
$$K(t) = [k_e(t)\ \ k_{xm}(t)\ \ k_{um}(t)] \quad (10)$$
$$e(t) = y(t) - y_m(t) \quad (11)$$

and shown in the block diagram in Fig. 2. Since the typical aircraft dynamics equations are not ASPR, a parallel feedforward compensator (PFC) is added. Details can be found in [9].

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

$$\dot{K}(t) = -e(t)z(t)^T\Gamma_I - \sigma K(t) \quad (12)$$

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.

2.4 Application of SAC to flight control

The author's group has applied SAC with PID controller to MIMO flight dynamics and the flight experiment results have been reported [4]. In Ref. [4], adaptive gains were updated for roll and yaw angle simultaneously. However, this method may not be appropriate for the fault tolerant flight

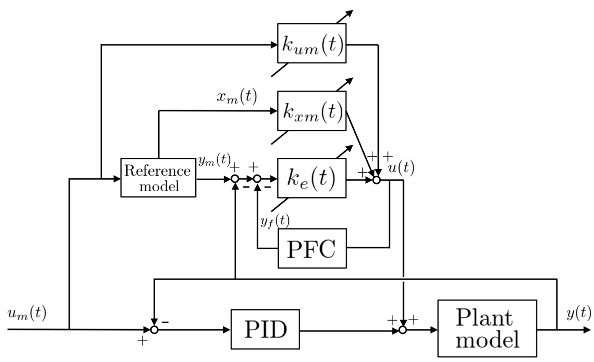


Fig. 2 The structure of SAC system with PID compensator.

controller considering pilot inputs. The reason is explained as follows.

In the case of pilot manual control, the roll and sideslip angle are mainly controlled by the aileron and rudder respectively. In addition, pilots firstly try to control the roll angle since the roll angle is the most inner loop in the flight dynamics. These facts suggest that adaptive gains of aileron inputs should be updated for only desired roll angle. This means that adaptive gains of aileron and rudder inputs are independently updated for roll and sideslip angle even in the case of MIMO lateral motion. Thus, the structure of SAC is a combination of two SISO systems, which means that in the case of the roll angle, SAC is applied for the transfer function from aileron input to roll angle, while another SAC takes care of the rudder to sideslip angle transfer function.

The reference models and adjustment parameters of the roll and sideslip angle are the same, and as follows.

$$0.05 \cdot \dot{x}_m(t) = -x_m(t) + u_m(t) \tag{13}$$

$$y_m(t) = x_m(t) \tag{14}$$

$$G_m(s) = \frac{1}{0.05s+1} \tag{15}$$

$$\Gamma_I = \mathrm{diag}(3, 0.01, 0.01) \tag{16}$$

$$\sigma = 0.01 \tag{17}$$

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

$$C_{PID}(s) = K_P + K_I \frac{1}{s} + K_D s \tag{18}$$

where the parameters of the PID compensator were set so as to have high target tracking performance before the fault occurs. The PID gains of the aileron input are $(K_P,\ K_I,\ K_D) = (3.0,\ 2.07,\ 0.5)$, and PID gains of the rudder input are $(K_P,\ K_I,\ K_D) = (8.0,\ 1.3,\ 0.03)$.

In this paper, we use the same PFC as in Ref. [4]. This PFC is designed via Iterative Linear Matrix Inequalities (ILMI). The idea of designing a PFC and the details of the ILMI algorithm are described in Ref. [2] and Ref. [10], respectively. Note that this PFC is designed only for the nominal plant model, which means that the ASPR condition may not be satisfied after the faults. Therefore, after designing the PFC for a nominal model, we confirmed that the PFC works appropriately for both the nominal and fault conditions through the ground and actual flight test [4].

Fig. 3 Flight simulator.

3 Pilot in the loop simulation

3.1 Simulation condition

Piloted simulation was carried out in a fixed-based flight simulator at The University of Tokyo (Fig. 3). In the experiment, we investigate the interaction between the SAC and the pilot's desired maneuver in the case of lateral directional motion, that is, the longitudinal motion is automatically controlled. The aileron and ruder are operated by a retired airline pilot. The aircraft dynamics model is JAXA's Multi-Purpose Aviation Laboratory (Mupal-α), a modified Do228-200.

We assume two fault cases (Table 1). The first is that the ailerons' effectiveness reduces to 20% of their ordinary state at 80s. The second is that both the aileron and rudder effectiveness reduce to 20% of their ordinary states at 80s. The reductions in aileron and rudder effectiveness are emulated by reducing the control gains and limits in the flight simulator. The pilot's task in the experiment is keeping the yaw angle 0 deg under moderate wind disturbance.

3.2 Time history anaylsis

The piloted simulation result in the case of Fault No. 1 is summarized in Fig. 4. Figure 4-(a) shows the time histories of a selection of the most important aircraft states. The dash-dotted line shows the manual control only case and the solid line is the manual control with the proposed FTFC system. In both cases, the behaviours of the aircraft states are similar before the faults occur on the aircraft. This fact suggests that the proposed FTFC system can work as usual aircraft dynamics for pilots.

Figures 4-(c) to (f) show the states related to the FTFC system. The FTFC system can track the ideal model output by adjusting to the faulty aircraft dynamics within the reduced deflection limits (Fig. 4-(c) and (d)). Adaptive gains for the aileron command mainly change in three parts: the beginning of the simulation, the timing of the fault occurrence, and at around 140s (Fig. 4-(e)). At the beginning of the simulation, the adaptive gains change in order to adjust to the pilot's desired maneuver. The second change of gains at about 80s is for adjusting to the faulty aircraft dynamics. The third adaptation at around 140s is due to the pilot's desired maneuver (see also the ideal model output in Fig. 4-(c)). When a stronger maneuver is required, larger adaptive gains are needed to relieve the pilot's workload, since the effectiveness of aileron reduces to 20% of its ordinary state. Adaptive gains for the rudder command are almost not different except for the beginning of the simulation (Fig. 4-(f)). This means that the adaptive gains for the rudder command do not impose additional workload on a pilot if there is no rudder fault after they adjust to the pilot desired maneuver at the beginning of the simulation. These facts suggest that the proposed FTFC system can work appropriately in both no fault and fault cases.

Table 1 Assumed scenarios for the piloted evaluation

Fault No.	Scenario characteristics
0	No fault (before 80s)
1	20% reduction of aileron effectiveness after 80s
2	20% reduction of aileron & rudder effectiveness after 80s

In the case of Fault No. 1, both methods (unsupported and supported manual cases) are almost the same before the fault occurs and even after the fault (Fig 4-(b)). This is considered to be because Fault No. 1 is a mild fault for manual control and may not impose significant additional workload on a pilot. However, more remarkable differences between the unsupported and supported cases can be seen in the case of Fault No. 2.

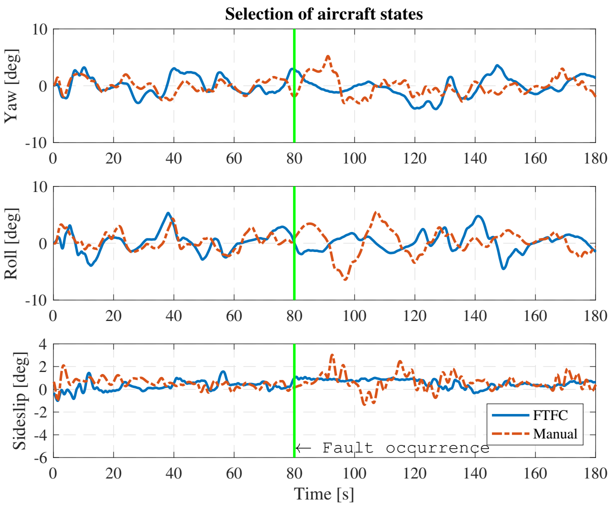
Figure 5 shows the piloted simulation result with Fault No. 2. In the case of manual control only, the control surface deflections are increased after the faults occur on the aircraft. This means that the pilot adapted his control to the situation, which means that the pilot workload is increased by the reduction of control surface effectiveness. On the other hand, in the case with the proposed system, the pilot's control inputs are similar even after the faults occur on the aircraft, which means that the FTFC system automatically reconfigures the control law according to the fault, and in effect relieves the pilot.

3.3 Pilot work anaysis

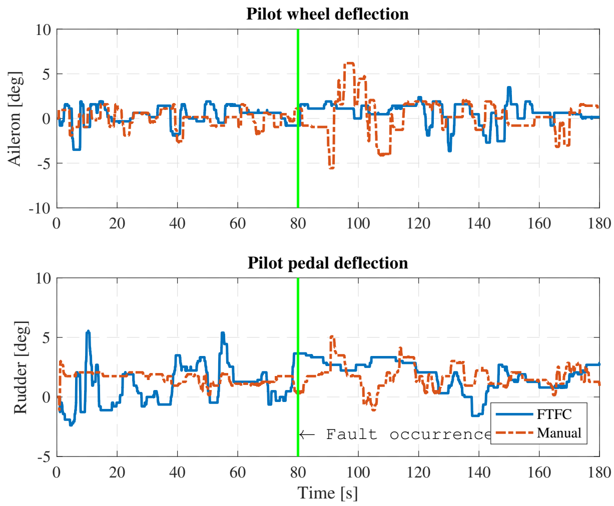
A pilot work analysis (or handling qualities analysis) is performed by calculating the average absolute deflection AVG_{defl}:

$$\text{AVG}_{\text{defl}} = \frac{1}{N}\sum_{k=1}^{N} |\delta_{ctrl}(k)| \tag{19}$$

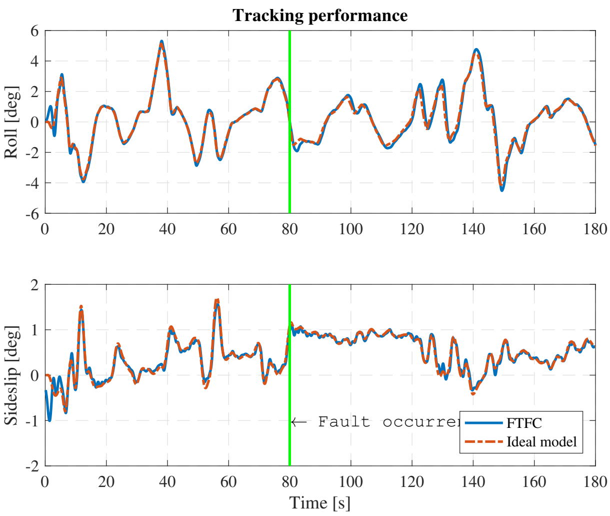
where $\delta_{ctrl}(t)$ is the pilot control input and N is the number of recorded data samples. In order to compare between the no fault case and the fault cases, the values of the average absolute deflection are normalized by those obtained in no fault case (Fault No. 0). Figure 6 shows the normalized average absolute aileron and rudder deflections. In the unsupported manual control case, the normalized average absolute deflections become larger due to the faults. On the other hand,



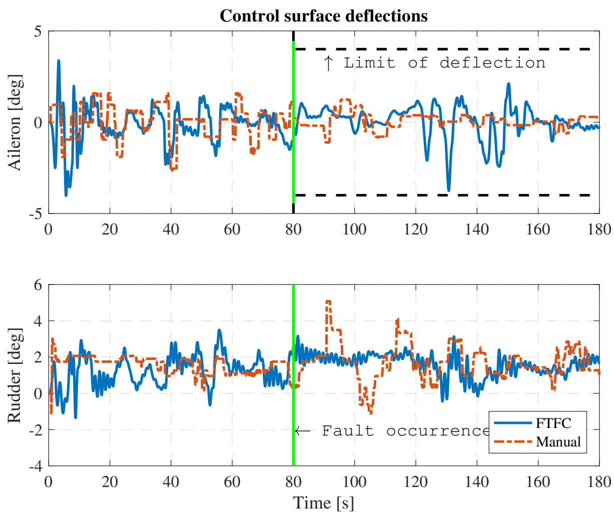
(a) Time histories of aircraft states.



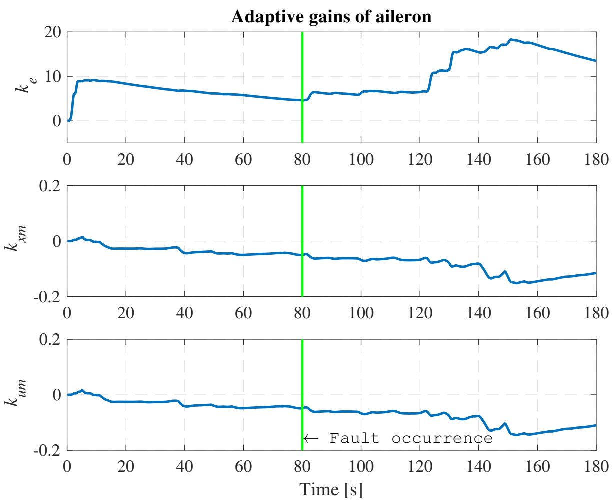
(b) Time histories of pilot commands.



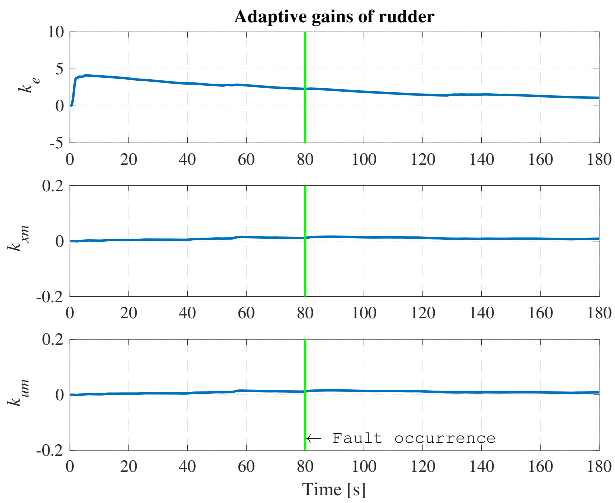
(c) Responses of roll and sideslip angle.



(d) Time histories of control surface deflections.

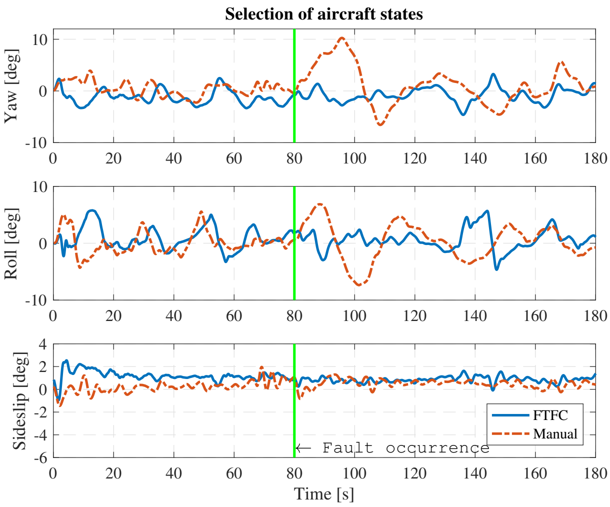


(e) Time histories of adaptive gains for aileron command.

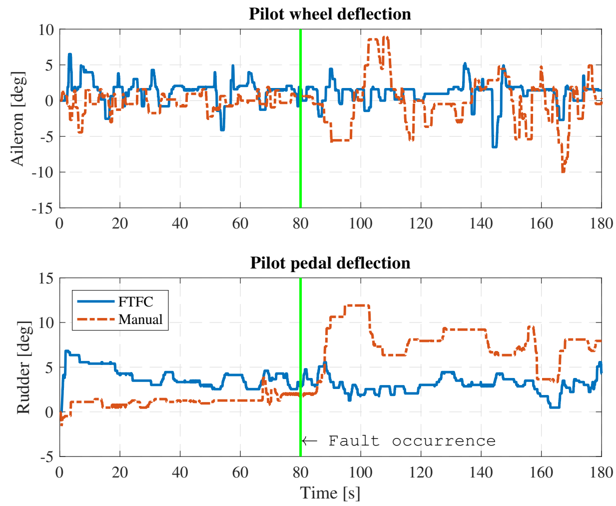


(f) Time histories of adaptive gains for rudder command.

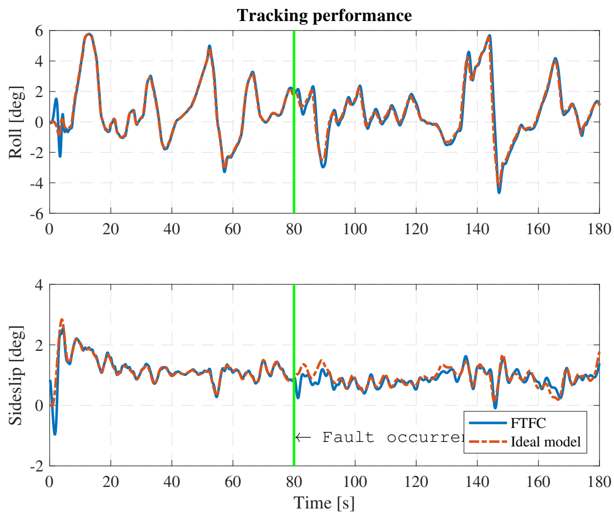
Fig. 4 States of FTFC systems (Fault No. 1: aileron effectiveness).



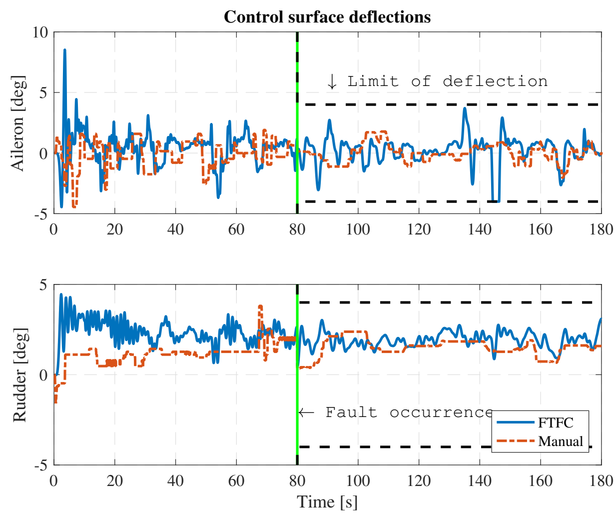
(a) Time histories of aircraft states.



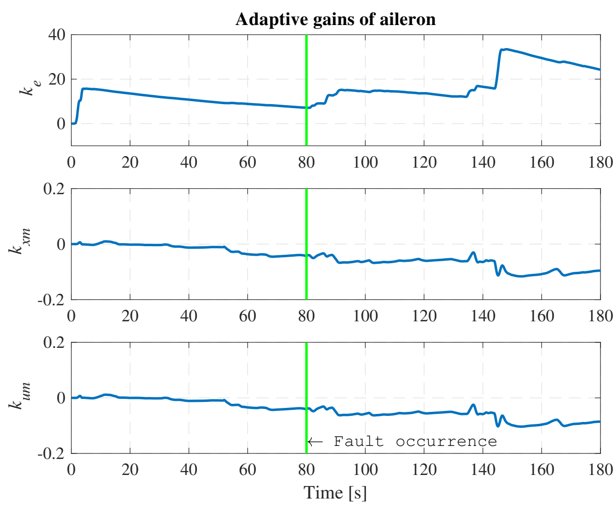
(b) Time histories of pilot commands.



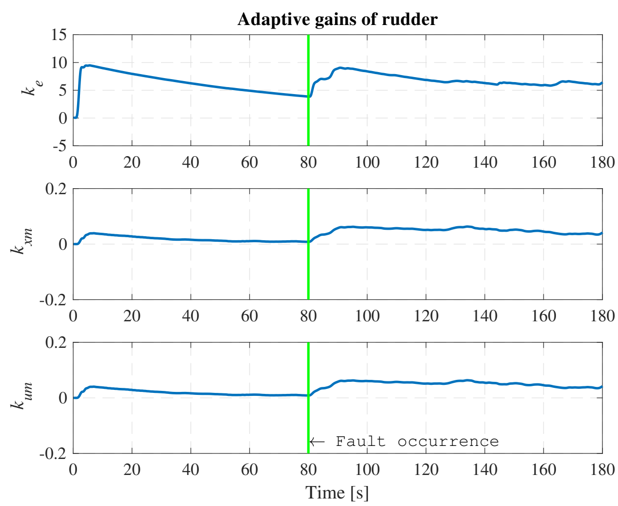
(c) Responses of roll and sideslip angle.



(d) Time histories of control surface deflections.



(e) Time histories of adaptive gains for aileron command.



(f) Time histories of adaptive gains for rudder command.

Fig. 5 States of FTFC systems (Fault No. 2: aileron & rudder effectiveness).

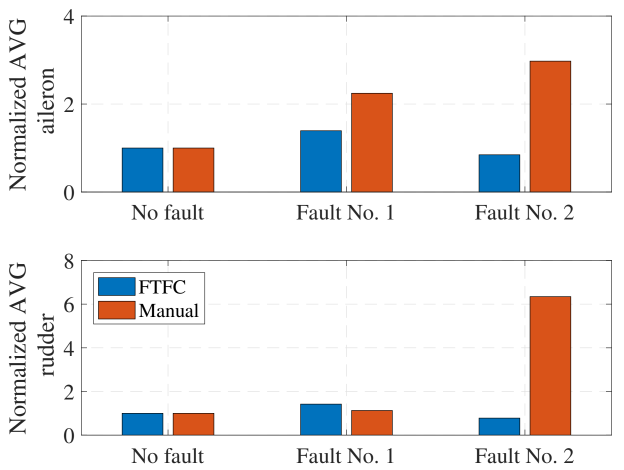


Fig. 6 Average absolute deflection of control surface deflections.

in the supported manual control case, the values are almost similar to the no fault case even after the faults occur on the aircraft. Now the system adapts instead of the pilot, the pilot will be able to attend to other issues like the failure's case or secondary effects.

4 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 desired maneuver. In the evaluation of pilot handling qualities, we have focused on investigating how much the pilot deflection changes according to the faults. The piloted simulation result has showed that the normalized absolute value is not different between the healthy and fault cases in the case of the supported manual 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 piloted evaluation is more difficult than that of the full-autopilot system due to the presence of a human pilot. In order to obtain more accurate results, our future works will include various kinds of simulations (or flight experiments) with more pilot's maneuvers and additional fault cases.

Acknowledgements

We would like to thank Mr. Tsuneharu Uemura for the technical assistance and useful comments in the flight simulation with his experience being a skilled pilot.

This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 690811 and the Japan New Energy and Industrial Technology Development Organization under grant agreement No. 062800, as a part of the EU/Japan joint research project entitled Validation of Integrated Safety-enhanced Intelligent flight cONtrol (VISION).

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