Lateral-directional controller design using a pilot model and flight simulator experiments

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ABSTRACT

A new controller design method of lateral-directional dynamics is proposed. This method is based on the formulated pilot model, and the controller is designed so that the pilot-aeroplane system attains the desired requirements. Robust stabilities and handling qualities can be taken into account. The proposed method was applied to B747 dynamics, and flight simulator experiments were performed, and the designed controller was verified.

NOMENCLATURE

d	gust input
d_Δ	output from uncertainties
p	roll rate
r	yaw rate
u	control input
u_H	output from operator model
u_K	output from controller
y_c	desired bank angle
y_H	input to operator model
y_K	input to controller
z	controlled output
z_e	filtered tracking error
z_Δ	input to uncertainties
β	sideslip angle
δ_a	aileron deflection angle
δ_r	rudder deflection angle
ϕ	bank angle
Ψ	heading angle
$\|G\|_\infty$	H_∞ norm of G
$\left[\begin{matrix} A & B \\ C & D \end{matrix}\right]$	$C(sI-A)^{-1}B+D$

1.0 INTRODUCTION

The main purposes of the flight controller are to maintain good handling qualities and to attain high manoeuvrability. The controller is designed so that these requirements are satisfied. Several controller design methods, which take the handling qualities into account, were proposed[1-4]. They depend on the definition of handling qualities using open-loop aeroplane dynamics[5-6].

The handling qualities of an aircraft should be evaluated by a human pilot. They are determined from the characteristics of a closed-loop system consisting of the aeroplane and the pilot. In addition, a trial-and-error process using a flight simulator is used to improve the flight controller. Here, the comment of the pilots is very important. This necessity of pilot evaluation motivated the

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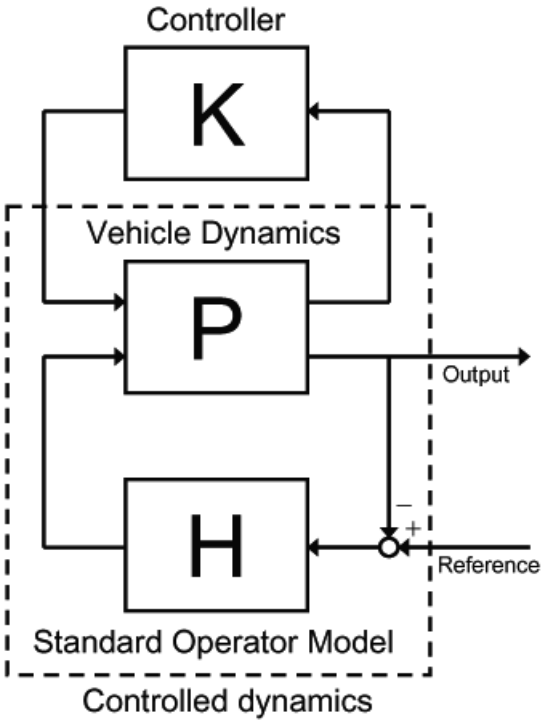


Figure 1. Standard operator model method.

development of pilot-in-the-loop analysis[7]. We investigated the pilot-in-the-loop analysis method and proposed the design of a controller using pilot dynamics (standard operator model method[8]). This method is based on the formulated pilot model, and the controller is designed so that the pilot-aeroplane system attains the desired closed-loop requirements. In addition, robust stabilities can be taken into account. Because the design requirements are formulated in mathematical form based on modern control theory, the controller can be solved without difficulty by a numerical method.

In the present paper, the standard operator model method is applied to lateral-directional flight controller design[9]. Because lateral-directional dynamics are affected by several control surfaces, the relations between the control surface operations and responses are complicated. However, using the proposed design method, it is easy to design a flight controller while taking the pilot behaviour into account. The controller can be modified by adjusting the pilot dynamics characteristic, which is used in the controller design. In addition, flight simulator tests were carried out, and the designed controller was verified.

2.0 LATERAL-DIRECTIONAL FLYING QUALITIES

There are several lateral-directional flying qualities. However, they are defined primarily as responses to aileron input[10]. To design lateral-directional controller, many handling quality features should be considered. Usually, the pilots use two lateral control devices, the rudder and the ailerons, to perform manoeuvres. This manual control should be coordinated, and ease of operation is a major factor of the handling qualities criteria. Thus, it is desired to design lateral-directional dynamics while evaluating actual pilot operations. This process depends on simulator experiments and actual flight tests. In particular, a recent flight control system that was developed in order to obtain high performances results in high-order systems is difficult to design. Saving cost and time is important in flight controller design.

3.0 STANDARD OPERATOR MODEL METHOD

The standard operator model method[8] was applied to longitudinal controller design. In this method, the formulated operator model is utilised for controller design. The closed-loop system is constructed from vehicle dynamics and the given pilot model, and the controller is designed to attain good closed-loop performances. In the present study, Ref. 8 is applied to aeroplane lateral-directional dynamics, and so is summarised briefly herein.

Figure 1. shows a block diagram of a closed-loop system. It contains an aeroplane, a controller and a standard operator model. The standard operator model is a typical pilot model, in which the designer should determine the pilot characteristics. Generally, the pilot characteristics can be determined from the identified pilot model of low workload in flight simulator experiments. In addition, the controller is designed so that the closed-loop system attains good performance and appropriate stabilities. The strategy of the pilot is to attain good manoeuvrability with a low workload. This strategy is formulated as design requirements in a mathematical problem, which can be solved numerically. The mathematical problem was formulated as an H_∞ control problem, as follows:

$$\|G_{ry}\|_\infty < \gamma$$

Here, G_{ry} is a pilot-aeroplane transfer function from the reference input to the output, as observed by the pilot (Fig. 1). The controller can be modified by adjusting the pilot dynamics characteristics used in the controller design.

4.0 APPLICATION TO LATERAL-DIRECTIONAL CONTROLLER DESIGN

The standard operator model method is applied to the lateral-directional controller[9]. The controlled plant is a B747 in landing configuration[11]. The linearised equations of motion are shown as follows:

$$\dot{\mathbf{x}} = Ax + B_1 d + B_2 u$$

$$\mathbf{x} = [\beta \; p \; r \; \phi \; \psi]^T$$

$$\boldsymbol{u} = [\delta_a \; \delta_r]^T$$

$$\mathbf{A} = \begin{bmatrix} -0{\cdot}090096 & 0{\cdot}14945 & -1 & 0{\cdot}14553 & 0 \\ -1{\cdot}33 & -0{\cdot}975 & 0{\cdot}327 & 0 & 0 \\ 0{\cdot}168 & -0{\cdot}166 & -0{\cdot}217 & 0 & 0 \\ 0 & 1 & 0{\cdot}14945 & 0 & 0 \\ 0 & 0 & 1{\cdot}0111 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B_1} = \begin{bmatrix} -0{\cdot}090096 \\ -1{\cdot}33 \\ 0{\cdot}168 \\ 0 \\ 0 \end{bmatrix}$$

$$\mathbf{B_2} = \begin{bmatrix} 0 & 0{\cdot}014964 \\ 0{\cdot}227 & 0{\cdot}0636 \\ 0{\cdot}0264 & -0{\cdot}151 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Here, d is a gust input along the Y axis. The yaw rate response to gust input is considered.

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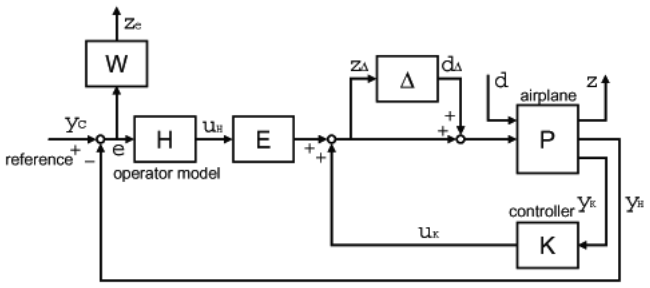


Figure 2. Closed-loop system.

$$
\begin{aligned}
z &= C_1 x + D_{11} d + D_{12} u \\
\mathbf{C_1} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\mathbf{D_{11}} &= 0 \\
\mathbf{D_{12}} &= 0
\end{aligned}
$$

The input to the controller, y_K, is the heading angle.

$$
\begin{aligned}
y_K &= C_{PK} x \\
\mathbf{C_{PK}} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned}
$$

It is assumed that pilot tries to track the desired heading angle input generating the appropriate bank angle and yaw rate. Then, input to the standard operator model, y_H, is the bank angle.

$$
\begin{aligned}
y_H &= C_{PH} x \\
\mathbf{C_{PH}} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix}
\end{aligned}
$$

In addition, the robust stabilities subject to multiplicative uncertainties are improved. Therefore, the actuator, sensor and structure dynamics are compensated. A block diagram of the closed-loop system is shown in Fig. 2.

The design requirements are as follows:

- Good tracking performances
- Good robust stability
- Decreased gust response

The above requirements are satisfied by decreasing the H_∞ norm of the transfer function from $\hat{\mathbf{d}} = [d \;\; d_\Delta^T \;\; y_c]^T$ to $\hat{\mathbf{z}} = [z \;\; z_\Delta^T \;\; z_e]^T$. Here, is the desired bank angle input, and z_e is the filtered tracking error. Let the transfer function be T_{zw}, and let the requirements be formulated as an H_∞ problem, as follows:

$$
\underset{K}{minimise} \left\| Tzw \right\|_\infty . \qquad \ldots (1)
$$

The generalised plant, which contains the aeroplane dynamics, the standard operator model and the weighting function, is as follows:

$$
\begin{aligned}
\dot{\hat{\mathbf{x}}}_{\mathbf{cl}} &= \hat{A}\hat{x} + \hat{B}_1 \hat{d} + \hat{B}_2 u_K \\
\hat{\mathbf{z}} &= \hat{C}_1 \hat{x} + \hat{D}_{11} \hat{d} + \hat{D}_{12} u_K \\
\mathbf{y_K} &= \hat{C}_2 \hat{x} + \hat{D}_{21} \hat{d} + \hat{D}_{22} u_K
\end{aligned}
$$

$$
\hat{\mathbf{A}} = \begin{bmatrix} A - B_2 E D_H C_{PH} & B_2 E C_H & 0 \\ -B_H C_{PH} & A_H & 0 \\ -B_W C_{PH} & 0 & A_W \end{bmatrix}
$$

$$
\hat{\mathbf{B}}_1 = \begin{bmatrix} B_1 & B_2 & B_2 E D_H \\ 0 & 0 & B_H \\ 0 & 0 & 0 \end{bmatrix}, \; \hat{\mathbf{B}}_2 = \begin{bmatrix} B_2 \\ 0 \\ 0 \end{bmatrix}
$$

$$
\hat{\mathbf{C}}_1 = \begin{bmatrix} C_1 - D_{12} E D_H C_{PH} & D_{12} E C_H & 0 \\ -E D_H C_{PH} & E C_H & 0 \\ 0 & 0 & C_W \end{bmatrix}
$$

$$
\hat{\mathbf{C}}_2 = \begin{bmatrix} C_{PK} & 0 & 0 \end{bmatrix}
$$

$$
\hat{\mathbf{D}}_{11} = \begin{bmatrix} D_{11} & D_{12} & D_{12} E D_H \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
$$

$$
\hat{\mathbf{D}}_{12} = \begin{bmatrix} D_{12} \\ I \\ 0 \end{bmatrix}
$$

$$
\hat{\mathbf{D}}_{21} = 0
$$

$$
\hat{\mathbf{D}}_{22} = 0
$$

$$
\mathbf{E} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
$$

Here, the weighting function is:

$$
\mathbf{W(s)} = \frac{1}{s+1} = \begin{bmatrix} A_W & B_W \\ C_W & D_W \end{bmatrix}.
$$

If the band width of the weighting function is wide and the gain is large, tracking performance for the desired input of high frequencies can be attained. The time constant and the gain were selected as a result of trade-off between the robust stabilities. The lead operation for high frequencies causes a high workload. Thus, a low-workload pilot model is formulated as a simple first-order lag.

$$
\mathbf{H(s)} = \frac{0{\cdot}1}{3s+1} = \begin{bmatrix} A_H & B_H \\ C_H & D_H \end{bmatrix}
$$

This standard pilot model reflects generalised features of actual pilot with low-order transfer function. The controller is optimised for the generalised pilot model. The H_∞ control problem Equation ((1)) was solved using the linear matrix inequalities method[12] (Matlab Robust Control Toolbox, The MathWorks), and the obtained controller is:

$$
\begin{aligned}
\dot{x}_K &= A_K x_K + B_K y_K \\
u_K &= C_K x_K + D_K y_K
\end{aligned}
$$

$$
\mathbf{A_K} = \begin{bmatrix}
-17{\cdot}48 & -0{\cdot}16 & 0{\cdot}13 & 0{\cdot}12 & -0{\cdot}19 & 0{\cdot}02 & -0{\cdot}05 \\
-14{\cdot}70 & -0{\cdot}85 & 0{\cdot}47 & 0{\cdot}55 & -0{\cdot}02 & -0{\cdot}08 & 0{\cdot}02 \\
26{\cdot}60 & 0{\cdot}68 & -1{\cdot}16 & -0{\cdot}24 & 0{\cdot}05 & 0{\cdot}05 & -0{\cdot}02 \\
168{\cdot}75 & 0{\cdot}77 & -0{\cdot}37 & -0{\cdot}97 & 0{\cdot}25 & 0{\cdot}14 & -0{\cdot}04 \\
568{\cdot}77 & 2{\cdot}93 & -2{\cdot}22 & -1{\cdot}01 & -0{\cdot}23 & 0{\cdot}32 & -0{\cdot}97 \\
-331{\cdot}35 & -1{\cdot}72 & 1{\cdot}40 & 0{\cdot}38 & -0{\cdot}09 & -0{\cdot}34 & 0{\cdot}36 \\
-396{\cdot}02 & -2{\cdot}05 & 1{\cdot}56 & 0{\cdot}68 & 0{\cdot}55 & -0{\cdot}53 & -0{\cdot}94
\end{bmatrix}
$$

$$
\mathbf{B_K} = \begin{bmatrix}
-17{\cdot}48 \\ -14{\cdot}70 \\ 26{\cdot}61 \\ 168{\cdot}76 \\ 568{\cdot}78 \\ -331{\cdot}36 \\ -396{\cdot}03
\end{bmatrix}
$$

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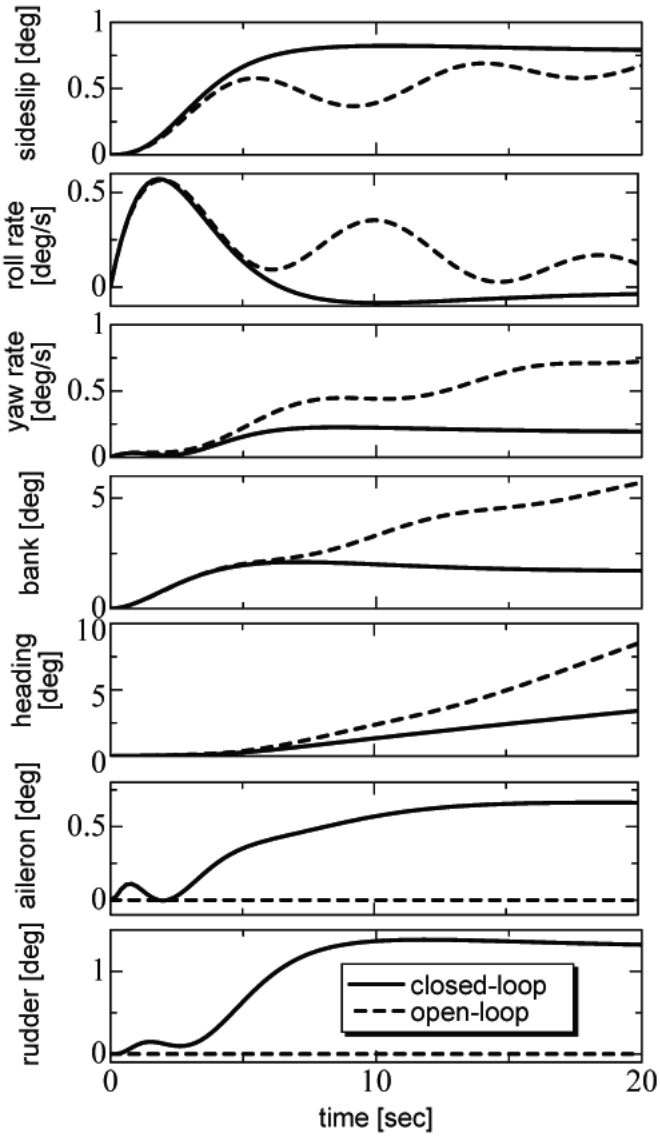


Figure 3. Step responses.

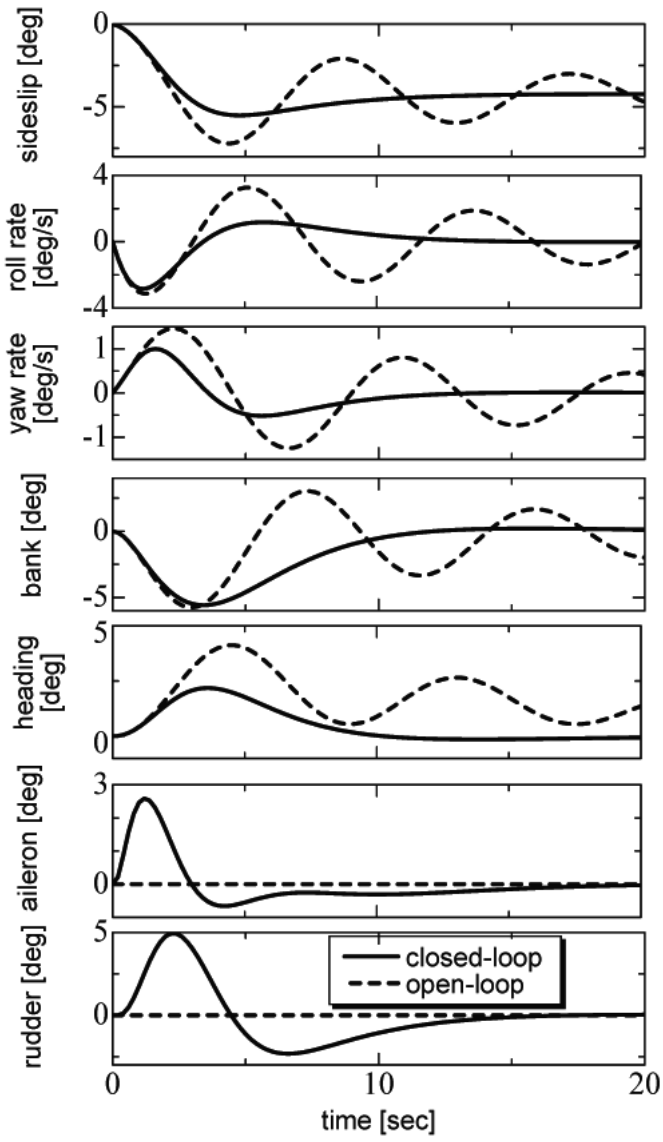


Figure 4. Gust responses.

$$\mathbf{C}_K = \begin{bmatrix} 0 & 0{\cdot}10 & 0{\cdot}06 & 0{\cdot}13 & 0{\cdot}14 & -0{\cdot}42 & -0{\cdot}68 \\ 0 & 0 & 0 & 0.01 & 0.49 & -0{\cdot}26 & 1{\cdot}07 \end{bmatrix}, \mathbf{D}_K = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Here, the minimised H_∞ norm is 2·93.

In order to evaluate the design requirements, a number of simulations were carried out. In these simulations, the closed-loop is constructed from the aeroplane dynamics and the controller. The responses to an aileron step input of 10° were simulated and shown in Fig. 3. Note that the aileron deflection angles of the closed-loop and the open-loop systems in Fig. 3 are the outputs from the controller, and they don't contain step input. The sideslip angle, roll rate and yaw rate responses of the open-loop system oscillate. The responses of the closed-loop system settle faster compared to the open-loop system. In addition, the responses to a gust input of 5m/sec along the Y axis were simulated (Fig. 4). The all responses of the open-loop system oscillate considerably compared to the closed-loop system. The controller is shown to decrease the gust response.

5.0 FLIGHT SIMULATOR EXPERIMENTS

In order to verify the designed controller, flight simulator tests were performed. The flight simulator of the Japan Aerospace Exploration Agency was used (Fig. 5). In this simulation, the motion was not emulated. The task imposed on the pilots was to maintain a heading angle of 0° under a gust disturbance. The disturbance was a lateral gust of white noise filtered with a low-pass weighting function, the cut-off frequency of which was 0·15rad/sec. The bank angle and heading angle were shown on the display of the simulator (Fig. 6). Four veteran pilots were tested (Subject 1, 2, 3 and 4). The pilots were allowed to practice, and the experiment was carried out for two minutes. The handling qualities were ranked in five grades by the simplified Cooper-Harper rating sheet. The tested dynamics were the bare dynamics of a B747 without SAS and B747 dynamics with the designed controller. In addition, the power of the tracking errors ($(1/T)\int_0^T \psi^2 dt$) were analysed and are shown in Table 1. They indicate that the designed controller decreases the tracking error. The reported ratings are shown in Table 2. The ratings of Subject 2 and 4 are improved. When better rating is desired, the standard operator model and the weighting function in the generalised plant should be modified. The pilot models were identified using the least-squares

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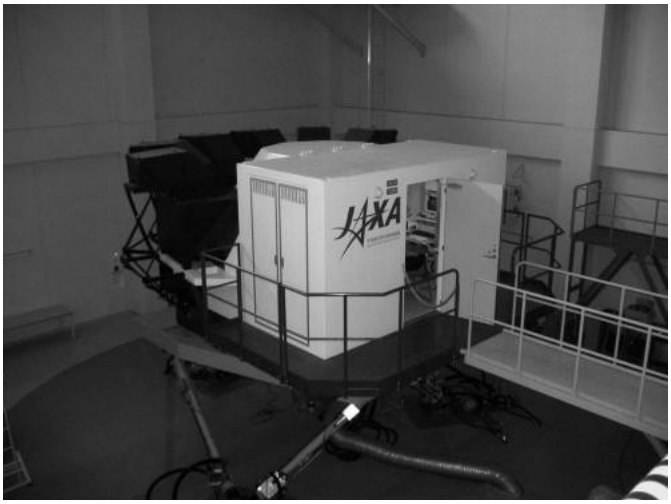


Figure 5. Flight simulator.



Figure 6. Display.

Table 1
Power of tracking error

Subject	bare dynamics	controlled dynamics
1	2·0	0·80
2	18·5	3·4
3	3·1	0·54
4	3·6	0·56
		($\times 10^{-3}$[rad^2])

Table 2
Commented handling qualities using the simplified Cooper-Harper rating sheet

Subject	bare dynamics	controlled dynamics
1	2	2
2	3	2
3	3	4
4	3·5	2

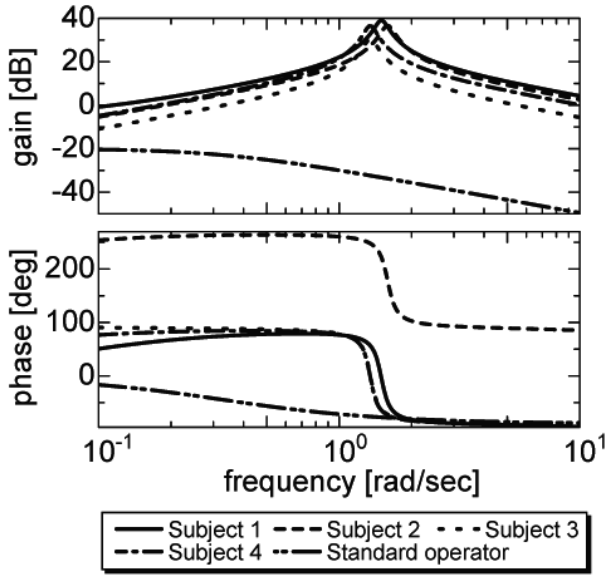


Figure 7. Pilot models of the controlled aeroplane.

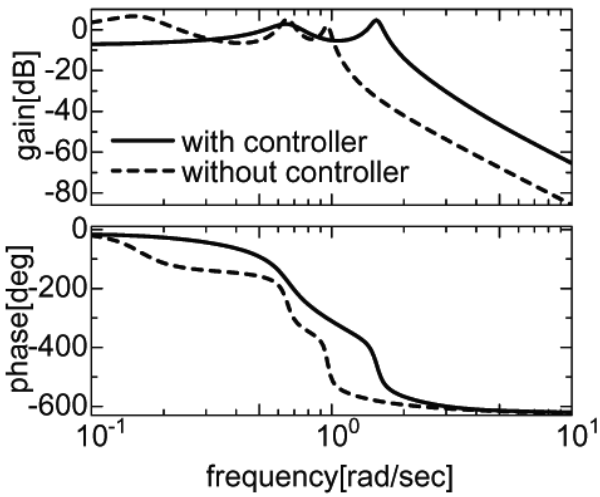


Figure 8. Pilot-aeroplane systems (Subject 4).

method, and the pilot-aeroplane transfer functions from the reference input to the heading angle output were constructed. Figure 7 shows the frequency responses of the identified pilot models. Subject 2 controlled the aircraft differently than the others. Also, the tracking performance of Subject 2 showed worse value for bare and controlled dynamics (Table 1). This may mean that practice and instruction of Subject 2 was not enough. However, the controller improved tracking performance of Subject 2. Except for Subject 2, they have similar characteristics. The standard operator model with low-gain and narrow bandwidth was used. The designed controller attains robust stabilities and tracking performances for the standard operator model. However, all subjects show higher gain and wider bandwidth than standard operator model. As a result of high gain manipulation, tracking performances were improved than the standard operator model's performances. Figure 8 shows the frequency responses of the constructed pilot-aeroplane transfer function of Subject 4. This figure shows that the designed controller widens the bandwidth of the closed-loop system and a high tracking performance is attained.

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6.0 CONCLUSION

The new design method of the lateral-directional flight controller was developed. Here, a standard pilot model is introduced and the controller is designed such that the closed-loop system, which consists of the standard pilot model and the vehicle dynamics, attains the desired requirements. This method is an attempt for the closed-loop system to be operated with a low workload, and high tracking performances can be attained. The controller can be modified by adjusting the pilot dynamics characteristic, which is used in the controller design. In addition, flight simulator tests were performed with the designed controller. The task to track the heading angle under a gust disturbance was imposed. From the obtained experimental results, decreased tracking error was confirmed.

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