ACTIVE FAULT-TOLERANT CONTROL SYSTEM DESIGN FOR A TWO-ENGINE BLEED AIR SYSTEM OF AN AIRCRAFT

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Abstract

In this paper, a simplified linear model of a two-engine bleed air system of an aircraft is developed based on the dynamics of system key components, then an active fault-tolerant controller is designed for this system using the pseudo-inverse method. Simulations based on the linear state-space model are conducted, and the results have shown that this design method can significantly improve system performance when faults occur on the pressure regulator of the bleed air control system.

1 Introduction

The environmental control system (ECS) of an aircraft provides favorable conditions for instruments and equipment to operate properly, for crew and passengers to work and travel in a safe and comfortable environment. For ECS, the main source of conditioning air is the engine bleed from high-pressure compressors. The bleed air pressure from each engine is controlled through pressure regulators. In practice, the pressure regulator dynamics may change slowly or abruptly due to various reasons. Owing to the fact that faults may occur, fault tolerance must be considered in the control system design.

In the past two decades, a large number of fault-tolerant control (FTC) design techniques have been proposed, and some of them have even been put into application, many of them are in the area of aircraft control system design [1, 2, 3, 4]. The main task to be dealt with in achieving fault tolerance is the design of a controller with a suitable structure and well-designed controller parameters to guarantee stability and satisfactory performance, not only when all of the control components are operational, but also when sensors, actuators or other system components malfunction. Among the proposed fault-tolerant control methods, the Pseudo-Inverse Method (PIM) is a widely used design approach [2, 5, 6, 7, 8] because of its simplicity in computation and implementation.

In this paper, an active fault-tolerant control is designed for a two-engine bleed air system (BAS) of an aircraft. A linearized model of a two-engine bleed air system is developed based on the dynamics of the key components. The transfer function block diagram and state-space representation are then derived. Based on the state-space model, a state feedback fault-tolerant controller is designed using the PIM. This active fault-tolerant controller reconfigures the state feedback controller gain matrix k in the presence of a fault. The fault considered herein is the time constant change of one of the pressure regulators by a factor of 50% from its nominal value.

Simulation results have shown that this active fault-tolerant control design can improve system performance significantly compared with the conventional non-reconfigured state feedback controller when the fault under consideration occurs.

2 Modeling of a Two-Engine Bleed Air System

2.1 Two-engine bleed air system

An illustrative diagram of a two-engine bleed air system under consideration is shown in Fig.1. The bleed with high-pressure from each channel, is controlled by a pressure regulator before it passes through a heat exchanger (HX). Each channel is instrumented with a pressure transducer and a temperature sensor downstream the HX. The bleed airflows with lower pressures and temperatures are merged into one stream to feed the downstream environmental control system.

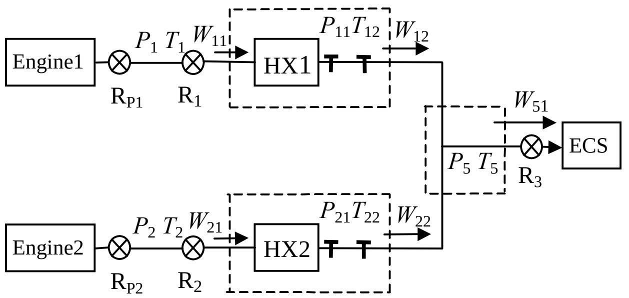

Fig.1: Illustrative diagram of a two-engine bleed air system

In Fig. 1, W, P and T denote flow rate in lb/min, absolute pressure in psia and temperature in degree Fahrenheit, respectively. R_1, R_2 and R_5 are pressure regulators, R_{P1} and R_{P2} are the primary pressure valves designed mainly for decreasing bleed pressures.

2.2 Linearized model of a two-engine bleed air system

For the two-engine bleed air system under consideration, the transfer function block diagram is shown in Fig. 2.

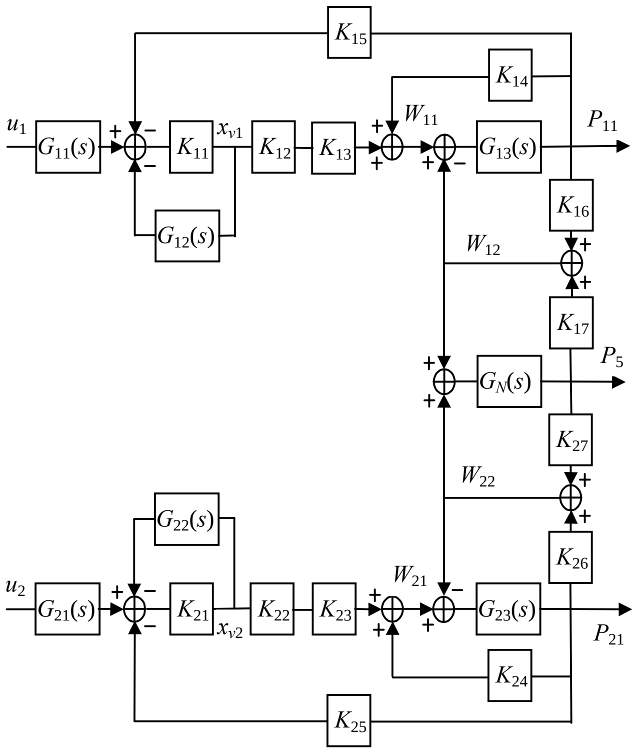

Fig. 2: The transfer function diagram of a two-engine BAS

The system inputs u_1 and u_2 are the driving currents of pressure regulators R_1 and R_2. The transfer functions in Fig. 2 have the following forms

$$G_{11}(s) = G_{21}(s) = k_1/(\tau_V s + 1) \tag{1}$$

$$G_{12}(s) = G_{22}(s) = k_2 \tau_V s/(\tau_V s + 1) \tag{2}$$

$$G_{13}(s) = G_{23}(s) = k_3/s \tag{3}$$

$$G_N(s) = k_N/(\tau_N s + 1) \tag{4}$$

At P_1=P_2=90 psia, T_1=T_2=563.2°F and mass flow rate of 150 lb/min for each channel, the coefficients in the above transfer functions are listed in Table 1.

k_1	5.2000	τ_V (sec)	0.1763
k_2	149.63		
k_3	222.04		
k_N	4.6900	τ_N (sec)	0.0260

Table 1: Coefficients in the transfer functions

All the gains in the transfer function block diagram are shown in Table 2.

K_{11}, K_{21}	0.00164
K_{12}, K_{22}	5.62980
K_{13}, K_{23}	1.43526
K_{14}, K_{24}	-0.01817
K_{15}, K_{25}	-0.03018
K_{16}, K_{26}	1.63400
K_{17}, K_{27}	-1.63400

Table 2: Gains in the transfer function block diagram

2.3 State-space representation

By defining the following state variables:

x_1: channel#1 pressure P_{11}

x_2: node pressure P_5

x_3: channel#2 pressure P_{21}

x_4: PR valve R_1 pressure command signal

x_5: PR valve R_2 pressure command signal

x_6: PR valve R_1 angular displacement

x_7: PR valve R_2 angular displacement

The following state-space representation is obtained from the transfer function block diagram in Fig.2.

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{5}$$

where

$$A = \begin{bmatrix} -43.8 & 29.3 & 0 & 5.05 & 0 & 6453 & 0 \\ 29.3 & -154 & 29.3 & 0 & 0 & 0 & 0 \\ 0 & 29.3 & -43.8 & 0 & 5.05 & 0 & 6453 \\ 0 & 0 & 0 & -6.18 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -6.18 & 0 & 0 \\ 2.24\times10^{-6} & 0 & 0 & 7.79\times10^{-4} & 0 & -5.19 & 0 \\ 0 & 0 & 2.24\times10^{-6} & 0 & 7.79\times10^{-4} & 0 & -5.19 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 32.1533 & 0 \\ 0 & 32.1533 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The state vector x, control input vector u and system output vector y are defined as

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7]^T$$

$$u = [u_1 \quad u_2]^T$$

$$y = [P_{11} \quad P_5 \quad P_{21}]^T$$

3 Fault-Tolerant Control Design

3.1 Pseudo-inverse method [8]

Let the nominal system be the form of Equation (5). Assume that the nominal closed-loop system is designed by using the state feedback $u = -kx$, and the closed-loop system then becomes

$$\begin{cases} \dot{x} = (A - Bk)x \\ y = Cx \end{cases} \tag{6}$$

where k is the state feedback gain matrix. Suppose that a fault has occurred in the system, and the system becomes

$$\begin{cases} \dot{x} = A_f x + B_f u \\ y = C_f x \end{cases} \tag{7}$$

and a new feedback gain is synthesized and the new closed-loop system becomes

$$\begin{cases} \dot{x} = (A_f - B_f k_f)x \\ y = C_f x \end{cases} \tag{8}$$

where k_f is the new feedback gain matrix to be determined. In PIM, the objective is to find a k_f so that the transition matrix in (8) approximates that in (6) in some sense. In this case, $A - Bk$ is equated to $A_f - B_f k_f$. The approximate solution for k_f is given by

$$k_f = B_f^{\ +}(A_f - A + Bk) \tag{9}$$

where $B_f^{\ +}$ denotes the pseudo-inverse of B_f, defined by

$$B_f^+ = (B_f^T B_f)^{-1} B_f^T \tag{10}$$

One of the key elements in fault-tolerant control design is the availability of the post-fault information of the system. In PIM, it is assumed that the process dynamics after the fault occurrence are available either from *a priori* information of the process or from an on-line fault detection and diagnosis scheme. It is noted that PIM does not guarantee the stability of the impaired system.

3.2 Fault-tolerant controller design for a two-engine bleed air system

For the nominal system given in Section 2.3, a state feedback controller has been designed. The corresponding state feedback gain matrix k is obtained as

$$k = 10^5 \times \begin{bmatrix} -0.097 & 0.39 & -0.087 & 0.003 & 0.002 & 4.45 & 2.73 \\ -0.102 & 0.46 & -0.112 & 0.002 & 0.004 & 3.25 & 4.96 \end{bmatrix}$$

The eigenvalues of the closed-loop system are

$$\Lambda = \begin{bmatrix} -364.34 \\ -88.06 \\ -27.90 \\ -6.98 \\ -5.73 \\ -4.97 \\ -5.17 \end{bmatrix}$$

The above controller is designed for nominal system. In fact, the characteristics of some system components may change. For the engine bleed air system, the time constant change of the pressure regulators is one of the most common faults that could happen in real system. In practice, the time constant τ_V of the pressure regulators may change by a factor of 50-100% from its nominal value due to wear and tear or other mechanic reasons. From the fault-tolerant control point of view, this kind of faults belongs to the class of system dynamic faults.

More precisely, the fault considered here is the time constant change of the pressure regulator R_1 by 50% from its nominal value. The nominal value of the time constant τ_V of pressure regulator R_1 is 0.1763 seconds. When the fault occurs, it becomes 0.2645 seconds. The performance of the closed-loop system can be affected significantly by the change in the time constants of the pressure regulators because of the fast engine bleed air system dynamics.

After the fault occurrence, the state matrix and the input matrix of the system become

$$A_f = \begin{bmatrix} -43.8 & 29.3 & 0 & 5.05 & 0 & 6453 & 0 \\ 29.3 & -154 & 29.3 & 0 & 0 & 0 & 0 \\ 0 & 29.3 & -43.8 & 0 & 5.05 & 0 & 6453 \\ 0 & 0 & 0 & -6.43 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -6.18 & 0 & 0 \\ 2.34 \times 10^{-6} & 0 & 0 & 8.1 \times 10^{-4} & 0 & -5.39 & 0 \\ 0 & 0 & 2.24 \times 10^{-6} & 0 & 7.8 \times 10^{-4} & 0 & -5.19 \end{bmatrix}$$

$$B_f = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 33.4213 & 0 \\ 0 & 32.1533 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The fault makes the eigenvalues of the closed-loop system deviate to

$$\Lambda = \begin{bmatrix} 5.5193 \\ -11.555 \\ 0.28573 \\ -1.9813 \\ -3.9882 \\ -5.9023 \\ -6.407 \end{bmatrix}$$

Note that two of the eigenvalues of the closed-loop system have changed from negative to positive, and the closed-loop system becomes unstable.

In order to stabilize the control system, a new controller needs to be reconfigured. Using the pseudo-inverse design method, the redesigned controller gain matrix k_f can be calculated using Equations (9) and (10), which is obtained as

$$k_f = 10^5 \times \begin{bmatrix} -0.093 & 0.38 & -0.083 & 0.003 & 0.002 & 4.28 & 2.63 \\ -0.102 & 0.46 & -0.112 & 0.002 & 0.003 & 3.25 & 4.97 \end{bmatrix}$$

The eigenvalues of the new closed-loop system are

$$\Lambda = \begin{bmatrix} -7.6548+3.0602i \\ -7.6548-3.0602i \\ -5.9118 \\ -3.9881 \\ -0.50774+1.1806i \\ -0.50774-1.1806i \\ -1.9796 \end{bmatrix}$$

4 Simulation Results

The simulation of the closed-loop system for the two-engine bleed air system has been conducted using step response tests. Since the two channels are symmetrical, step changes are only applied to the bleed on regulator R_1 setpoint.

Fig. 3 illustrates the system pressure responses of the normal closed-loop system. It can be seen that all system outputs reach the steady states within one second.

For the faulty system whose parameters have changed to (A_f, B_f, C), the system pressure responses with the original feedback gain matrix k are shown in Fig. 4. The results are unacceptable because the closed-loop system is unstable.

Fig. 5 shows the pressure responses of the faulty system with the newly designed feedback gain matrix k_f. The closed-loop system is stable but the performance is degraded.

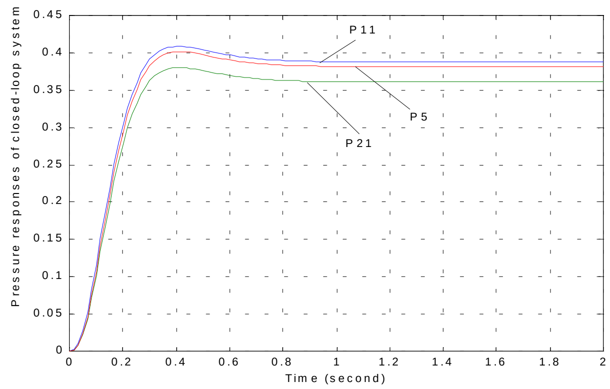

Fig. 3: System pressure responses of the nominal closed-loop system

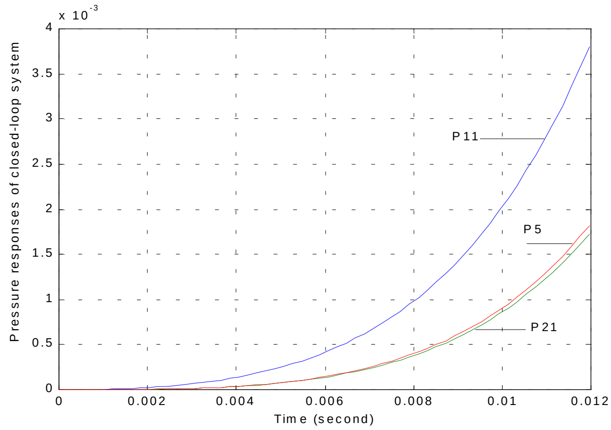

Fig. 4: System pressure responses of the faulty system without controller reconfiguration

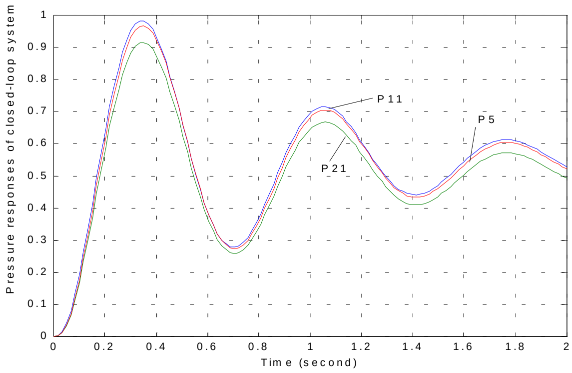

Fig. 5: System pressure responses of the faulty system with controller reconfiguration

5 Concluding Remarks And Future Work

In this paper, a simplified linearized model of a two-engine bleed air system of an aircraft is developed. Based on the model, a state feedback fault-tolerant controller is designed using the pseudo-inverse method.

Simulation results have shown that the active fault-tolerant control design using pseudo-inverse method improves system performance significantly compared with a non-reconfigured regular state feedback controller. A drawback of the PIM design method is that the stability of impaired system is not guaranteed and this may lead to unacceptable system behaviour. For a two-engine bleed air system, this means that the closed-loop system may become unstable if one of the time constant of the pressure regulators gets large enough.

To validate the effectiveness of this design method, an engine bleed air system test rig is being developed in our laboratory. As future work, the proposed method will be investigated experimentally.

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