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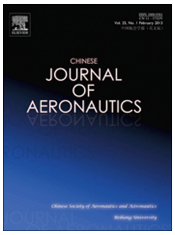

Fault mode probability factor based fault-tolerant control for dissimilar redundant actuation system

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Monte Carlo simulation;
Moving window

Abstract This paper presents a Fault Mode Probability Factor (FMPF) based Fault-Tolerant Control (FTC) strategy for multiple faults of Dissimilar Redundant Actuation System (DRAS) composed of Hydraulic Actuator (HA) and Electro-Hydrostatic Actuator (EHA). The long-term service and severe working conditions can result in multiple gradual faults which can ultimately degrade the system performance, resulting in the system model drift into the fault state characterized with parameter uncertainty. The paper proposes to address this problem by using the historical statistics of the multiple gradual faults and the proposed FMPF to amend the system model with parameter uncertainty. To balance the system model precision and computation time, a Moving Window (MW) method is used to determine the applied historical statistics. The FMPF based FTC strategy is developed for the amended system model where the system estimation and Linear Quadratic Regulator (LQR) are updated at the end of system sampling period. The simulations of DRAS system subjected to multiple faults have been performed and the results indicate the effectiveness of the proposed approach.

1. Introduction

Dissimilar Redundant Actuation Systems (DRAS), composed of Hydraulic Actuator (HA) and Electro-Hydrostatic Actuator (EHA), have been increasingly gaining consideration for the application in the large commercial aircraft due to their ability to avoid possible common mode failures.[1–3] DRAS has the advantage of fast response and high reliability associated with HA actuator, while avoiding common mode failure by introducing redundant EHA.[4] The research on DRAS system has become the mainstream of the large aircraft development programs. The latest Airbus aircraft, A380 and A350, have adopted DRAS system of 2H/2E type.[5]

The HA systems commonly experience gradual faults caused by oil leakage and constriction of oil flow which ultimately lead to the system performance degradation. Although

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these faults may have limited initial side-effect, over the long life-time they can result in increasingly adverse effects on the actuation system and impact the overall system performance. Therefore, measures must be taken to maintain certain level of acceptable system performance under the gradually increasing system fault conditions. The Fault-Tolerant Control (FTC) techniques[6–8] are commonly used to remedy the faults and maintain the aircraft system safety at a high level, and could also be applied to designing the FTC mechanism for the actuation system with gradual faults.

Design of FTC system requires that the system parameters be known, which is difficult to realize in real application.[9] Researchers have proposed various control methods for uncertain systems operating under very specific working conditions and for short period of time, specifically, for the cases when gradual faults do not have significant effect on the system performance. However, there are few control methods for systems with varying and uncertain parameters over long period of time, which prompted many researchers to focus on the system identification techniques[10–13] commonly applied to systems under normal operating conditions and over a specific time period. However, when system faults occur, the corresponding system parameters would drift, which would increase the identification errors of the parameter values. When the system suffers multiple faults of different severity levels, the system parameters would present uncertainty. Therefore, traditional approaches addressing system identification are inadequate for effective control design for the systems with increasing errors of parameters. This is especially evident in the case of a system with changing parameters caused by the gradual faults of the imprecise system model. The robust control techniques,[14,15] adaptive design techniques[16,17] and the Linear Parameter Varying (LPV) control design methods[18] can deal with the system uncertainty to some degree, but they exhibit limitations when applied to systems with multiple gradual faults which occur over a long working period.

Design of an effective FTC mechanism for DRAS experiencing gradual faults, is a complex problem which involves not only system identification over a long period of time but also design of the fault-tolerant controller. This paper proposes a Fault Mode Probability Factor (FMPF) based FTC strategy for multiple fault modes of DRAS over a long working period. Since the identification errors would increase due to the multiple gradual faults, the cycle of sampling method is used to record the multiple fault modes and provide the historical statistics as the fault information. Applying the proposed FMPF with expectation operator, the historical statistics can be used to estimate current degree and values of multiple faults. Finally, the amended system model based on FMPF can be obtained and used to design the fault-tolerant controller. Based on the amended system model, the control gain can be determined using Linear Quadratic Regulator (LQR).[19–21] To balance the system model precision and the computation time, a Moving Window (MW) method is used to determine the amount of applied historical statistics, following a certain window size, at the end of the most recent sampling period, new system parameter estimation results are imported into the applied historical statistics while the oldest set is removed, and then the chosen historical statistics are processed by using the FMPF to update the system parameters. The updated system parameters are then used to modify the control law to compensate for the effects of the changed gradual faults. In this paper, the Monte Carlo method is used to provide simulation data for different periods. Several case studies of DRAS, subjected to multiple faults, are performed to analyze the effectiveness of this method and associated design approach.

The main contribution of this paper is the FMPF based FTC strategy for multiple fault modes of DRAS under long term working conditions, where the control gain of the fault-tolerant controller is updated with each sampled data set. This approach allows the system performance to be maintained within reasonable range even under changed working conditions caused by the gradual faults. Compared with the existing FTC design methods, the proposed FMPF approach applies the expectation operator on the historical statistics resulting in a novel way to comprehensively utilize the system statistical information, where law of large numbers and central limit theorem can be used to provide theoretical foundations, and meanwhile, the MW method balances the system model precision and the computation time.

Notation: Throughout this paper, the superscript T specifies matrix transposition, Δspecifies parameter error. The symbol P stands for probability and E expectation operator. $\mathrm{Re}\{\boldsymbol{\lambda}(\cdot)\}$ is the form of eigenvalue real part. $w(t) \in L_2[0, \infty)$ is a quadratic differential function. $\max(\cdot)$ and $\max(\cdot)$ express maximum value and minimum value respectively.

2. System description

The DRAS system is composed of one HA system and one EHA system as shown in Fig. 1. In the normal operating condition, only HA drives the control surface while EHA is in the follower mode, i.e. backup mode. This type of active/passive (A/P) operating mode, known as $H_\mathrm{A}/E_\mathrm{P}$ mode, is the most common operating mode since HA system has better performance than EHA system. Consequently, the proposed FTC strategy is developed for this operating mode and leaves the $E_\mathrm{A}/H_\mathrm{P}$ operating mode as an alternate FTC strategy.

2.1. Modeling of H_A/E_P mode under normal operating condition

The model of $H_\mathrm{A}/E_\mathrm{P}$ system, used in this work, has been previously developed and published by this research group.[22] The model is based on the assumption that the control surface is a rigid body of known mass and inertial moments. The forces acting on the system include the HA cylinder force, F_h, inertial and damping load of the EHA system, and aerodynamic force, F_L. The state space representation of the system is given as follows:

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{G}\boldsymbol{w}(t) \\ \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{1}$$

where the state vector is defined as $\boldsymbol{x}(t) = [x_\mathrm{h}, \dot{x}_\mathrm{h}, P_\mathrm{h}, x_\mathrm{v}]^\mathrm{T}$, x_h and $\dot{x}_\mathrm{h}$ are the velocity and acceleration of the piston respectively, P_h is the cylinder pressure, and x_v is the servo valve displacement; $\boldsymbol{u}(t)$ is the system input to be designed; $\boldsymbol{y}(t)$ is the system output; $\mathbf{w}(t) = F_\mathrm{L}$ is unknown disturbance. The state, input, output, and disturbance matrices are as follows[23]:

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