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Adaptive decoupling synchronous control of dissimilar redundant actuation system for large civil aircraft

Cun Shi [a], Xingjian Wang [a,*], Shaoping Wang [a], Jun Wang [a], Mileta M. Tomovic [b]

[a] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[b] College of Engineering and Technology, Old Dominion University, Norfolk, VA 23529, USA

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ABSTRACT

In order to meet the increasing reliability requirements of actuation system for large civil aircraft, the novel distributed dissimilar redundant actuation system composed of one hydraulic actuator (HA) and one electro-hydrostatic actuator (EHA) has been applied to the design of advanced aircraft. This configuration can greatly improve the system reliability and effectively avoid potential common-mode/common-cause (CM/CC) failure. However, this actuation configuration can exhibit force fighting problem between HA and EHA due to their different driving mechanisms and rigid coupling when they operate in the active/active mode, which may even cause damage to the control surface. To resolve this problem, an adaptive decoupling synchronous controller (ADSC) is proposed in this study. The coupling effect between HA and EHA is taken into account, and an adaptive decoupling controller is designed to eliminate the coupling term. Parameter adaption law is designed for the parametric uncertainties. In addition, a feed-forward compensator is proposed to compensate for the difference between HA and EHA by accelerating the dynamic response of EHA. Finally, the comparative simulation results indicate that the proposed ADSC controller has high speed/high robustness performances and can effectively reduce the force fighting between HA and EHA.

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1. Introduction

The reliability of aircraft actuation systems is of great concern when designing new aircraft. The problem is gaining increased importance as aircraft are becoming bigger and increasingly more complex. Traditional redundant actuation system, for example, two hydraulic actuators with the same parameters driving one control surface, cannot meet the increasing reliability requirements of a large civil aircraft. The main reason is that the common-mode/common-cause (CM/CC) failure phenomenon has been inherent in the conventional actuation systems. Potential CM/CC failures are the results of an event(s) which, because of dependencies, causes a coincidence of failure states of components in two or more separate channels of a redundancy system. This is leading to the defined system failing to perform its intended function [1]. As observed in [2], the addition of redundant modules is not a solution to CM/CC failure. A natural component of the study of CM/CC failures is the study of diversity. As early as in 1970, diversity was identified as an effective antidote for CM/CC failures [3]. The same principles have been applied when implementing dissimilar redundant actuation system. For example, each elevator of A380 is driven by one hydraulic actuator (HA) and one electro-hydrostatic actuator (EHA) [4].

Dissimilar redundant actuation system conforms to the developing trend of the future actuation system, which is composed of actuators driven by different mechanism, such as conventional hydraulic actuation system and the power by wire (PBW) actuation system. The conventional hydraulic actuation system has been widely used in modern industry due to its virtues of small size-to-power ratio and the ability to apply very large force and torque [5]. On the other hand, the PBW actuation system has high reliability on account that it uses flexible cables for power transmission and gets rid of the central hydraulic power, such as EHA. This has been one of the major development directions of PBW, which have been introduced by different researchers in [6–10]. Besides, EHA produce high force with a cleaner and more energy efficient way [11]. Consequently, the dissimilar redundant actuation system composed of HA and EHA combines the advanced features of both, while avoiding the CM/CC failures and improving the reliability of the actuation system.

There are two traditional operating modes for the dissimilar redundant actuation system, which are active/active mode (A/A) and active/passive mode (A/P) [12,13]. In A/P mode the passive chan-

* Corresponding author.
E-mail address: wangxj@buaa.edu.cn (X. Wang).

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nel is isolated from the bypass-valve and there is no force fighting. In A/A mode two actuators actively drive the control surface at the same time to deliver large torque. It is obvious that HA and EHA have different driving principles and natural behavior, which may result in response difference. A serious force fighting problem can occur when these two actuators are operated in A/A mode due to rigid coupling. This may affect the accuracy of the tracking performance or even damage the control surface.

INSA University, the TUHH University and GOODRICH Company [14–16] have built the hybrid actuation system test bench for performance analysis. Cochoy et al. presented an active/no-load mode strategy [17], which extended the original position control loops with additional state-difference feedback approach (position-difference, velocity-difference and force-difference) to realize the position control and force equalization between HA and EMA (electro-mechanical actuator). Cochoy et al. [15] also proposed a MIMO control method based on state observer to reduce the force fighting. The difference between the average forces with the actual actuator force was introduced to an integrator to generate a position demand to eliminate force fighting [18]. Various static force equalizations and dynamic force equalizations of a hybrid actuation system which consist of HA and EMA were studied [19–21]. However, few papers have discussed the force fighting problem between HA and EHA, which is more complex due to high-order characteristic of EHA.

The pistons of HA and EHA are rigidly connected together by means of control surface, which will lead to mutual influence to the output of these two actuators. The faster actuator will be slowed down by the shower, and the slower actuator will be sped up by the faster. If the coupling effect can't be eliminated, the control problem will become very complicated and the force fighting cannot be reduced effectively. Aiming at reducing the coupling effect between different channels, a robust adaptive fuzzy method which approximated the coupling term by a T-S fuzzy system was proposed [22]. An adaptive fuzzy terminal sliding mode controller was designed for the two joint manipulators [23]. The robust optimal control theory was used to solve the coupling problem [24], and the coupling terms between different channels are regarded as disturbance and a synchronous controller based on QFT theory is designed. To decouple different channels of the multivariable system, a robust decoupling control synthesis procedure for multi-loop control systems has been presented [25]. An adaptive PID speed control scheme for permanent magnet synchronous motor (PMSM) drives is proposed [26].

An adaptive decoupling synchronous controller (ADSC) has been proposed in this paper for the synchronization motion control of the dissimilar redundant actuation system. In particular, the coupling term will be presented by the coupling analysis, and then an adaptive decoupling controller will be designed to eliminate the coupling term and a parameter adaption law is designed for the parametric uncertainties. In addition, a feed-forward compensator is proposed to compensate the difference within HA and EHA aiming at speeding up dynamic response of EHA. Finally, a simulation environment of the dissimilar redundant actuation system is built in the MATLAB/Simulink, and multiple comparisons with the classical PID and a State-difference Feedback approach is made to verify the effectiveness of the proposed ADSC controller.

The paper is organized as follows. Coupling models of the dissimilar redundant actuation system are presented in Section 2. The proposed ADSC controller is designed in Section 3, and the comparative simulation results are presented in Section 4. Finally, the conclusions are presented in Section 5.

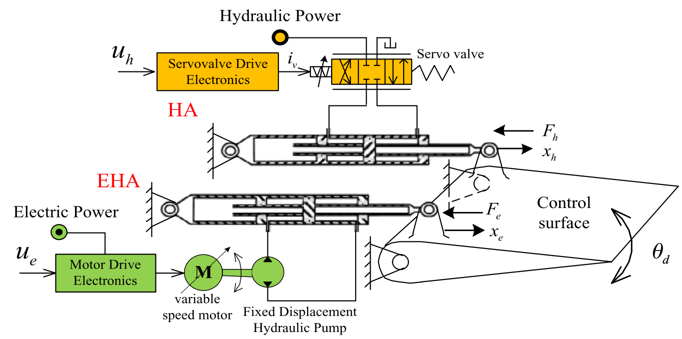

Fig. 1. Parallel driving structure of the dissimilar redundant actuation system.

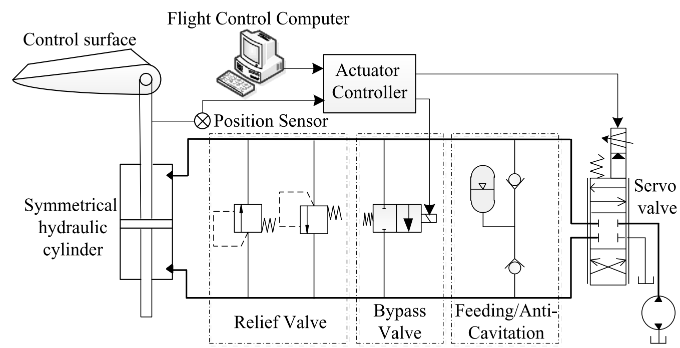

Fig. 2. The structure of the HA system.

2. Coupling model

The parallel driving structure of the dissimilar redundant actuation system is shown in Fig. 1. The system has one HA which consists of a servo valve and a hydraulic cylinder, and one EHA which consists of a variable speed motor, a fixed displacement hydraulic pump as well as a hydraulic cylinder.

2.1. HA model

It consists of servo valve, symmetrical hydraulic cylinder and other accessories (see Fig. 2). In the servo valve section, the spool valve displacement x_v is related to the current i_v by a first-order function [27]:

$$\tau_v \dot{x}_v = -x_v + K_v i_v \tag{1}$$

where τ_v and K_v are the time constant and gain of the servo valve respectively. The load flow Q_h is related to the spool valve displacement x_v and the load pressure P_h [28]:

$$Q_h = C_d \omega x_v \sqrt{\frac{p_s - \mathrm{sgn}(x_v) P_h}{\rho}} \tag{2}$$

In equation (2), the load flow Q_h is linear around the null opening and null load pressure:

$$Q_h = K_q x_v - K_c P_h \tag{3}$$

where $K_q = \partial Q_h / \partial x_v$ and $K_c = -\partial Q_h / \partial P_h$, C_d is the discharge coefficient, ω is the area gradient, p_s is the supply pressure of the fluid, K_q and K_c are the flow/opening gain and the flow/pressure gain. Neglecting external leakage effects, the actuator dynamics can be described [28]:

$$Q_h = A_h \dot{x}_h + \frac{V_h}{4E_h} \dot{P}_h + C_{hl} P_h \tag{4}$$

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