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Modelling and Simulation of Dissimilar Triplex Redundant Hybrid Actuation System

[1]Haitao Qi, [2]Yan Lang and [3]Yongling Fu
[1]Engineering Training Center, Beihang University, 37 Xueyuan Road,
Haidian District, Beijing 100191, China
[2]Beijing Institute of Control Engineering, 16 South 3th Street of Zhongguancun,
Haidian District, Beijing 100190, China
[3]School of Mechanical Engineering and Automation, Beihang University,
37 Xueyuan Road, Haidian District, Beijing 100191, China

Abstract: Triplex Redundant Hybrid Actuation System (TRHAS) with dissimilar redundancies conforms to the development trend of future actuation systems in more electric aircraft. It is composed of a traditional Servo Valve Controlled Hydraulic Actuator (SHA), an Electro-hydrostatic Actuator (EHA) and an Electro-mechanical Actuator (EMA). The structure and operating principle of TRHAS are represented and its linear mathematical model and simulation model in AMESim are established. The operating modes are simulated and analyzed preliminarily. Displacement response curves are given and the force fighting phenomenon is analyzed. All of these works lay the foundation for the future force equalization control.

Key words: Dissimilar redundant, hybrid actuation system, actuators, operating mode, force fighting

INTRODUCTION

The requirements of safety and reliability are higher than before as the development of modern aircraft. Only increasing the number of redundancy to meet these higher requirements is not enough. Dissimilarity in each redundant which called hybrid actuation is needed (CAAC, 2001). Power-by-Wire actuators are good choices for the dissimilar redundant actuation system (Moir and Seabridge, 2008; Botten *et al*., 2000; ATEM, 2004). The hybrid actuation with dual redundant which consisted of SHA and EMA were studied by Cochoy *et al*. (2007), Qi *et al*. (2009a) and Fu *et al*. (2010). For the dual redundant hybrid actuation system with EHA and EMA also has been proposed by Fu *et al*. (2012).

This study describes a Triplex Redundant Hybrid Actuation System (TRHAS) which is composed of SHA, EHA and EMA. The structure and operating principle of TRHAS are represented firstly. Then, its linear mathematical model is established. Finally, simulation analysis of the operating mode is proposed based on AMESim.

MODELLING

Figure 1 displays the schematic of the dissimilar TRHAS, it is clear that a unique control surface is driven by SHA, EHA and EMA. The mechanical compliances at anchorage to airframe and transmission to the load are merged for modelling purposed at the transmission level. This allows meeting the causality requirements for simulation (Qi *et al*., 2009b).

The SHA combines a constant pressure supply, a flow servo valve, a symmetrical cylinder and additional hydraulic components. The input signals of SHA are the servo valve control current i_v^* and the load force F_s while the functional output signal is the cylinder displacement x_s.

The EHA which is the type of fixed pump displacement and variable motor speed, combines a brushless direct current motor, a bidirectional fixed displacement pump, a symmetrical cylinder and additional hydraulic components. The input signals of EHA are the control voltage of the motor u_h^* and the load force F_h while the functional output signal is the cylinder displacement x_h.

The EMA consists of a brushless direct current motor, a roller-screw and a jack rod. In the design under study, the nut is directly driven by the motor while the screw translates. The input signals of EMA are the control voltage of the motor u_e^* and the load force F_e while the output signal is the EMA extension x_e.

The inputs of control surface model are the actuators extension x_s, x_h, x_e and air load F_L. The outputs are the

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Corresponding Author: Haitao Qi, Engineering Training Center, Beihang University, 37 Xueyuan Road, Haidian District, Beijing 100191, China

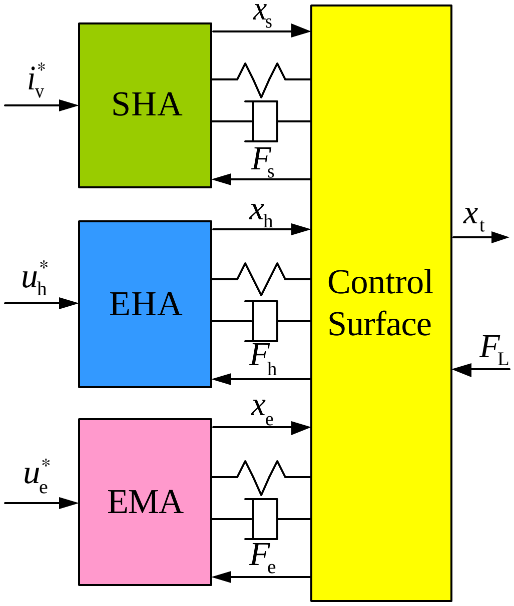

Fig. 1: Schematic of the TRHAS

load position x_t and forces F_s, F_h, F_e that are demanded to the SHA, EHA and EMA actuators, respectively.

SHA: Additional components like mode selector valve or relief valves are not included in the models as they are not active in normal conditions. Assuming the servo valve amplifier is proportional and the gain is k_V, the response of servo valve is second order, the following are the basic equations:

- Flow control equation

$$Q_{fs}(s) = \frac{K_Q k_V \omega_V^2}{s^2 + 2\xi_V \omega_V s + \omega_V^2} i_V^*(s) - K_c p_{fs}(s) \tag{1}$$

- Flow continuity equation

$$Q_{fs}(s) = A_{ts} s x_s(s) + \frac{V_{ts}}{4\beta_s} s p_{fs}(s) + C_{1s} p_{fs}(s) \tag{2}$$

- Force balance equation

$$A_{ts} p_{fs}(s) = m_{ps} s^2 x_s(s) + B_{hs} s x_s(s) + F_s(s) \tag{3}$$

where K_Q is the no-load flow gain, ξv is the damping coefficient of the servo valve; ω_V is the Eigen frequency of the servo valve, K_c is the flow-pressure coefficient, P_{fs} is the load pressure, A_{ts} is the piston area, V_{ts} is the total volume of the SHA, β_s is the bulk modulus of elasticity, C_{1s} is the leakage coefficient, m_{ps} is the piston mass and B_{hs} is the viscous damping of the SHA.

EHA: Additional components like mode selector valve, relief valves and accumulator are not included in the models as they are not active in normal conditions. Ignoring the commutation process of BLDCM, the following are the basic equations:

- Electromotive force balance equation

$$u_h^*(s) = E_h(s) + R_{Ch} i_{Ch}(s) + L_{Ch} s i_{Ch}(s) \tag{4}$$

- Torque balance equation

$$T_{mh}(s) = T_{Lh}(s) + J_{eh} s \omega_h(s) + B_{eh} \omega_h(s) \tag{5}$$

- Back electromotive force equation

$$E_h(s) = C_{eh} \omega_h(s) \tag{6}$$

- Electromagnetic torque equation

$$T_{mh}(s) = C_{mh} i_{Ch}(s) \tag{7}$$

- Load torque equation

$$T_{Lh}(s) = \frac{q_b}{2\pi} p_{fh}(s) \tag{8}$$

- Flow control equation

$$Q_{fh}(s) = \frac{q_b}{2\pi} \omega_h(s) \tag{9}$$

- Flow continuity equation

$$Q_{fh}(s) = A_{th} s x_h(s) + \frac{V_{th}}{4\beta_h} s p_{fh}(s) + C_{lh} p_{fh}(s) \tag{10}$$

- Force balance equation

$$A_{th} p_{fh}(s) = m_{ph} s^2 x_h(s) + B_{hh} s x_h(s) + F_h(s) \tag{11}$$

where, E_h is the back electromotive force (BKF), R_{Ch} is the resistance of motor, L_{Ch} is the inductance of motor, i_{Ch} is the current of motor, T_{mh} is the electromagnetic torque, T_{Lh} is the load torque, J_{eh} is the total inertia of motor and pump, B_{eh} is the total viscous damping of motor and pump, ω_h is the rotational speed of the BLDCM, C_{eh} is the back electromotive force coefficient of the BLDCM, C_{mh} is the electromagnetic torque coefficient of the BLDCM, p_{fh} is the load pressure,

A_{th} is the piston area, V_{th} is the total volume of the EHA, β_h is the bulk modulus of elasticity, C_{1h} is the leakage coefficient, m_{ph} is the piston mass and B_{hh} is the viscous damping of the EHA.

EMA: Ignoring the commutation process of BLDCM, the following are the basic equations:

- Electromotive force balance equation

$$u_e^*(s) = E_e(s) + R_{Ce}i_{Ce}(s) + L_{Ce}si_{Ce}(s) \tag{12}$$

- Torque balance equation

$$T_{me}(s) = T_{Le}(s) + J_{ee}s\omega_e(s) + B_{ee}\omega_e(s) \tag{13}$$

- Back electromotive force equation

$$E_e(s) = C_{ee}\omega_e(s) \tag{14}$$

- Electromagnetic torque equation

$$T_{me}(s) = C_{me}i_{Ce}(s) \tag{15}$$

- Load force equation of the roller-screw

$$F_e(s) = \frac{1}{r}T_{Le}(s) \tag{16}$$

- Output displacement equation of the roller-screw

$$x_e(s) = \frac{1}{s}r\omega_e(s) \tag{17}$$

where, E_e is the back electromotive force, R_{Ce} is the resistance of motor, L_{Ce} is the inductance of motor, i_{Ce} is the current of motor, T_{me} is the electromagnetic torque, T_{Le} is the load torque, J_{ee} is the inertia of EMA, B_{ee} is the viscous damping of EMA, ω_e is the rotational speed of the BLDCM, C_{ee} is the back electromotive force coefficient of the BLDCM, C_{me} is the electromagnetic torque coefficient of the BLDCM, $r = l/2\pi$ is the transfer ratio, l is the screw pitch.

Control surface: The control surface is modeled as a unique and rigid body representing the load inertia. Equivalent structural stiffness and damping are introduced between the actuators and the load. The equation of the motion is:

- Electromotive force balance equation

$$m_t s^2 x_t(s) = F_s(s) + F_h(s) + F_e(s) - F_L(s) \tag{18}$$

where, m_t is the reduced mass of the control surface. Then:

$$F_s(s) = K_t[x_s(s) - x_t(s)] \tag{19}$$

$$F_h(s) = K_t[x_h(s) - x_t(s)] \tag{20}$$

$$F_e(s) = K_t[x_e(s) - x_t(s)] \tag{21}$$

where, K_t is the spring stiffness of the control surface.

SIMULATION AND ANALYSIS

To accurately reflect the actual response of the system, the whole system model is built in the LMS Imagine.Lab AMESim simulation environment, as shown in Fig. 2. The different operating modes are simulated and analyzed. The simulation parameters are shown in Table 1. The displacement and force responses of these three actuators are analyzed for a 10 mm position step demand occurring at 0.1 s and a 10 kN load step occurring at 1.0 s.

Active/Active/Active mode: SHA, EHA and EMA are controlled in active mode. Figure 3 displays the actuators displacement and force responses. It can be noticed that from Fig. 3a, the response of SHA is the fastest, EMA is faster and EHA is the slowest which will inevitably lead to the force fighting, as shown in Fig. 3b.

Active/Passive/Active mode: Both SHA and EMA are controlled in active mode and EHA with mode selector

Table 1: System parameters

Model parameter	Value
SHA supply pressure [bar]	210
SHA rod diameter [mm]	50
SHA piston diameter [mm]	110
SHA piston mass [kg]	3
SHA servo valve nominal flow rate [L/min]	45
SHA servo valve corresponding pressure drop [bar]	70
SHA stroke [mm]	100
EHA rod diameter [mm]	50
EHA piston diameter [mm]	95
EHA piston mass [kg]	2
EHA stroke [mm]	100
EHA pump pressure [bar]	210
EHA pump displacement [mL/r]	3
EHA resistance of motor [O]	1
EHA inductance of motor [H]	0.01
EHA back EMF coefficient [V/rad/s]	0.25
EMA resistance of motor [O]	1.6
EMA inductance of motor [H]	0.01
EMA back EMF coefficient [V/rad/s]	0.15
EMA screw pitch [mm]	3
Control surface spring stiffness [N/m]	5×108
Control surface reduced mass [kg]	600

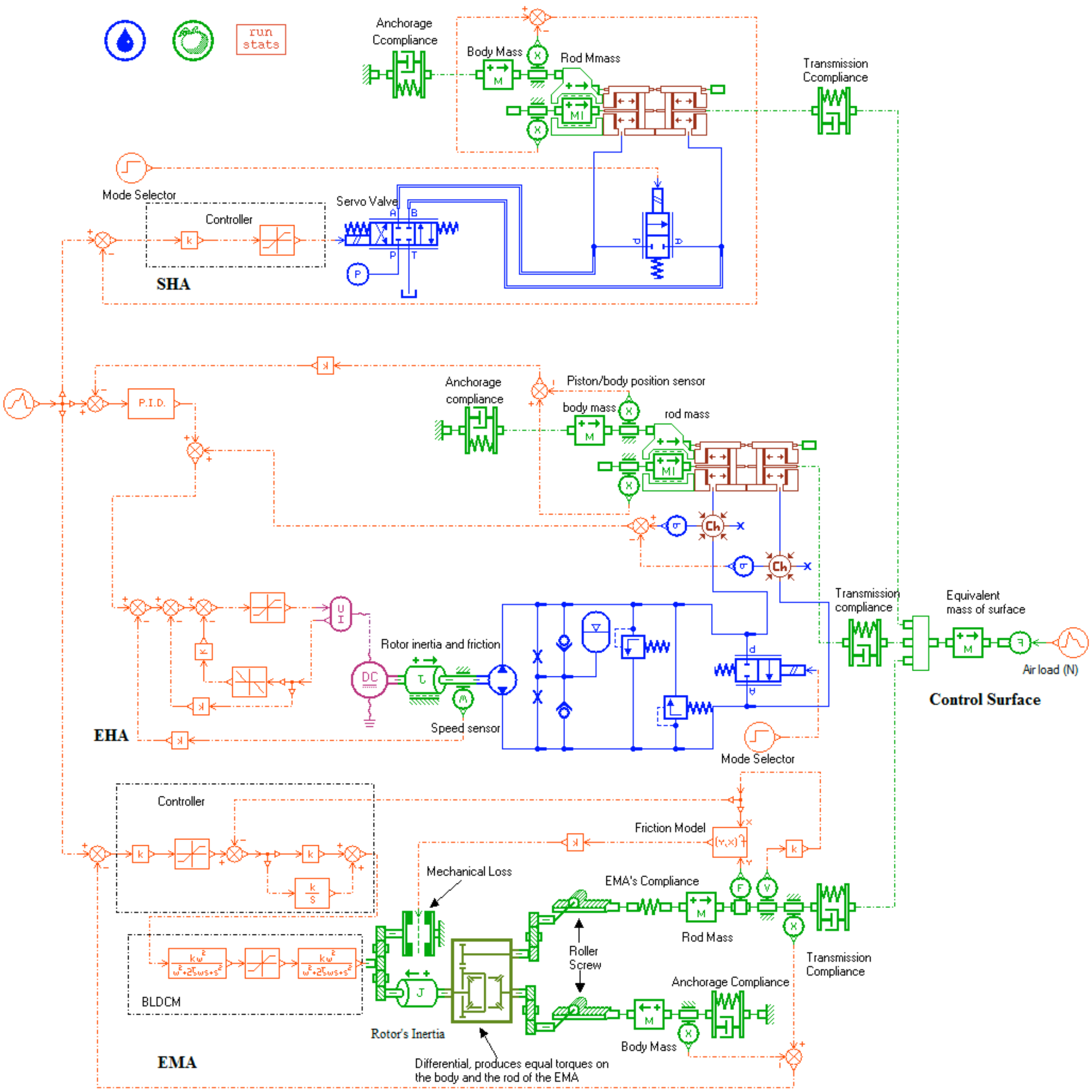

Fig. 2: Simulation Model of the dissimilar triplex redundant hybrid actuation system based on AMESim

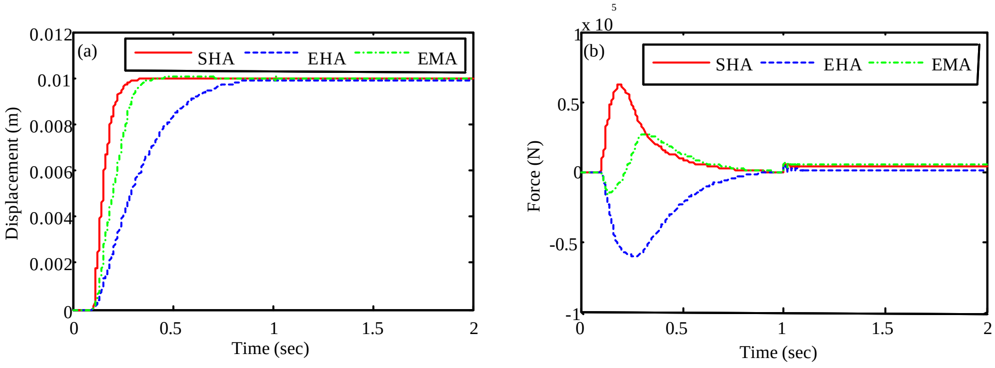

Fig. 3(a-b): Responses of the actuators operating in Active/Active/Active mode (a) Displacement (b) Force valve is controlled in passive mode. Figure 4 displays the actuators displacement and force responses. It can be noticed that from Fig. 4a, the response of SHA is the fastest, EHA operation is followed by EMA. And the external load force is mainly undertaken by SHA and EMA as shown in Fig. 4b.

Active/Active/Passive mode: Both SHA and EHA are controlled in active mode and EMA is passively to follow the movement of the control surface. Figure 5 displays the actuators displacement and force responses. It can be noticed that from Fig. 5a, the response of SHA is the fastest, EMA operation is followed by EHA, but existing a large delay. And the external load force is mainly undertaken by SHA and also need to provide great force to drive the EMA passively follow as shown in Fig. 5b.

Passive/Active/Active mode: Both EHA and EMA are controlled in active mode and SHA with mode selector valve is passively to follow the movement of the control surface. Fig.6 displays the actuators displacement and force responses. It can be noticed that from Fig. 6a, the response of EMA is the fastest, SHA follows with EMA and EHA response slow. The external load force is mainly undertaken by EMA as shown in Fig. 6b.

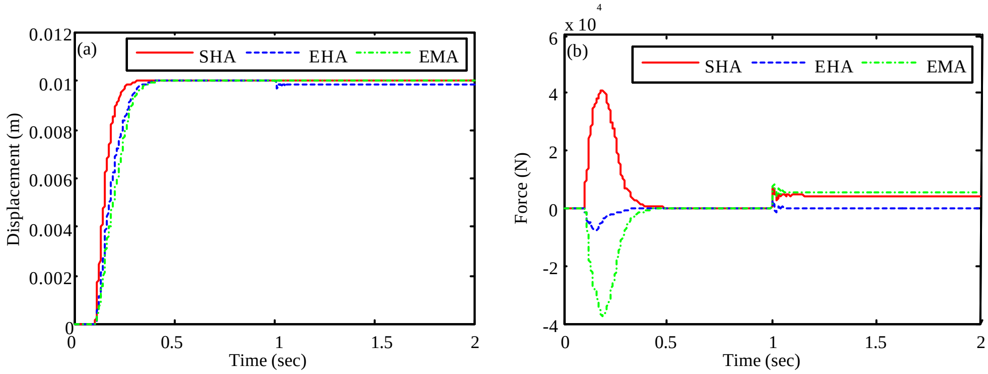

Fig. 4: Responses of the actuators operating in Active/Passive/Active mode (a) Displacement (b) Force

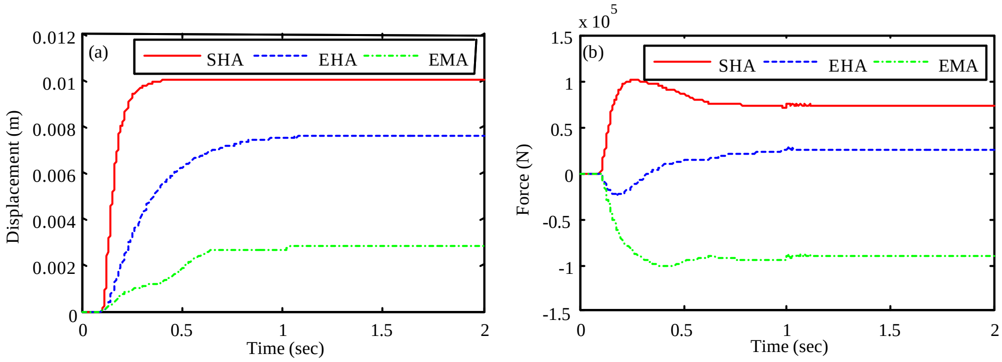

Fig. 5: Responses of the actuators operating in Active/Active/Passive mode (a) Displacement (b) Force

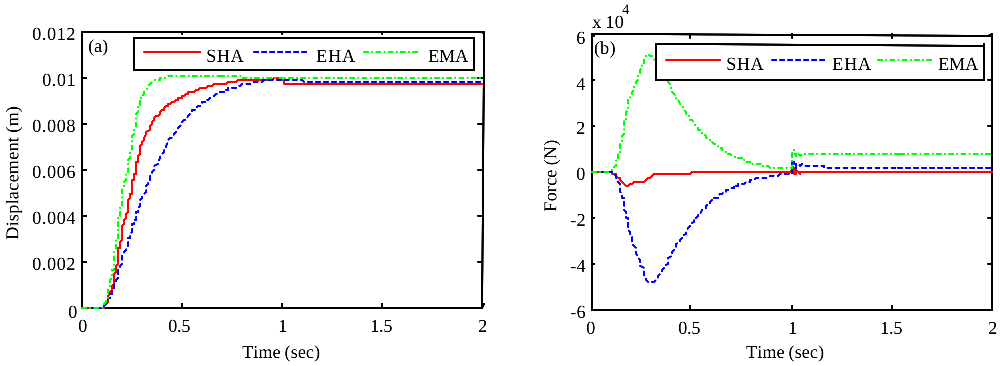

Fig. 6: Responses of the actuators operating in Passive/Active/Active mode (a) Displacement (b) Force

CONCLUSION

Due to the different physical principle of the actuators which are used in the dissimilar triplex redundant hybrid actuation system and the different load characteristics, when they are applied to drive a unique load, each channel tries to produce a given load position that is different. Then the force fighting will occur inevitably. Through the modeling and simulation of the dissimilar triplex redundant hybrid actuation system, it can be noticed that the force fighting is existed in all different operating modes. Of course, they are different in different modes. Therefore, the force equalization control have to be adopted in the dissimilar triplex redundant hybrid actuation system in actual use.

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