Fault Injection of Electro-Hydrostatic Actuator and its Influence Analysis of Aircraft Flight Performance

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Abstract—**Airborne actuation system is one of the key flight control subsystems to realize flight attitude and trajectory control. Its performance directly affects the flight quality of aircraft. This paper discusses the influence of Electro-Hydrostatic Actuator (EHA) failure on flight performance of aircraft. This paper first describes the development of EHA, introduces its structure and working principle, decomposes the electro-hydrostatic actuator into the original component level, analyses and models them respectively, and proposes a fault injection scheme for possible faults. Finally, assuming that the actuator on the rudder of an aircraft fails, the impact on the flight performance of the aircraft is carried out. In this paper, the control performance of aircraft under different faults is simulated and analyzed, which provides a theoretical basis for fault-tolerant control of aircraft under faults.**

Keywords-component; EHA; Analysis and Modeling; fault injection; flight control

I. INTRODUCTION

Airborne actuation system is one of the key flight control subsystems to realize flight attitude and trajectory control. Its performance directly affects the flight quality of aircraft. So it is necessary to study the influence of EHA failure on aircraft control performance.

Electro-Hydrostatic Actuator(EHA) is a new type of servo actuator. Because of its high integration, high power ratio, high reliability, high efficiency and easy installation and maintenance, it can replace the traditional centralized oil source valve-controlled hydraulic actuation system, and is widely used in heavy-duty occasions of aircraft, ships, robots and other mobile platforms. In the 1980s, the U.S. Air Force, Navy and NASA endorsed the concept of all-electric/multi-electric aircraft [1], in which electric actuator is an essential part of all-electric/multi-electric aircraft [2], so it also develops rapidly with the research of all-electric/multi-electric aircraft [3]. EHA is one of the earliest electric actuators studied and developed. Another kind of electric actuator, Electro-Mechanical Actuator(EMA), is also developing rapidly. Compared with EMA, EHA has the advantages of small size, large power and flexible control. First, the U.S. Air Force, NASA and Honeywell sponsored laboratory research on electric actuators such as Ai Research and Johnson Space Center, respectively. Then Lockheed conducted flight tests on C141 and C130 transports, including EHA and EMA of various power levels and principles [4]. By the 1990s, after accumulating a variety of research experience on electric actuators, the United States focused on testing EHA with constant displacement and variable speed and EMA with double motor-reducer-ball screw on F-18, and achieved good results [5-7]. Europe has also launched a research and development project for electric actuators, which carried out flight tests with EHA mounted on the aileron of the A321 [8]. By the beginning of the 21st century, the latest aircraft in service in Europe and the United States had formally applied the electro-actuation technology to varying degrees. The main flight control surface of F35 fighter aircraft in the United States was all operated by EHA, and the secondary flight control surface of B787 civil aircraft was operated by EMA [9]. Both A400M and A380 in Europe use EHA as backup steering gear on the main flight control surface.

At present, EHA has been successfully applied to the main flight control rudder of aircraft, and has obvious advantages over conventional hydraulic actuation, and will continue to develop rapidly in the future. Airbus has proposed to devote itself to EHA research and development in the same life as the aircraft, so that it can be used as the main actuator of flight control, not just as a backup, and its focus is to extend the life of the pump [10-11]. Tokyo University scholars proposed that EHA be used in wearable booster robots, and it has advantages that rigid actuators do not have [12]. In addition, experts and scholars have proposed that EHA be used in submarines, active suspension of automobiles, tilting control of rail trains, construction machinery and other equipment. ISO published the first edition of Aviation EHA Requirements Specification Standard (ISO 22072) in 2005, and revised the second edition in 2011 to give a typical framework of EHA. It is pointed out in the standard that EHA is a bi-directional variable speed motor driven bi-directional constant displacement hydraulic pump, and the motor, pump and electronic modules can be assembled into a standard integrated electro-hydrostatic module. Aviation EHA is generally used as a position servo system [13].

The research and development of EHA in developed countries or regions such as the United States, Europe and Japan started earlier. At present, EHA has been formally applied in aerospace, military industry and robotics. China has carried out theoretical and technical research on EHA in the early stage, and now has begun the development of formal products. EHA is promoting the renewal of the field of hydraulic servo actuation, and is expected to become a general technology of large equipment. Therefore, it is necessary to study the fault mode and fault diagnosis of EHA, so as to open up a broader space for the use of EHA.

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This paper introduces the development of electro-hydraulic servo actuator, introduces its structure and working principle, decomposes the electro-hydraulic servo actuator into the original component level, analyses and models them respectively, and proposes a fault injection scheme for possible faults. Finally, assuming the actuator on the rudder fails, it will affect the flight performance of the aircraft. In this paper, the control performance of aircraft under different faults is simulated and analyzed, which provides a theoretical basis for fault tolerant control of aircraft.

II. STRUCTURE AND WORKING PRINCIPLE OF EHA

Fig.1 is a typical structural diagram of EHA. In this structure, the main components of electrostatic actuator include servo motor, quantitative plunger pump, accumulator, symmetrical hydraulic cylinder, one-way valve, bypass valve and safety valve. The servo motor is responsible for converting electrical energy into mechanical energy, receiving the electrical signal from the controller, and outputting the corresponding speed signal. Quantitative plunger pump is responsible for converting mechanical energy into liquid pressure energy, receiving motor output speed signal, output flow. The one-way valve and accumulator constitute the oil tank of EHA closed circuit. On the one hand, they compensate for the oil loss caused by the leakage of components, on the other hand, they guarantee the lowest pressure of the system and prevent cavitation phenomenon, and at the same time, they can reduce the system pulsation. Relief valve relief protection is carried out when the system pressure exceeds the limit. Bypass valves are used for fault isolation. Because of the change of flow rate in the system pipeline, the pressure difference between the two chambers forms, which drives the piston rod to move, and drives the flight control rudder surface to deflect in a certain angle through the hinge connected with the flight control rudder surface.

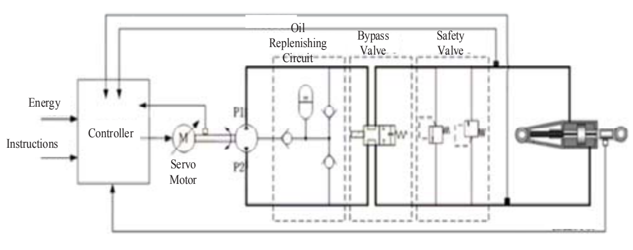

Figure 1. Typical structure sketch of EHA

III. MODELING OF ELECTROSTATIC HYDRAULIC ACTUATOR

According to the working principle of EHA components, motors, hydraulic pumps and cylinders are the key components affecting the performance of EHA. So the servo motor, pump control cylinder and actuator cylinder are modeled separately in this paper, and then the whole model of electrostatic actuator is obtained by integrating the models of each part.

A. Motor model

EHA adopts brushless DC motor, and its potential balance equation can be expressed as

$$u_e = K_e \omega_e + L_e \frac{di_e}{dt} + R_e i_e \tag{1}$$

where u_e is the motor control voltage, i_e is the motor current, K_e is the back EMF coefficient of the motor, ω_e is the motor speed, R_e is the armature resistance of motor, L_e is the armature inductance of motor .

The torque balance equation of motor can be expressed as

$$K_m i_e = T_e + J_m \frac{d\omega_e}{dt} + B_m \omega_e \tag{2}$$

where K_m is the electromagnetic torque constant of motor, T_e is the motor output torque, $B_m = B_e + B_p$ is the total load damping coefficient of motor-pump, $J_m = J_e + J_p$ is the total moment of inertia of motor-pump.

B. Pump Control Cylinder Model

Based on the working mode of EHA and the requirement of speed and load of the whole system, a bidirectional quantitative plunger pump and a symmetrical hydraulic cylinder are selected. For the convenience of analysis, it is considered that the pump and the motor are rigidly connected, they have the same speed, and the output torque of the motor is the input torque of the pump. Assuming that the total efficiency of the hydraulic pump is 1, the input torque of the pump is:

$$T_e = \frac{V_n(P_a - P_b)}{\omega} = \frac{V(P_a - P_b)}{2\pi} = V_p(P_a - P_b) \tag{3}$$

where V is the displacement of the pump, P_a and P_b are the outlet and inlet pressure of the pump respectively, $V_p = V/(2\pi)$.

In order to simplify the model, the following assumptions are made for the hydraulic pump: assuming that both the internal and external leakage coefficients of the pump are 0, and without considering the change of oil volume, the flow equation of the pump can be expressed as follows:

$$q_a = q_b = V_n = V_p \omega_e \tag{4}$$

Because of the symmetry of EHA, the pressure drop between pump and actuator barrel is not considered, and the flow loss of hydraulic pipeline between pump and actuator barrel is assumed to be zero, and we get

$$\begin{cases} q_a = q_1, q_b = q_2 \\ p_a = P_1, p_b = P_2 \end{cases} \tag{5}$$

where p_1 and q_1 are the inlet pressure and flow rate of hydraulic cylinder respectively, p_2 and q_2 are the outlet pressure and flow rate of hydraulic cylinder respectively.

Because of the symmetry of actuator cylinder, the load pressure P_e and load flow Q_e of EHA system can be expressed as:

$$\begin{cases} P_e = P_1 - P_2 = P_a - P_b \\ Q_e = (q_1 + q_2)/2 = (q_a + q_b)/2 \end{cases} \tag{6}$$

It is assumed that the temperature of the oil is constant, that is, the elastic modulus can be considered unchanged, and the leakage inside and outside the actuating cylinder is laminar flow. The initial working state of the hydraulic cylinder is in the middle, that is, the volume of the two chambers is equal. Considering the liquid compression and the mechanical expansion of the cylinder structure, the flow continuity equation of the hydraulic cylinder can be expressed as:

$$V_P \omega_e = A_e \frac{dx_e}{dt} + \frac{V_e}{4E_e}\frac{dP_e}{dt} + C_{el}P_e \tag{7}$$

where A_e is the effective area of hydraulic cylinder piston, x_e is displacement of piston in hydraulic cylinder, V_e is the total volume of hydraulic cylinder, C_{el} is the total leakage coefficient of hydraulic cylinder, and $C_{el} = C_{eli} + 0.5C_{ele}$, C_{eli} and C_{ele} are the internal and external leakage coefficients of hydraulic cylinders respectively, E_e is the effective bulk modulus of elasticity.

Similar to the hydraulic actuating system, the force acting on the piston rod of the hydraulic cylinder is regarded as the external load of the whole actuating cylinder, expressed by F_e, which is the output force of the piston rod, and the force balance equation of the hydraulic cylinder is as:

$$A_eP_e = m_e \frac{d^2x_e}{dt^2} + B_e \frac{dx_e}{dt} + F_e \tag{8}$$

Laplacian transformations of (3), (7) and (8) are carried out to obtain the block diagram model of the transfer function of the pump control cylinder.

C. Actuator Cylinder Model

In order to simplify the model, it is generally considered that the actuator is rigidly connected with the load, but for the servo system with large inertia, the influence of structural stiffness on the system performance can't be neglected. Therefore, a spring with stiffness *K* is used to represent the stiffness of the connection between the actuator and the rudder surface. Fig. 2 is the schematic diagram of actuator driving rudder surface. The relationship between actuator driving force F_d and external load force F_h acting on piston rod is as:

$$F_h = F_d = K(\mathrm{x}_h - \mathrm{x}_d) \tag{9}$$

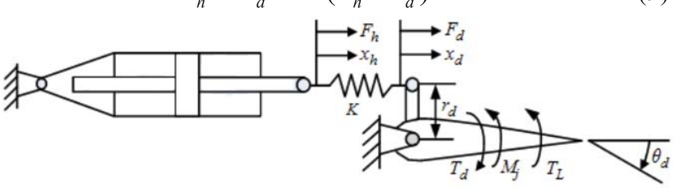

Figure 2. Principle diagram of actuator driving rudder surface

D. EHA Model

Based on the above independent model of each part of EHA, the whole model of EHA can be obtained. The model of the whole EHA system can be obtained by adding the double closed-loop control of motor and the position closed-loop control of the whole EHA system. The model of the whole EHA system can be obtained as shown in Fig. 3.

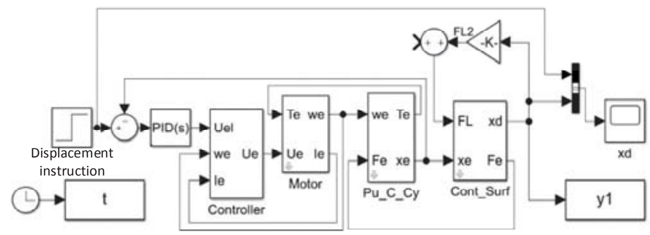

Figure 3. EHA system model

The response curve of the model to step input is shown in Fig. 4.

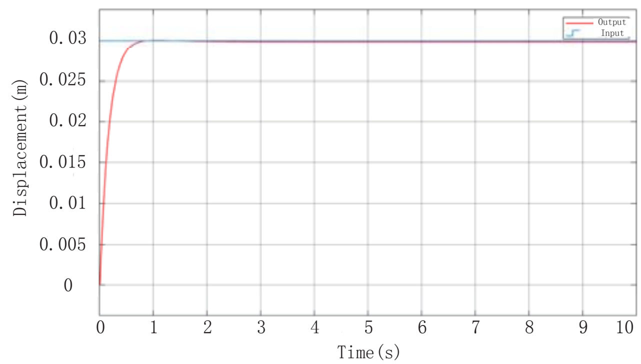

Figure 4. Rudder displacement and displacement instruction simulation curve

From Fig. 4, when the error band is 2%, the system response time is 0.6s; the overshoot is 0.2%, almost no overshoot; and the steady-state error is about 0.4%. Based on the above analysis, the simulation model of EHA system can be used to simulate the working state of real electro-hydrostatic actuator.

IV. Fault Injection Scheme of EHA

Common faults of EHA include motor faults, actuator faults and LVDT sensor faults. In this section, the common fault modes of the main components of EHA are analyzed. According to the frequency of fault occurrence and the sensors that can be installed in the actual EHA system, the types of faults that need to be injected are determined, and the scheme of fault injection is designed, and the fault model is established. Finally, the influence of the above faults on the whole machine is analyzed.

A. Failure Mode Analysis

1) Fault Analysis of Motor

Common fault modes of motors include winding short circuit caused by insulation drop, bearing faults of various forms such as wear, corrosion, indentation and fracture, or motor blockage caused by foreign body entry, magnetic steel shedding, serious bearing wear, etc. Because the data bit current and speed are generally measurable in EHA, bearing wear is usually diagnosed by vibration signals. However, motor overload, damp winding, friction between stator and rotor and many other reasons will lead to motor winding insulation decline and motor short circuit, which is a relatively common fault mode. Therefore, in this paper, the fault model of motor winding breaking is established.

2) Fault Analysis of Actuating Cylinder

Common faults of actuator barrel include leakage, pump shell rupture, piston rod creeping and stuck. There are two kinds of sensors on the actuating cylinder, one is the pressure sensor for measuring the pressure of the left and right chambers, and the other is the LVDT for measuring the output displacement of the piston rod. Therefore, this paper models the piston rod crawling and jamming faults.

3) LVDT Fault Analysis

Common faults of sensors include intermittent signal, abnormal signal jump and signal disappearance. In this paper, three kinds of faults are modeled and injected.

B. Fault Injection Scheme

1) Short-circuit fault injection of motor

When the motor winding is seriously short-circuited, the winding resistance is zero. The relationship between coil self-inductance and coil turns and coil area can be expressed as $L_s = \left(\mu * S * N^2\right) / L$, where μ is the initial permeability of materials, S is the cross-sectional area of conductor, N is the number of coils, L is the effective length of conductor, so the winding self-inductance will also be reduced to near zero.

The torque constant and back EMF constant of motor can be expressed as $K_T = K_B = rBLZ_D$, where r is the air gap radius of motor, B is the magnetic induction intensity, L is the effective length of conductor, Z_D is the conductor number. The total number of conductors makes the torque constant of the motor change. Therefore, the injection mode of motor winding breaking fault is to adjust the motor resistance, inductance, torque constant and back EMF constant.

The model simulation curves are shown in Figs. 5-7.

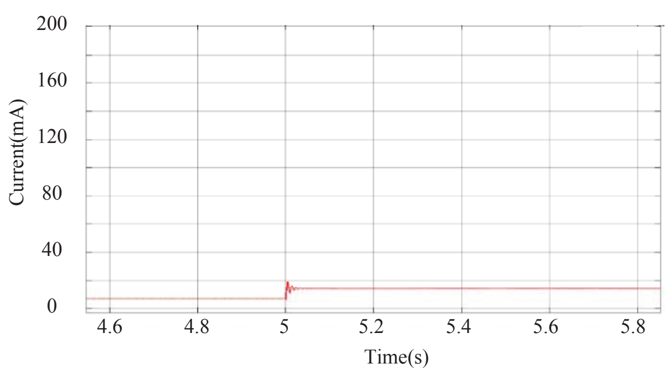

Figure 5. Motor current waveform

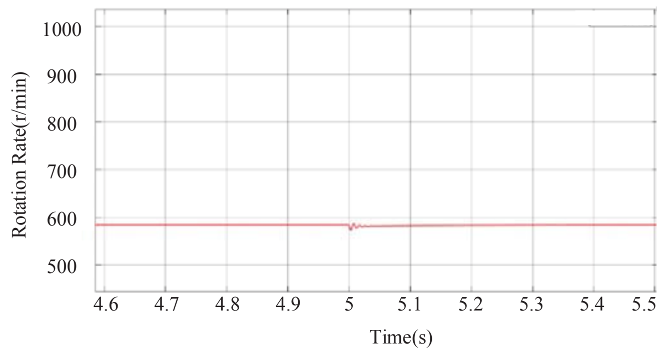

Figure 6. Motor speed waveform

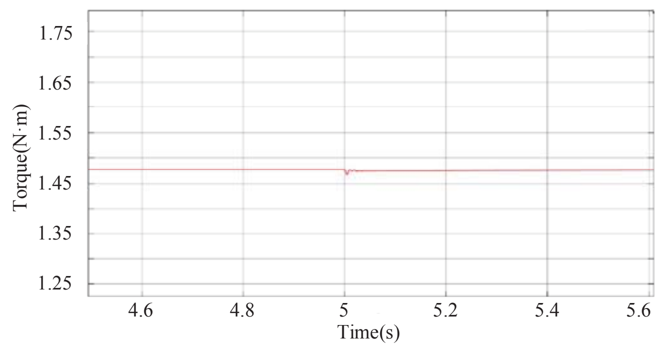

Figure 7. Motor torque waveform

As can be seen from the above figure, when the motor is short-circuited, the current of the motor obviously increases and quickly stabilizes at a larger value, while the speed and output torque of the motor only oscillate at the instant of the motor short-circuiting, and then stabilize again. Although the short-circuit fault will not affect the output speed and torque of the motor obviously, the current will increase obviously, and the influence may not be obvious when the motor works in the low power state, but when the motor works in the high power state, the current may exceed the rated range and cause the coil to heat rapidly, which eventually leads to the coil fusing and the motor winding breaking. Then it has a great impact on the whole EHA system.

2) Crawling fault of actuator

When the hydraulic cylinder and piston rod wear, oil pollution is serious or oil viscosity is large, the hydraulic cylinder will crawl at low speed. This will increase the pulsation in the system, lead to the vibration intensification in the system, and will seriously affect the life of each part of the system. In severe cases, the system will fail. So simulation analysis is carried out for this kind of fault. A sinusoidal function is multiplied by a square wave signal, and the positive part of the sinusoidal function is retained. Then the signal is multiplied by the piston rod velocity signal to simulate the piston rod crawling.

The output displacement waveform of the piston rod is shown in Fig. 8.

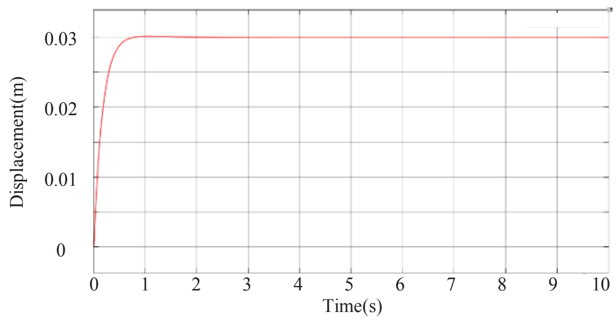

Figure 8. Output displacement of piston rod

It can be seen from the figure that the crawling state of the hydraulic cylinder has no obvious influence on the whole system, and only causes a minimal fluctuation of the system.

When the internal wear of the hydraulic cylinder is serious or the oil pollution is serious, it will lead to the jam of the hydraulic cylinder. Therefore, the fault mode is simulated by changing the piston rod speed to zero so as to keep the output displacement of the hydraulic cylinder unchanged.

The output displacement of the piston rod is shown in Fig. 9 (assuming that the piston rod is stuck at 30 degrees).

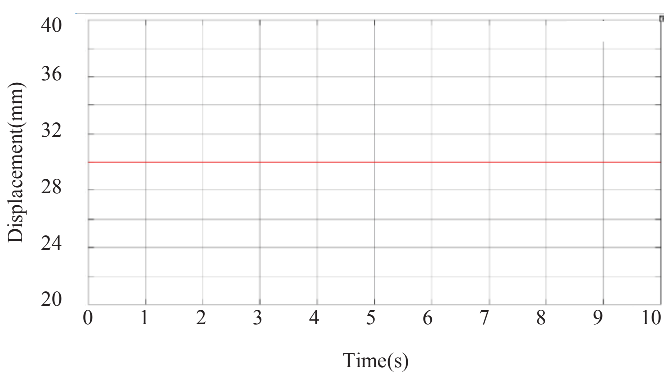

Figure 9. Output displacement of piston rod

It can be seen from the figure that when the piston rod is stuck, the actuator can't follow the instructions to output, which will lead to the actuator can't complete the intended function. And the angle of piston rod jamming will affect the flight attitude of the whole aircraft in varying degrees.

3) LVDT fault

The linear displacement sensor is used to measure the output displacement of the piston rod of the hydraulic cylinder and feedback to the controller for production control residual. So the signal of linear displacement sensor will directly determine the control signal and the action of EHA. It is necessary to inject and analyze three common fault modes of linear displacement sensor. The simulation method is to multiply the displacement signal with square wave, random wave and zero and feed back to the controller to simulate the three faults of the sensor.

The output angle waveforms of LVDT actuators in three different fault modes are shown in Fig. 10 to Fig. 12.

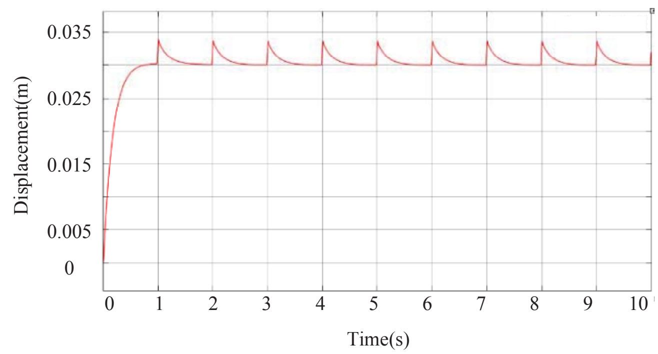

Figure 10. Sensor signal is intermittent

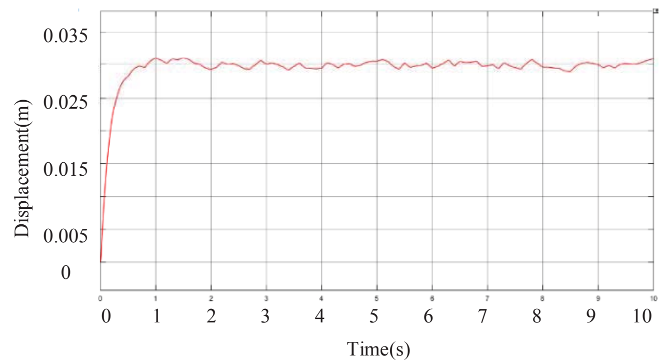

Figure 11. Sensor signal hopping

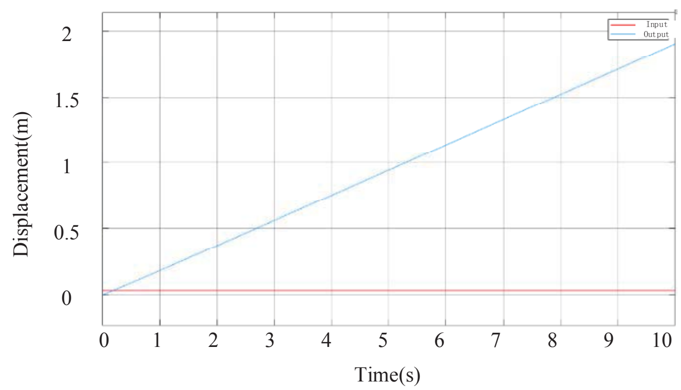

Figure 12. Sensor signal disappearance

From the above figures, it can be seen that the output of the actuator can't be stabilized because the feedback of displacement signal received by the control computer is always slightly different from the displacement command, so the actuator has been slightly adjusted and can't be stabilized. Interruption of sensor signal will cause oscillation of actuator output, which will have a more obvious impact on the actuator, and may increase the burden of the actuator, thereby leading to the deterioration of the performance of the actuator. The disappearance of sensor signal will have a huge impact on the actuator, and the system will continue to send instructions because it can't accept the output of the actuator, resulting in the actuator to the limit position. Ultimately, the actuator loses its function and may have a greater impact on the aircraft.

V. SIMULATTION AND CONCLUTION

Aiming at the above failure modes, this paper injects the fault into the whole flight control simulation model under the conditions of altitude 7777 meters, course 5 degrees and flight speed 311 m/s, and obtains the following results.

Short circuit and piston rod crawling faults have little influence on aircraft attitude, but cause small oscillation and delay of the system, which can be neglected.

Aiming at the different characteristics of piston rod stuck angle which has different influence on aircraft flight attitude, this paper simulates the rudder stuck in 3 degrees, and gets the following results.

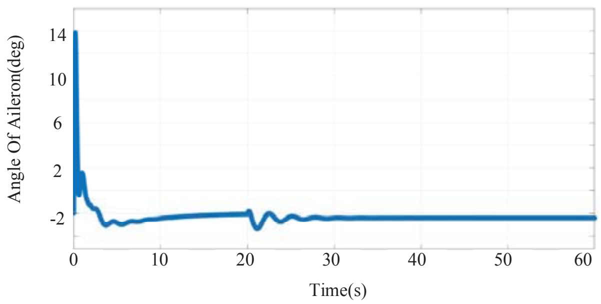

Figure 13. Angle change of aileron when rudder is stuck at 3 degrees

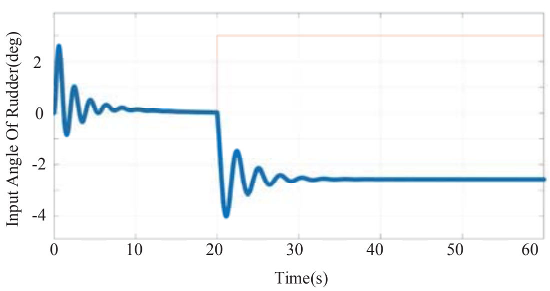

Figure 14. Input instruction of rudder

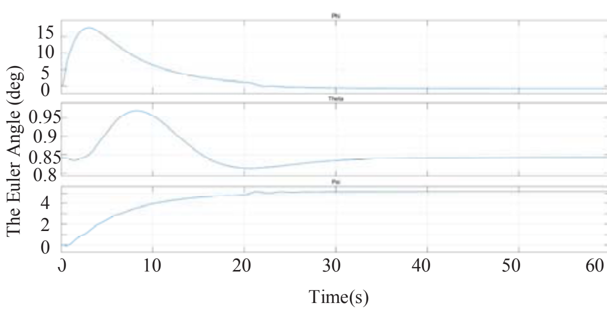

Figure 15. The Euler Angle change of aircraft

When the rudder is stuck in the position of 3 degrees, the aileron will undertake some adjustment work. The course angle and roll angle of the whole flight will fluctuate. At the same time, because the pitch of the elevator is also involved in the regulation, there is a slight steady-state error in the height. However, the overall flight attitude of the aircraft has not changed significantly.

In addition, the intermittent and jump fault of LVDT signal will lead to the delay of rudder response, and the performance of inner loop control will be significantly reduced, but due to the external loop feedback, the overall effect is not much. The disappearance of LVDT signal will lead to loss of feedback in the inner loop and divergence, which will lead to the failure of the overall system control. Although the overall control of the aircraft does not diverge due to the existence of feedback in the outer loop, the altitude and speed of the aircraft are greatly affected.

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