Parameters Modeling and Fault Simulation for Flight Control System Based on SIMULINK

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***Abstract*—The establishment of flight control system parameters modeling and fault simulation is the basis of fault diagnosis. In this paper, the flight control system simulation model is established by MATLAB / SIMULINK. We describe the modules and implementation methods of the flight control system parameters modeling in detail. In addition, the simulation of the failure mode and realization is introduced. Finally, we do some simulations and make some analysis to the simulation results. The simulation results show that our methods are well.**

Keywords-flight control system ; simulation model ; fault simulation ; Simulink ;

I. INTRODUCTION

High-quality flight control system is critical to the flight safety of modern high performance aircraft[1-3]. The main function of the flight control system is to stabilize the attitude of the aircraft, to control the flight path, to monitor flight parameters, to enhance the aircraft stability, to improve flight quality and maneuverability. With the development of new technologies such as active control technology, redundancy technology and fault tolerant control, flight control system has evolved from autopilot to integrated control system. The aircraft control system was also developed from machinery control system to the Fly-by-Wire System. But the flight control system becomes more and more complex, for flight safety, the reliability and safety of flight control systems are becoming more and more important. During the flight of the aircraft, if the flight control system can accurately identify fault type and take reasonable measures, it is significant to the flight safety. Therefore, the flight control system is very necessary for real-time monitoring and fault diagnosis[4-7]. The mathematical model and fault simulation of flight control system are the basis of fault diagnosis. The flight control system simulation model is established by using computer simulation technology, and the fault data of flight control system can be obtained with less input and faster speed. On the basis of simulation data, the feasibility and effectiveness of intelligent algorithm in fault diagnosis of flight control system are verified.

Flight control system has complex structure, diverse fault modes. According to the basic composition of the flight control system, fault modes of the flight control system mainly include sensor fault, flight control computer fault, servo-actuation system fault. In this paper, the flight control system simulation model is established by MATLAB / SIMULINK. The model includes six-degree-of-freedom motion equation, Aerodynamic force and moment, environment module and dynamic pressure and Mach number calculation module. Then the model is trimmed and linearized, and the altitude maintenance system is designed to maintain the aircraft longitudinal stability. Based on that, few fault modes are simulated, for example, sensor, actuator and control surface damage[8-12].

II. FLIGHT DYNAMICS MODEL OF AIRCRAFT

A. Coordinate Frame

1) Earth-surface Inertial Reference Frame

$S_g - O_g x_g y_g z_g$

Take ground as origin O_g . $O_g x_g$ and $O_g y_g$ are in the ground plane, $O_g x_g$ pointes to the north, $O_g y_g$ is perpendicular to $O_g x_g$ and pointes to the east. $O_g z_g$ is perpendicular to the ground, and pointes to the geocentre.

2) Aircraft-body Coordinate Frame $S_b - O_b x_b y_b z_b$

Take aircraft barycenter as origin O_b . The coordinate frame are fixed to the airplane. $O_b x_b$ and $O_b z_b$ are in the aircraft symmetrical plane, $O_b x_b$ pointes to the front. $O_b y_b$ is perpendicular to the aircraft symmetrical plane and pointes to the right. $O_b z_b$ is perpendicular to $O_b x_b$ and pointes to the below.

3) Wind Coordinate Frame $S_a - O_a x_a y_a z_a$

Take aircraft barycenter as origin O_a . $O_a x_a$ is consistent with flight speed. $O_a z_a$ is in the aircraft symmetrical plane and perpendicular to $O_a x_a$, it pointes the ventral. $O_a y_a$ is perpendicular to $x_a O_a z_a$ and pointes to the right [13].

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B. Aircraft Dynamics Model

The aircraft is subjected to the action of the external force F and the external moment M during the flight, where is generated by the atmosphere and the engine. The kinetic equation of the aircraft can be derived from Newton's second law. Newton's second law can be expressed as follows.

$$F = m(\frac{\partial V}{\partial t} + \Omega \times V)$$
$$M = \frac{\partial (I \cdot \Omega)}{\partial t} + \Omega \times (I \cdot \Omega) \quad (1)$$

$V = [u \quad v \quad w]^T$ is velocity vector at the center of gravity of airplane, $\Omega = [p \quad q \quad r]^T$ is the angular velocity component at the center of gravity, $F = [X \quad Y \quad Z]^T$ is resultant force vector, $M = [M_x \quad M_y \quad M_z]^T$ is resultant moment vector, m is aircraft quality, I is solid moment of inertia:

$$I = \begin{bmatrix} I_x & 0 & -I_{xz} \\ 0 & I_y & 0 \\ -I_{xz} & 0 & I_z \end{bmatrix} \quad (2)$$

The aircraft dynamic equation is obtained:

$$X = m(\dot{u} + wq - vr)$$
$$Y = m(\dot{v} + ur - wp) \quad (3)$$
$$Z = m(\dot{w} + vp - uq)$$

$$L = \dot{p}I_x - \dot{r}I_{xz} + qr(I_z - I_y) - pqI_{xz}$$
$$M = \dot{q}I_y + pr(I_x - I_z) + (p^2 - r^2)I_{xz} \quad (4)$$
$$N = \dot{r}I_z - \dot{p}I_{xz} + pq(I_y - I_z) + qrI_{xz}$$

C. Aircraft Kinematics Model

In order to describe the movement of the aircraft relative to the ground, it is necessary to establish the geometric relationship between the attitude angle change rate and the angular velocity components, where is called aircraft kinematics equation.

$$\dot{\theta} = -r\sin\varphi + q\cos\varphi$$
$$\dot{\psi} = (-r\cos\varphi - q\sin\varphi)/\cos\theta \quad (5)$$
$$\dot{\varphi} = (p + (r\cos\varphi + q\sin\varphi))/\tan\theta$$

For the Equation 5 transformation, we get another form of the nonlinear motion equation of the aircraft, see Equation 6.

$$\dot{u} = -g\sin\theta - qw + rv + \frac{1}{m}X$$
$$\dot{v} = g\sin\varphi\cos\theta - ru + pw + \frac{1}{m}Y$$
$$\dot{w} = g\cos\varphi\cos\theta - pv + qu + \frac{1}{m}Z$$
$$\dot{p} = [I_zL + I_{xz}N - (I_z^2 + I^2{}_{xz} - I_yI_z)qr - I_{xz}(I_y - I_x - I_z)pr]/(I_xI_z - I^2{}_{xz})$$
$$\dot{q} = [M - (I_x - I_z)pr + I_{xz}(p^2 - r^2)]/I_y$$
$$\dot{r} = [I_xN + I_{xz}L - (I_xI_y - I_x^2 - I^2{}_{xz})pq - I_{xz}(I_y + I_x - I_z)qr]/(I_xI_z - I^2{}_{xz})$$
$$\dot{\theta} = -r\sin\varphi + q\cos\varphi$$
$$\dot{\psi} = (-r\cos\varphi - q\sin\varphi)/\cos\theta$$
$$\dot{\varphi} = (p + (r\cos\varphi + q\sin\varphi))/\tan\theta$$
$$(6)$$

In (5) and (6), θ is angle of pitch, ψ is yaw angle, φ is roll angle. q is pitch angular rate, r is yaw angular rate, p is roll angular rate. u, v, w is the projection of the velocity vector on three coordinate axes of the aircraft-body coordinate frame.

III. FLIGHT CONTROL SYSTEM PARAMETER MODEL

The model consists of two parts: the flight simulation model and the altitude maintenance system, as shown in Fig 1. The flight simulation model calculates the current flight state based on the control instruction; the altitude maintenance system calculates the control instruction based on the feedback flight state, and keeps the aircraft flying at the specified altitude.

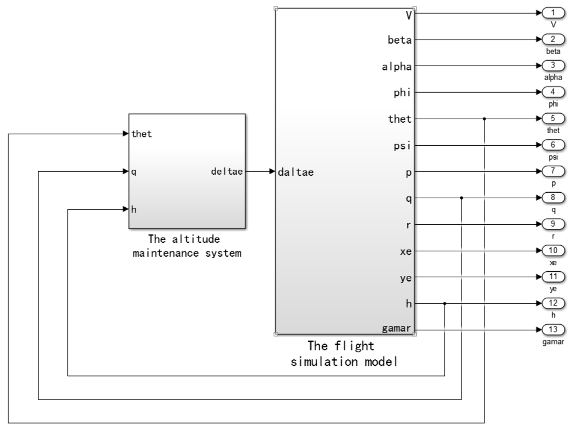


Fig 1. Flight control system parameter model

A. The Flight Simulation Model

The flight simulation model includes aerodynamic force and moment, six-degree-of-freedom motion equation, environment module and dynamic pressure and Mach number calculation module.

1) Aerodynamic Force and Moment Module

Fig 2 shows the aerodynamic force and moment module. Aircraft is affected mainly by the aerodynamic force and moment, the engine power and gravity. The module calculates the aerodynamics and moments of the aircraft, and the accuracy of the model is directly related to the fidelity of the entire dynamical system. The aerodynamic coefficients is the key to calculate aerodynamic and moment. The aerodynamic modeling is based on the aircraft aerodynamic data.

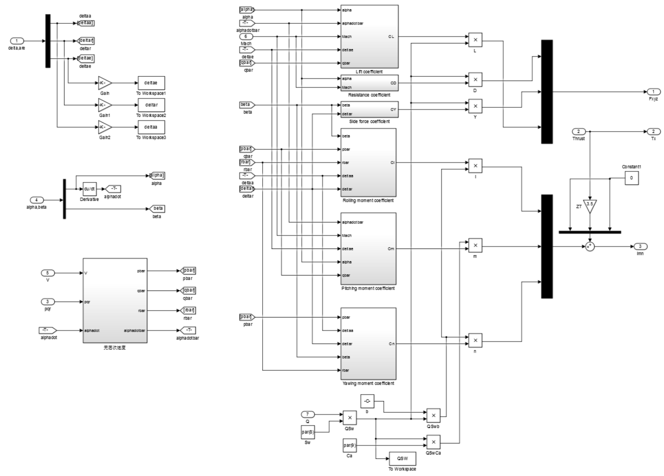


Fig 2. Aerodynamic force and moment module

The input, output and function of the aerodynamic force and moment module are shown in Table 1.

TABLE I. INPUT, OUTPUT AND FUNCTION OF THE AERODYNAMIC FORCE AND MOMENT MODULE

input	aileron deflection angle, rudder deflection angle, elevator deflection angle; rate of pitch, rate of roll, yaw rate; side slip angle, angle of attack; flight speed, Mach number, dynamic pressure, thrust
output	lift, drag and side force; pitching moment, roll moment and yaw moment; thrust and moment of thrust
function	calculate the aerodynamic force, the aerodynamic moment and the moment generated by the thrust

2) Six-degree-of-freedom Motion Equation

The description of the flight status is very complex, especially in the case of maneuver missions, where the whole system is a time-varying, non-linear, strongly coupled system, and it is quite difficult to confirm mathematical model.

In this paper, the S-function is used to describe the 12 first-order, coupled ordinary differential equations which is six-degrees-of-freedom of the aircraft. As shown in Figure 3.

```
%%%%%%%%%%%%%%%%%%%%%%%%Force equations%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ga=Iab*Ibg*G;
sys(1)=1/mass*(I*cos(alpha)*cos(beta)-D+Ga(1));
sys(2)=1/(mass*V)*(-I*cos(alpha)*sin(beta)+Y-mass*V*(-p*sin(alpha)+r*cos(alpha)+Ga(2)));
sys(3)=1/(mass*V*cos(beta))*(-I*sin(alpha)-L+mass*V*(-p*cos(alpha)*sin(beta)+q*cos(beta)-r*sin(alpha)*sin(beta))+Ga(3));
%%%%%%%%%%%%%%%%%%%%%%%%Motion equations%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sys(4)=p+(r*cos(phi)+q*sin(phi))*tan(thet);
sys(5)=q*cos(phi)-r*sin(phi);
sys(6)=1/cos(thet)*(r*cos(phi)+q*sin(phi));
%%%%%%%%%%%%%%%%%%%%%%%%Moment equations%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sys(7)=(c1*r+c2*p)*q+c3*Lbar+c4*N;
sys(8)=c5*p*r-c6*(p^2-r^2)+c7*M;
sys(9)=(c8*p-c2*r)*q+c4*Lbar+c9*N;
%%%%%%%%%%%%%%%%%%%%%%%%Navigation equations%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
U=V*cos(alpha)*cos(beta);
v=V*sin(beta);
w=V*sin(alpha)*cos(beta);
nav=Ibg'*[U;v;w];
sys(10)=nav(1);
sys(11)=nav(2);
sys(12)=-nav(3);
```

Fig 3. S-function of six-degrees-of-freedom motion module

The input, output and function of the Six-degree-of-freedom Motion Equation module are shown in Table 2.

TABLE II. INPUT, OUTPUT AND FUNCTION OF THE SIX-DEGREE-OF-FREEDOM MOTION EQUATION MODULE

input	lift, drag and side force; pitching moment, roll moment and yaw moment; thrust and gravity;
output	pitch angle, roll angle, yaw angle; rate of pitch, rate of roll, yaw rate; side slip angle, angle of attack; flight speed, three-dimensional spatial position coordinates
function	according to the external force and moment, calculate the flight status of the aircraft

3) Environment module

The flight performance of the aircraft is closely related to the main parameters of the atmosphere, for example, temperature, pressure and density. However, these parameters vary with geography, season, time, height, and meteorological conditions. Thus, as the atmospheric state changes, the aircraft's aerodynamic and flight performance should also change.

The COESA Atmosphere Model and the Gravity Model WGS84 Gravity Model are used to encapsulate the ambient modules to provide atmospheric ambient temperature, pressure, air density, speed of sound, and gravitational acceleration. The model is as shown in Figure 4.

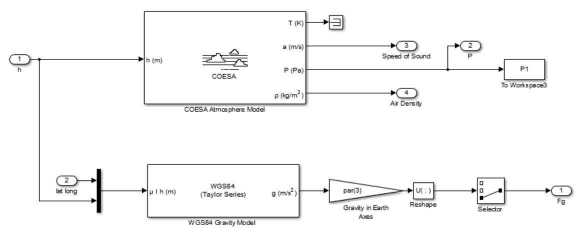


Fig 4. Environment module

The input, output and function of the environment module are shown in Table 3.

TABLE III. INPUT, OUTPUT AND FUNCTION OF THE ENVIRONMENT MODULE

input	flight altitude, latitude and longitude
output	temperature, pressure, air density, sound velocity, and gravity
function	provide flight environment parameter information

4) Dynamic Pressure and Mach Number Calculation Module

Dynamic pressure and Mach number are very important parameters in flight of aircraft. According to the formula (7),

$$M = \frac{V}{a} \;, Q = \frac{1}{2}\rho V^2 \tag{7}$$

Where ρ is the air density, V is the flight speed, a is the speed of sound, the formula (3) can calculate the Mach number and dynamic pressure. The model is as shown in Figure 5.

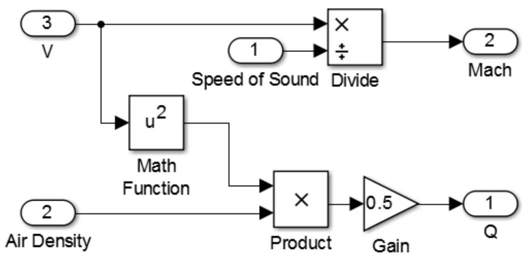


Fig 5. Dynamic pressure and Mach number calculation module

B. Altitude Maintenance System

Altitude maintenance is of great importance to the aircraft. In general, cruising at an altitude is the most economical and the longest voyage. In the cruise flight, the aircraft is always to maintain a constant height form, which also meet the original intention of the design. Therefore, altitude maintenance system is the most commonly and meaningful.

The change of height is always caused by the change of pitch angle, so the altitude maintenance system is implemented with the pitch angle control system as an internal loop. And the altitude maintenance system requires a steady-state zero-error, so the altitude maintenance loop as the outer loop generally adopts the form of proportional and integral.

The approximate design method is used to treat the altitude maintenance system as a second-order system.

Firstly, the constraint condition: flight altitude $h = 40,000 ft$, Mach number $M = 0.9$. The aircraft simulation model is trimmed and the equilibrium point is solved under the condition. Then, the nonlinear model is linearized at the equilibrium point, and the longitudinal motion equation of the aircraft is separated and simplified. The approximate model of the transfer function model of the pitch angle is obtained by Laplace transform [14].

$$\frac{\Delta q}{\Delta \delta_e} = \frac{-1.1231 s}{s^2 + 0.4419 s + 1.485} \tag{8}$$

$$\frac{\Delta \theta}{\Delta \delta_e} = \frac{-1.1231}{s^2 + 0.4419 s + 1.485} \tag{9}$$

In this paper, the frequency method is used to design the altitude maintenance. In the model, the pitch angle controller is as the inner loop and the altitude maintenance is as the outer loop, as shown in Fig 6.

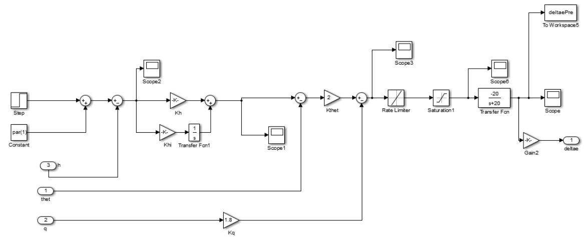


Fig 6. The altitude maintenance

IV. FAULT SIMULATION OF FLIGHT CONTROL SYSTEM

Fault simulation means that the fault is injected during the system simulation according to the pre-set fault time, the fault mode and the fault level, so that the system can switch from the normal operation state to the fault state.

A. Sensor fault simulation

The sensor fault includes three kinds of locking, constant gain and constant deviation.

1) Locking

Injection method: pre-set the lock position and lock time. The sensor is operated normally before the lock time, and the sensor output gradually deviates from the normal position until it reaches and remains in the lock position, and thereafter no longer responds to changes of the input commands.

$$\begin{cases} y_{out} = y_{in}, t < t_{fault} \\ y_{out} = d, t \geq t_{fault} \end{cases} \tag{10}$$

Where d is the lock position, t_{fault} is the lock time. Using SIMULINK, the pitch angle sensor lock fault is simulated. In the model, we use the Counter Limited module and Switch module to set the lock position and lock time. As shown in figure 7.

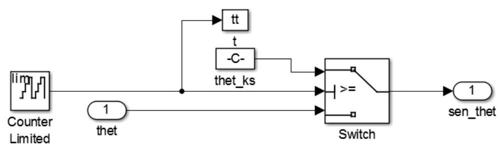


Fig7. Simulation of sensor lock fault

2) Constant gain

Injection method: pre-set the gain value and the fault time. After the fault time, the sensor output gradually deviates from the normal position and eventually maintains a constant proportional relationship with the instruction input, and thereafter the sensor output is proportional to changes of the input command.

$$\begin{cases} y_{out} = y_{in}, t < t_{fault} \\ y_{out} = s y_{in}, t \geq t_{fault} \end{cases} \tag{11}$$

Where s is the gain value, t_{fault} is the fault time. In the model, we use the Counter Limited module, Gain module and Switch module to set the gain value and fault time. As shown in figure 8.

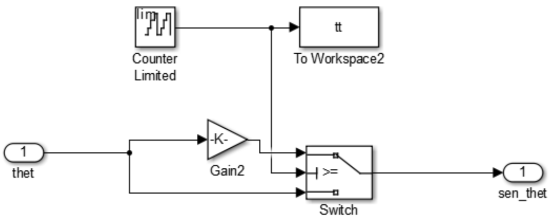


Fig 8. Simulation of sensor constant gain

3) Constant deviation

Injection method: pre-set the deviation value and the fault time. After the fault time, the sensor output gradually deviates from the normal position and eventually maintains a constant difference with the instruction input, and thereafter the sensor output is responsive to changes of the input command, but maintains a constant deviation from the normal actuator output.

$$\begin{cases} y_{out} = y_{in}, \quad t < t_{fault} \\ y_{out} = y_{in} + d, t \geq t_{fault} \end{cases} \tag{12}$$

Where d is the deviation value, t_{fault} is the fault time. In the model, we use the Constant module and Switch module to set the deviation value and fault time. As shown in figure 9.

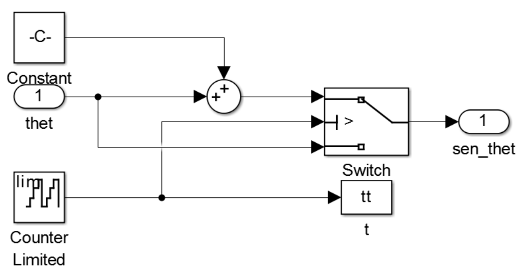


Fig 9. Simulation of sensor constant deviation

B. Actuator failure simulation

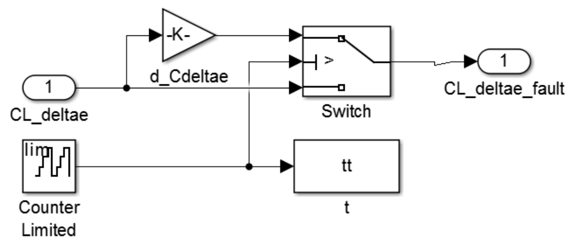
The fault is injected into the elevator actuator, and the failure mode includes the locking, constant deviation, constant gain. The form of the actuator failure injection is the same as that of the sensor failure.

C. Simulation of Control Surface Damage

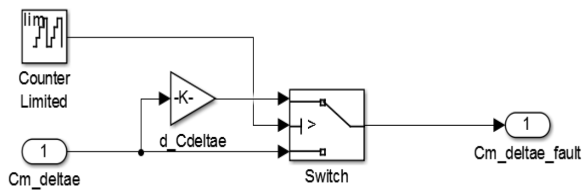
The aerodynamic parameter model of aircraft control surface damage is very different from the aerodynamic parameter model of normal flight conditions. The aerodynamic interpolation formula of the control surface damage k% is deduced by using the air flow coefficient data of the normal pneumatic coefficient of the airplane and the pneumatic damage of the control surface.

$$\begin{aligned} &\mathrm{coef}(k\%) = \mathrm{coef}(normal) \\ &+[\mathrm{coef}(damage100\%) - \mathrm{coef}(normal)] \cdot k\% \end{aligned} \tag{13}$$

According to the principle, the control surface damage can be simulated by changing the relevant aerodynamic coefficient. And the control surface damage of the elevator is simulated by changing the derivative of the pitching moment coefficient to the elevator deflection angle $C_{m\delta_e}$, and the derivative of the lift coefficient to the elevator deflection angle $C_{L\delta_e}$. Under the aerodynamic module and moment module, we change $C_{m\delta_e}$ in the pitch moment coefficient calculation module and change $C_{L\delta_e}$ in the lift coefficient calculation module. As shown in Figure 10.



(a) $C_{L\delta_e}$ parameter setting



(b) $C_{m\delta_e}$ parameter setting

Fig 10. Simulation of Control Surface Damage

V. SIMULATION RESULTS

The parameters of the flight control system include flight speed, angle of attack, speed of pitch angle, angle of pitch, flight altitude, roll angular rate, yaw rate, roll angle, yaw angle, atmospheric total pressure, Mach number, static pressure. In this paper, we focus on the angle of attack, speed of pitch angle, angle of pitch, flight altitude, elevator angle, Mach number.

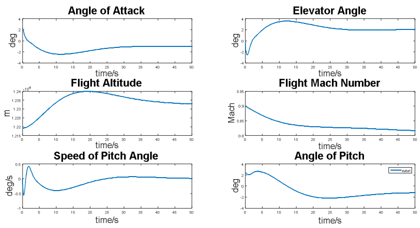


Fig 11 Model parameter output of normal condition

The simulation model is set up for flight altitude 12192m, flight Maher number 0.9, simulation time 50S. Under the normal condition, the model parameters are shown in figure 11.

Based on the flight control system simulation model, we set the pitch angle sensor lock fault. The fault injection time is 10S, and the lock angle is 1 degree, the model parameter output shown in Figure 12. Figure 12 shows that after setting the fault, the angle of pitch stuck at 1 degree, other parameters have also changed, for example, the height cannot be maintained.

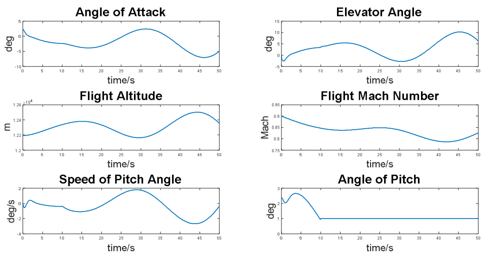


Fig 12 Model parameter output of sensor lock fault

Based on the flight control system simulation model, we set the control surface damage fault. The fault injection time is 10S, and the damage coefficient is 0.3, the model parameter output shown in Figure 13.

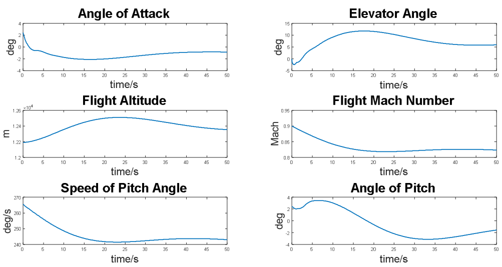


Fig 13 Model parameter output of control surface damage

VI. Conclusion

Based on the flight dynamics model of the aircraft, a model of flight simulation system is established by MATLAB / SIMULINK simulation software. The model includes six-degree-of-freedom motion equation module, aerodynamic and torque module, environmental module and dynamic pressure and Mach number calculation module. Then using the Trim function, the model is trimmed and linearized, and the aircraft longitudinal control law - the altitude maintenance system is designed to maintain the aircraft longitudinal stability. Aiming at the problems of common flight control system failure, sensor locking, constant deviation, constant gain fault, actuator locking, constant deviation, constant gain fault, control surface damage fault are simulated. Finally, we obtained the output of parameter simulation and fault simulation.

Simulation model and fault simulation data can provide support for flight control system fault diagnosis and fault isolation. The model does not take into account the impact of the aircraft level stabilization surface, slatted sliver, spoiler. In addition, the model only considers the longitudinal flight, takeoff, landing, lateral control are not considered. This is our next job.

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