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Aircraft Anti-Skid Brake Control Based on High-Speed on-off Valve

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ABSTRACT: Aircraft hydraulic brake system usually use pressure servo valve for anti-skid brake control. As pressure servo valve realizes the pressure closed loop by hydraulic feedback loop, this structure increased the complexity of the processing and manufacturing, restricted the pressure closed loop parameters adjustment, and increased the difficulty of debugging the system design. Pressure servo valve is expensive and difficult to process poor ability to resist pollution. This paper proposed a slip ratio large closed loop aircraft anti-skid brake control method based on high-speed on-off valve, built the model of aircraft ground vertical taxiing and slip ratio large closed loop control algorithm in the MATLAB/SIMULINK, and built the model of aircraft hydraulic brake system based on on-off valve in the AMESim and a joint simulation was carried out. The simulation results show that the aircraft anti-skid brake control method based on high-speed on-off valve is feasible, and the on-off valve is cheap with strong ability to resist pollution, easy processing and manufacturing and so on, showing a good application prospect.

Keywords: aircraft anti-skid brake; high-speed on-off valve; slip ratio; large close loop

1 INTRODUCTION

Aircraft brake system is an important component of modern aircraft, mainly used in the dissipation of the ground aircraft taxiing kinetic energy, ensuring the aircraft brake to stop, shortening the distance of the aircraft taxiing, preventing excessive wear of wheels, and cooperating with the other airborne systems to achieve the aircraft turning and stop function. It is an important system to ensure the safety of takeoff and landing [1,2]. Because of fast response speed, big load stiffness, high power density, technical maturity, and other advantages, hydraulic brake system is still widely used [3]. Because of the nonlinear characteristics of tire and road surface adhesion [4], during the aircraft brake, it is easy to find the wheels skid and lock phenomenon, leading to too large brake distance=, and wheels wear seriously, even puncture, aircraft is out of control, and other accidents. In order to prevent the occurrence of such phenomena, anti-skid brake control has become the necessary function in the aircraft brake system. Anti-skid control mainly by monitoring the status of wheels (slip velocity or slip ratio) to determine whether the skid occurred, and then adjust the brake pressure to stop the wheels into the state of skid, ensure the brake safety and improve the brake efficiency [5,6]. Pressure servo valve can output the pressure which is proportional to the control signal, and has the high frequency response, suitable for direct pressure control. So the pressure servo valve is usually used as the component of brake pressure control in the aircraft hydraulic brake system. The pressure servo valve is a two-level structure, the forerunner level is usually the nozzle flapper or jet pipe controlled by torque motor, the secondary is the slide valve, and through the internal oil output load pressure feedback to the valve core of the slide valve, make up the oil pressure closed loop [7]. Although this structure realized the pressure control, it brought some problems. First, it increased the feedback convex shoulder on the valve core of slide valve, and increased the matching surface, process complex; Second, pressure closed loop is determined by the design and manufacture, and it is hard to readjust the closed loop circuit parameters after the completion of manufacture , and it increased the difficulty of the design and debugging; Third, the traditional pressure servo valve is expensive, hard to process and manufacture with poor ability to resist pollution, and other disadvantages [8,9].

To solve these problems, this paper proposed a slip ratio large close loop aircraft anti-skid brake control method based on high-speed on-off valve. High-speed on-off valve as a new type of digital electro-hydraulic conversion element, by means of controlling electromagnet suction, makes the valve core movement at a high speed in forward and reverse direction, so as to realize the function of fluid flow in the valve inlet on-off alternately. Because of simple structure, convenient control, fast response speed, strong ability to resist pollution and so on, it has been widely used in vehicle electronic control system [10,11]. Its performance is usually described by the time of on and off, and there are only two limit work states on and off, it can convert digital signal directly into the fluid pulse signal, easily to realize the combination of computer control technology and hydraulic fluid technology [12]. Using high-speed on-off valve, and through the pressure sensor installed on the brake actuator to complete pressure closed loop control. It can be effective

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for anti-skid brake control, and improve the reliability of brake system and get better performance of pressure control.

This paper built the model of aircraft hydraulic brake system based on high-speed on-off valve in the AMESim, and built the model of aircraft taxiing perpendicular to the ground and slip ratio larger-close-loop control algorithm in the MATLAB/SIMULINK, and a joint simulation was carried out. On this basis, analyzed the correct feasibility of aircraft anti-skid brake control method based on high-speed on-off valve.

2 HIGH-SPEED ON-OFF VALVE MODEL

High-speed on-off valve switch mechanism by using electromagnetic force and the spring resisting force to drive the valve core to realize on and off. On-off valve is controlled by digital signal; it can be directly connected with the computer, and does not need D/A conversion. Compared with the existing servo valve it has simple structure, good process, strong ability to resist pollution and interference, low cost, good repeatability, reliable work and small power and so on.

According to the principle of electromagnetism, pour control electric current i into the control coil and the number of the coil turns is N, the magnetic circuit generates the magnetic flux. The expression for magnetic fluxφ is:

$$\Phi = \frac{iN}{R_g} \tag{1}$$

In the expression: i is the coil current, N is the coil turns. Rg is the air-gap reluctance, its expression is:

$$R_g = \frac{l}{\mu_0 A} \tag{2}$$

In the expression: l is the air gap length, A is the air gap area, μ_0 is the vacuum permeability. The armature axial electromagnet suction F is:

$$F = \frac{(iN)^2}{2R_g l} \tag{3}$$

High-speed on-off valve structure schematic is shown in Figure 1. For iron core of magnetizer, the permeability is much higher than vacuum permeability. Ignore the reluctance of the iron core, and only consider the air and nonferromagnetic material resistance [13], so the high-speed on-off valve turned into an equivalent magnetic circuit can be shown in Figure 2.

According to the principle of electromagnetism, we can calculate the high-speed on-off valve working air gap resistance R_1 and non-working air gap resistance R_2:

$$R_1 = \frac{4(g_0 \text{-} x_v)}{\mu_0 \pi a^2} = \frac{4g_v}{\mu_0 \pi a^2} \tag{4}$$

$$R_2 = \frac{b}{\mu_0 \pi c d} \tag{5}$$

Where, g_0 is the initial air gap length, g_v is the working air gap length, x_v is the valve core displacement, and c is the average radius of the nonmagnetic materials lining, which is:

$$c = \frac{a+b}{2} \tag{6}$$

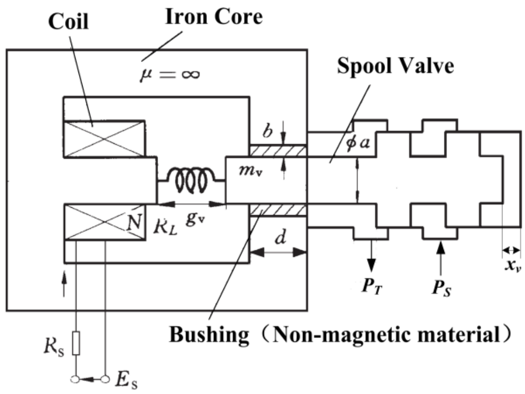


Figure 1. High-speed on-off valve structure schematic

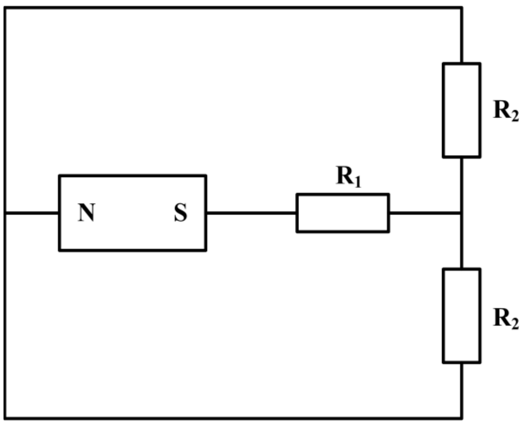


Figure2. High-speed on-off valve magnetic circuit equivalent diagrams

We can get the magnet flux is:

$$\Phi = \frac{iN}{R_1 + R_2/2} \tag{7}$$

Magnetic circuit voltage balance equation is:

$$(R_S + R_L)\mathrm{i} + N\frac{d\Phi}{dt} = E_S \tag{8}$$

Where, R_S is the conductor resistance, R_L is the coil resistance, and E_S is the power supply voltage.

Ignore the pretightening force of spring and the valve core friction, and the expression for valve core displacement is:

$$m_v x_v'' + B x_v' + K x_v = F \tag{9}$$

Where, m_v is the mass of the valve core, x_v is the valve core displacement, B is the damping of valve core movement, and K is the spring stiffness.

3 AIRCRAFT HYDRAULIC BRAKE SYSTEM MODEL

At present, the hydraulic power aircraft brake system is most widely used. Traditional aircraft hydraulic brake system consists of the brake pedal, the brake controller, valve group, velocity sensor, brake actuator and other hydraulic accessories [14]. Brake pedal collects pilot brake instruction, the brake controller utilizes the control instruction and the sensor signal to control the brake valve group and adjust the oil pressure of brake actuator, realize the brake.

Only consider anti-skid control, and ignore the backup and the secondary components, the model of the brake pipe and the brake actuator in aircraft hydraulic brake system were built. The system is shown in Figure 3.

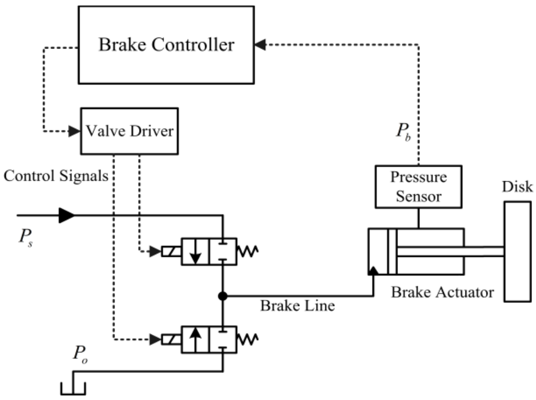


Figure 3. High-speed on-off valve anti-skid brake system diagram

At present, most of the hydraulic brake system modeling often ignores the hydraulic line model, or only considers pipeline volume effect. In fact, the brake pipeline will introduce underdamped oscillation effect, which should not be neglected. Assuming that the hydraulic brake pipe is the rigid pipe, in which the oil is laminar flow, the import and export of oil pipeline dynamic space can be expressed as two-port model in the Laplace space:

$$\begin{bmatrix} P_v \\ Q_v \end{bmatrix} = \begin{bmatrix} \cosh\Gamma(s) & -Z(s)\sinh\Gamma(s) \\ \frac{1}{Z(s)}\sinh\Gamma(s) & \cosh\Gamma(s) \end{bmatrix} \begin{bmatrix} P_b \\ Q_b \end{bmatrix} \tag{10}$$

For the model is infinite dimensional linear systems, we can accurately analysis line frequency characteristic. In the expression, the linear characteristic impedance Z(s) and propagator Γ(s) is respectively determined by the oil viscosity and pipe size:

$$\begin{cases} Z(s) = \rho c \Big/ \pi r^2 \sqrt{1 - \dfrac{2J_1(j\sqrt{sr^2/\upsilon})}{j\sqrt{sr^2/\upsilon}\,J_0(j\sqrt{sr^2/\upsilon})}} \\ \Gamma(s) = Ls \Big/ c\sqrt{1 - \dfrac{2J_1(j\sqrt{sr^2/\upsilon})}{j\sqrt{sr^2/\upsilon}\,J_0(j\sqrt{sr^2/\upsilon})}} \end{cases} \tag{11}$$

ρ is the oil density; c is the wave velocity in the oil; r is the radius of inner pipeline; L is the pipe length;J_0 and J_1 are zero order and first order of the first kind Bessel function respectively; u is the oil dynamic viscosity.

For brake actuator, because of the stroke is lesser, ignore the dynamic process of the piston movement, the brake chamber pressure P_b is:

$$c_b P_b' = Q_b \tag{12}$$

Where,

$$c_b = \frac{V_L}{\beta_e} + \frac{A_b^2}{K_b} \tag{13}$$

V_L is the brake piston volume, β_e is the oil elastic modulus, K_b is the equivalent stiffness of brake plate, and Q_b is the import flow of the fluid chamber.

The brake moment T_b applied on the main wheels is provided by the brake actuator and can be expressed as:

$$T_b = f_c P_b A_b R_b \tag{14}$$

f_c is the brake disc friction coefficient; A_b is the total area of the piston; R_b is the outer diameter of brake disc.

4 AIRCRAFT TAXIING MODEL

In order to carry out control simulation for aircraft anti-skid brake system, we need to build a kinetic model of the aircraft taxiing, mainly describe the body ground motion and force of wheels. On the body movement modeling, this paper used the longitudinal motion equation of single degree of freedom body, for the landing gear's single degree of freedom longitudinal oscillation is only considered, the tire model using magic formula [15].

Considering the movement of the vertical degree of freedom, when the plane landed and simplifying the aircraft to the single host wheel, the body model to single landing gear. Assuming that the body is rigid quality, the landing gear axis perpendicular to the ground and through the body's center of mass, only consider the landing gear's longitudinal oscillation, the simplified stress state of the aircraft taxiing model is shown in Figure 4.

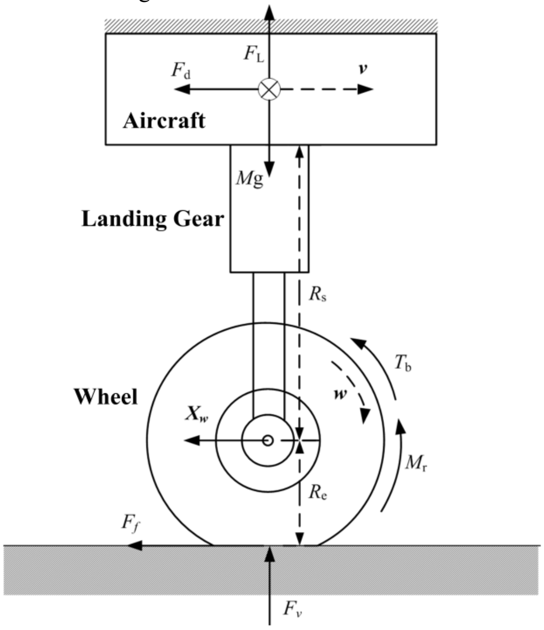


Figure 4. The stress state of the aircraft taxiing model

According to Newton's law, the simplified equation is:
(1) The longitudinal force balance.

$$Mv' = -F_d - F_f \quad (15)$$

(2) The normal force balance.

$$Mg - F_L = F_v \quad (16)$$

(3) The longitudinal oscillation moment balance with the center of the body.

$$(I_t X_w'' + B_t X_w' + K_t X_w) R_s = F_f (R_e + R_s) \quad (17)$$

(4) The wheel's moment balance.

$$Iw' = F_f R_e - T_b - M_r \quad (18)$$

M is the quality of the body; V is the longitudinal velocity; F_d is the aerodynamic drag; F_f and F_v respectively represent the friction and the normal support force between the host wheel and the ground; F_L is the gas lift; I_t is the rotational inertia of the landing gear's longitudinal oscillation; B_t and K_t respectively represent the landing gear's longitudinal oscillation damping coefficient and stiffness coefficient; X_w is the landing gear's longitudinal oscillation displacement in the center of the wheel; R_s and R_e are the longitudinal oscillation radius of the landing gear and the host wheel's effective turning radius; I is the rotational inertia of the host wheel; T_b and M_r represent the wheel's braking torque and rolling resistance moment. The aerodynamic drag force F_d and lift F_L were figured out in the expression (19):

$$\left.\begin{aligned} F_d &= \frac{1}{2} c_x S_w \rho_a v^2 \\ F_L &= \frac{1}{2} c_y S_w \rho_a v^2 \end{aligned}\right\} \quad (19)$$

c_x and c_y are aerodynamic drag coefficient and lift coefficient respectively; S_w is the wing area; ρ_a is the air density.

The friction between the host wheel and the ground can be modeled by "magic formula" [15], "Magic formula" expressed the friction as the function of tire slip ratio：

$$F_f = D\sin\langle C\arctan\{Bs_r - E[Bs_r - \arctan(Bs_r)]\}\rangle \quad (20)$$

s_r is the tire slip ratio; B, C, D and E are curve fitting coefficient, they have connection with the tire property, ground property and the normal support force. They can be figured out by the following expression:

$$\begin{cases} D = a_{b1}F_v^2 + a_{b2}F_v \\ C = 1.65 \\ B = \dfrac{a_{b3}F_v^2 + a_{b4}F_v}{CD\exp(a_{b5}F_v)} \\ E = a_{b6}F_v^2 + a_{b7}F_v + a_{b8} \end{cases} \quad (21)$$

a_{b1}~a_{b8} are the curve coefficient between the wheel and the ground. Defined the friction coefficient μ between the wheel and the ground as:

$$\mu = \frac{F_f}{F_v} \quad (22)$$

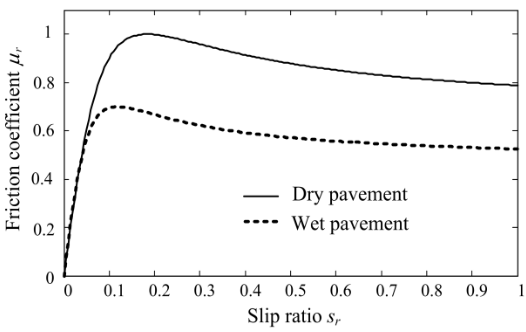


Figure 5. The relationship between friction coefficient and slip ratio curve

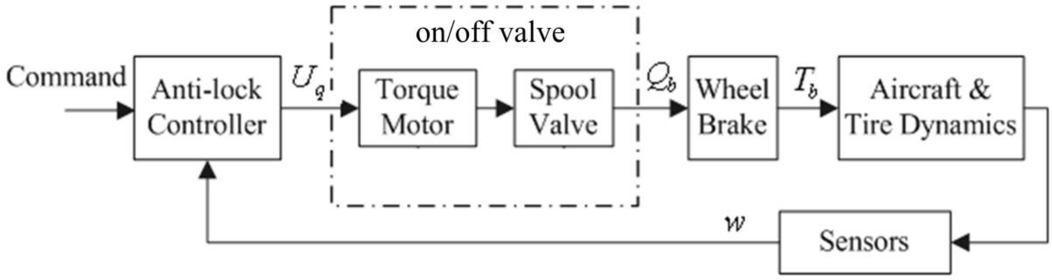


Figure 6. The aircraft anti-skid brake system diagram based on high-speed on-off valve pressure closed loop.

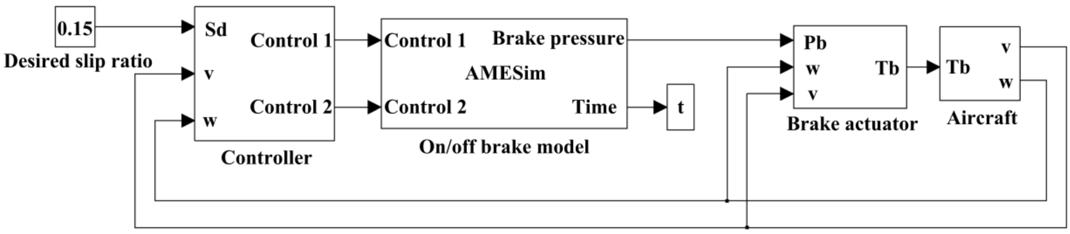


Figure 7. MATLAB/SIMULINK model diagram.

When the normal force is constant, the friction coefficient and the slip ratio curve on the different ground are shown in Figure 5.

The slip ratio S_r is defined as the ratio of the difference between the axis linear velocity and relative rolling linear velocity to the axis linear velocity. Because of the existence of the landing gear's longitudinal motion, the wheel axis linear velocity is not equal to the body linear velocity, therefore, the calculation formula of the slip ratio is:

$$s_r = \frac{v - X_w' - wR_e}{v - X_w'} \quad (23)$$

In addition, in the process of wheel rolling, rolling resistance moment still exists, and its value can be expressed as:

$$M_r = (f_0 + f_1 v^{2.5}) R_e \quad (24)$$

f_0 and f_1 are the rolling resistance moment coefficients respectively.

5 LARGE CLOSED LOOP CONTROL ALGORITHM OF THE SLIP RATIO

The output flow of the on-off valve is not directly controlled by the pressure of the pressure servo valve, and can only achieve two discrete state of control about on and off. So the control input of the system is the brake flow Q_b, and the control input range is the brake flow relative to the two discrete state of on-off valve, it can be defined as a set contains two values, that is:

$$Q_b \in \{q_1, -q_2\} \quad (25)$$

q_1 and q_2 represent the oil flows of on-off valve opened inflows into and closed outflows from the brake actuator. Therefore, the control input signal turned into the flow from the pressure, and the control input signal is discrete and limited. This article took the tire slip ratio as the system state variables, and the designed control algorithm controlled the slip ratio to a given objective slip ratio. Therefore, the designed control algorithm has the following structure:

$$Q_b = \Phi[f(x)] = \begin{cases} q_1 & \text{if } f(x) < 0 \\ 0 & \text{if } f(x) = 0 \\ -q_2 & \text{if } f(x) > 0 \end{cases} \quad (26)$$

Φ(•) represents a discontinuous switching function; *f*(*x*) represents the continuous differentiable state feedback functions, that is, the switching surface of the system. In this way, the system can achieve the control of Q_b, according to the feedback value of the switching surface *f (x)* output flow instructions.

Through the analysis, the brake pressure closed loop control proved to be feasibility based on high-speed on-off valve and installed pressure sensor near the brake actuator. The aircraft anti-skid brake system chart based on high-speed on-off valve pres-

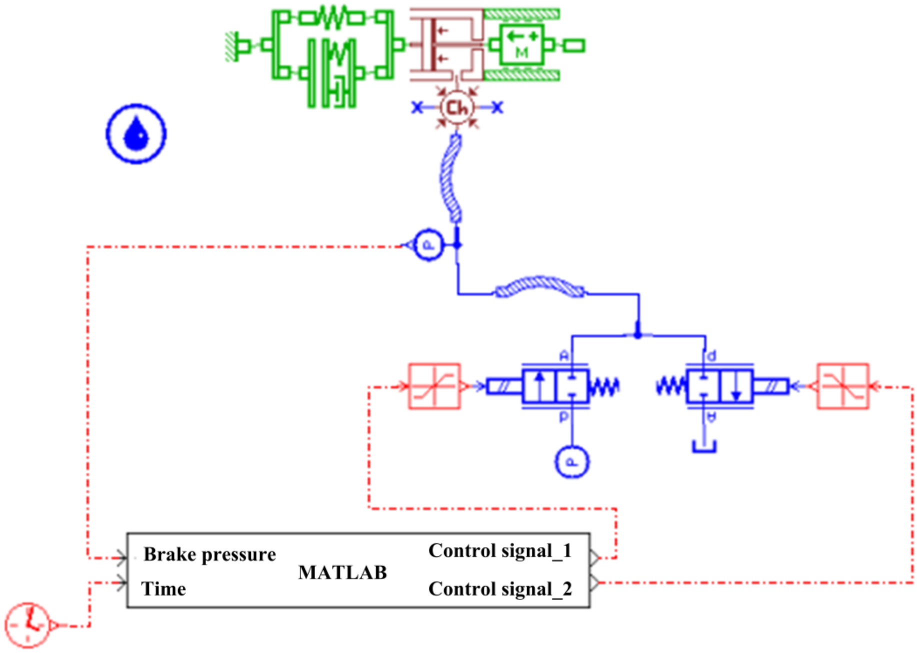


Figure 8. AMESim model diagram

sure closed loop is shown in figure 6. Anti-skid brake controller given discrete voltage control signal U_q. Through the high-speed on-off valve outputted brake flow, the brake torque are generated from the model of wheel, finally figured out the aircraft model to obtain the aircraft speed and the wheel speed. Anti-skid brake control system controlled slip ratio or slip speed by the closed loop and removed the closed loop inside the pressure.

6 AMESIM AND MATLAB JOINT SIMULATION ANALYSIS

This paper built the model of aircraft ground vertical taxiing and slip ratio large closed loop control algorithm in the MATLAB/SIMULINK, and built the model of aircraft hydraulic brake system based on on-off valve in the AMESim and a joint simulation was carried out. The simulation results show that the aircraft anti-skid brake control method based on high-speed on-off valve is feasible.

6.1 *MATLAB/SIMULINK model*

As a graphical work platform based on MATLAB, SIMULINK is a famous simulation integration environment in the field of system simulation. It has been widely applied in many fields. With the help of MATLAB powerful computing capacity, SIMULINK simulation technology can effectively solve the problem of numerical processing.

The model of aircraft ground vertical taxiing and slip ratio large closed loop control algorithm were built in the MATLAB/SIMULINK is shown in Figure 7.

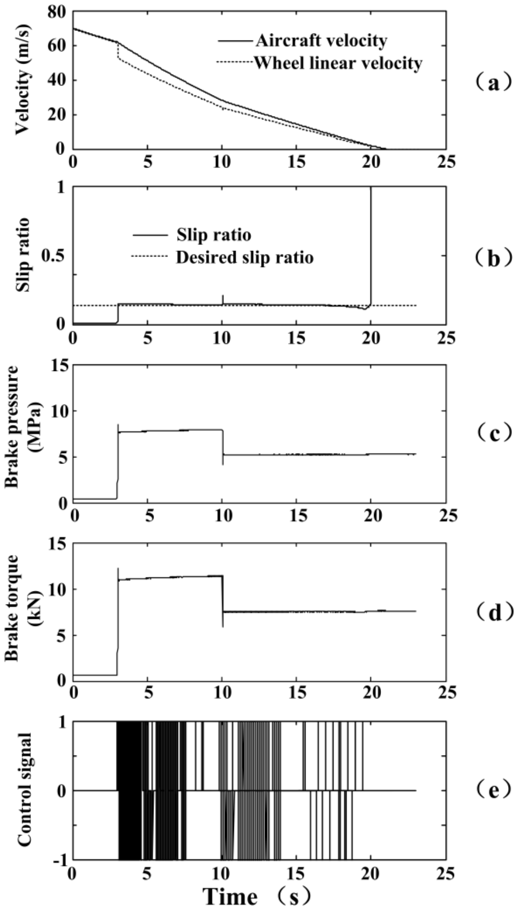
6.2 *AMESim model*

AMESim software has friendly interface, convenient operation, and we can design system through a variety of models and achieve the target of modeling and simulation rapidly. AMESim also provides the MATLAB interface, easy to conduct joint simulation. They both played the AMESim simulation efficiency of prominent fluid machinery and with the help of SIMULINK powerful numerical processing ability, and make the system simulation effect more perfect.

The Model of aircraft hydraulic brake system based on high-speed on-off valve was built in AMESim which is shown in Figure 8.

Joint simulation was carried out at the aircraft wheel grounding, linear velocity is 70 *m/s*, until the aircraft stopped. In the process, the anti-skid brake control began to work at 3 seconds after landing, the reference deceleration is 3.5 m/s^2. When the brake takes 10 seconds, the wet runway to dry runway mutation happens. When the aircraft speed is less than 5 *m/s*, stops the anti-skid brake control system, and maintains the brake pressure unchanged until the aircraft stops. The simulation step size is 1 millisecond.

Joint simulation results are shown in Figure 9. The simulation curves show that the brake pressure and brake torque can be maintained in a stable value, slip ratio can preferably track the set value, wheel speed and aircraft speed is kept in a stable difference, until the aircraft stopped.



(a) Velocity of aircraft and wheel. (b)Slip ratio.
(c) Brake pressure. (d)Brake torque. (e) Control signal.

Figure 9. Anti-skid brake simulation results based on the on-off valve

7 CONCLUSION

This paper analyzed the disadvantages of the aircraft anti-skid brake system based on traditional pressure servo valve, and put forward the slip ratio large closed loop aircraft anti-skid brake control method based on high-speed on-off valve. A joint simulation was carried out in MATLAB and AEMSim. The simulation results show that the aircraft anti-skid brake control method based on high-speed on-off valve is feasible, and the on-off valve is cheap, strong ability to resist pollution, easy processing and manufacturing and so on, showing a good application prospect.

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