The Adaptive Control of Aircraft Brake Based on Asymmetric Barrier Lyapunov Function

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Abstract: Considering the complexity, non-linearity and uncertainty of aircraft antiskid control system, the author takes such shortcomings of traditional "PD + PBM" control methods into account as low braking efficiency and deep skidding on hybrid runways, and puts forward the constraint control algorithm of slip rate based on asymmetric barrier Lyapunov function, which meets the purpose of adaptive full-regulation from the concept of system integration that the slip ratio is also satisfied in the stable region where it is constrained, so as to improve the braking efficiency. By comparing with the simulation results of the traditional "PD + PBM" control algorithm, the author tries to show that the braking process has a good follow-up performance and a smooth brake curve, which avoids the problem of low-speed skidding, optimizes the braking performance and improves braking efficiency based on adaptive control algorithm of slip rate constraint.

1 INTRODUCTION

Aircraft anti-skid braking system is a complex non-linear and uncertain system, which is affected by many uncertainties during the landing brake process of aircraft. It makes the structural parameters have time-varying characteristics. Therefore, it is the key and difficulty in the field of aircraft brakes how to ensure the superiority of braking performance through system design. However, the design of system control algorithm is the key factor affecting the braking performance of the system and the most important factor in system design. At present, the conventional "PID with pressure offset" control is mostly used in practical engineering in China, that is, the "PD + PBM" control method. Although the system has some intelligence through the PBM pressure bias design and the performance of the dry runway is good, the system still has the problems of low speed slippage and poor adaptability to the wet runway. In the AC NO.25-7A, this method was identified as "quasi-regulation" mode, and wet runway braking efficiency was only identified as 50%. While such overseas professional manufacturers are now using adaptive "full regulation" control method as Goodrich, Safran and Meggitt. "Full regulation" control mode was identified as the braking efficiency of 80%, which can meet the requirements for braking performance.

Some research has been made on adaptive control theory of aircraft braking system at home and abroad, mainly including feedback linearization theory (TANELLI M, ASTOLFI A, SAVARESI S M, 2008), fuzzy control (R.Babuska, H.B.Verbruggen, 1996), iterative learning (MI C T, LIN H, ZHANG Y, 2005), robust control (BASLAMISLI S C，K SE I E, ANLAS G,2007), synovial control (TANELLI M, FERRARA A, 2013; CHO D-W, CHOI S, 1999; CHOI S, CHO D-W, 2001; HEBDEN R G, EDWARDS C, SPURGEON S K, 2004), model- control (Shi Wei, Liu Wensheng, Chen Jianqun, 2012), etc. But the confidentiality and competition is taken into account, the relevant literature abroad only involves a brief description of the principle for its aircraft brake control, without the specific control algorithm in detail. However, most domestic methods are devoted to obtaining better control performance by adjusting the expected value of slip ratio. Direct consideration is rarely given to the working state of the aircraft anti-skid braking system and its impact on the entire aircraft system.

Based on this, the author presents a slip-rate-adaptive control based on asymmetric barrier Lyapunov function. The adaptive control law is designed based on the stability of the constrained slip ratio. On the one hand, the system works in a stable area from the system integration level; on the

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other hand, it achieves the purpose of adaptive full-regulation, thus improves braking efficiency.

2 NONLINEAR MATHEMATICAL MODEL OF AIRCRAFT ANTI-SKID BRAKING SYSTEM

2.1 Aircraft ground friction model and dynamic model

The brake control needs to establish a simplified mathematical model on the basis of reasonable assumptions (Wang Jisen, 2001; Qiu Yanan, 2016).Taking aerodynamic characteristics into account, the equilibrium equations in the longitudinal, vertical and pitch directions are:

$$\begin{cases} T_0 + K_V V_X - F_X - nf_1 = mV_X \\ G - F_y - nN_1 - N_2 = 0 \\ N_2 b - (T_0 + K_V V_X)h_t = nN_1 a + nf_1 h \end{cases} \tag{1}$$

In which,

$F_X = 0.5\rho C_X SV_X^2$, $\quad F_y = 0.5\rho C_y SV_X^2$, $f_1 = \mu N_1$

Assuming that the landing gear is a rigid body, that is, ignoring the heading speed caused by the deformation of the landing gear. According to the principle of brake rotor inertia, the equation of wheel dynamics is

$$\dot{\omega} = \frac{M_j - M_S}{J} = \frac{\mu N_1 R_g - M_s}{J} \tag{2}$$

$$V_\omega = \omega R_g \tag{3}$$

By formula (1) ~ (3) :

$$\dot{V}_X = \frac{T_0 + K_V V_X}{m} - \frac{\rho C_y SV_X^2}{2m} - \mu \frac{\left(g - \frac{\rho C_y SV_X^2}{2m}\right)b - \frac{T_0 + K_V V_X}{m} h_t}{a + b + \mu h} \tag{4}$$

$$\dot{\omega} = \mu R_g \frac{1}{nJ} \frac{\left(mg - \frac{1}{2}\rho C_y SV_X^2\right)b}{a + b + \mu h} - \mu R_g \frac{1}{nJ} \frac{(T_0 + K_V V_X)h_t}{a + b + \mu h} - \frac{M_S}{J} \tag{5}$$

In the process of landing braking, the wheel speed of aircraft is less than or equal to the longitudinal speed of aircraft under the braking torque, that is, $V_\omega \le V_X$, the rate of relative movement is defined as slip rate, namely:

$$\sigma = \frac{V_X - V_\omega}{V_X} = 1 - \frac{\omega R_g}{V_X} \tag{6}$$

The derivation of the above formula can be obtained:

$$\dot{\sigma} = -\frac{R_g}{V_X}\dot{\omega} + \frac{R_g \omega}{V_X^2} = \frac{(1-\sigma)\dot{V}_X - R_g \dot{\omega}}{V_X} \tag{7}$$

The formula (4) and formula (5) are put into the above formula, and then:

$$\dot{\sigma} = \frac{1-\sigma}{V_X} \cdot \frac{T_0 + K_V V_X - F_X - n\mu N_1}{m} - \frac{R_g^2 \mu N_1}{V_X J} + \frac{R_g}{V_X J} M_S = f(\sigma) + \frac{R_g}{V_X J} M_S \tag{8}$$

In which,

$$f(\sigma) = \frac{1-\sigma}{V_X} \cdot \frac{T_0 + K_V V_X - F_X - n\mu N_1}{m} - \frac{R_g^2 \mu N_1}{V_X J} \tag{9}$$

The definition of parameters in the above formula is the same as (Wang Jisen, 2001; Qiu Yanan, 2016) in the references.

2.2 Drive Mechanism and Actuator Model

For aircraft hydraulic brake system, the drive mechanism is composed of hydraulic servo valve, which converts the brake current into brake pressure via hydraulic servo valve and applies to the brake of the actuator to convert it into braking torque, which interacts with the combined torque provided by the ground, in order to decelerate the aircraft until it stops the aircraft.

2.2.1 The mathematical model of brake pressure servo valve

Electro-hydraulic servo valve is an important part of the aircraft hydraulic control system, and the pressure characteristics of electro-hydraulic servo valve is one of the important features of the servo valve by changing the input port of the control current size and direction. The output pressure can be changed in the size of the direction, according to the nozzle baffle servo valve structure and working principle (Chen Zhaoguo, Li Zhigang, Huang Qi, 2005), and the pressure equation of the dynamic equation is:

$$\frac{P_L}{X_f} = \frac{k_q}{\frac{V_t}{4\beta_e}s + k_c} \tag{10}$$

$$X_f = r\theta \tag{11}$$

$$\frac{\theta}{\Delta I} = \frac{1/k_{mf} \cdot k_t}{\frac{s^2}{\omega_{mf}^2} + \frac{2\xi_{mf}}{\omega_{mf}}s + 1} \tag{12}$$

The anti-Laplace transformation of the formula (10) is:

$$\dot{P}_L = -\frac{4\beta_e k_c}{V_t} P_L + \frac{4\beta_e k_q}{V_t} X_f \tag{13}$$

The formula (11) is brought intoit and then:

$$\dot{P}_L = -\frac{4\beta_e k_c}{V_t} P_L + \frac{4\beta_e k_q r}{V_t} \theta \tag{14}$$

Similarly, the anti-Laplace transform of the formula (12) is:

$$\dot{\theta} = -\frac{\omega_{mf}}{2\xi_{mf}}(\theta + \frac{\ddot{\theta}}{\omega_{mf}^2}) + \frac{k_t \omega_{mf}}{2\xi_{mf} k_{mf}} \cdot \Delta I \tag{15}$$

The meaning of the letters in the above formula is described in (Chen Zhaoguo, Li Zhigang, Huang Qi, 2005) of the references.

2.2.2 The mathematical model of brake device

Through the overlap and installation of dynamic and static disks, the brake device forms a larger friction area, and absorbs the heat transformed by kinetic energy in the process of aircraft braking, that is, the so-called "hot reservoir". The pressure-torque characteristic of the braking device is one of the key factors that influence the control performance of the aircraft. The mathematic model is derived as follows.

The friction outer radius of brake is defined as R, the friction inner radius as r_0, and the ring of the friction surface is taken as dr, which is shown in Figure 1.

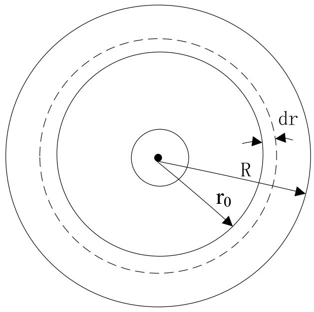


Figure 1: Diagram for friction surface of brake device

Assumptions: (1) the friction coefficient remains constant during braking;(2) the thrust force of piston on the brake disc is even.

The pistons thrust per unit area is:

$$F_p = S_T / \left[\left(R^2 - \mathrm{r}_0^2\right) \cdot \pi\right] \tag{16}$$

The ring dr is taken, then the piston thrust withstood by ring dr is:

$$dF = F_p \cdot dr \tag{17}$$

The friction generated by piston ring dr is:

$$df = \mu_s \cdot dF = \mu_s F_p \cdot \mathrm{dr} \cdot 2\pi r \tag{18}$$

Torque generated by piston ring dr is

$$dM_s = r \cdot df = r\mu_s F_p \cdot dr \cdot 2\pi r \tag{19}$$

Then the torque generated from the upper piston thrust $r_0 \to R$ is:

$$\begin{aligned} M_s &= \int_{r_0}^{R} r\mu_s F_p \cdot 2\pi r dr \\ &= \int_{r_0}^{R} 2r^2 \mu_s \cdot \frac{S_T}{R^2 - \mathrm{r}_0^2} dr \\ &= \frac{2}{3}\mu_s S_T \frac{R^2 + Rr_0 + \mathrm{r}_0^2}{\mathrm{R} + \mathrm{r}_0} \end{aligned} \tag{20}$$

In the formula:

μ_s ——friction coefficient of brake disc, $\mu_s = f(P, v)$

S_T ——total piston thrust, $S_T = P_L * S * n$

P_L ——brake pressure;

S ——piston area;

n ——piston number.

Namely, the relationship between brake torque and brake pressure is:

$$M_S = \frac{2}{3}\mu_s \mathrm{n} S \frac{R^2 + Rr_0 + r_0^2}{R + r_0} P_L = KP_L \quad (21)$$

In which,

$$K = \frac{2}{3}\mu_s \mathrm{n} S \frac{R^2 + Rr_0 + r_0^2}{R + r_0}$$

The overall nonlinear mathematical model of aircraft brake control system in the above can be sorted out:

$$\begin{cases} \dot{\sigma} = f(\sigma) + \dfrac{R_g K}{V_X J} P_L \\ \dot{P}_L = -\dfrac{4\beta_e k_c}{V_t} P_L + \dfrac{4\beta_e k_q r}{V_t}\theta \\ \dot{\theta} = -\dfrac{\omega_{mf}}{2\xi_{mf}}(\theta + \dfrac{\ddot{\theta}}{\omega_{mf}^2}) + \dfrac{k_t \omega_{mf}}{2\xi_{mf} k_{mf}} \cdot \Delta I \end{cases} \quad (22)$$

Equation (22) can then be written as the following equation of state with strict feedback, namely:

$$\begin{cases} \dot{x}_i = f_i(\overline{x}_i) + g_i(\overline{x}_i) x_{i+1}, i = 1,2, \\ \dot{x}_3 = f_3(\overline{x_3}) + g_3(\overline{x_3})u, \\ y = x_1, \end{cases} \quad (23)$$

In which:

$$x_1 = \sigma \quad f_1 = f(\sigma) \quad g_1 = \frac{R_g K}{V_X J}$$

$$x_2 = P_L \quad f_2 = -\frac{4\beta_e k_c}{V_t} P_L \quad g_2 = \frac{4\beta_e k_q r}{V_t}$$

$$x_3 = \theta \;\; f_3 = -\frac{\omega_{mf}}{2\xi_{mf}}(\theta + \frac{\ddot{\theta}}{\omega_{mf}^2}) \;\; g_3 = \frac{k_t \omega_{mf}}{2\xi_{mf} k_{mf}}$$

$$u = \Delta I$$

3 THE CONSTRAINT CONTROLLER DESIGN OF SLIP RATE BASED ON ASYMMETRIC BARRIER LYAPUNOV FUNCTION

Considering the stability and instability of the slip ratio in the aircraft anti-skid braking system, the control method is designed as shown in Figure 2. The slip ratio is divided into the stable and unstable regions by the slip ratio σ^* corresponding to the maximum combination coefficient $\mu_{\max}$ .When $0 < A < \sigma^*$ is for the stable area, then $\sigma^* < A < 1$ for the unstable area. The purpose of the constraint adaptive controller design for slip rate based on asymmetric barrier Lyapunov function is to ensure that the brake control system works at the optimal slip ratio σ^* and the working range is confined in the stable region of the tire runway model. Meanwhile, the tracking error of slip ratio σ converges to a small set of zeroes.

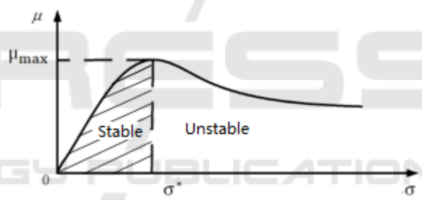


Figure 2: Friction model for tire runway

The error items $S_1 = y - y_d = \sigma - \sigma^*$, $S_i = x_i - z_i$ and $i = 2,3$ are defined. During the operation for the entire control system of aircraft brake, the adaptive controller will stop when the aircraft reaches the non-slip failure speed (typically 25Km / h), so the speed of aircraft $V_X > 0$ .Then for all $t > 0, g_i > 0$ and $i = 1,2,3$ is known, which is a prerequisite for the control method.

The initial value $\sigma(0) < \sigma^*$ of slip rate is defined. The constant $k_{c1} = 0.25$ is selected as the output constraint for the upper bound of slip rate, and the output constraint $k_{c2} = \sigma(0)$ for the lower bound of the slip rate. Then from the constrained lower bound $k_{a1}(t) = y_d - k_{c2} = \sigma^* - \sigma(0)$ and the constrained upper bound $k_{b1}(t)=k_{c1}-y_d=k_{c1}-\sigma^*$ of corresponding tracking error S_1,it is easy to judge that both $k_{a1}(t)$ and $k_{b1}(t)$ are bounded.

Virtual filter function z_2 is introduced, and from:

$$\tau_{i+1}\dot{z}_{i+1}+z_{i+1}=\alpha_i\,,\quad z_{i+1}(0)=\alpha_i(0)\,,\quad i=1,2$$

The first-order filter error is obtained:

$$\chi_{i+1}=z_{i+1}-\alpha_i\,,\quad \dot{z}_{i+1}=-\frac{\chi_{i+1}}{\tau_{i+1}}$$

Based on asymmetric barrier Lyapunov function, the following Lyapunov function is constructed:

$$\begin{cases} V_1=\dfrac{1-q}{2}\log\dfrac{k_{a1}^2(t)}{k_{a1}^2(t)-S_1^2} \\ +\dfrac{q}{2}\log\dfrac{k_{b1}^2(t)}{k_{b1}^2(t)-S_1^2}+\dfrac{1}{2}\chi_2^2 \\ V_2=V_1+\dfrac{1}{2}S_2^2+\dfrac{1}{2}\chi_3^2 \\ V_3=V_2+\dfrac{1}{2}S_3^2 \end{cases} \tag{24}$$

In which,

$$q=\begin{cases}1, S_1>0\\ 0, S_1\le 0\end{cases}$$

Based on the above analysis and combined with the characteristics of slip control for aircraft braking control system, the constraint control law of slip ratio for the braking control system is obtained:

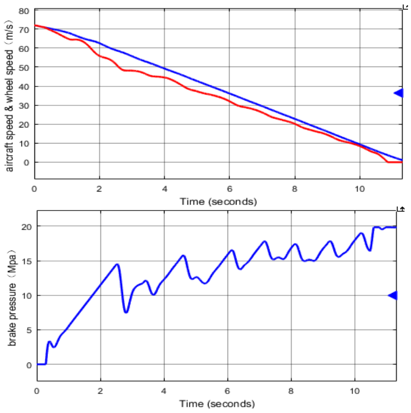
$$\begin{cases} \tau_{i+1}\dot{z}_{i+1}+z_{i+1}=\alpha_i, z_{i+1}(0)=\alpha_i(0), \\ i=1,2 \\ \alpha_1=\dfrac{1}{g_1}\left[-k_1S_1-f_1+\dot{y}_d\right] \\ \alpha_2=\dfrac{1}{g_2}\left[-k_2S_2-g_1S_1(\dfrac{1-q}{k_{a1}^2(t)-S_1^2})\right] \\ \dfrac{1}{g_2}\left[-g_1S(\dfrac{q}{k_{b1}^2(t)-S_1^2})-f_2-\dfrac{\chi_2}{\tau_2}\right] \\ u=\dfrac{1}{g_3}\left[-k_3S_3-f_3-g_2S_2-\dfrac{\chi_3}{\tau_3}\right] \end{cases} \tag{25}$$

Formula (23) is substituted into the above formula, the output restraint control law of slip ratio for the aircraft anti-skid braking system is obtained based on asymmetric barrier Lyapunov function as follows:

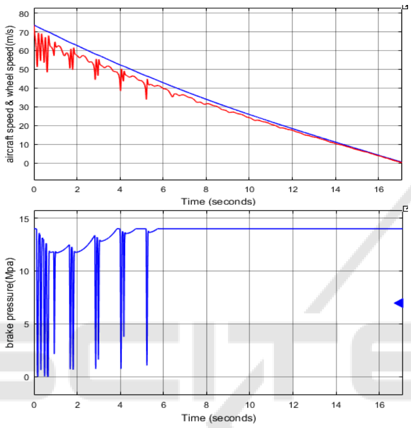
$$\begin{cases} \tau_{i+1}\dot{z}_{i+1}+z_{i+1}=\alpha_i, z_{i+1}(0)=\alpha_i(0), \\ i=1,2 \\ \alpha_1=\dfrac{V_XJ}{R_gK}\left[-k_1S_1-f(\sigma)+\dot{y}_d\right] \\ \alpha_2=-\dfrac{V_t}{4\beta_ek_qr}\dfrac{R_gKS_1}{V_XJ}(\dfrac{1-q}{k_{a1}^2(t)-S_1^2}) \\ -\dfrac{V_tk_2S_2}{4\beta_ek_qr}-\dfrac{V_t}{4\beta_ek_qr}\dfrac{R_gKS_1}{V_XJ}(\dfrac{q}{k_{b1}^2(t)-S_1^2}) \\ +\dfrac{V_t}{4\beta_ek_qr}\left[\dfrac{4\beta_ek_c}{V_t}P_L-\dfrac{\chi_2}{\tau_2}\right] \\ u=\dfrac{2\xi_{mf}k_{mf}}{k_t\omega_{mf}}\left[-k_3S_3+\dfrac{\omega_{mf}}{2\xi_{mf}}(\theta+\dfrac{\ddot{\theta}}{\omega_{mf}^2})\right] \\ \dfrac{2\xi_{mf}k_{mf}}{k_t\omega_{mf}}\left[-\dfrac{4\beta_ek_qr}{V_t}S_2-\dfrac{\chi_3}{\tau_3}\right] \end{cases} \tag{26}$$

4 RESULT ANALYSIS OF PERFORMANCE SIMULATION

Through the simulation of the entire anti-skid braking system of aircraft with Matlab, there are the following two hypotheses: (1) assuming that the aircraft does not perform turning operations during braking, but maintains a straight-line movement landing;(2) assuming that the load and grounding conditions of both left and right main landing gears are the same, and the brake control system is simplified into a single-wheel control model. Based on the above assumptions, the control law based on the slip rate constraint and the control law of the traditional “PD + PBM”were simulated and analyzed under different runway conditions. The simulation curves of the wheel speed and the brake pressure are seen in Figure 3 ~ Figure 5.



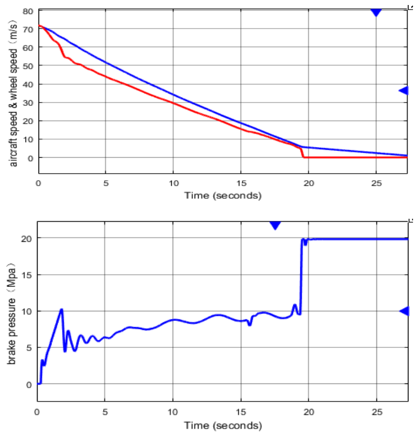
(a) Simulation curves of adaptive control law



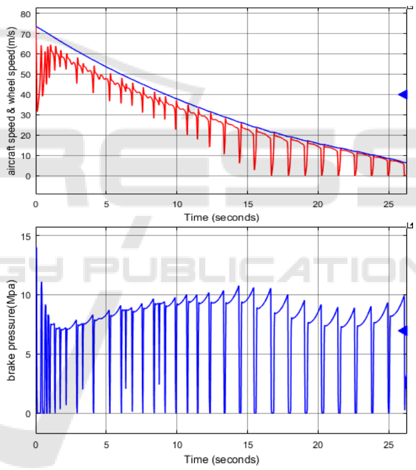
(b) Simulation curves of traditional PD + PBM control law

Figure 3: Simulation results under dry runway conditions

It can be seen from Figure 3, the adaptive control algorithm based on the slip rate constraint can be compared with the traditional PD + PBM control algorithm under the condition of dry runway. The brake control system under the adaptive control algorithm can be adjusted in the maximum range (0-21Mpa) within the regulation of brake pressure. The maximum can be adjusted to 20.8Mpa, so as to obtain a larger braking torque, braking efficiency is higher, the slip rate of about 95% efficiency, and braking distance of 372m; and throughout the braking process, the system can work near the optimal slip ratio corresponding to the maximum binding coefficient and always stay in a stable region of the curve $\mu - \sigma$. The slip rate always fluctuates around 0.13 except for the initial slow pressure rise until the anti-slip is released. Under the traditional PD + PBM control algorithm, the maximum braking pressure is limited to 13Mpain order to prevent torque charge, the utilization rate of the ground is reduced, the system cannot obtain the maximum braking torque, and the braking distance increases to 574.4mrelative to the adaptive control algorithm, slip rate efficiency is about 85.5%, and braking efficiency is significantly reduced.



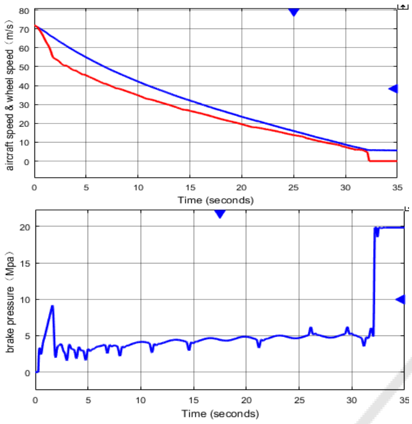
(a) Simulation curves of adaptive control law



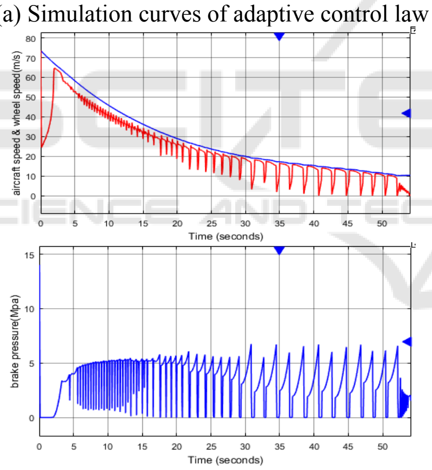
(b) The Simulation Curves of Traditional PD + PBM Control Law

Figure 4: Simulation results under wet runway conditions

It can be shown in Figure 4 that the combination coefficient provided by the ground reduces under wet runway conditions. To balance the matching torque, the brake pressure provided by the brake control system reduces accordingly. The maximum brake pressure is down to about 8Mpa. However, during the entire braking process, the brake pressure under the adaptive control algorithm based on the slip rate constraint can respond quickly and can be accurately adjusted within a small range. In addition to the slowly rising phase of the initial pressure, the slip rate always fluctuates around 0.15 until the slip at the 19.4s is released. No deep slippage appears in the process of entire braking, which can maintain a higher braking efficiency. The braking efficiency is about 88% and the braking distance 711.8m; but under the wet runway condition, the wheel in the traditional PD + PBM control is always in a slippery condition, and many deep slippage occurs, which makes the tire more wear and tear and reduces the service life of the tire and the braking efficiency. The braking efficiency is 74.8% and the braking distance is 871.1m.



(a) Simulation curves of adaptive control law



(b) Simulation curves of traditional PD + PBM control law

Figure 5: Simulation results under Ice runway conditions

As can be seen from Figure 5, the combination coefficient provided by the ground significantly reduces under the ice runway conditions. In order to prevent the occurrence of bodily defects and locking, the maximum braking force of the brake device applied by the brake control system is significantly reduced, about 5Mpa. However, the adaptive control algorithm based on slip rate constraint is smoother throughout the braking process and does not appear deep slipping. The braking time is 32.8s and the braking distance is 883.2m. However, the braking time of the conventional PD + PBM control law is 52.3s and the braking distance is 1543m. The response of the brake pressure regulation is slow during the entire braking process. There is deep slippage, which is worse than the adaptive control algorithm based on the slip ratio constraint.

5 CONCLUSION

Based on the analysis of the non-linear mathematic model for the aircraft anti-skid braking system, the author puts forward an adaptive control method of slip ratio constraint based on asymmetric barrier Lyapunov function. The simulation tests show that under different conditions of dry, wet and ice conditions:

(1) The anti-skid braking system of aircraft has the characteristics of high-order non-linear parameters such as time-varying. Due to the influence of runway environment, design parameters of driving mechanism and actuator, aerodynamics and other factors, linear control theory cannot guarantee that brake operating point is located in a stable region.

(2) Compared with the traditional PD + PBM control algorithm, the adaptive control of slip rate constraint based on the asymmetric Lyapunov function can quickly adjust the brake pressure so that the system can maintain the curve $\mu-\sigma$ under all conditions in the stable area, the system can make full use of the frictional resistance provided by the ground, make the whole brake control system and the wheel have a good match, and reduce the frequency of skidding, shorten the braking distance and improve the braking efficiency.

(3) Through the application of adaptive control method, no slippage or lock-up occurs, the wear on the braking device is reduced and the service life of the brake disc is increased, thereby the economy of use is improved.

To sum up, the adaptive control method of slip rate constraint asymmetric barrier based on Lyapunov function is a design method with high performance and economy, which will be an important evaluation index in the field of civil aircraft development. Therefore, this method is proposed to provide the direction and basis for engineering application in the field of adaptive full-regulation control of aircraft skid braking system.

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