Simulation of Aircraft Anti-skidding Braking System Considering Dynamic Contact Force between Road and Wheels

Bingchu Li¹, Shuangyuan Wang¹,*, Chengjin Qin² and Liang Gong²

¹School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai, China.
²School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China.

*E-mail: wsy1986@sina.com

Abstract. Aircraft anti-skidding braking system (ABS) was a nonlinear mechatronics system influenced by various factors. The road-wheel friction was one of the key factors affect system dynamics, which depends both on vertical contact force and skidding ratio. However, the vertical contact force was generally considered as constant in existing simulation and analysis methods. This paper investigated a simulation method considering dynamic vertical contact force and its influence on system dynamics. It was found that the landing gear shock absorber of aircraft leaded to dynamic vertical wheel-road contact force, and had significant influence on braking distance. The influence of dynamic vertical contact force was analyzed under three conditions. The proposed method considering dynamic contact force could significantly enhance the accuracy of aircraft anti-skidding braking system simulation.

1. Introduction

Research on aircraft anti-skid braking system had drawn great attention due to its critical influence on aircraft safety. Anti-skid braking system (ABS) was a highly nonlinear mechatronics system consist of braking actuation, friction panel, shock absorber, wheels and tires [1]. The complexity in components of ABS resulted in elusive dynamic characteristic, which depended on road condition, abrasion, temperature, and so on.

The central objective of ABS was to guarantee the safety of aircraft during landing, including components safety and reasonable braking distance. The slip ratio between wheels and road, which has significantly impact on friction force, was generally set as the control targets of ABS to ensure most efficient braking. Various control methods had been proposed for ABS [2-4] in face of highly nonlinear characteristic.

The assessment of control methods was an important issue in ABS design, however, due to the high cost of experiments for aircraft ABS, simulation became an efficient way for evaluation of anti-skid control algorithms before physical experiments.

Both digital simulation and half-physical simulation had been proposed for ABS design. In [5], a scheme for digital simulation platform of ABS was proposed, the simulation platform consist of commercial software, including EASY5, ADAMS/Aircraft and MATLAB/Simulink, which showed an effective and easy-implemented toolkit for ABS development. A semi-physical simulation platform was proposed in [6], a hardware interface was developed for the exchange of information between aircraft digital model and physical prototype of ABS, the digital aircraft model can be used to simulate
a wide range of road condition. The dynamic characteristic of actuators in ABS prototype was included in semi-physical simulation to improve accuracy.

To improve the accuracy in all kinds of simulation methods, it was necessary to consider more phenomenon that had significant impacts on system dynamics in simulation model. In [7], an aircraft dynamic model considering side wind was built, upon which a differential braking control law to keep predefined slip ratio was evaluated, simulation results show that side wind may lead to incorrect course and can be eliminated using the proposed differential braking control law. In [8], the modeling of a new braking actuator, the Electro-Hydrostatic Actuator (EHA), was described based on MATLAB/Simulink, the effects of physical parameters in actuators on system dynamics were analyzed, which proved to be an effective way to improve simulation accuracy.

All existing simulation methods considered the landing process as a constant road-wheel contact force process, while eventually the airplane bounced due to the shock absorber mechanism. This paper investigates the contact force oscillation during landing due to shock absorber, a simulation model considering vertical dynamic contact force was built and used to analyze the influence of contact force oscillation on system dynamics. It was revealed that contact force oscillation seriously influenced braking distance, and prolonged braking distance depended on road condition.

2. Introduction to ABS system

2.1. Structure of anti-skid braking system

ABS was consisted of braking controller, actuators, sensors and wheels. The controller acquired the speed of aircraft and wheels, then generated appropriate braking forces to reduce speed in fast and stable manner. The wheel-road friction was the key parameter to be controlled, which depended on slip ratio, contact force between road and wheels, and road condition. The slip ratio should be kept in a region where the wheel-road friction coefficient was maximum. The structure of ABS was given in Figure 1.

2.2. Model of aircraft during landing

The mechanical model during landing was given in Figure 2. The tangential equation is given as follows:
\[ m_A \ddot{V}_x + F_x + F_p + nF_f - T_x = 0 \]  

where \( V_x \), \( m_A \) and \( n \) denote the longitudinal speed, mass and number of wheels of aircraft, respectively. \( F_x \), \( F_p \), \( F_f \) and \( T_x \) denote the external force of aircraft, namely aerodynamic drag, drag parachute resistance, wheel-road friction and engine thrust, respectively.

\[ xV = A \]

\[ Am \]

\[ n \]

\[ \text{where} \]

\[ xF \], \( PF \), \( fF \) and \( eT \) denote the external force of aircraft, namely aerodynamic drag, drag parachute resistance, wheel-road friction and engine thrust, respectively.

The vertical equation of aircraft is given as follows:

\[ m_A \ddot{V}_y + nF_h - G = 0 \]  

Where \( F_h \) is the support force from vibration absorber, \( G \) is the gravity of aircraft. The dynamic model of wheels is given:

\[ J_w \omega + F_f + B_w \omega + T_b = 0 \]  

Where \( J_w \), \( \omega \) and \( R_w \) denote the inertia, rotational speed and radius, respectively. \( B_w \) is the friction coefficient of wheel shaft, \( T_b \) is the braking force given by the actuator. Equation (1-3) give the dynamic model of aircraft during landing process.

2.3. Model of shock absorber

Due to existence of shock absorber, the pressure for the land is changing during landing. The principle of shock absorber can be represented as a spring-mass-damping model:

\[ m_A \dddot{P}_y + c_A \dot{P}_y + k_A P_y = G \]  

\[ F_h = c_A \dot{P}_y + k_A P_y \]  

Where \( P_y \) is the height of aircraft, \( c_A \) and \( k_A \) is the damping rate and spring rate of vibration absorber, which can be obtained from absorber manufacturer.

3. Simulation method

The simulation model considering absorber can be built in Matlab/Simulink according to the dynamic model of aircraft and components given in equation (1-5). Several assumptions are made to simplify the simulation process:

- The landing process depends only on the main wheels of aircraft.
- The aircraft was balanced during landing, the contact force for wheels on both sides are equal.

3.1. System simulation method

The whole simulation model was consisted of six modules, namely drogue chute model, engine model, undercarriage model, fatigue model, wheel model, wheel-road friction model, actuator model and controller, as shown in Figure 3. In this paper, the PI control method was used to generate appropriate braking force.
3.2. Shock absorber simulation
To avoid damage of wheels due to huge shock, the shock absorber was used to restrain sudden change of wheel load. The shock absorber can be represented as a mass-spring-damping model. The contact force oscillation was considered as the result of an impulse applying on a second-order system as shown in Figure 4. The damping and spring rate in the absorber model can be acquired from physical parameters of shock absorber. The contact force was applied when calculating road friction in wheel-road friction model.

4. Simulation results
The parameters of aircraft used for simulation are given in Table 1.

Table 1. Aircraft parameters in simulation.

| Parameters                        | Value         |
|-----------------------------------|---------------|
| Mass of aircraft                  | 28407 kg      |
| Residual thrust                   | 426 kg        |
| Initial speed                     | 72 m/s        |
| Drag umbrella area                | 20 m²         |
| Drag parachute coefficient        | 0.128         |
| Wing Area                         | 50 m²         |
| Resistance coefficient of taxiing | 0.1027        |
| Lift coefficient of taxiing       | 0.6           |
| Air density                       | 1.293 kg/m³   |
Angle of pitch | 0
Initial height of center of gravity | 2.18 m
Inertia of wheel | 1.85 \( \text{kg} \cdot \text{m}^2 \)
Initial speed of wheel | 135.85 \( \text{rad} / \text{s} \)
Radius of wheel | 0.53 m
Number of wheels | 4
Damping coefficient of buffer | 8000
Spring coefficient of buffer | 122529

Figure 5 gives the detailed road-wheel attachment coefficient in different road condition.

4.1. Braking process under constant and dynamic load
According to Figure 5, the target slip ratio was set to 0.1, 0.15 and 0.2 in dry, wet and iced road condition, respectively.

Figure 6 shows the braking process of ABS with PI control on dry road. The proportional coefficient \( P \) and integral coefficient \( I \) are carefully tuned to get better performance, which are finally set to 100000 and 9270000, respectively. Figure 6 (a) shows the speed response after ABS works under constant load, Figure 6 (b) shows the speed response after ABS works under dynamic contact force. The slip ratio reached the target value within 2.4 seconds with constant contact force; while with dynamic contact force, the slip ratio heavily oscillated and reached the target value at 8.4 seconds. Figure 6 (c) gives a comparison of braking distance with constant and dynamic contact force, it shows that dynamic contact force significantly deteriorates the braking distance, prolonged to 331 meters from 88 meters.
Figure 6. Simulation results in dry pavement. (a): Speed response with constant contact force; (b): Speed response with dynamic contact force; (c): Comparison of braking distance between constant and dynamic contact force.

Figure 7. Simulation results in wet pavement. (a): Speed response with constant contact force; (b): Speed response with dynamic contact force; (c): Comparison of braking distance between constant and dynamic contact force.

Figure 8. Simulation results in iced pavement. (a): Speed response with constant contact force; (b): Speed response with dynamic contact force; (c): Comparison of braking distance between constant and dynamic contact force.

Figure 7 shows the braking process with wet road. The proportional coefficient P and integral coefficient I are carefully tuned to get better performance, which are finally set to 130000 and 9270000, respectively. Figure 7 (a) shows the speed response after ABS works under constant contact force, while Figure 7 (b) shows the results under dynamic contact force. Figure 7 (c) shows that the aircraft stopped within 180 meters with constant contact force, while the braking distance is 660 meters with dynamic contact force. Comparing with the braking distance under dynamic contact force with dry road, it shows that the braking distance deteriorates more serious with wet road when considering dynamic contact force.

Figure 8 shows the braking process with iced road. The proportional coefficient P and integral coefficient I are set to 100000 and 9270000, respectively. Figure 8 (a) shows the speed response after ABS works under constant contact force, while Figure 8 (b) shows the results under dynamic contact force. Figure 8 (c) shows that the aircraft stopped within 321 meters with constant load, while the braking distance is 1260 meters with dynamic load. The braking distance increased 939 meters with dynamic load comparing with constant load, which was more serious than wet road.

It can be concluded that the dynamic contact force has more significant effect on road with worse attachment.

4.2. Effect of absorber parameters
The effect of physical parameters of shock absorber on braking process was studied. Figure 9 (a) shows the load variation during braking with different spring coefficient, Figure 9 (b) shows braking distance with different spring coefficient on dry road. It can be seen from Figure 9 that the spring coefficient has significant effect for the braking process of aircraft, the braking distance increased as spring coefficient increase.
Figure 9. Effect of spring coefficient on braking process. (a) Contact force variation; (b) braking distance.

5. Conclusion
Aircraft anti-skidding braking system (ABS) is a complex nonlinear system, this paper proposed an effective way to improve the accuracy of ABS simulation model, by considering the dynamic vertical contact force between wheels and road. The simulation model is discussed in detail. Simulation is implemented to evaluated the performance of simulation model considering dynamic vertical contact force. It is found that the landing gear shock absorber of aircraft leaded to dynamic vertical wheel-road contact force, and has significant influence on braking distance. The influence of dynamic vertical contact force depends on the road condition and absorber physical parameters.

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