Modelling and Simulation of an Anti-skid Braking System for Rail Vehicles

Tianhe Ma, Mengling Wu and Chun Tian
Institute of Rail Transit, Tongji University, No. 4800 Caoan Highway, Shanghai 201804, PRC.
Email: chtian@tongji.edu.cn

Abstract. Pneumatic braking systems are widely used on rail vehicles. Anti-skid control systems are equipped to prevent wheels from locking and ensure braking distances in low adhesion conditions. To model and simulate an anti-skid pneumatic braking system, a concise modelling method was proposed. By dividing the pneumatic braking control unit into two parts, the complex model was simplified according to its working principle. The pneumatic model, kinematic model, adhesion force model and controller model were established and simulated with MATLAB/Simulink and AMESim. The results show that this method is suitable for anti-skid control modelling and simulation and can be used for controller development and verification.

1. Introduction
Rail transit is now booming all over the world, and tremendous progress has been made. Safety, comfort, and efficiency are the most important mission of rail transit, and these significantly depend on the performance of the braking system of rail vehicles. When braking, a train slows down by the longitudinal force between wheel and rail, which known as the adhesion force. However, the wheel/rail adhesion may be deteriorated dramatically in some circumstances, such as rainy/snowy/foggy days, dead leaves, oil or any other contaminants on the track [1-2]. In these circumstances, the adhesive force between wheel and rail cannot balance the braking torque anymore, which will cause wheel sliding or even locking. So a wheel slide protection system (WSP) is usually equipped to implement anti-skid.

There have been scholars devoting to research anti-skid braking systems. Li [3-4] introduced the composition of the anti-skid control system used in high-speed trains and metros and described its basic working principle. Although both dynamic brake and pneumatic friction brake are used in modern metro and high-speed rail vehicles, the anti-skid control takes effect separately. For a pneumatic braking system, brake cylinder pressure is adjusted with electromagnetic valves [5], so the anti-skid system prevents the wheel from deep sliding and lock by releasing the compressed air of brake cylinders also through valves, which known as anti-skid valves. Lee et al. [6] proposed a control algorithm for WSP valves and validated them by hardware-in-the-loop simulation. And there are other advanced anti-skid control methods developed recently [7-9]. But control methods need to be verified before it actually implemented to a physical controller and then equipped to a real train. There are also extensive researches about modelling and simulation of pneumatic braking and anti-skid systems. Diao et al. [10] established the train dynamics model, pneumatic braking system model and wheel-rail adhesion model for a high-speed train. Luo et al. [11] developed models of an electro-pneumatic brake on subway trains. In this paper, a model of the anti-skid pneumatic braking system is established.
The model includes vehicle and wheelset motion, wheel/rail longitudinal adhesive force, anti-skid controller, and the WSP pneumatics.

The remaining parts of this paper are organized as follows. The next section analyses the anti-skid braking system and establishes the models. Then the third section introduces the simulation with the model. And the fourth section shows and discusses the simulation results. Finally, conclusions are drawn.

2. Modelling

2.1. Pneumatic Model

Now bogie-controlled pneumatic braking systems are the most widely used systems on metro trains. A typical pneumatic brake control unit (PBCU) of bogie-controlled brake systems is shown in Figure 1. It can be mainly divided into two parts: load-weighed emergency pressure pre-control part (part 1) in upstream and Service Brake/WSP pressure adjusting part (part 2) in downstream. For load-weighed emergency pressure pre-control part, it provides a pressure at emergency braking level considering changes in ridership. For Service Brake/WSP pressure adjusting part, it adjusts the output pressure further according to specific braking commands and whether the wheel is sliding. The link-valves are used to cut the air pipe connection of two axles of the bogie when the wheel’s sliding occurs and reconnect the two axles when the sliding is eliminated.

Figure 1. Scheme diagram of the pneumatic brake control unit.

So we can find that the second part of the PBCU directly controls the final output pressure and decides when to switch from braking and anti-skidding. So the anti-skid pneumatic braking system was simplified as Figure 2. Moreover, for the Service Brake/WSP pressure adjusting part in Figure 1, it includes “pairs” of an pilot electromagnetic valve with a pneumatic-controlled valve. In Figure 2, such a pair was simplified to one electromagnetic valve.
2.2. Kinematic Model
To simplify the complex dynamics of a whole vehicle, the kinematic model was built in a concise form:

\[ J_w \cdot \dot{\omega}_i = R_w \cdot F_{aw} - R_w \cdot F_{bw} \]  
\[ M \cdot \dot{v} = - \sum_{i=1}^{n} F_{aw} \]  

Where \( \omega \) is the angular velocity of a wheel pair rotation, \( J_w \) is the moment of inertia of a wheel pair, \( R_w \) is the radius of wheel, \( F_{aw} \) is the adhesive force between wheels and rails, \( F_{bw} \) is the equivalent braking force at the radius of wheel, \( M \) is vehicle mass, \( v \) is vehicle speed, and subscript \( i \) means the \( i \) th wheelset. And the braking force (the equivalent force of friction torque at the radius of the wheel) can be calculated by brake cylinder pressure:

\[ F_b = 2f \cdot \phi \cdot \rho \cdot \eta \cdot S \cdot \left( p - \frac{F}{S} \right) \]  

Where \( f, \phi, \rho, \eta, S \) are brake friction coefficient, ratio of brake radius and wheel radius, brake leverage, mechanical efficiency, effective acting area of brake cylinder piston and reset spring force respectively.

2.3. Longitudinal Force Model
According to Polach’s model [12], the longitudinal adhesion force can be modelled as

\[ F_a = \frac{2Q\mu_0}{\pi} \left[ (1-A)e^{-B\Delta v} + A \right] \left[ \frac{k_A e^{\Delta v}}{1+(k_A e^{\Delta v})} + \arctan(k_A e^{\Delta v}) \right] \]  
\[ \varepsilon = \frac{1}{4} \frac{G\pi ab C_{11}}{Q\mu} s \]  

Where \( Q \) is wheel load, \( k_A, k_s \) are reduction factors in the area of adhesion and slip separately, \( a, b \) are lengths of half-axes of the contact ellipse, \( G \) is shear module, \( s \) is slip ratio, \( C_{11} \) is coefficient from Kalker’s linear theory [13], \( \mu \) is friction coefficient between wheel and rail, \( \mu_0 \) is the maximum friction coefficient at zero creep velocity, \( A \) is ratio of friction coefficient at infinity slip velocity and \( \mu_0, B \) is coefficient of exponential friction decrease, \( \Delta v \) is longitudinal creep velocity.

2.4. Controller Model
The control diagram is shown in figure 3. Since the system using the same valves both for braking and WSP, its control logic should be switchable. When there is a braking command, the output pressure of the PBCU is closed-loop controlled according to the target brake cylinder pressure. And at the same time speeds of all the axles and the vehicle are monitoring and wheel sliding is detected. When an axle is found sliding and the sliding is large enough, the pressure control of such axle will be switched to anti-skid control mode. Many kinds of anti-skid control methods can be set here to stop wheel sliding.
and prevent it from locking. One of the most common methods is discharging when sliding occurs and holding when sliding is controllable and charging when adhesion is fully recovered.

3. Simulation and Results
According to the models in section 2, a simulation was realized with MATLAB/Simulink and AMESim. As is shown in figure 4, the pneumatic model contains two electromagnetic valves and two cylinders each axle as well as a link-valve. Control signals were given to each valve and pressures were measured by transducers. In this figure, inlet/hold valves are to let the compressed air in when braking and cut the airflow when releasing or the wheel is sliding, and vent valves are to vent air when releasing or sliding.

Simulation results are shown in the figures below. The adhesion condition is shown in figure 5. The adhesion coefficient changes from a high value to a low one and finally to a high value again during braking. The control signals of the service brake/WSP valves are shown in figure 6. And as is shown in figure 7, the pressure of brake cylinders declines when wheel sliding occurs and continues to adjust during sliding, and finally rises when adhesion recovery. In figure 8, speeds of the vehicle and four

![Figure 3. Control diagram.](image-url)

![Figure 4. The simplified pneumatic model.](image-url)
Axes are shown, from which we can easily find when the wheel is sliding, the anti-skid system worked very well to prevent locking.

![Figure 5. Adhesion condition.](image1)

![Figure 6. Control signals of the service brake/WSP valves.](image2)

![Figure 7. Brake cylinder pressure of the sliding axle.](image3)

![Figure 8. Speeds of the vehicle and four axles.](image4)

4. Conclusions
A method of modelling and simulation of the anti-skid control system for a pneumatic braking system was developed. And the method is well verified by co-simulation with MATLAB/Simulink and AMESim. From the simulation results, we can see: With this method, the pressures, speeds, control signals, etc. can be simulated during the braking and anti-skidding process. The efficient simplification of the pneumatic braking system helps to focus on the most significant part of the anti-skid system. Concise model is suitable for quick design and simulation as well as early verifications of the control system.

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