Modeling and Control of Automotive Antilock Brake Systems through PI and Neural Network Arithmetic

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***Abstract*—The control logic of automotive Antilock Brake Systems (ABS) is introduced in this paper, which integrates PI controller and Neural Network arithmetic. A novelty of this paper is the ability to achieve superior performance through self-tuning controller which can realize robust control. Vehicle system and controller modeling and simulation are executed on software in the loop simulation platform with Matlab/Simulink. Some typical cases are simulated to verify the effect of the control algorithm. Results show that the self-tuning controller can improve the vehicle performance dramatically than traditional PI controller.**

Keywords-Automotive; Antilock Brake Systems; PI controller; Neural Network;

I. INTRODUCTION

Nowadays, ABS has become one of the most popular active safety devices on vehicles. Varies of control theories have been used in the research of ABS to improve its performance. As one of the earliest control strategies, PID is widely adopted in process control and motion control due to its simplicity and reliability.

However, as a typical non-linear and time-variant system, it is hardly to obtain a vehicle model which is simple and accurate enough. Therefore, it is almost impossible to satisfy the demand of variable working states of a vehicle by a traditional PID controller. Consequently, bad adaption to varying driving conditions happens because of improper tuning to PID parameters.

In recent years, the development of intelligent control provided new approaches to complex, dynamic and uncertain vehicle system [1-3].

Such approaches include Artificial Neural Network (ANN, or NN for short) which work by imitating the natural neurons in the brain [4-5]. As a new interesting tool for dynamic system identification, modeling and control, NN has been well studied and highly developed.[6-8] The special ability to process nonlinear and adaptable information enables NN to work effectively in the fields of expert system, mode identification, intelligent control, combinatorial optimization and predication. NN is also used in control systems to deal with their nonlinearity and uncertainty and to achieve the identification function of approach system. After development of more than 50 years, there has been many forms of NN. BP NN is the most widely used one in approximation of function, mode identification and classification, data compression, and so on. Actually, 80 to 90 percent of NN models were made by BP NN or its modified forms.

By combining of BP NN and PID control, the PID control parameters are tuned online. Therefore, both of the features of simplicity and reliability from PID and ability of resolving non-linear problem from NN could be maintained. Therefore, the non-linear and dynamic problem of ABS control could be solved effectively. As a result, optimal control effects are achieved [9-14].

In this paper, an incremental PI ABS controller and a self-tuning PI ABS controller based on BP neural network are designed. And then, a series of two-wheel vehicle models are studied and Modeled via Matlab/Simulink. At last, panic braking simulation is preceded, and the effects of the controller are compared and validated.

II. CONTROLLER DESIGN

A. Traditional PI Controller

To compare with the new controller, a traditional incremental numerical PI controller was designed first, which is illustrated in Fig. 1. The error between actual slip ratio and expected slip ratio was selected as the input of the controller, and the output was expected variation of brake pressure.

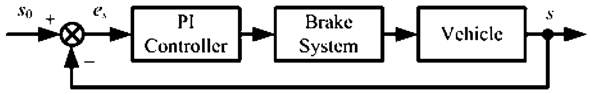

Figure 1. Traditional ABS PI controller

$$e_s = s_0 - s \tag{1}$$

$$\Delta u(k) = k_p(e_s(k) - e_s(k-1)) + k_i e_s(k) \tag{2}$$

B. Neural Network Tuning PI Controller

Fig. 2 illustrates the structure of NN tuning PI controller. An incremental PI controller, whose parameters k_p and k_i were tuned online by a BP NN tuner, was also adopted. And BP NN was designed to be a single hidden layer network, as shown in Fig. 3.The vehicle speed, wheel speed, error between actual slip ratio and expected slip ratio and its change rate were adopted as the input of the network. There were 20 neurons in the hidden layer. The output included k_p and k_i of the PI controller.

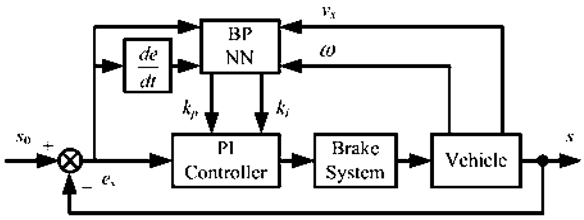

Figure 2. Self-tuning PI ABS controller based on neural network

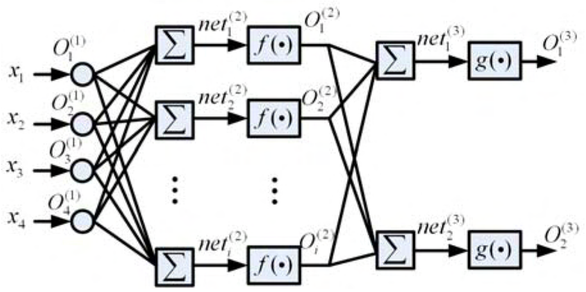

Figure 3. Structure of BP neural network

The input of input layer:

$$O_j^{(1)} = x(j) \qquad j = 1,2,\cdots 4 \tag{3}$$

The input and output of hidden layer:

$$net_i^{(2)}(k) = \sum_{j=1}^{4} w_{ij}^{(2)} O_j^{(1)}(k) \tag{4}$$

$$O_i^{(2)}(k) = f\left(net_i^{(2)}(k)\right) \qquad (i = 1,2,\cdots 20) \tag{5}$$

where $w_{ij}^{(2)}$ is weight coefficients of hidden layer, and $f(\bullet)$ is activation function of hidden neurons.

$$f(\bullet) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{6}$$

The input and output of output layer:

$$net_l^{(3)}(k) = \sum_{i=1}^{20} w_{li}^{(3)} O_i^{(2)}(k) \tag{7}$$

$$O_l^{(3)}(k) = g\left(net_l^{3}(k)\right) \qquad (l = 1,2) \tag{8}$$

where $g(\bullet)$ is activation function of output neurons.

$$g(\bullet) = \frac{1}{2}\left(1 + \tanh(x)\right) = \frac{e^x}{e^x + e^{-x}} \tag{9}$$

The parameters of PI controller:

$$\begin{cases} k_p = T_p O_1^{(3)}(k) \\ k_i = T_i O_2^{(3)}(k) \end{cases} \tag{10}$$

where T_p and T_i are the proportional coefficients.

Performance index function is

$$E(k) = \frac{1}{2}\left(s_0 - s(k)\right)^2 \tag{11}$$

Learning algorithm for weight coefficients of hidden layer:

$$\Delta w_{ij}^{(2)}(k) = \alpha \Delta w_{ij}^{(2)}(k-1) + \eta \delta_i^{'(2)} O_j^{(1)}(k) \tag{12}$$

$$\delta_i^{'(2)} = f'\left(net_i^{(2)}(k)\right) \sum_{l=1}^{3} \delta_l^{'(3)} w_{li}^{(3)}(k) \qquad (i = 1,2,\cdots,20) \tag{13}$$

Learning algorithm for weight coefficients of output layer:

$$\Delta w_{li}^{(3)}(k) = \alpha \Delta w_{li}^{(3)}(k-1) + \eta \delta_l^{'(3)} O_i^{(2)}(\mathrm{k}) \tag{14}$$

$$\delta_l^{'(3)} = error(k) \cdot sign\left(\frac{\partial s(k)}{\partial \Delta u(k)}\right) \cdot \frac{\partial \Delta u(k)}{\partial O_l^{(3)}(k)} \cdot g'\left(net_l^{(3)}(k)\right) \qquad (l = 1, 2) \tag{15}$$

Using PI control arithmetic, we get:

$$\frac{\partial \Delta u(k)}{\partial O_1^{(3)}} = T_p\left(e_s(k) - e_s(k-1)\right) \tag{16}$$

$$\frac{\partial \Delta u(k)}{\partial O_2^{(3)}} = T_i \cdot e_s(k) \tag{17}$$

III. VEHICLE MODELLING

Fig. 4 shows a two-wheel vehicle model which was used in this paper. Parameters used in simulation are shown in Table I. The vehicle system model is as below:

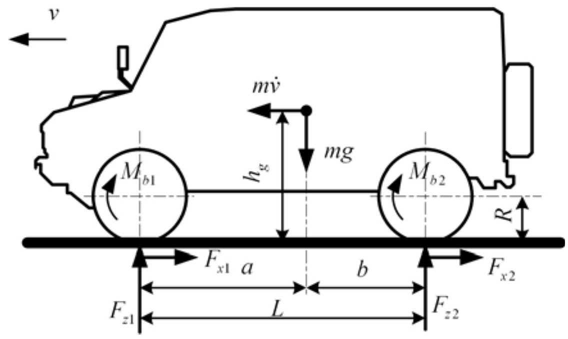

Figure 4. Two-wheel vehicle model

TABLE I. VEHICLE PARAMETERS

Symbol	Parameter	Value
R / m	Wheel radius	0.40
I_ω / kgm^2	Wheel inertia	2.864
c_x / kNm^{-1}	Wheel longitudinal stiffness	186.9
M / kg	Mass of the vehicle	4400
L / m	Wheelbase	2.8
b / m	Distance between mass center and rear axle	1.57
h_g / m	Height of mass center	0.8
p_{max} / Mpa	Max pressure of brake system	14
K_{bf}	Constant of front brake	6.025e-4
K_{br}	Constant of rear brake	2.796e-4
T_b	Time constant of brake system	0.3

$$I_{\omega i}\dot{\omega}_i = M_{bi} - F_{xi}R \qquad i = 1,2 \tag{18}$$

$$F_{z1} = M \cdot \left(g \cdot b + \dot{v} \cdot h_g\right) / L \tag{19}$$

$$F_{z2} = M \cdot \left(g \cdot b - \dot{v} \cdot h_g\right) / L \tag{20}$$

$$\dot{v} = \left(F_{x1} + F_{x2}\right) / M \tag{21}$$

Tire model

$$F_x = \begin{cases} c_x s l_n^2 + \mu F_z (1 - 3l_n^2 + 2l_n^3) & s < 3\mu F_z / c_x \\ \mu F_z & s \ge 3\mu F_z / c_x \end{cases} \tag{22}$$

Where,

$$l_n = 1 - s \cdot c_x / (3\mu F_z) \tag{23}$$

Bake system model:

$$M_b = K_b \cdot p \tag{24}$$

$$p = \frac{p_{\max}}{T_b s + 1} \tag{25}$$

where s is Laplacian.

IV. SIMULATION

Vehicle model and controller models were written via Matlab/Simulink, and simulation was carried out. Table II shows parameters used in simulation. The parameters k_p and k_i were obtained by tuning on high μ road braking simulation for the incremental PI control. And they were used not only in incremental PI controller but also as the initial value of NN tuning PI controller.

TABLE II. SIMULATION PARAMETERS

Symbol	Parameter	Value
V_0 / ms^{-1}	Initial vehicle speed	22
μ_p	Peak coefficient of adhesion for high μ road	0.8
	Peak coefficient of adhesion for high μ road	0.3
K_p	(Initial) Proportional factor of PI controller for front axle	4.8433
	(Initial) Proportional factor of PI controller for rear axle	47.934
K_i	(Initial) Integral factor of PI controller for front axle	2.5388
	(Initial) Integral factor of PI controller for rear axle	12.778

Fig. 5 to Fig. 7 illustrate the results of a vehicle's panic braking on high μ road without ABS control, with PI ABS control and NN PI ABS control respectively, where, v_f-linear speed of front wheel, v_r-linear speed of rear speed, v-vehicle speed, v_0-target speed, p_f-brake pressure of front axle, p_r-brake pressure of rear axle. In each figure, speed curves are on the upper and break pressure curves are on the bottom. (same as below)

Fig. 8 to Fig. 10 show the results that a vehicle brake on low μ road without ABS control, with PI ABS control and NN PI ABS control respectively.

The results show that the wheels locked rapidly without ABS, whether on low μ road or not. And the locking of braking wheels could be restrained by the usage of both controllers. Therefore, the stop time is reduced and the effective deceleration is raised. However, it is also important to note that:

First, because the PI parameters were obtained by manually tuning on high µ road, the performance of incremental PI controller is almost the same with self-tuning PI controller based on NN on high µ road, as shown in Fig.6 and Fig. 7.

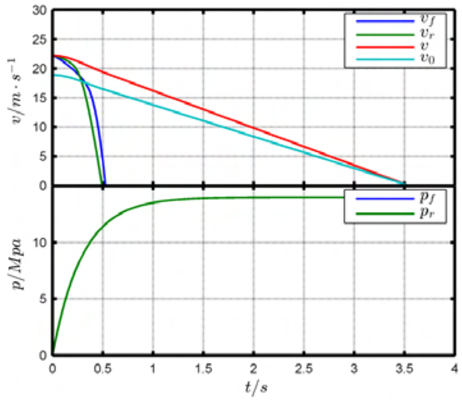

Figure 5. Speed and brake pressure at the time of panic braking on high µ road without ABS control.

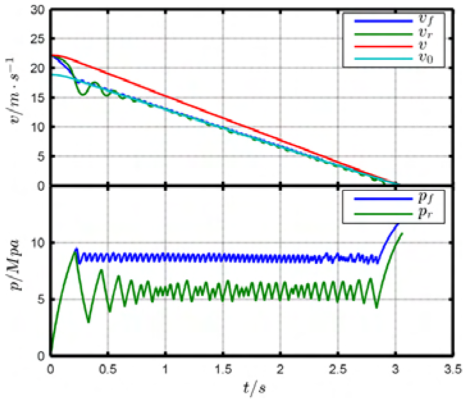

Figure 6. Speed and brake pressure at the time of panic braking on high µ road with incremental PI ABS control.

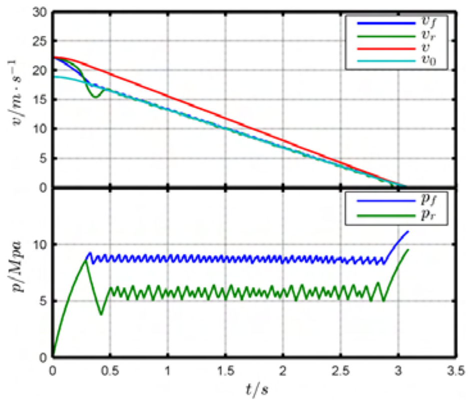

Figure 7. Speed and brake pressure at the time of panic braking on high µ road with NN tuning PI ABS control.

Second, using incremental PI controller, the fluctuation of brake pressure and wheel speed is much more obvious on low μ road than on the higher one, as shown in Fig. 9. It indicates that the parameters k_p and k_i are not suitable any more. While using BP NN tuning PI controller, the fluctuation is significantly reduced, as shown in Fig. 10 contrast with Fig. 9. Consequently, the total stop time is further reduced too. It indicates that the parameters are well tuned and the PI controller works more effectively.

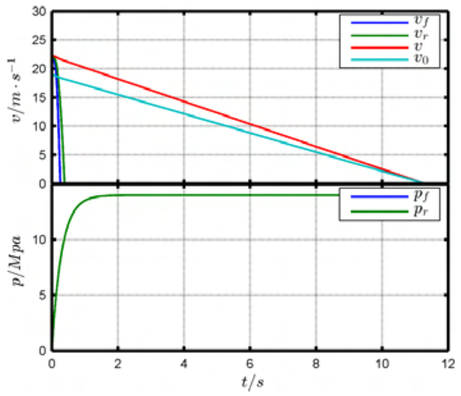

Figure 8. Speed and brake pressure at the time of panic braking on low µ road without ABS control.

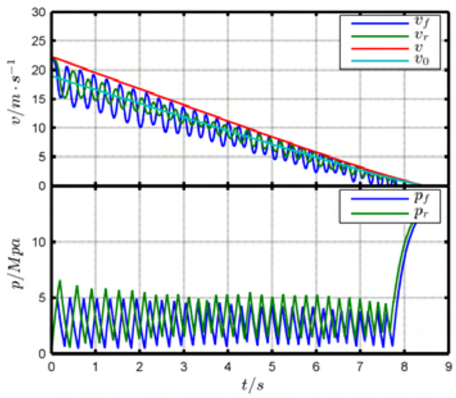

Figure 9. Speed and brake pressure at the time of panic braking on low µ road with incremental PI ABS control.

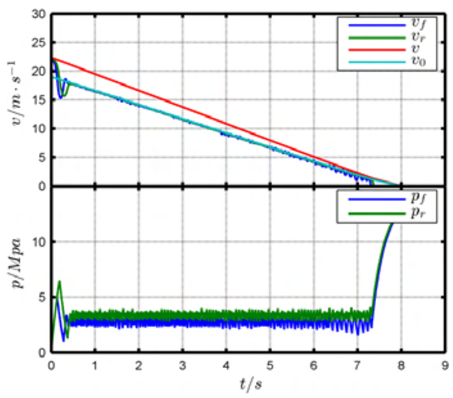

Figure 10. Speed and brake pressure at the time of panic braking on low µ road with NN tuning PI ABS control.

IV. CONCLUSION

Although ABS function could be executed by a basis PI controller, a single series of parameters can't fulfill the demands of different road conditions. In this paper, a BP Neural Network was integrated in the controller to tune PI parameters online. Furthermore, a two-wheeled vehicle model written in Matlab/Simulink was used to examine the effects of the modification. It is shown that the suitability and robustness of the controller on different road conditions were improved obviously. Further research concentrates on integrating the controller into an ICC (Integrated Chassis Control) system.

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