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New Structure Design and Simulation of Brake by Wire System Based on Giant-magnetostrictive Material

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Abstract: Existing electronic mechanical brake by wire system has several disadvantages. For instance, system actuators are complex, response speed slower, larger vibration noise, etc. This paper discusses a new type brake by wire system based on giant-magnetostrictive material. The new type brake by wire system model was set up under Matlab/Simulink software environment. PID control method was used to control the brake by wire system. Simulation results shows that the new type brake by wire system achieves better braking performance compared with hydraulic braking system. This work provides a new idea for researching automobile brake by wire system. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Giant-magnetostrictive material, Brake by wire, Control, Simulation, Automobile.

1. Introduction

With the development of the society and the progress of science and technology, people put forward higher requirements about automobile performance. The future automobile is required active safety, environmental protection, automobile lightweighting etc. At present, electronic technology has been widely used in automobile control system. Automobile power performance and handling stability, safety, fuel economy have been greatly improved. The application of new functional material is one of the research hotspot of automobile technology. Giant-magnetostrictive material as one of new functional material shows a good application prospect in micro-motor, precision valve and vibration control engineering field.

EMB actuator design, control system design, stability control, and distribution of braking force, braking and hardware in the loop test were carried out by professor Li [1-3]. Pedal force simulation research of brake by wire system was carried out by A. Hildebrandt and A. M. Harsha [4, 5]. Sohel Anwar adopted nonlinear sliding mode control method to control brake by wire system on low adhesion coefficient road surface, system noise and vibration was reduced [6]. W. Xiang used fuzzy logic control method to control lateral stability and yawing stability of brake by wire system [7]. P. Krishnamurthy and W. Lu designed robust controller for brake by wire system [8]. Brake by wire system design and development method was presented by M. Roberts and T. Chhaya [9].

As we all know, most of existing brake by wire system used motor as braking power and supplemented by retarding mechanism and motion transformation mechanism. The motor which is used as braking power often works in the blocked situation and is required high reliability of working. Retarding mechanism and motion transformation mechanism

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convert motor's rotary motion into linear motion. Retarding mechanism and motion transformation mechanism commonly consist of planetary gear reducer and ball screw. This structure significantly increased the complexity of the actuator and assembly costs. At the same time, actuator response time of braking system is increased as a result of the existence of transmission mechanism. Based on above reasons, active safety performance of electronic mechanical brake by wire system should be further improved.

Based on the characteristics and advantages of giant-magnetostrictive material, the paper put giant-magnetostrictive material into brake by wire system. Simulation results shows that the new type brake by wire system achieves better braking performance compared with hydraulic braking system. This work provides a new idea for researching automobile brake by wire system.

2. System Structure and Working Principle

The braking system adopts H type structure. Giant-magnetostrictive material rod is used as braking power. The GMM rod generates axial displacement under the action of magnetic field coming from electromagnetic coil. Axial displacement pushes the compliant mechanism and friction plate clamps the brake disc. System structure is shown in Fig. 1.

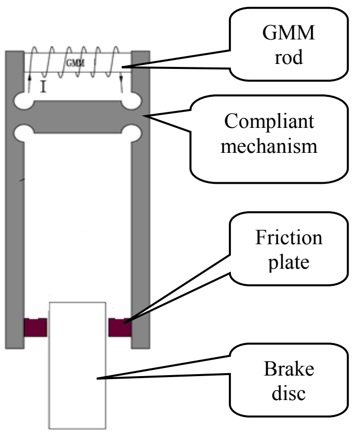

Fig. 1. H type structure of braking system.

3. System Model

3.1. Vehicle Dynamic Model

Two DOF of vehicle model is considered. Single wheel vehicle model is shown in Fig.2.

Longitudinal motion equation

$$\frac{1}{4}m\dot{v} = -F_x \quad (1)$$

Rotary motion equation

$$J_\omega \dot{\omega} = M - F_x R \quad (2)$$

adhesive force

$$F_x = u_x F_z \quad (3)$$

where m is the vehicle mass, $\dot{v}$ is the acceleration, F_x is the adhesive force, R is the rolling radius, u_x is the adhesion coefficient, J_w is the rotational inertia, ω is the angular velocity, F_z is the normal reaction, M is the braking torque.

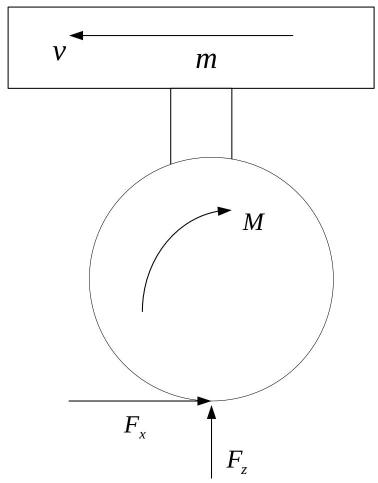

Fig. 2. Single wheel vehicle model.

3.2. Tire Model

Tyre model is simplified as follows:

if $S \le S_t$,

$$u_x = \frac{u_b}{S_t} \times S \quad (4)$$

if $S > S_t$,

$$u_x = \frac{u_b - u_g \times s_t}{1 - S_t} - \frac{u_b - u_g}{1 - S_t} \times s \quad (5)$$

where u_x is the longitudinal adhesion coefficient, S is the slip ratio, u_b is the peak adhesion coefficient, u_g is the sliding adhesion coefficient, S_t is the slip ratio corresponding to peak adhesion coefficient.

3.3. Brake Model

Brake model consists of giant-magnetostrictive actuator model, H type compliant mechanism model and brake disc model. Brake model takes output voltage that is coming from electronic control unit as input variable and takes break torque as output variable. Sub-system model is established as follows.

3.4. Giant-magnetostrictive Actuator Model

GMM actuator displacement output characteristic refers to the relationship between input current and output displacement. Under the condition of considering thermal deformation, GMM rod axial magnetostriction constitutive equation as follows:

$$\varepsilon_3 = s_{33}^H \sigma_3 + d_{33} H_3 + \alpha_{33} \Delta T , \tag{6}$$

$$B_3 = d_{33} \sigma_3 + u_{33}^{\sigma} H_3 , \tag{7}$$

where ε_3 is the axial strain, s_{33}^H is the longitudinal flexibility coefficient at constant magnetic field, σ_3 is the axial stress, d_{33} is the axial dynamic magnetostrictive coefficient, H_3 is the average driving magnetic field strength, α_{33} is the coefficient of thermal expansion, B_3 is the magnetic strength, u_{33}^{σ} is the magnetic permeability at constant compressive stress, ΔT is the temperature rise.

GMM actuator output force f is equal to the product of axial stress and the equivalent sectional area. Output force f shows as follows.

$$\begin{aligned} f = -A_3 \sigma_3 = \frac{-A_3}{S_{33}^H} \{ \frac{\Delta l}{l_3} - \alpha_{33} \Delta T - \\ d_{33} [(NI)_{actu} / (u_3 A_3 \sum_{i=1}^{3} R_{Mi}) + H_{bias}]\} \end{aligned} , \tag{8}$$

where A_i is the equivalent sectional area, I is the exciting current, N is the number of turns, φ_i is the magnetic flux, l_i is the length of a magnetic pat, u_i is the material permeability, R_{Mi} is the magnetic resistance, H_{bias} is the bias magnetic field strength. Subscript i = 1, 2, 3, respectively stands for ferromagnetic material, air gap and GMM rod.

If other parameters are determined, actuator output force f is only relevant to input current I and GMM rod strain $\Delta l / l_3$. If Δl =0, the biggest potential output force of GMM rod can be calculated as follows.

$$\begin{aligned} f_{\max} = \frac{A_3}{S_{33}^H} \{ \alpha_{33} \Delta T + d_{33} [(NI)_{actu} / \\ (u_3 A_3 \sum_{i=1}^{3} R_{Mi}) + H_{bias}]\} \end{aligned} , \tag{9}$$

Formulas (8), (9) express the relationship of static function between input current and the GMM actuator output force. Because the GMM rod usually maintains expansion amount near the largest displacement during braking process, maximum displacement ($\Delta l = 280\,\mu m$) is adopted during debugging process.

3.5. H Type Compliant Mechanism Model

According to the mechanism design, unilateral brake disc compression force F_0 shows as follows.

$$F_0 = 1/2 f , \tag{10}$$

where F_0 is the unilateral brake disc compression force.

3.6. Brake Disc Model

Assume that the surface between brake disc and friction plate ideally contacts and contact pressure distribution is uniform, braking torque M can be calculated as follows.

$$M = 2 f' F_0 r , \tag{11}$$

where M is the braking torque, f' is the coefficient of friction, r is the brake disc radius.

According to formulas of (8), (10), (11), the whole system brake model shows as follows.

$$\begin{aligned} M = \frac{-f' A_3 r}{S_{33}^H} \{ \frac{\Delta l}{l_3} - \alpha_{33} \Delta T - d_{33} [(NI)_{actu} / \\ (u_3 A_3 \sum_{i=1}^{3} R_{Mi}) + H_{bias}]\} \end{aligned} \tag{12}$$

4. Simulation and Results Analysis

Under Matlab/Simulink software environment, on the basis of establishing subsystem model, the overall simulation model is shown in Fig. 3. The initial speed and optimal slip ratio are selected as input signals. Wheel speed, braking distance, vehicle speed and actual slip ratio are selected as output signals.

Vehicle initial speed is 27.8 *m/s* (100 *km/h*). The car brake on the drying of concrete pavement.

Parameters and values we used are shown in Table 1 (Appendix). The simulation results are shown in Fig. 4 ~ Fig. 7. Fig. 4 shows that vehicle speed and wheel speed change more smoothly in the process of brake. Slope of each curve is deceleration. We can know that vehicle deceleration and wheel angular velocity are both constant values according to Fig. 4, so braking force is constant value. Compared with traditional hydraulic braking system, H type brake by wire system more smoothly in the process of brake. Riding comfort can be significantly improved during brake process.

Fig. 5 shows that slip ratio is maintained nearby optimal slip ratio ($s = 0.2$). Coefficient of road adhesion can be fully used. Compared with traditional hydraulic braking system, amplitude of slip ratio fluctuates smaller.

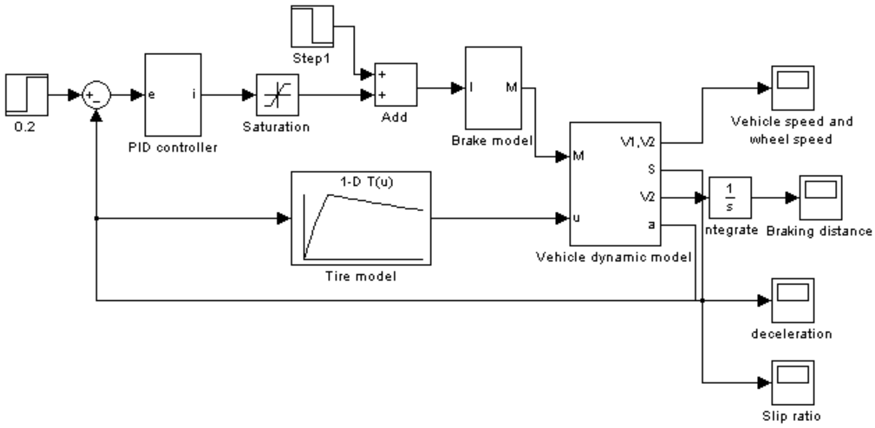

Fig. 3. Simulation model.

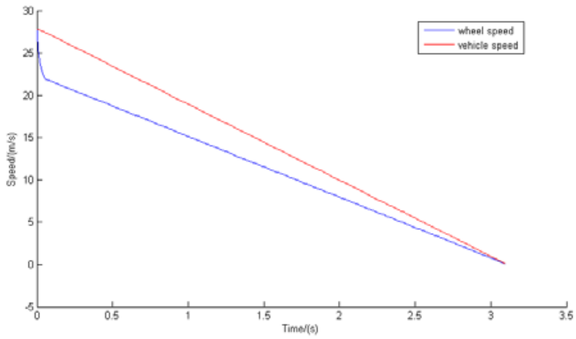

Fig. 4. Simulation curve of vehicle speed and wheel speed.

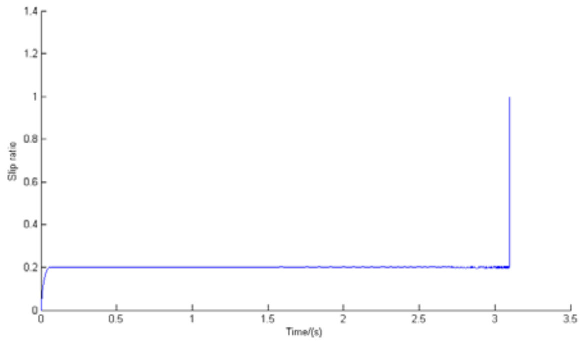

Fig. 5. Simulation curve of slip ratio.

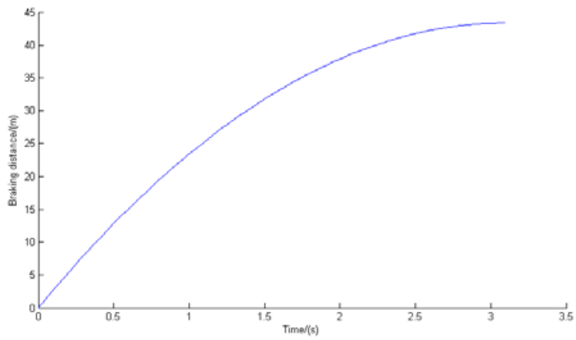

Fig. 6. Simulation curve of braking distance.

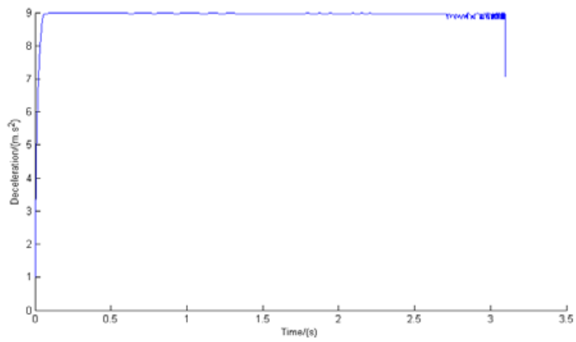

Fig. 7. Simulation curve of braking deceleration.

Fig. 6 shows that braking distance is 43.4 *m*, braking distance is shortened about 2.64 *m* (calculated by average deceleration of 8.44 m/s^2). The shortened braking distance is very important when emergency happens. If response time of hydraulic system is considered (calculated by 0.1 second), braking distance of traditional hydraulic braking system will increase 2.784 *m*. H type brake by wire system based on GMM significantly increased the automobile braking performance. Fig. 7 shows that braking deceleration is maintained at around 8.9 m/s^2. Amplitude of braking deceleration fluctuates smaller during whole braking process.

5. Conclusions

1) Compared with traditional hydraulic braking system, H type brake by wire system more smoothly in the process of brake. Riding comfort can be significantly improved during brake process.

2) H type brake by wire system based on GMM significantly increased the automobile braking performance.

3) H type brake by wire system based on GMM provides a new idea for researching automobile brake by wire system.

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Appendix

Table 1. Parameters and values.

Parameters	Parameter values/unit	Parameters	Parameter values/unit
Vehicle mass	1140 (kg)	Magnetic field strength	0~80 (KA/M)
Initial speed	27.8 (m/s)	GMM rod load	0~2000 (N)
Rolling radius	0.416 (m)	Number of turns	1350 (turns)
Rotational inertia	1.2 ($kg \cdot m^2$)	Peak adhesion coefficient	0.9 (None)
Gravitational acceleration	9.8 (m/s^2)	Bias magnetic field strength	20000 (H)
Coefficient of friction	0.256 (None)	GMM rod Under Pressure	200~700 (MPa)
Brake disc radius	0.125 (m)	GMM rod maximum stroke	280 (μm)
Optimal slip ratio	0.2 (None)	GMM rod size	Φ20*50 (mm*mm)
Giant-magnetostrictive rate	0.04×10^{-6} (m/A)	Flexure hinge minimum thickness	3.5 (mm)
Young modulus	(2.5~3.5) $\times10^{10}$ (N/m^2)	Magnetic permeability	3~15 (None)
Coefficient of thermal expansion	8×10^{6} (1/°C)	Leverage ratio of compliant mechanisms	1:2 (None)
The Curie temperature	380 (°C)	Sliding adhesion coefficient	0.7 (None)

References

[1]. Li Jing, Zhang Jian, Yang Kun, Development of ECU software and hardware in the loop simulation for stability control of vehicle with electro mechanical brake, *Journal of Jilin University (Engineering and Technology Edition)*, Vol. 41, No. 4, 2011, pp. 893-897.

[2]. Yang Kun, Li Jing, Li Youde, Study of EBD/ABS based on electromechanical brake system, *Journal of System Simulation*, Vol. 21, No. 6, 2009, pp. 1785-1788.

[3]. Yang Kun, Li Jing, Guo Lishu, Design and simulation of electromechanical brake system, *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 39, No. 8, 2008, pp. 24-27.

[4]. A. Hildebrandt, O. Sawodny, R. Trutschel, K. Augsburg, Nonlinear control design for implementation of specific pedal feeling in brake-by-wire car design concepts, in *Proceedings of the American Control Conference*, Vol. 2, 2004, pp. 1463-1468.

[5]. A. M. Harsha, S. Abeykoon, K. Ohnishi, Implementation of pedal feeling for brake by wire system using bilateral control, in *Proceedings of the IEEE International Symposium on Industrial Electronics*, 2008, pp. 1347-1352.

[6]. Sohel Anwar, Anti-lock braking control of a hybrid brake by wire system, *Institutions of Mechanical Engineers, IMechE Proceedings,* 2006, Vol. 220, pp. 1101-1117.

[7]. W. Xiang, P. C. Richardson, C. Zhao, S. Mohammad, Automobile brake-by-wire control system design and analysis, *IEEE Transactions on Vehicular Technology*, Vol. 57, Issue 1, January 2008, pp. 138-145.

[8]. P. Krishnamurthy, W. Lu, F. Khorrami, A. Keyhani, A robust force controller for an SRM based electromechanical brake system. *Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference,* 2005, pp.2006-2011.

[9]. M. Roberts, T. Chhaya, An approach to the safety design and development of a brake by wire control system, in *Proceedings of the SAE World Congress and Exhibition,* 2011.