Cam-actuated Brake Pedal Controller Design Using Fuzzy Logic and Pedal Force Adaptation for Autonomous Vehicles

Jiwon Oh, Korea Advanced Institute of Science and Technology
Seibum Choi, Korea Advanced Institute of Science and Technology
Sangyol Yoon, Korea Advanced Institute of Science and Technology
Unghui Lee, Korea Advanced Institute of Science and Technology
D. Hyunchul Shim, Korea Advanced Institute of Science and Technology

School of Mechanical Aerospace & Systems Engineering,
Division of Mechanical Engineering, Korea Advanced Institute of Science and Technology,
291 Daehak-ro(373-1 Guseong-dong), Yuseong-gu, Daejeon, 305-701,Republic of Korea
Phone: (82)42-350-4160
Fax: (82)42-350-4110
E-mail: jwo@kaist.ac.kr

This paper proposes the cam-actuated brake pedal system and its controller applied for the autonomous vehicle velocity tracking. Using the vehicle speed information from vehicle CAN and the desired vehicle velocity, fuzzy logic controller generates the desired brake pedal angle. Tracking this value is done by controlling the motor through brake pedal force adaptation to counter the extremely nonlinear nature of the automotive brake system, and by using the cam angle given by an encoder. The integrated brake controller performance is tested both with using CarSim, a well-known vehicle simulation tool, and an actual autonomous vehicle with the proposed system mounted.

Vehicle Dynamics, Modeling and Simulation, Integrated Chassis Control, Intelligent Transportation Systems

1. INTRODUCTION

For the given desired velocity, accurate and fast tracking control of the autonomous vehicle velocity is crucial for its reliability and safety. The importance of the tracking ability is amplified when it comes to braking, since nearly all cases of emergency involve sudden reduction in velocity.

In addition, accurate longitudinal speed tracking may be crucial in the areas other than autonomous vehicle development as well, such as ACC (adaptive cruise control), ROM (roll over mitigation), and highway platoon control. This is known to require a complex modeling of the brake system, or a risky assumption of disregarding the nonlinearity involved in the relationship between the control input and the vehicle velocity. Such requirements have served obstacles in the previous efforts to develop a wholly satisfactory vehicle velocity tracking algorithm .[1)-5)]

The paper proposes a motor-driven cam-type actuator so that the rotational motion of the motor can be directly engaged in pressing the pedal. Such system is particularly suited to vehicle pedal control, since it produces swift motion, provides flexibility for additional human input in case of emergency, and takes up less space than other types of actuators. Another main contribution of this study is the separation of the desired brake angle generation and the desired angle tracking control, which gives fairly robust vehicle velocity tracking while braking without having to use the pre-defined complex relationship between the pedal angle and the vehicle motion.

The basic structure of the paper is as follows. Section 2 deals with the brake controller design, that consists of the fuzzy logic described in section 2.1 which generates the desired brake angle generation, followed by modeling of the actuator system described in section 2.2 which enables the calculation of feedforward control input. Also, section 2.3 focuses on designing the lower level controller for tracking the desired brake angle using an adaptive scheme. Section 3 presents the simulation and actual vehicle-based test results to validate the suggested algorithm.

2. BRAKE CONTROLLER DESIGN

2.1 Desired Cam Angle Generation

In order to eliminate the need for complex modeling of the relationship between the brake pedal input and the actual braking force that decelerates the vehicle so that the control scheme can be applied to any general environment, a fuzzy logic controller is designed which generates the desired cam angle generation.

Shown in table 1 are the fuzzy rules for generating the desired brake angle. The first input for the fuzzy system is the difference between the desired and current velocity, $v_{ref} - v_{car}$, and it consists of five categories: too slow, slower, tracking right, faster, and too fast, shortened as TS, SR, TR, FR, and TF, respectively.

Table 1 Fuzzy rules for desired brake angle generation

		V_{ref}		
		ST: 0	CR: 3	DR: 10
$V_{ref} - V_{car}$	TS: 10	FB	NB	NB
	SR: 5	FB	NB	NB
	TR: 0	MB	LB	NB
	FR: -5	FB	MB	MB
	TF: -10	FB	FB	FB

As the second input, the target velocity v_{ref} is divided into three categories: stop, creep, and drive, abbreviated as ST, CR, and DR, respectively. The output variable consists of four fuzzy membership functions: no brake, low brake, medium brake, and full brake, shown in the table as NB, LB, MB, and FB, respectively.

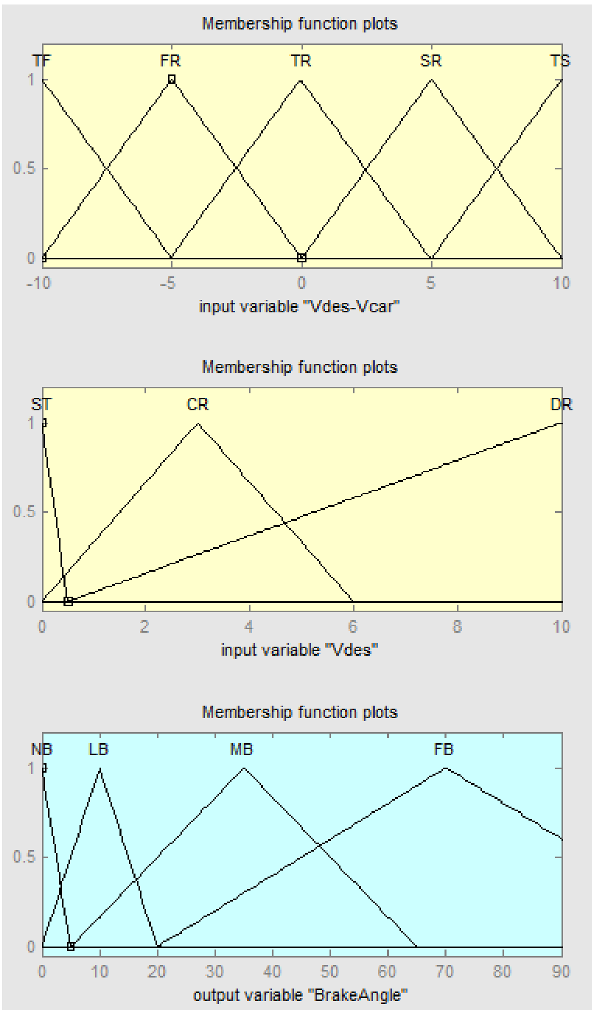

Fig. 2 Fuzzy membership functions of the input and output variables

The shapes of the mentioned membership functions are shown in fig. 2.

To display the characteristic of the designed fuzzy logic system, the resulting fuzzy surface is shown in fig. 3.

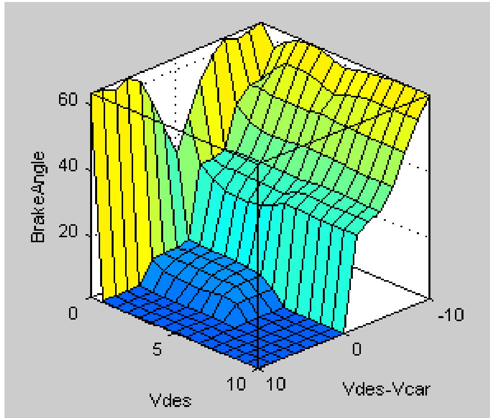

Fig. 3 Resulting fuzzy surface for desired brake angle generation

2.2 System Modeling

The cam actuator is modeled as shown in fig. 4. Through modeling the system, we earn two benefits: convenience of being able to verify the controller effectiveness using the model, and opportunity to directly use the model in designing the controller.

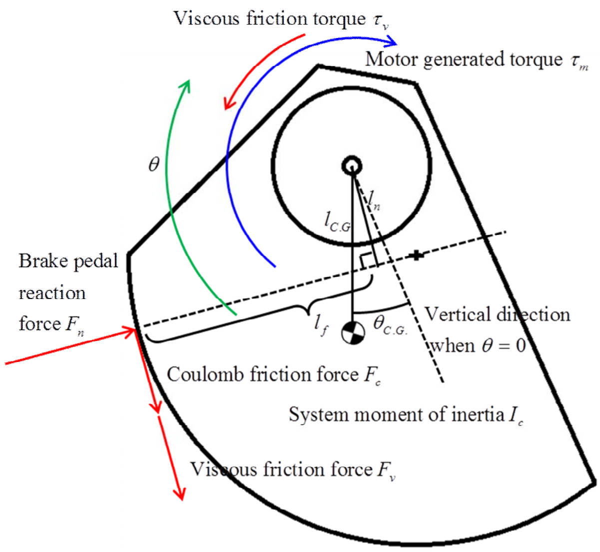

Fig. 4 Cam actuator modeling

The following equation is obtained through the moment balance relationship based on the forces and torques acting on the cam.

$$I_c \ddot{\theta} = \tau_m - \tau_{normal} - \tau_{friction} - \tau_v - \tau_g \quad (1)$$

τ_m, τ_{normal}, $\tau_{friction}$, τ_v, and τ_g represent the motor torque, load torque from the pedal reaction force, coulomb and viscous friction forces, viscous friction torque, and gravity load torque, respectively. These are modeled as shown from (2) to (5).

$$\tau_{normal} = F_n l_n \tag{2}$$

$$\begin{aligned}\tau_{friction} &= F_c l_f \operatorname{sgn}\left(\dot{\theta}\right) + F_v l_f \\ &= F_n \mu_{coul} l_f \operatorname{sgn}\left(\dot{\theta}\right) + F_n \mu_{visc} l_f \dot{\theta}\end{aligned} \tag{3}$$

$$\tau_v = b\dot{\theta} \tag{4}$$

$$\tau_g = mgl_{C.G.} \sin\left(\theta + \theta_{C.G.}\right) \tag{5}$$

Substituting each load into (1) leads to the following model shown in (6).

$$\begin{aligned}I_c\ddot{\theta} &= \tau_m - F_n l_n - \left(F_c l_f \operatorname{sgn}\left(\dot{\theta}\right) + F_v l_f\right) \\ &\quad - b\dot{\theta} - mgl_{C.G.} \sin\left(\theta + \theta_{C.G.}\right) \\ &= \tau_m - F_n\left(l_n + \mu_{coul} l_f \operatorname{sgn}\left(\dot{\theta}\right) + \mu_{visc} l_f \dot{\theta}\right) \\ &\quad - b\dot{\theta} - mgl_{C.G.} \sin\left(\theta + \theta_{C.G.}\right)\end{aligned} \tag{6}$$

To verify the modeling accuracy, model of the cam actuator system is compared to the actual system mounted on the vehicle. This is done by recording the cam behavior while providing certain sets of PWM input to the motor. The outcome is then compared with that obtained by the model when it is given the identical set of PWM input. The result displayed in fig. 5 shows that the steady state cam angles of the model coincide with those of the actual system with fairly high accuracy.

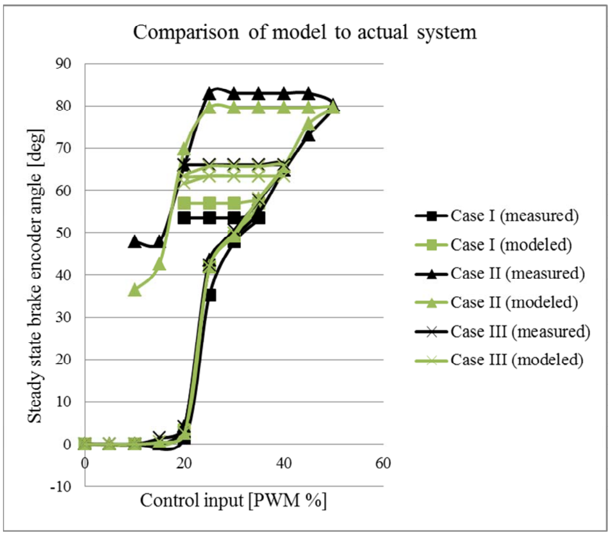

Fig. 5 Modeling verification result

2.3 Desired Cam Angle Tracking Controller Design

For tracking the desired brake angle generated by the fuzzy system, the tracking controller must be designed. A block diagram representing the basic structure of the controller is shown in fig. 6.

From the controller's viewpoint, unknown variables in the model serve difficulty for high performance. Notice in (6) , however, that the only unknown variable is F_n and others like μ_{coul}, μ_{visc}, and b can be considered tuning constants, since their variations can be assumed small compared to F_n. Regarding such background, an adaptive scheme applied to F_n seems favorable for the sake of increasing controller performance.

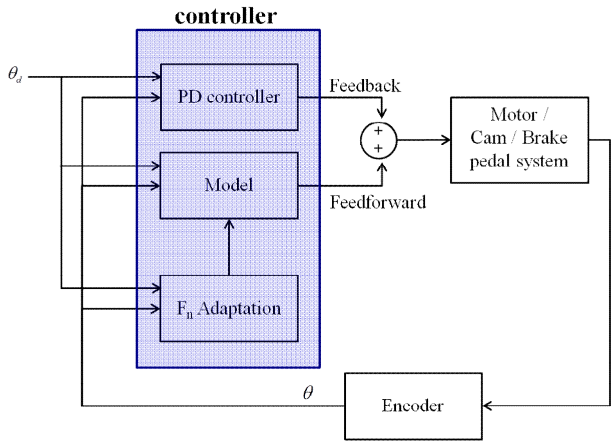

Fig. 6 Block diagram of the cam angle tracking controller

Before applying the adaptive scheme, the reverse design approach for feedback control is considered.

$$\text{Let } \gamma = l_n + \mu_{coul} l_f \operatorname{sgn}\left(\dot{\theta}\right) + \mu_{visc} l_f \dot{\theta} \tag{7}$$

This simplifies (6) to the following.

$$I_c\ddot{\theta} = \tau_m - F_n\gamma - b\dot{\theta} \tag{8}$$

where τ_m is the control input. Now let $s = \theta - \theta_d$. For the reverse design approach, we want to satisfy the following.

$$\ddot{s} + 2\lambda'\dot{s} + \lambda'^2 s = 0 \tag{9}$$

Assuming that the estimated reaction force, $\hat{F}_n$, is available, the following is reached.

$$\begin{aligned}\ddot{s} &= \ddot{\theta} - \ddot{\theta}_d \\ &= -\frac{\hat{F}_n}{I_c}\gamma + \frac{\tau_m - b\dot{\theta}}{I_c} - \ddot{\theta}_d + 2\lambda'\dot{s} + \lambda'^2 s \equiv 0\end{aligned} \tag{10}$$

$$\Rightarrow -\hat{F}_n\gamma + \tau_m - b\dot{\theta} - I_c\ddot{\theta}_d + 2\lambda\dot{s} + \lambda^2 s = 0 \tag{11}$$

$$\begin{aligned}\Rightarrow \quad \tau_m &= \hat{F}_n\gamma + b\dot{\theta} + I_c\ddot{\theta}_d \\ &\quad - 2\lambda\left(\dot{\theta} - \dot{\theta}_d\right) - \lambda^2\left(\theta - \theta_d\right)\end{aligned} \tag{12}$$

Substituting the control input (12) into the model in (8) gives the following.

$$\begin{aligned}I_c\ddot{\theta} &= -\left(F_n - \hat{F}_n\right)\gamma + I_c\ddot{\theta}_d \\ &\quad - 2\lambda\left(\dot{\theta} - \dot{\theta}_d\right) - \lambda^2\left(\theta - \theta_d\right)\end{aligned} \tag{13}$$

$$\begin{aligned}\Rightarrow I_c\left(\ddot{\theta} - \ddot{\theta}_d\right) &= -\left(F_n - \hat{F}_n\right)\gamma \\ &\quad - 2\lambda\left(\dot{\theta} - \dot{\theta}_d\right) - \lambda^2\left(\theta - \theta_d\right)\end{aligned} \tag{14}$$

$$\Rightarrow \ddot{s} = -\left(F_n - \hat{F}_n\right)\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s} - \frac{\lambda^2}{I_c}s \qquad (15)$$

Here, to decrease the burden on adaptation, F_n may be divided into the nominal and unknown parts, and perform adaptation only on the unknown part. The nominal part is obtained from the toughly known shape of the pedal reaction force plot versus pedal travel. Let $\xi = F_n - F_n^*$, and $\hat{\xi} = \hat{F}_n - F_n^*$, with $\tilde{\xi} = \xi - \hat{\xi}$. Then (15) becomes the following.

$$\begin{aligned}\ddot{s} &= -\left(F_n - \left(F_n^* + \hat{\xi}\right)\right)\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s} - \frac{\lambda^2}{I_c}s \\ &= -\left(\xi - \hat{\xi}\right)\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s} - \frac{\lambda^2}{I_c}s \\ &= -\tilde{\xi}\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s} - \frac{\lambda^2}{I_c}s\end{aligned} \qquad (16)$$

In order to prove the stability, Lyapunov approach is used. A radially unbounded, decrescent, and positive definite Lyapunov candidate function is chosen as shown in (17).

$$V = \frac{\lambda^2}{2I_c}s^2 + \frac{1}{2}\dot{s}^2 + \frac{1}{2k_a}\tilde{\xi}^2 \qquad (17)$$

Assuming that ξ is slowly varying, taking derivative of (17) leads to the following results.

$$\begin{aligned}\dot{V} &= \frac{\lambda^2}{I_c}s\dot{s} + \dot{s}\ddot{s} - \frac{1}{k_a}\tilde{\xi}\dot{\hat{\xi}} \\ &= \frac{\lambda^2}{I_c}s\dot{s} + \dot{s}\left(-\tilde{\xi}\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s} - \frac{\lambda^2}{I_c}s\right) - \frac{1}{k_a}\tilde{\xi}\dot{\hat{\xi}} \\ &= \cancel{\frac{\lambda^2}{I_c}s\dot{s}} - \dot{s}\tilde{\xi}\frac{\gamma}{I_c} - \frac{2\lambda}{I_c}\dot{s}^2 - \cancel{\frac{\lambda^2}{I_c}s\dot{s}} - \frac{1}{k_a}\tilde{\xi}\dot{\hat{\xi}} \\ &= -\frac{2\lambda}{I_c}\dot{s}^2 + \tilde{\xi}\left(-\dot{s}\frac{\gamma}{I_c} - \frac{1}{k_a}\dot{\hat{\xi}}\right)\end{aligned} \qquad (18)$$

To satisfy the stability condition the adaptive law is chosen to be the following.

$$\dot{\hat{\xi}} = -k_a\frac{\gamma}{I_c}\dot{s} = -k_a\frac{\gamma}{I_c}\left(\dot{\theta} - \dot{\theta}_d\right) \qquad (19)$$

3. VERIFICATION

3.1 Simulation Results

With simulation based on the designed model, the tracking performance of the cam-type actuator controller is tested.

The first case is when the desired brake angle forms a sinusoidal wave. The tracking results and the errors are plotted in fig. 7 in which the performance of the suggested algorithm is compared to that of a simple feedback controller.

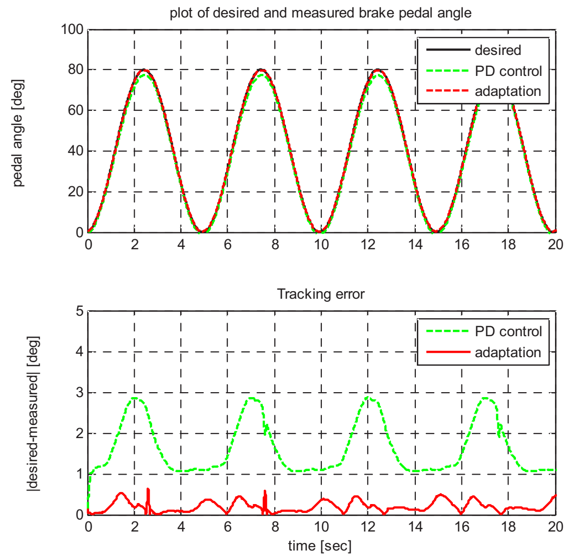

Fig. 7 Tracking control simulation result with sinusoidal wave reference

The following result shown in fig. 8 presents the tracking performance in case of varying step input. The results show that the proposed cam angle tracking controller performs with higher accuracy than the feedback controller.

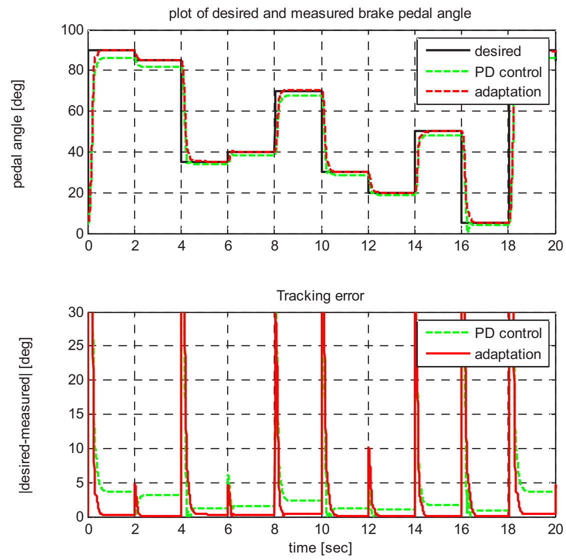

Fig. 8 Tracking control simulation result with varying step reference

3.2 Actual Test Results

Validation of the algorithm as a whole is done using an actual vehicle with the cam actuator mounted. Shown in fig. 9 are the results of the vehicle velocity tracking tests. The acceleration pedal is controlled with the system described in previous work[10].

The test consists of three sets of vehicle deceleration: 30 to 0, 40 to 10, and 30 to 20 to 10 km/h. It can be seen that the vehicle accurately and quickly respond to the given reference to track the desired velocity. Compared with the simulation results, the actual brake angle tracking performance seems decreased. This is accounted by the unmodeled static friction property in the motor and inaccurate input generation by the motor driver. Despite the limitations, the fuzzy logic and the tracking controller harmoniously work together to guarantee robust velocity tracking performance.

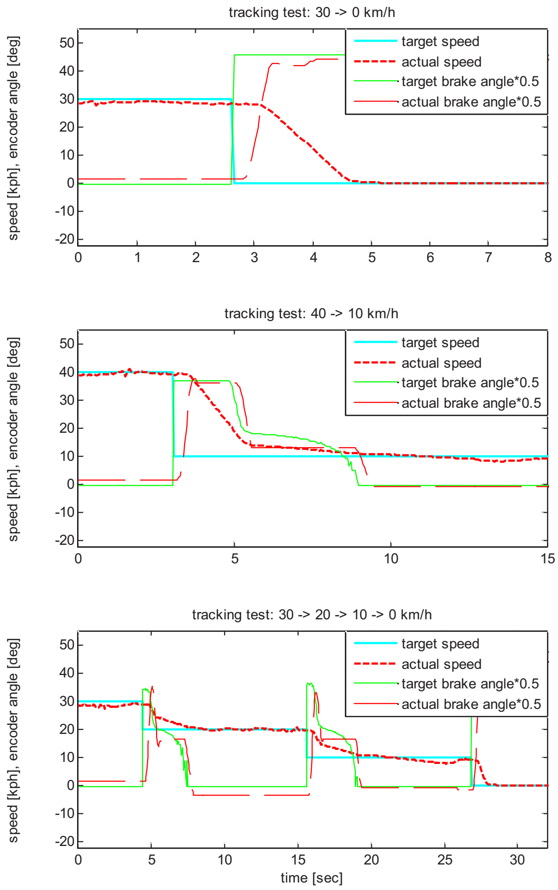

Fig. 9 Vehicle velocity tracking test results

4. CONCLUSION

With a unique type of actuator that uses a motor-cam system to press the brake pedal, fast and reliable vehicle velocity tracking performance is reached through the suggested algorithm. This contribution saves space for the hardware, and gives freedom to install the actuator system onto the existing production vehicles. Another contribution of this work is that the controller does not require a complex map of the brake system, and this advantage is obtained through the use of fuzzy system and the brake pedal force adaptation.

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