

Power Assisted Braking Control Based on a Novel Mechatronic Booster

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ABSTRACT

This paper presents a power assisted braking control based on a novel mechatronic booster system. A brake pedal feel control unit is first discussed which includes a pedal emulator with an angular sensor to detect driver's pedal travel, a signal processing module with a Kalman filter for sensor signal conditioning, and a driver braking intention detection and behavior recognition module based on the displacement and velocity of the pedal travel. A power assisted braking control is then presented as the core of the system which consists of controls on basic power assist, velocity compensation and friction compensation. The friction is estimated based on a generic algorithm offline. A motor controller is designed to provide the desired torque for the power assist. Finally, a novel mechatronic booster system is designed and built with an experimental platform set up with a widely adopted rapid prototype system using dSPACE products, such as MicroAutoBox, RapidPro, etc. Extensive experiments have been conducted which demonstrate the validity and effectiveness of the proposed control for the power assisted braking system.

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INTRODUCTION

Vacuum booster is still widely used in conventional vehicles, in which the vacuum source is usually generated by intake manifold of the engine or a vacuum pump. However, there is rapid growth of electric vehicles in the market [1]. For pure electric vehicles the conventional vacuum source is no longer available because there is no engine. A vacuum generator, such as the electric vacuum pump with vacuum tank, or a brake booster system becomes necessary.

Although vacuum generator, such as the electric vacuum pump with vacuum tank, has the advantages of low cost, high efficiency, light weight, etc., and can effectively provide stable vacuum source for brake assist, their disadvantages or deficiencies are apparent. In case of continuous and frequent braking, it may lose power assisted braking since a longer time is needed to establish the vacuum, and a larger active braking force is hard to achieve by vacuum booster. In some cases, the vehicle braking performance may deteriorate caused by vacuum booster contaminated, as the lubricating oil exists inside of the vacuum pump.

A great deal of research has been found from the literature on brake booster. Yasuo Konishi et al. developed a new hydraulic brake actuator for active brake control systems [2]. The new hydraulic brake actuator is composed of hydraulic brake booster unit, a power supply unit and a control valve unit. Kurokawa et al. developed a new hydraulic brake booster with much reduced weight and size [3], in addition to improvement on base braking performance and vehicle dynamics control. Yeo, et al. built a smart booster system [4], which used a permanent magnet synchronous motor to replace the conventional vacuum booster. Two types of smart booster systems

were investigated for different applications, and the samples of both types of smart booster systems were built to validate the feasibility of the proposed systems. A brake booster system called iBooster has also been developed by Bosch. As the core of automatic driving technologies, the brake pressurization rate of iBooster is three times of the conventional braking system. As a brake booster system with mechanical and electrical integration, the active braking can be easily realized using iBooster. An extra brake pressure can be applied with iBooster in case of emergency braking, or lack of drag torque while RBS (Regenerative Braking System) working, for hybrid or electric vehicles [5].

However, those brake boosters mentioned above have more complex structure and higher cost. This paper presents a novel mechatronic booster, which has a more compact structure and lower cost, as shown in Fig 1. Besides, this novel booster has a flexible application form, as shown in Fig 2 (a) and (b), respectively. Then a power assisted braking control strategy for pedal force is proposed based on the novel brake booster system, which contains a signal processing module, a driver braking behavior recognition based on the displacement and velocity of the push rod, a brake power assistance control module, which is the core part of the power assisted braking control, composed of the basic power assisted braking control, velocity compensation control, friction compensation control, etc., and a motor controller, which is used for the realization of the desired torque.

Then, an experiment platform is built with the mechatronic booster brake system and the products of dSPACE, such as MicroAutoBox, RapidPro, and extensive experiments have been conducted, which demonstrate the validity and effectiveness of the proposed control strategy for the pedal force.

DESCRIPTION AND CONTROL STRUCTURE OF THE NOVEL MECHATRONIC BOOSTER

In this paper, the mechatronic booster brake system mainly includes the brake pedal, push rod, the mechatronic booster, the master cylinder, etc., as shown in Fig 1. An angle sensor of the brake pedal, an angle sensor and current sensor of the motor are included in the brake system. The mechatronic booster is composed of the motor, worm gear and worm, gear-rack, etc. In Fig 2, structure (a) could meet most requirements of a brake system such as power assisted braking, active braking, etc. While structure (b) could achieve brake energy recovery in small pedal displacement because of the idle stroke between rack and push rod. This paper mainly studies on structure (a) for power assisted braking control.

The mechatronic booster, which is driven by motor directly, has the advantages of fast response, variable power assistance ratio, compact structure, etc. Compared with the conventional vacuum booster, the mechatronic booster is more suitable for EVs and other new energy vehicles which can avoid the problems of vacuum booster effectively, such as lack of brake power in the case of continuous and frequent braking.

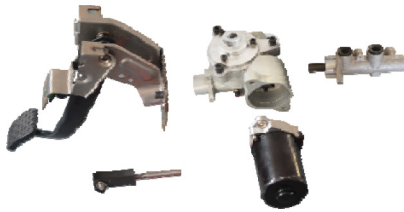


Figure 1. The novel mechatronic booster brake system.

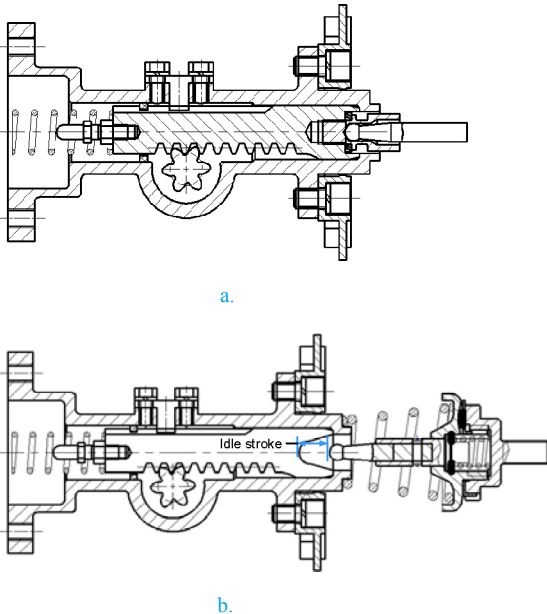


Figure 2. The structure diagram of the mechatronic booster.

The structure of the power assisted braking control for pedal force mainly contains a signal processing module, a driver braking behavior recognition based on the displacement and velocity of the push rod, a brake power assistance control module which is the core

part of the power assisted braking control, and a motor controller used for the realization of the desired torque. The signal processing module is used for the angle sensor filtering, and then outputs the displacement, velocity of the push rod, etc. The driver braking behavior recognition module is used for the judgment of emergency braking, normal braking, and the braking state (depressing, holding, releasing). The brake power assistance control module is to determine the desired control torque (desired current of motor), based on the sensor signal and the driver braking behavior. The motor control module is used for the realization of the desired torque, and then a good brake feel can be ensured.

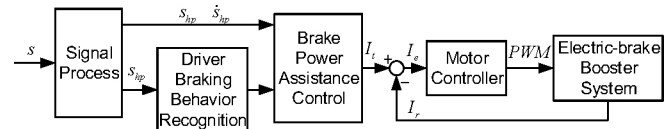


Figure 3. The control structure of the novel mechatronic booster brake system.

SIGNAL PROCESSING

Kalman filter was proposed in 1960 by R.E.Kalman, one of the founders of modern control theory. It is a kind of highly efficient recursive filter (autoregressive filter), which has low requirements on computation and memory, thus it can be implemented in real-time on computers. The method can deal with many problems, such as non-stationary random process filtering, time varying system filtering, system signal or state estimation. Therefore, the pedal angle sensor signal and the motor angle sensor signal are processed with Kalman filter. The pedal angle signal processing is showed here as an example [6, 7].

To facilitate the following application, the pedal angle is converted to the push rod displacement of the pedal, as follows,

$$s = P_{\theta} \cdot R_{ratio} \quad (1)$$

where, s is the displacement of the pedal push rod, P_{θ} is the pedal angle and R_{ratio} is the brake pedal leverage.

Set the push rod displacement as $s(t)$, then according to two-order Taylor expansion, $s(t)$ at moment $t + \Delta t$ can be expressed as:

$$s(t + \Delta t) = s(t) + \Delta t \times \dot{s}(t) + \frac{1}{2} \Delta t^2 \times \ddot{s}(t) + w_1(t) \quad (2)$$

The first order derivative and second order derivative are as follows:

$$\dot{s}(t + \Delta t) = \dot{s}(t) + \Delta t \times \ddot{s}(t) + w_2(t) \quad (3)$$

$$\ddot{s}(t + \Delta t) = \ddot{s}(t) + w_3(t) \quad (4)$$

where, $t + \Delta t$ indicates any moment in the neighborhood of the moment t , and $w_1(t)$, $w_2(t)$ and $w_3(t)$ are the remainders of Taylor expression.

The sampling period of the system is defined as T , then the system state space equation of the Kalman filter can be expressed as:

$$\begin{cases} \mathbf{X}(k+1) = \mathbf{A}\mathbf{X}(k) + \mathbf{W}(k) \\ \mathbf{Y}(k) = \mathbf{H}\mathbf{X}(k) + \mathbf{e}(k) \end{cases}$$

$$\mathbf{A} = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{W}(k) = \begin{bmatrix} w_1(k) \\ w_2(k) \\ w_3(k) \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
(5)

where, $\mathbf{X}(k) = [s(k) \quad \dot{s}(k) \quad \ddot{s}(k)]^T$ is the state vector of the system at moment k , $\mathbf{A}$ is the system matrix, $\mathbf{W}(k)$ is the system noise, $\mathbf{Y}(k)$ is the measurement signal, $\mathbf{H}$ is the signal observation matrix, and $\mathbf{e}(k) = [e_1(k) \quad e_2(k) \quad e_3(k)]^T$ is the noise matrix of signal observation.

The covariance matrix $\mathbf{R}(k)$ of noise matrix $\mathbf{e}(k)$ is a constant positive definite matrix. Since the noise of the displacement signal is large, the diagonal elements of $\mathbf{R}(k)$ should be correspondingly larger.

With the given initial value $\mathbf{X}(0|0)$ and $\mathbf{P}(0|0)$, the optimal state estimation $\mathbf{X}(k|k)$ can be determined with iterative calculation using observed quantity $\mathbf{Y}(k)$.

$$\begin{cases} \mathbf{X}(k|k-1) = \mathbf{A}\mathbf{X}(k-1|k-1) \\ \mathbf{P}(k|k-1) = \mathbf{A}\mathbf{P}(k-1|k-1)\mathbf{A}^T + \mathbf{Q} \\ \mathbf{X}(k|k) = \mathbf{X}(k|k-1) + \mathbf{K}(\mathbf{Y}(k) - \mathbf{H}\mathbf{X}(k|k-1)) \\ \mathbf{K}(k) = \mathbf{P}(k|k-1)\mathbf{H}^T(\mathbf{H}\mathbf{P}(k|k-1)\mathbf{H}^T + \mathbf{R})^{-1} \\ \mathbf{P}(k|k) = (\mathbf{I} - \mathbf{K}(k)\mathbf{H})\mathbf{P}(k|k-1) \end{cases}$$
(6)

where, $\mathbf{X}(k|k)$ is the optimal state estimation of the state vector $\mathbf{X}(k)$, $\mathbf{X}(k|k-1)$ is the predicted value, $\mathbf{P}(k|k)$ is the covariance matrix of the filtering error, $\mathbf{P}(k|k-1)$ is the predicted covariance matrix of the error, $\mathbf{K}(k)$ is the gain coefficient matrix, $\mathbf{Q}$ and $\mathbf{R}$ are the covariance matrices of the system noise $\mathbf{W}(k)$ and the observed noise $\mathbf{e}(k)$, respectively.

DRIVER BRAKING BEHAVIOR RECOGNITION

Scholars have done a lot of research on pattern recognition of the driver's behavior, which mainly based on fuzzy reasoning, neural network or statistics methods (such as hidden Markov method). For braking process, it can be divided into emergency brake, conventional brake and so on.

In this paper, to simplify the braking behavior identify problems, the method of logic threshold is used for the driver braking behavior recognition, and the equation can be expressed as follows:

$$B_{Mode} = \begin{cases} 2, & \dot{s}(t) \geq F_{thresh}(s(t)), s(t) > s_{thresh} \\ 1, & \dot{s}(t) < F_{thresh}(s(t)), s(t) > s_{thresh} \\ 0, & s(t) \leq s_{thresh} \end{cases}$$
(7)

where, $B_{Mode} = 2$ characterize the driver's emergency braking behavior, $B_{Mode} = 1$ characterize the driver's conventional braking behavior, $B_{Mode} = 0$ means no braking is expected, $F_{thresh}(s(t))$ is the velocity threshold function of $s(t)$, it can be obtained through experimental data, and s_{thresh} is free travel of the pedal push rod.

The brake pedal displacement or velocity is needed in the power assisted braking mechanism of this paper to judge current stage of the driver's operation on the brake pedal. The following function shows the correspondence between the flag number and the driver's operation stage, which includes depressing the pedal, holding the pedal and releasing the pedal. It should be noticed that the accuracy of the flag number judgment affects the effect of power assisted braking and the pedal feel, which is more important than the identification of emergency brake or conventional brake.

$$Flag = \begin{cases} 1, & \text{depressing} \\ 0, & \text{holding} \\ -1, & \text{releasing} \end{cases}$$
(8)

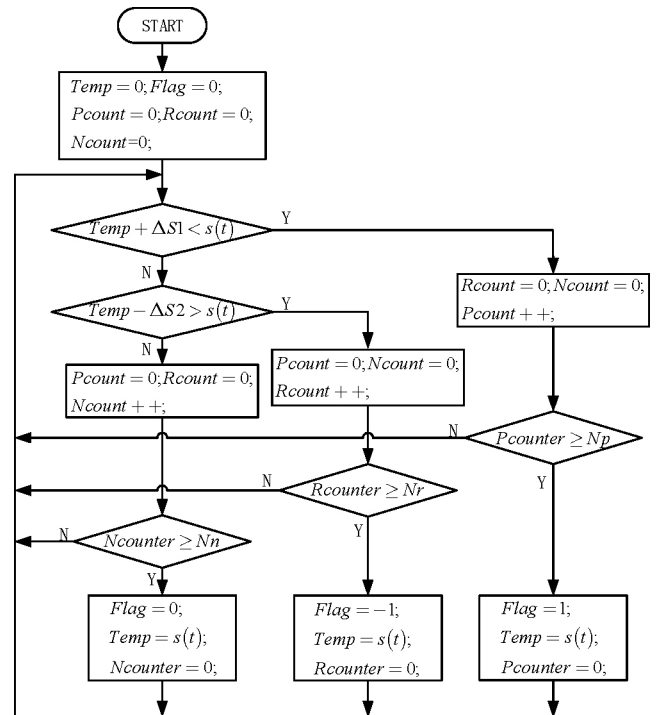


Figure 4. The flow chart for the judgment.

In order to avoid the misjudgment of $Flag$, a method of cumulative judgment is used with the signal of the push rod displacement, and the flow chart is shown as Fig 4. The value of $Flag$ is decided by setting the threshold $\Delta S1$, $\Delta S2$ and the cumulative number Np , Nr , Nn . The misjudgment rate will be smaller with the larger value of $\Delta S1$, $\Delta S2$, Np , Nr , Nn , but the delay time will also be longer. So, in order to ensure the accuracy of the $Flag$ value and a shorter delay time, lots of experiments are needed to determine the values of threshold and cumulative number.