Implementation of Pedal Feeling for Brake by Wire System Using Bilateral Control

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Abstract- **Brake-By-Wire means that the direct mechanical link between brake pedal and braking cylinder is completely replaced by an electromechanical braking system. This concept, originally used for aircraft and military only, has distinct advantages for implementing in new car designs. However brake pedal feeling should be identical to the conventional brake pedal. Ideally, the pedal should behave like a conventional brake. Bilateral control is proposed to be used to for brake by wire system. In conventional brake system, a physical spring is used to move the pedal to its "pedal parking position". In this study, this spring is replaced by a virtual spring. Virtual spring damper model is used within the bilateral control system. Experiment uses a bilateral controlled master slave system. Even though this experiment system is not a brake by wire system, this bilateral system is capable enough to show the applicability of the proposed concept. Braking feeling could be transferred from the slave side to the pedal. Virtual spring behaved identically to a physical spring.**

I. Introduction

Braking literally means the reducing speed of a vehicle. Brakes squeeze against a drum or disc, and the pressure of the squeezing action is what slows down the motion. In precise terms, brake pads or shoes that press against the brake drum or rotor convert that energy into thermal energy. The cooling of the brakes dissipates the heat and the vehicle slows down.

Types of brakes vary from a simple brake that is used in a bicycle to a complex braking system in a modern vehicle. Main different types depend on how the riders braking intension is carried to the brake actuator and how the friction is applied to the rotating wheel.

Typical type of brake uses hydraulics to connect the user signal to the brake actuator. This is the most popular type used for braking and it is widely used in automobiles. This single-circuit hydraulic systems have three basic components - the master cylinder, the slave cylinder and the reservoir. They are joined together with hydraulic hose and filled with a non-compressible hydraulic fluid. When the brake pedal is pressed, small piston assembly in the master cylinder is moved. Because the brake fluid does not compress, that pressure is instantaneously transferred through the hydraulic brake line to the slave cylinder where it acts on another piston assembly, pushing it out. That slave assembly is either connected to a lever to activate the brakes, or more commonly, is the brake caliper itself. Because of the arrangement of the slave cylinder, heat from the brakes can be transferred back into the brake fluid. Even though this conventional method has been used for decades, it has some inherent disadvantages.

A. Brake By Wire

Brake-by-wire system separates the pedal and the brake actuators using an electrical signal. As the name suggests the separation is by a wire. This Technology, transmits drivers braking intension by wire rather than mechanically or hydraulically as in the conventional case.

A still similar system is not commercialized. Reliability of the electronic system may be questionable. However brake by wire systems has the potential of entering to the market due to its technical merits.

The vibrations, which normally occur through the brake pedal when ABS intervenes, can be eliminated as the actuators are matched to the input using a wire. Electronics is much reliable if designed properly than in the conventional case. If one brake horse is broken the total brake system would be lost in the conventional case. But where as in the brake by wire system, each wheel is controlled separately which improves the reliability of the system.

Assistance functions like Anti Blocking Systems, Brake Assistants and Electronic Stability Programs can be realized by changing software. Advanced traction control mechanisms can be incorporated easily with the brake by wire option. Different automakers would be able to customize the "brake feeling" according to the design. Accordingly automaker can make the brake be felt as "soft" or "hard".

B. Brake by wire system as a Bilateral control system

As the word "bilateral" literally means, bilateral control is about controlling bilaterally. Slave side is controlled through the position and force information from the master side and the master side is controlled by the position and force information from the slave side. Therefore, this system enables the slave side environment to be reflected in the master side and master side operating intention reflected in the slave side.

In a Brake by wire system, braking intension should be transferred from the pedal to the actuator. Braking should be felt back to the driver using the pedal. Usually power assist function should be in action to assist the driver for controlling the pedal. If bilateral system is used above functionalities can be easily incorporated to brake by wire system. Power assist function is possible with power scaling [5] in bilateral control. In this study, no force sensors are used [4] [5] as they are costly and they add noise to the system. Reaction torque observer is used instead. Reaction torque observer is capable of transmitting vivid sensation from the slave side to the master side. Unfortunately Bilateral control system is not used in brake by wire systems [1] [2] [3]. In this study bilateral control system is proposed to be used for brake by wire system.

In some experiments [1], both in Master side and Slave sides use hydraulics which is not required in Brake by wire. Master side hydraulic pump is used only to recreate pedal feeling. Ideally master pedal should be capable enough to convey the braking intension and to recreate braking feeling back to the driver. There fore in this study a rotary motor is used at the pedal side. Slave side also uses an identical rotary motor. In practical experiments slave side motor should be large enough to control hydraulic brakes. In bilateral control, with power scaling a good brake by wire system can be made.

C. Pedal Feeling

Driver is sensitive to the brake feeling. Brake pedal should behave as in the conventional brake system. Usually torsional spring is used in conventional brake system to locate the pedal to its "parking position". However if brake by wire system is implemented it is not practical to have a spring. Therefore in this paper a novel method is proposed to locate the pedal to its parking position in brake by wire environment. Physical tortional spring is replaced by a virtual spring acting in the bilateral control system.

II. Modeling

Following figure depicts the sketch of a braking pedal.

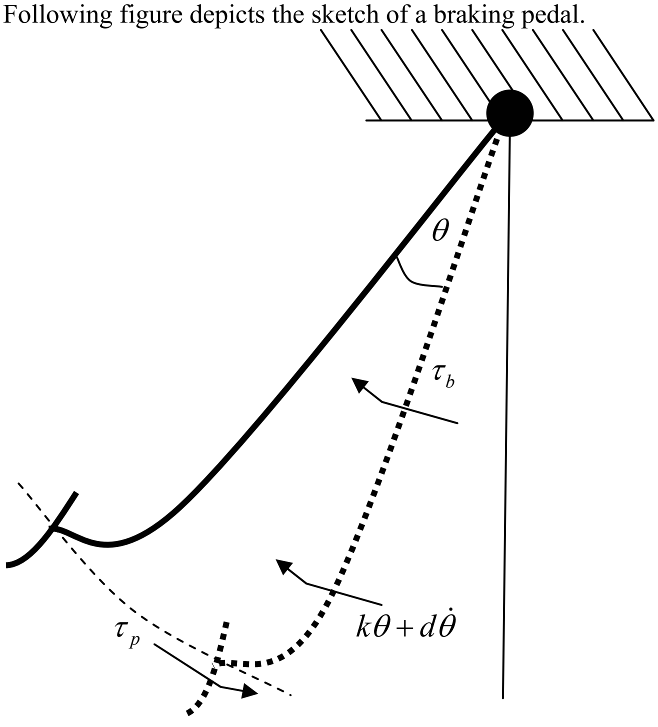

Fig. 1 Sketch of the brake pedal

Pedal is suspended on a hinged joint. The displacement angel is θ. τ_p is the torque on the pedal by the driver. τ_b is the reaction torque coming from the master side actuator. In conventional brakes, the brake feeling depends on used mechanical elements like springs, oil dampers, cylinders, length, diameter of the oil line, and the design of the wheel brake. Usually a spring is used to bring back the pedal after pressing operation is completed. This pedal spring is proposed to be removed with a virtual tortional spring. Considering the above factors, spring constant *k* and damping coefficient *b* can be decided. If the pedal has inertia *J,* dynamic equation can be described as follows.

$$J\ddot{\theta} = \tau_p - [\tau_b + (k\theta + d\dot{\theta})] \qquad (1)$$

III. Bilateral Control

In this section bilateral control is introduced. Fig.2 . shows the basic structure.

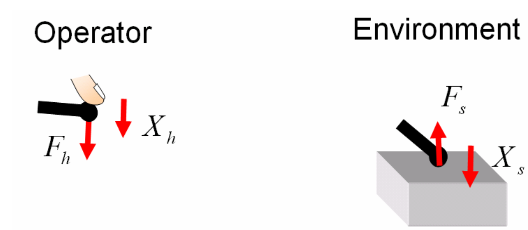

Fig. 2 . Bilateral Control.

Position and force information is transmitted from the slave side to the master side and master side to the slave side as well. Environment reaction is recreated at the master side. Master's operating intension is also transmitted to the slave side so that slave starts to move according to the master. If human operator exerts F_h force at the master side, and the manipulator moves by X_h, then the impedance of the master side is Z_m. This can be shown by the following equation.

$$X_h = \frac{1}{Z_m} F_h \qquad (2)$$

Similarly, slave side reaction can also be shown by the following equation.

$$F_s = -Z_e X_s \qquad (3)$$

Ideally, position of master and slave should be equal. Addition of forces at master and slave manipulators should be zero.

$$X_h - X_s = 0 \qquad (4)$$

$$F_h + F_s = 0 \qquad (5)$$

However, in applications where master and slave are different, position and Torque scaling may be used. Above discussion is true for rotary master slave systems where positions become the angles and forces become toques.

IV. DISTURBANCE OBSERVER AND REACTION TORQUE OBSERVER

This section initially explains the basics of the disturbance observer and its variant reaction torque observer. Then the discussion is extended to explain how these observers are used in this research.

A. Disturbance Observer

Dynamic equation of a motor is expressed by (6).

$$J\ddot{\theta} = \tau_g - \tau_l \quad (6)$$

Where,

J	:	Normal Inertia
θ	:	Angle
τ_g	:	Generated torque
τ_l	:	Load torque

Generated force τ_g ,

$$\tau_g = K_t I_a = K_t I_a^{ref} \quad (7)$$

K_t is the torque coefficient. It is a function of flux position of the motor. I_a is the load current. With a fast switching power supply it is possible to approximate the load current I_a as the torque current reference I_a^{ref}.

Load τ_l can be represented as (8).

$$\tau_l = \tau_{\text{int}} + \tau_{ext} + (\tau + D\dot{\theta}) \quad (8)$$

Where,

τ_{int}: Interactive torque including cariolis and gravity terms.

τ_{ext} : Reaction force of the mechanic load

τ : Coulomb friction

$D\dot{\theta}$: Viscous friction

By subtracting (7) by (8), (6) can be re-written as (9).

$$J\ddot{\theta} = K_t I_a^{ref} - (\tau_{\text{int}} + \tau_{ext} + \tau + D\ddot{\theta}) \quad (9)$$

Parameters of a system are subjected to variations and estimation errors. Parameters of (12) K_t and J can be re-written in terms of nominal values and variations.

$$J = J_n + \Delta J \quad (10)$$

$$K_t = K_{tn} + \Delta K_t \quad (11)$$

The total disturbance to the system τ_{dis} is represented as,

$$\begin{aligned}\tau_{dis} &= \tau_l + \Delta J\ddot{\theta} - \Delta K_t I_a^{ref} \\ &= \tau_{\text{int}} + \tau_{ext} + \tau + D\dot{\theta} \\ &\quad + (J - J_n)\ddot{\theta} + (K_{tn} - K_t) I_a^{ref}\end{aligned} \quad (12)$$

Disturbance Observer is shown in Figure 9a. Disturbance is calculated from I_a^{ref} and $\dot{\theta}^{res}$. Disturbance is fed to a first order low-pass filter to calculate the estimated disturbance force. Estimated disturbance $\hat{\tau}_{dis}$ is given by (13).

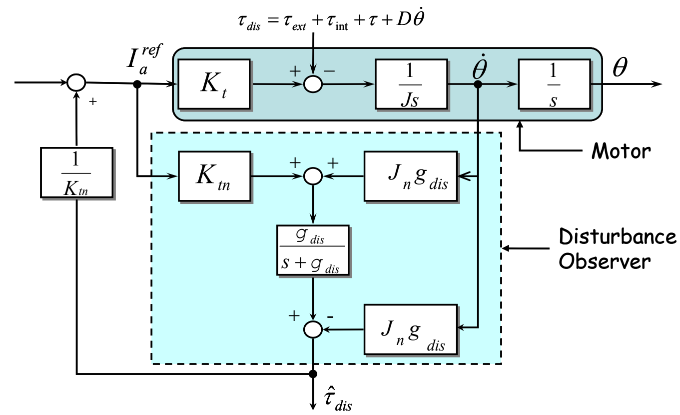

Figure 3a : Disturbance Observer with the motor.

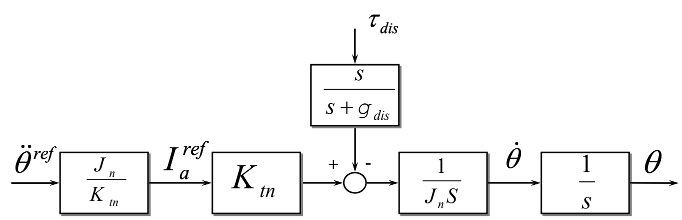

Figure 3b : Disturbance Observer as an acceleration controller.

$$\hat{\tau}_{dis} = \frac{g_{dis}}{s + g_{dis}} \tau_{dis} \quad (13)$$

Cut off frequency of the low-pass filter is represented as g_{dis}. Robust control system is attained by using the disturbance observer. This system can be represented as an acceleration control system [6] as shown in Figure 3b.

B. Reaction Torque Observer

Identification of the disturbance force is not only effective for realization of robust motion control but also to identify parameters as well. When the velocity $\dot{\theta}$ is constant, (12) yields terms with only the friction effects. This enables to identify the friction effects of the system. External forces also could be identified using disturbance observer [6]. Therefore, if frictional elements are known beforehand K_{tn} and M_n parameters could be adjusted so that they are very close to the actual values. Thus the disturbance observer could identify the external forces as depicted in (14).

$$\hat{\tau}_{reac} = \frac{g_{ob}}{s+g_{ob}}(I_a^{ref}K_{tn} + g_{ob}J_n\dot{\theta} - \tau_{\text{int}} - \tau_g - \tau - D\dot{\theta}) - g_{ob}J_n\dot{\theta} \quad ....(14)$$

Where,

$\hat{\tau}_{reac}$	:	Estimated reaction force
τ_{int}	:	Interactive force
τ_g	:	Gravity force
τ	:	Coulomb friction
$D\dot{\theta}$	:	Viscous friction
g_{ob}	:	Cut off frequency of the reaction torque observer

After the identification process, disturbance observer acts as a reaction torque observer. Usually for practical applications, disturbance observer and reaction torque observer could be identical, provided the cut off frequencies are equal.

Fig. 4. depicts reaction torque observer with the steps to identify the external torques.

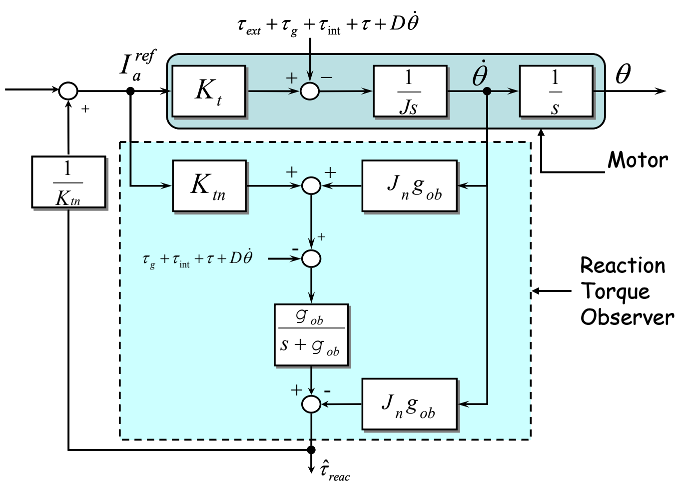

Fig. 4. Reaction torque Observer.

V. Control System

Fig. 5 depicts the total control system. In this study model represents a Spring damper model. Parameters are set such that the system is critically damped. Master and slave side manipulators are controlled with two identical PD controllers. As for this experiment, Inertias of the Master side motor and Slave side are equal. Position outputs of the master and slave are exchanged as inputs to the slave and master respectively. *Disturbance Observer* is used to cancel out the disturbances and to have robust motion control. Its variant, Reaction Force Observer is used as the force sensor. There are no physical force sensors used in this experiment. Position and force scaling factors are set to 1, so that virtually there is no scaling involved.

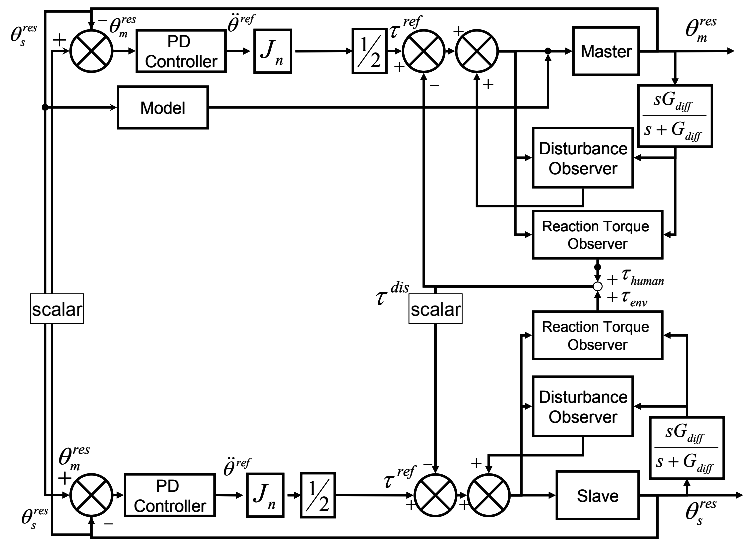

Fig. 5. Total Control System

VI. Experimental Setup

For the experiment, real brake by wire system is not used. However, experimental system is sufficient to demonstrate the applicability of the proposed system. On pedal (master) side, shaft fitted rotary motor is used. No physical spring is used to bring back the pedal to its parking position. Fig. 6a shows the arrangement of the master pedal.

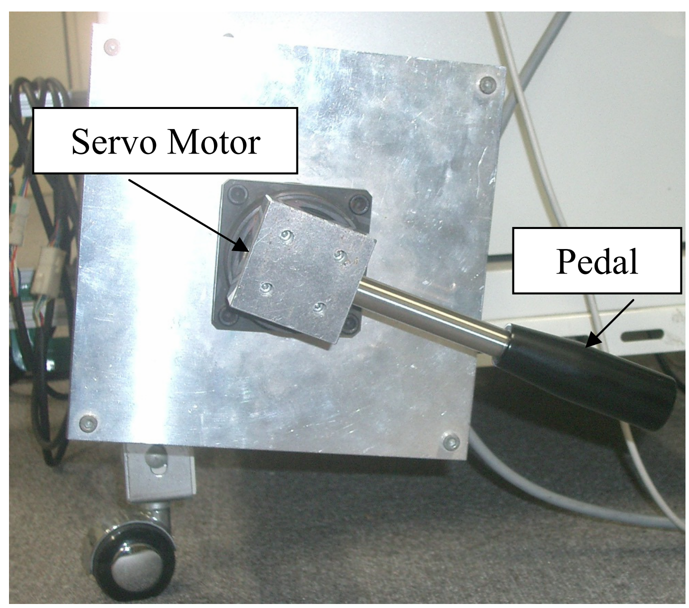

Fig. 6a Master -Pedal

Slave side does not have a real braking equipments. Instead, slave motor similar to the master motor is used. Small coil spring is used as the slave load. Fig. 6b shows the Slave manipulator.

Fig. 6a Slave – Manipulator

VII. Experimental Results

Master side pedal was pressed several times. Pedal returned to its parking position as if it is having a real tortional spring. When the slave side comes in contact with the environment, environment was felt at the master side. Physical spring used as the environment could be felt at the master side.

Following parameters were used in the experiment as shown in table 1.

Table 1. Experimental Parameters

K_p Position gain	900
K_v Velocity gain	60
Sampling time	0.0001s
k Spring constant	0.05
d damping constant	0.03271
G_{dis} gain of the disturbance observer	400
G_{dis} gain of the reaction torque. observer	400
G_{diff} gain of the pseudo-derivative	500

Fig. 7 shows the position response of the master and slave manipulators. Master slave responses show a perfect match. Once the pedal is pressed, It returned to its original parking position showing the properties of the virtual spring.

Fig. 8 shows the Toque angle relationship. Variation shows some nonlinearity. This may be due to the mechanical errors and nonlinearity of the spring used.

Fig. 9 shows the Torque response of the master manipulator.

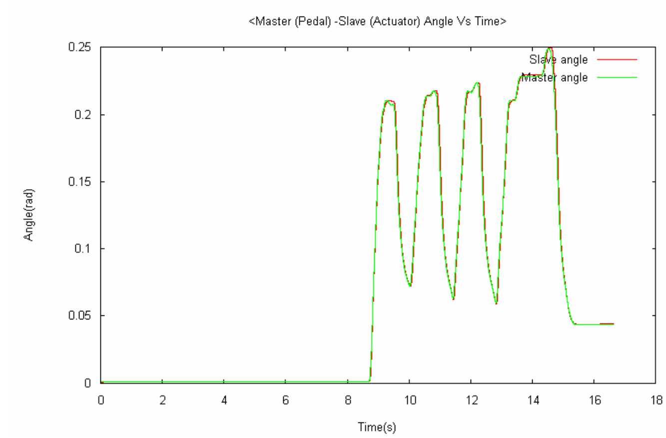

Fig. 7 Position response of Master and Slave

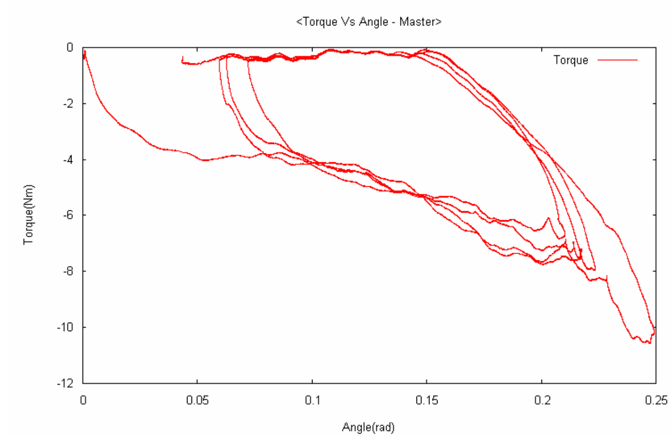

Fig. 8 Torque angle relationship

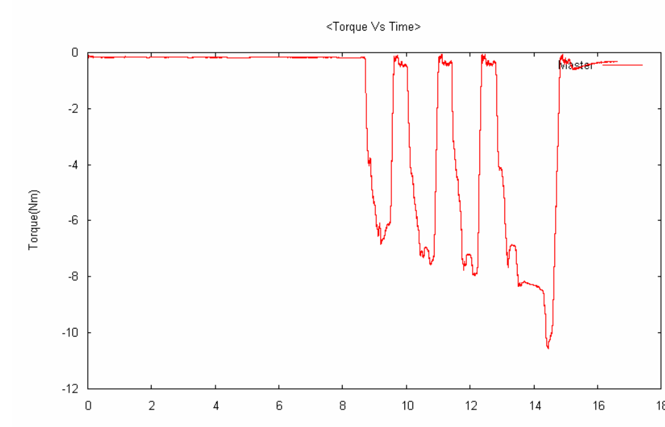

Fig. 9 Torque response – Master Manipulator

VIII. Conclusion

This paper proposed a novel method to locate the pedal to its parking position. Proposed bilateral control system is a good candidate for future Brake by wire systems. Experimental system did not use any real brake by wire system. However used prototype is capable enough to demonstrate the applicability of the proposed method.

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