Simulation of Brake by Wire System with Dynamic Force Control

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***Abstract*—By wire technology is recently developed to improve the reliability, safety, and performance of vehicular drive tech-nology. Brake system is the most important control system for vehicle safety. By wire technology development has encouraged the development of brake by wire systems to reduce traditional mechanical and hydraulic systems usage in automobiles. This paper proposes a novel brake by wire controller that uses a reaction force based bilateral motor controlling method. The pro-posed system uses two linear actuators with disturbance observer and reaction force observers to provide pedal force amplification and pedal retraction capabilities. The system includes a force controller to provide pedal feel to drivers. Electro mechanical brake position control is used to provide the brake force. The proposed system is simulated for different conditions to measure the performance and robustness. The simulation results provide evidence for robustness, force amplification, and pedal and brake retraction capabilities of the system.**

***Index Terms*—Bilateral tele-operation, Brake by wire, By wire technology, Force control, Pedal feeling, Reaction force observer**.

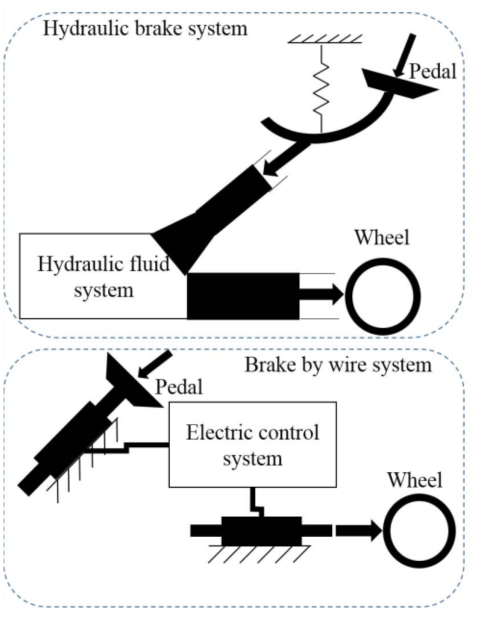

Fig. 1. Brake systems

I. Introduction

Land transportation has an utmost importance in developed society. In last few decades land transportation improved with the technological development to run faster and efficiently while providing needs of many developed and developing economies. Land transport systems mainly include automobile transport and train transportation systems. These systems are developed improved to reduce travel time and increase efficiency. The fast transport systems introduce a high importance on brake systems [1].

Vehicle braking in emergencies is important to prevent accidents, therefore reliable and fast responses of the braking system is crucial for vehicle safety [2]. Drum brakes were the first modern day vehicle brake systems developed by French manufacturer Louis Renault, in 1902 [3]. In early stages mechanical linkages were used to transfer the braking intention to the wheel. Hydraulic controllers then became famous removing the mechanical force transfer mechanisms from brake systems. Disc brake systems use hydraulic systems to brake control and commonly use in light weight vehicles. Anti-lock Brake Systems (ABS), Electronic Brake-force Distribution (EBD) are later developed to improve safety [4].

Conventional brake system contains brake pedal and brake pads. The human foot force is increased in the conventional brake system using fluid dynamic principles [5]. And the new improved hydraulic systems contains brake boost technology [6]. The brake pedal and discs were retracted from pressed position to its original position using an overhanging spring mechanism that connects the pedal to the vehicle body. Brake by wire systems were developed in recent years with the development of drive by wire technology. These systems are designed to reduce the mechanical and hydraulic system usage in vehicles [7]. Brake by wire system transfer pedal force to the wheel brake discs using electrical and electronic circuits without any intervention of hydraulic force transfer mechanisms. The brake by wire control system introduce dynamic brake controllability, auto brake control and avoid problems in hydraulic systems including costs of pumps and oil seals [8].

Electro Mechanical Brake (EMB) pads are introduced in [9] providing means of brake actuation in disk brakes in

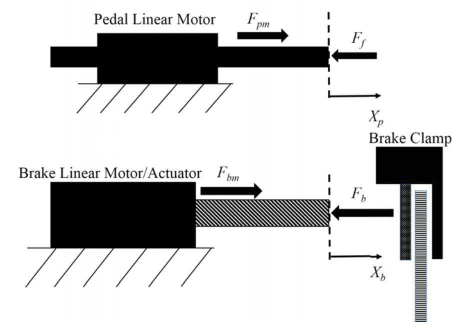

Fig. 2. Proposed Brake by wire hardware model

brake by wire systems. EMBs can be used in disk brakes providing necessary brake clamp forces. The disk brake clamp force measurement was done in [10], providing necessary means to assess the forces and sensor requirements of the system. The developed controllers in these research does not provide bilateral control to create interaction with brake pedal and EMB. The EMB control and available sensory data is provided in [11] indicating that the system include force sensors and resolvers for position sensing. The pedal feel was developed with bilateral control in [12] but the controller is a conventional bilateral system which does not contain brake boost capability. Therefore the controller will introduce the total brake actuator disturbance force to the pedal. It is necessary to create a brake by wire with bilateral pedal feel and brake boost to provide sensation of braking to the driver while reducing the brake clamp force to a acceptable level.

This paper introduce a novel method of brake by wire with bilateral force control. The proposed method provides pedal feel and brake boost from pedal force to brake force using position control and Reaction Force Observer (RFOB) [13] based bilateral force control system. The multiplication scalars allow to produce brake boost and pedal feel control for different vehicle types. In addition this novel method retracts the pedal using spring effects in the pedal motor. A hypothetical spring is installed in between brake pedal and vehicle body similar to the conventional vehicle braking system and small damper to stabilize the system.

The brake by wire system model in consideration is shown in Fig.1. The modeled system contains two linear actuators as pedal actuator and brake actuator in the model. Brake by wire controller can easily be used for rotary motors or linear motors. The brake clamp force used in simulation was selected considering the clamp force readings generated for different motor rotational angles [14] in EMB brush-less direct current motor, and creating a linearized clamp force vs. linear deflection model.

Brake pedal spring effect has also added to the controller as a virtual spring to provide the pedal spring feeling to the driver. Brake pedal feeling is important in automobile braking system. The feeling of pedal force has the ability to provide information about the brake displacement to the driver [12]. The system is simulated in Matlab simulation environment to

TABLE I
SYMBOL DESCRIPTION

Symbol	Description
X_p	Padel motor displacement (m)
X_b	Brake motor displacement (m)
F_{pm}	Padel motor force (N)
F_{bm}	Brake motor force (N)
F_f	Foot force (N)
F_b	Brake force (N)
F_{bme}	Mechanical brake force/ Clamp force (N)
F_{sp}	Spring effect force on pedal (N)
F_{bp}	Brake effect force on pedal (N)
M_{bp}	Brake pad mass (kg)
M_b	Brake motor mass (kg)
M_{bn}	Brake motor nominal mass (kg)
M_p	Pedal motor mass (kg)
M_{pn}	Pedal motor nominal mass (kg)
G	RFOB gain
β	Frictional damping coefficient (N/m^2)
K_{fp}	Pedal motor force constant (N/A)
K_{fpn}	Pedal motor nominal force constant (N/A)
K_{fb}	Brake motor force constant (N/A)
K_{fbn}	Brake motor nominal force constant (N/A)
K_s	Pedal spring effect coefficient (N/m)
C_s	Pedal damping effect coefficient (N/^{2})
K_b	Pedal motor brake effect coefficient
K_{scale}	Pedal position scaling coefficient
K_{Pp}	Pedal PID controller proportional coefficient
K_{Ip}	Pedal PID controller integral coefficient
K_{Dp}	Pedal PID controller derivative coefficient
K_{Pb}	Brake PID controller proportional coefficient
K_{Ib}	Brake PID controller integral coefficient
K_{Db}	Brake PID controller derivative coefficient
Y	Current sensor transfer function

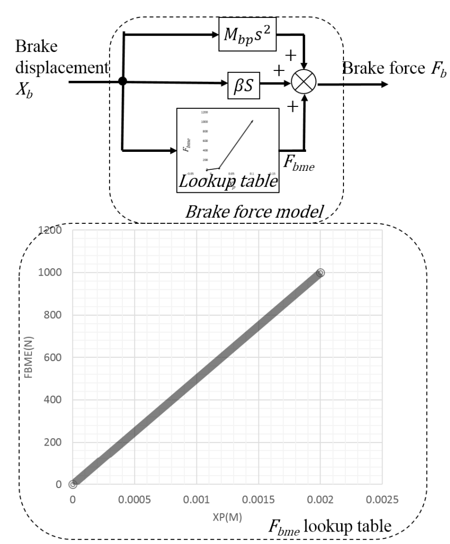

Fig. 3. Proposed Brake by wire brake motor environment model

evaluate the brake performance in different conditions.

The brake by wire system is mathematically modeled in section II including controlling method. Additionally section II presents the control block diagram that has been used in the simulation and its parameters. Simulation results of this paper is illustrated in section III including time response of the system at different conditions. Finally the conclusion of this novel method is described in section IV using simulation results.

II. MODELLING

The conventional brake system use a hydraulic pump system to send the foot force to the brake pads and vice versa as shown in Fig. 1. A simple model of the proposed brake by wire system where an electrical controller sends the forces to pedal actuator and brake pad actuator shown in Fig. 1 . This modeled controller transfer foot force to brake pads and brake force experience by brake motor back to the pedal. In addition spring that connects the brake pedal to the vehicle body is modeled to give a spring effect to the brake by wire system. Table I describes the symbols that are used in modeling of this paper. The position and forces of the two linear actuator control system are shown in Fig. 2. The system is modeled using two linear actuators to show forces from foot and brake clamps. The model is linearized and the forces acting on the linear actuators are directly taken in to account such that the actuators can be changed to a BLDC motor based linear actuators [14] such as in EMB.

The proposed model has a larger brake motor than the pedal motor to depict that large brake forces acting on the brake actuator. The motor forces of pedal motor and brake motor are measured in the direction of X_p and X_b and brake force and foot force are measured in opposite direction to the motor forces.

Considering the pedal motor and brake motor in Fig. 2 we could formulate pedal actuator Newtons equation (1) and brake actuator Newtons equation (2), where F_f is the force excreted on the brake pedal by the driver and F_b is the force excreted on brake motor due to brake pad forces.

$$F_{pm} - F_f = M_p X_p s^2 \tag{1}$$

$$F_{bm} - F_b = M_b X_b s^2 \tag{2}$$

The brake force F_b experienced by motor is a function of X_b and modeled as a combination of mechanical brake force or brake clamp force F_{bme}, frictional damping effect, and effects of the brake pad weight M_{bp} as in (3). The brake clamp force is converted to the linearized graph shown in Fig.3 considering the clamp force measurements given in [14]. The EMB clamp force to rotary action is converted to the linear deflection to clamp force graph such that the brake actuator type won't effect the system implementation.

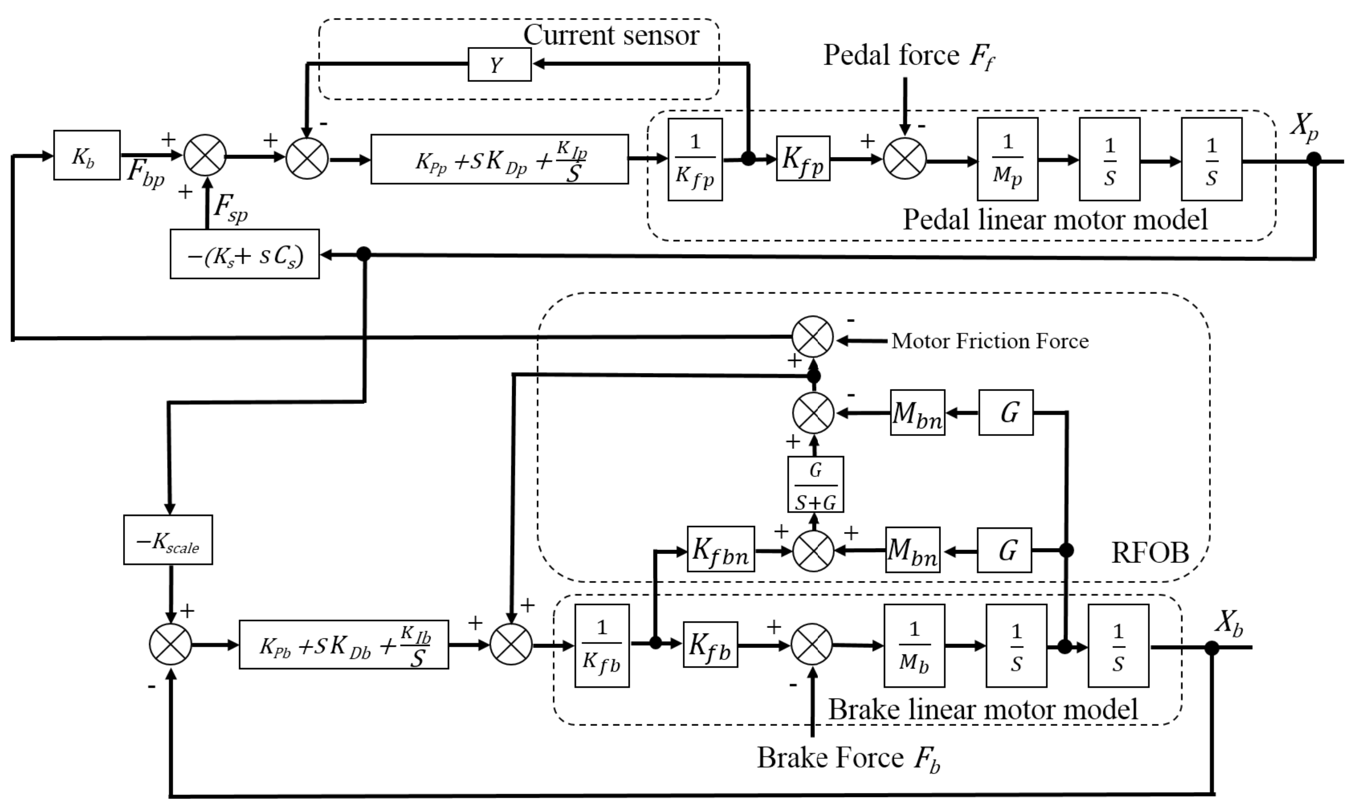

Fig. 4. Proposed Brake by wire controller

$$F_b = F_{bme} + \beta X_b s + M_{bp} X_b s^2 \quad (3)$$

The brake by wire controller consists of a pedal control motor force controller and a brake motor position controller. The pedal motor force controller contain a spring damper effect and a brake effect. The spring damper effect force on pedal F_{sp} could be derive as (4),

$$F_{sp} = -((K_s + sC_s)X_p \quad (4)$$

The Reaction Force Observer (RFOB) in brake actuator is used to measure the brake force F_b applied on the brake actuator as shown in the system block diagram in Fig. 4. The brake effect on foot is provided by brake effect force on pedal F_{bp} as in (5),

$$F_{bp} = K_b F_b \quad (5)$$

The pedal motor force controller take F_{sp} and F_{bp} for force reference as derived in (6). The pedal feel could be varied by changing pedal spring coefficient K_s, damper coefficient C_s and pedal motor brake effect coefficient K_b. Increasing the K_s and K_b values hardens the brake pedal. The K_b provides a portion of applied brake force to the drivers pedal giving driver information about the applied brake force. A current sensor is used to control the applied pedal motor force.

$$F_{ref} = K_b F_b - (K_s + sC_s)X_p \quad (6)$$

The break motor consists of a position controller as shown in Fig. 4. A value proportional to pedal motor displacement X_p , is provided as the position controller reference. The controller error then converted to brake motor force F_{bm}. The brake motor force could be derived as (7),

$$F_{bm} = (-K_{scale} X_p - X_b)(K_{pb} + \frac{K_{Ib}}{s} + K_{Db} s) \quad (7)$$

A Disturbance Observer is used in this controller to compensate any sudden changes occur in the brake motor environment. The brake motor reference could be changed using position scaling coefficient K_{scale}. K_{scale} should be selected considering the maximum available pedal displacement and full brake clamp or actuator displacement. Using equations (1), (2), (7), and (6) we could derive new simplified pedal motor Newtons equation (8) and brake motor Newtons equation (9) as,

$$K_b F_b - (K_s + sC_s)X_p - F_f = M_p X_p s^2 \quad (8)$$

$$(-K_{scale} X_p - X_b)(K_{pb} + \frac{K_{Ib}}{s} + K_{Db} s) - F_b = M_b X_b s^2 \quad (9)$$

The proposed system provide brake by wire brake boost and in addition give spring effect and bilateral brake feel to the driver. The scaling factors could be used to change the pedal motor force levels to produce faster responses, high brake boost levels, and increased pedal force sensation levels.

TABLE II
MODEL PARAMETERS

Parameter	parameter value
Maximum $\lvert Xp \rvert$	0.1m
Brake pad touch Xb	0.002m
M_{bp}	0.5kg
M_b	1.1kg
M_{bn}	1.1kg
M_p	0.2kg
M_{pn}	0.2kg
G	100
β	0.2N/m^2
K_{fp}	24N/A
K_{fpn}	24N/A
K_{fb}	47N/A
K_{fbn}	47N/A
K_s	1000N/m
C_s	10N/m^2
K_b	1
K_{scale}	0.02
K_{Pp}	0.0013
K_{Ip}	0
K_{Dp}	0.0006
K_{Pb}	3298307.44
K_{Ib}	0
K_{Db}	6724.81
Y	24

III. SIMULATION AND RESULTS

Table II shows the parameter values used in the simulation. The brake by wire system model was simulated using Matlab Simulink simulation environment using the block diagram in Fig. 4. The parameters were selected considering the clamp forces of EMBs. The system has been simulated for different conditions to evaluate the performance of the system. The controller coefficient were selected to considering a full pedal movement of 0.1m. The brake by wire system provide pedal force amplification and provide consistent pedal motor force throughout the range.

The frequency response of this system between pedal force

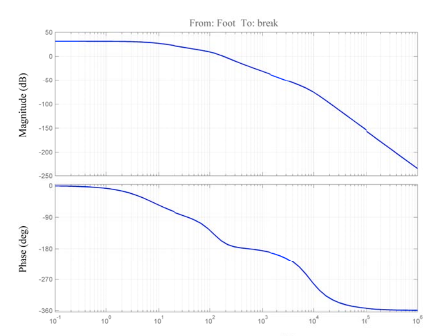

Fig. 5. Frequency response of the brake by wire system

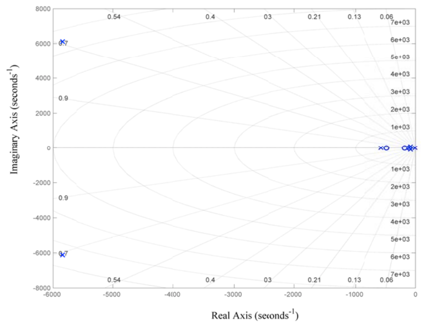

Fig. 6. Pole zero diagram of the brake by wire system

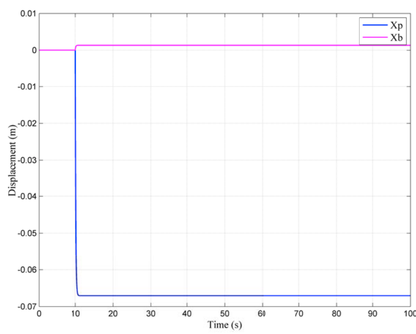

Fig. 7. Step input position response of the system

and brake force is shown in Fig. 5. The modeled brake by wire system provides good force amplification up to 100Hz frequency range. The frequency range is more than adequate to provide brake boost because the pedal force or human foot force usually resides on the force amplification frequency range. Evidence of the modeled system force amplification capability and applicability is evident from Fig 5.

Fig.6 shows the pole-zero diagram of the brake by wire system. Four poles and three zeros are present in linearized brake by wire model pole zero diagram. All the system poles are in the left hand side of the imaginary axis. There are no poles on the imaginary axis therefore system shows no oscillations.

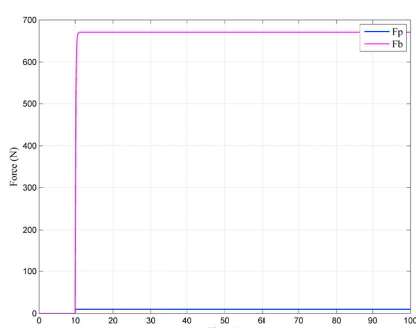

Fig. 8. Step input force response of the system

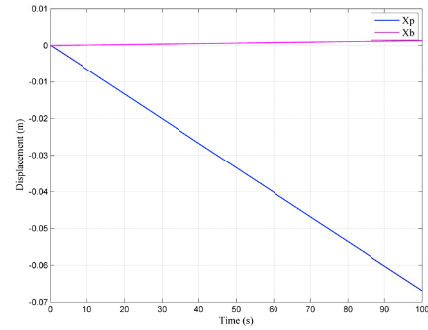

Fig. 9. Ramp input position response of the system

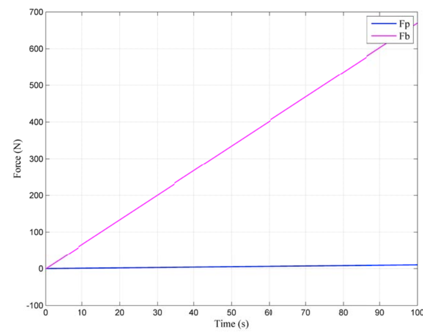

Fig. 10. Ramp input force response of the system

The modeled brake by wire system can be categorized as a stable system considering the pole zero diagram and frequency response.

The modeled brake by wire system time domain response is simulated for a step brake application. The modeled system response for step pedal force is shown in Fig. 7 and Fig.8. Fig.7 contains the position displacement of brake pedal and brake motor. The Motor forces are shown in Fig.8 for the step input. The step force has contracted the brake pedal and the pedal movement has generated amplified brake force through the brake motor position controller scalars and provides brake boost.

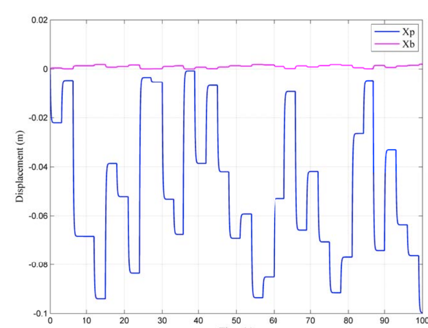

Fig. 11. Random input position response of the system

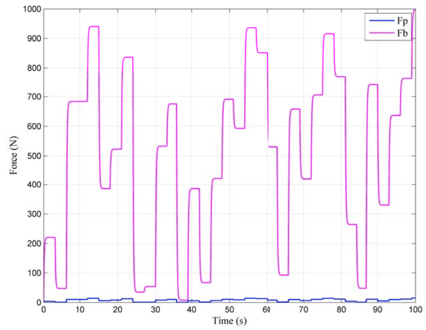

Fig. 12. Random input force response of the system

The system was simulated in time domain for ramp brake application and results are shown in Fig.9 and Fig.10. Fig 9 shows the pedal and brake displacement of the system for a ramp pedal force input. The brake pedal forces and motor forces are shown in the Fig.10. The pedal displacement has caused the brake system to provide boosted while following the pedal movement as in Fig.10 and Fig 9.

The system response for a random brake application is shown in Fig.11 and Fig.12. The system has amplified the pedal force as shown in Fig.12. The brake pedal and brake motor displacement for random force application is shown in Fig.11. The proposed system correctly amplify and followed the drivers pedal providing brake boost with smooth transitions. The system shows good force amplification and pedal spring effect for dynamic force changes.

The simulation results shows the performance of modeled brake by wire system. The system response has simulated for step, ramp and random inputs. The force amplification capability of the system was evaluated using frequency response of the system.

IV. Conclusion

The proposed brake by wire system was simulated to provide applicability of the system. The brake by wire system simulation results shows the force amplification capabilities and pedal retraction capabilities. The simulated brake by wire system have good stability and performance in the force range. The hardware designer should consider the available brake pedal movements and brake motor movement in designing and selecting the controller parameters. The modeled system should contain motor current sensors and encoders or resolvers to measure required parameters. The brake motor linear actuation should provided by a linear motor or rotary to linear motion converter after considering the brake clamp forces; because high it is recommended to use rotary to linear actuators for high clamp force applications. The simulation results shows the applicability of the proposed novel brake by wire system.

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