

An Approach to Vehicle Brake-By-Wire Optimal Control Tracking Strategy

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ABSTRACT

In this paper, an optimal control tracking strategy for a brake-by-wire system is developed and tested on a laboratory setup consisting of a driving motor, clutch and gearbox system, rotating inertia and an electro-mechanical brake actuator. The presented brake by wire system consists of a brake pedal sub-system connected to the electro-mechanical brake actuator through an electronic control module handling the optimal control logic. A mathematical model of the proposed brake-by-wire control system is presented. The presented mathematical model is simulated and validated against the experimental data. The good agreement between both simulation results and experimental validates the mathematical model. The validated mathematical model is then used to test the proposed optimal control tracking strategy against different levels of disturbances that are difficult to emulate in the laboratory. The developed control logic ensures optimal control effort of the electro-mechanical brake actuator and, at the same time, efficient tracking between the brake pedal command and the braking deceleration profile. Consequently, the introduced logic plays a major role in keeping the tracking between the braking system command and its output as high as possible while not sacrificing the power supply (i.e. high drained electric current) in case of emergency situations. This provides acceptable braking performance while maximizing the system battery life and protects the brake actuator driver against high current.

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INTRODUCTION

Over the past few years, researches have been directed towards expanding development in the field of X-by-wire systems. This generic term means that the conventional mechanical and hydraulic connections between the commanded input and actuating subsystems are replaced with electrical wires carrying the operating electrical signals. The first appearance of this concept was in the aviation field because of the high potential role it can play in reducing the space and weight allocated to the mechanical/hydraulic connections in addition to boosting the aircraft performance via more consistent and responsive communications between the different subsystems. After that, the automotive industry was motivated to implement this new technology in the different types of vehicles.

The Brake-By-Wire (BBW) system is the successor to the conventional hydraulic braking system because of its potential role it can play in making the vehicle braking system more safe, responsive and reliable. Mechanical/hydraulic connections elimination produced a novel way of communication between the different vehicle subsystems via a fault-tolerant architecture [1, 2]. This communication

network provides the fulfillment of the stringent requirements of safety critical control applications in different vehicle subsystems.

The existence of the electrical wires between the input/output subsystems and control units simplifies the actuators control process compare to conventional braking systems, so different control algorithms were proposed to achieve efficient braking performance at different environments and operating conditions [3, 4]. On the other hand, the brake-by-wire system provides the possibility to actuate the braking function as an integrated sub-system of the automatic collision avoidance system. Collision warning and collision avoidance systems decrease accidents severity and play a major role in increasing vehicle safety [5].

The conventional hydraulic braking system has inherent feedback force on the pedal through the hydraulic lines, so one of the main issues in every brake-by-wire system is to emulate the feedback pedal feeling in the conventional hydraulic braking system as a consequence of removing hydraulic lines, vacuum booster and master cylinder. New ideas for pedal feel emulator were investigated [6, 7].

Yaw stability of an automotive vehicle in a steering maneuver is critical to the overall safety of the vehicle. Different control algorithms have been proposed to actuate each tire brake individually to create counteracting torque preventing the vehicle from either under-steering or over-steering in a handling maneuver [8, 9].

In the automated highway systems, heavy vehicles are supposed to be grouped in platoons in order to increase traffic capacity while maintaining small sufficient separating distances. So, increasing the braking capability of tractors and semi-trailers and reducing the delay of the actuating braking signals in air brake systems are critical issues. These issues can be addressed by implementation of BBW systems, by benefiting from its fast transmitting real-time signals rather than the delay associated with air brake lines [10].

Plenty of researches in the field of electric vehicles have been devoted to the introduction of ways increasing the driving range by means of increasing the electric storage capacity and/or recovered fraction of the energy released in order to be recycled and stored for further applications; propelling, accessory systems,...etc. Furthermore, these regenerative braking systems can be used in the BBW vehicles as additional power sources for the applications of air-conditioning, power-steering, heating systems, etc. Therefore, the regenerative braking systems have been proposed and pursued in order to achieve the previously stated requirements [11,12,13,14,15,16,17,18].

Another prominent technology in this hardware evolution is the magnetic particle brake. It is an electro-mechanical brake actuator based on the magneto-rheological fluid. The induced magnetic field links the fine floating ferrite particles to the rotating brake disk. It has the advantage of consuming lower electrical power and producing higher resistive torque, while having a lower weight for the same output resistive torque in comparison to a typical DC motor. On the other hand, these types of brake actuators need complex control logics due to their inherent hysteresis and lower bandwidth compared to electro-mechanical actuators [19,20,21].

Another type of electrically actuated proportional braking actuator was introduced in [22]. The proposed type has a motor-driven ball screw which compresses a multiple-disk mechanism (wafer disc springs) to induce the required resistive torque. Unlike magnetic particle brakes (i.e. magneto-rheological or electro-rheological fluid brakes), the proposed actuator has the ability to be designed in either normally unlocked or locked configuration, which in turn provides a potential safety in case of any power failure.

The main significant obstacle facing the dependence on fully electrically-driven brake actuators is the need for high electrical power to induce sufficient braking torque. As a result, different type of electric brake actuator (called wedge brake) was introduced and pursued to resolve the aforementioned issue [23,24,25,26]. Its operating principle utilizes the wedge action of introducing a brake actuator with high self-reinforcement capability in order to reduce the

required electrical energy for producing the same sufficient retarding torque.

It is apparent from the previous research review that a little work has been done when it comes to optimal control of the braking actuator from an energy-saving point of view. In this paper, an optimal control strategy is introduced that insures minimum control effort which results in minimum actuator power consumption, while simultaneously providing efficient braking performance at different operating conditions and environmental disturbances.

PROPOSED BRAKE-BY-WIRE SYSTEM LAB SETUP CONFIGURATION

The proposed brake-by-wire experimental lab setup has two different braking systems mounted on its two halves: a conventional hydro-mechanical braking and a BBW system. Both systems are using the hydro-mechanical braking system brake pedal equipped with a position sensor for braking the same rotor disc. While testing the BBW system, the caliper of the hydro-mechanical braking system is unmounted, while using a dummy fixed disc between its two pads. In this way, two advantages can be gained:

- First, it assures that there is no contribution from the hydro-mechanical system to the braking torque at the time of testing the BBW system.
- Second, keeping the hydro-mechanical system configuration intact provides a simple and effective way of emulating the pedal feel, since more pedal depression results in higher resistive feedback force.

As shown in Fig. 1, the proposed mechanical lab setup consists of an AC induction motor (with the type of totally enclosed fan ventilated cage) used for generating the required mechanical rotating energy. This rotational power is transmitted to a dry friction clutch and then a gearbox to arrive at the inertia element (a cast iron flywheel). The flywheel works as an energy storage element that needs to be braked down based on the braking friction torque exerted on the rotor disc which is connected to the flywheel via a flexible coupling.

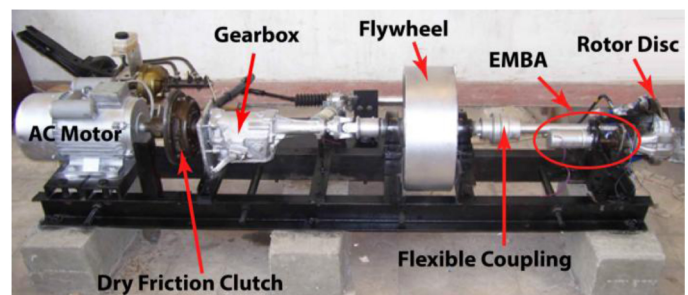


Figure 1. BBW mechanical setup layout

In Fig. 2, an enhanced Electro-Mechanical Brake Actuator (EMBA) is used for braking the rotating inertia through a disc brake and pad arrangement. The EMBA comprises a 12V geared DC motor and a power screw mechanism to convert rotational motion to translational motion via a non-rotating nut in order to engage contact between the brake pads and the rotor disc and thus, braking phase occurs.

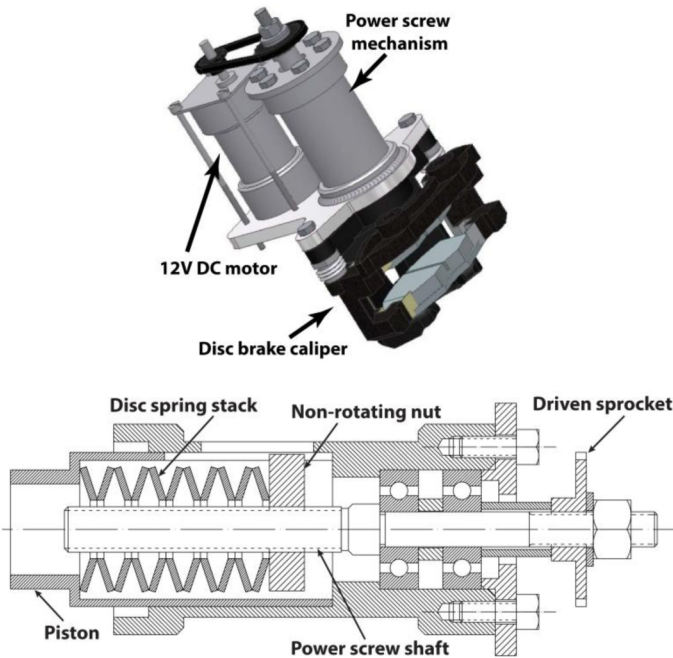


Figure 2. Electromechanical brake actuator (EMBA) configuration

The rotational motion of the DC motor is translated through a 1:2 speed reduction ratio by a sprocket-chain coupling. The reduction ratio provides a mean of doubling the torque built at the power screw terminal at the expense of halving the translated rotational speed. The axial advance is driving a guided nut (non-rotating nut) and pressing it against a set of disc spring elements.

In order to provide the DC motor enough time to build up torque during the braking phase, a set of 11 disc spring elements stacked in series is placed between the linearly translating nut and the piston. Furthermore, using the stacked-in-series disc spring elements provides an easy way to estimate the braking clamp force by observing the displacement of the moving nut. This displacement (after deriving a relationship between the springs' deflection and their accumulated force) can be translated into the built-up clamping force value.

Figure 3. shows the load-deflection diagram of the disk spring stack used in the developed EMBA.

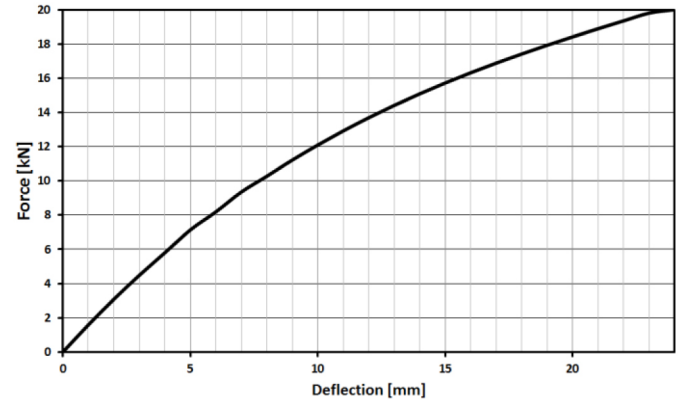


Figure 3. Load-deflection plot of the disk spring stack in series

THE PROPOSED BRAKE-BY-WIRE SYSTEM MODELING

Figure 4 shows a representative schematic for the proposed brake-by-wire system.

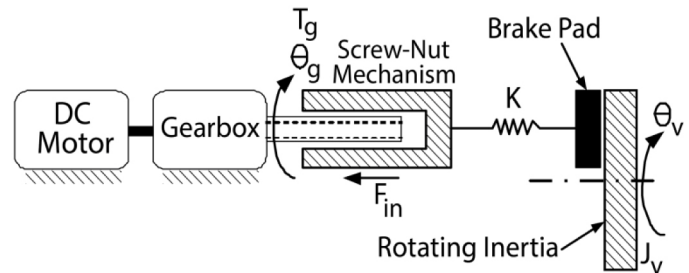


Figure 4. BBW System Schematic

The DC Motor electrical and Mechanical equations could be given by

$$V_m(t) = L_m \dot{I}_m(t) + R_m I_m(t) + K_{em} \dot{\theta}_m(t) \quad (1)$$

$$J_m \ddot{\theta}_m(t) = K_{tm} I_m(t) - C_m \dot{\theta}_m(t) - \frac{T_g(t)}{r_s} \quad (2)$$

where V_m is the motor voltage command, L_m is the motor armature inductance, R_m is the motor armature resistance, I_m is the motor current, K_{em} is the motor back-emf constant, $\dot{\theta}_m$ is the motor angular speed, J_m is the motor rotating inertia, K_{tm} is the motor torque constant, C_m is the motor viscous damping coefficient, T_g is the DC motor gearbox resisting torque, and r_s is the gearbox reduction ratio. The relationship between the gearbox input and output torques and speeds is given by