Control of an Electro-Mechanical Brake-By-Wire System Using Sliding Mode Control

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***Abstract*— Brake-By-Wire (BBW) system is a new and promising vehicular braking control scheme. It replaces the conventional hydraulic or electro-hydraulic devices by electromechanical actuators and emerged communication networks. The brake-by-wire systems, such as EMB (Electro-Mechanical Brake), is applied to the intelligent vehicles since the brake-by-wire units are lighter in weights and have faster response compared to conventional hydraulic brake units. In this paper a mathematical model for BBW system is established. A controller based on sliding mode strategy is modeled and simulated. A test rig has been established to validate the model and test the results of simulation. The tests show that the actual results match the simulated with accepted error.**

Keywords—Braking system, Brake by wire, Sliding mode control, modeling and validation, mathmatical model.

I. Introduction

In the past few years X-by-Wire systems have been introduced in many applications such as aviation and automobile due to their safety and high performance they could give on replacing the conventional systems (hydraulic, mechanical and pneumatic ones). In this paper an open loop brake by wire system is going to be tested on a lab setup for the mathematical model verification, which offers an opportunity to simulate the system sliding mode being controlled.

The sliding mode control approach is recognized as one of the efficient tools used to design robust controllers for complex high order nonlinear dynamic plants operating under uncertainty conditions. The research in this area was initiated in the former Soviet Union about 40 years ago. Later on, within the last two decades, the sliding mode control methodology has received much more attention from the international control community[1].

The Brake-By-Wire system is the successor to the conventional hydraulic braking system because of the potential role it can play in making the vehicle braking system more safe, more responsive and reliable. Mechanical/Hydraulic connections elimination produced a novel way of communication between the different vehicle subsystems via a fault-tolerant architecture [2, 3]. 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 input/output subsystems and control units simplifies the actuator control process compared to conventional braking systems; As a result, different control algorithms were proposed to achieve efficient braking performance at different environments and operating conditions[4, 5].

On the other hand, the brake by wire system provides the possibility to actuate the braking function as an integrated subsystem of the automatic collision avoidance system. The collision warning and collision avoidance system decrease accidents severity and play a major role in increasing vehicle safety[6].

In the automated highway systems, heavy vehicles are supposed to be grouped in platoons in order to increase traffic capacity while maintaining a small, yet sufficient separating distance. 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[7].

Plenty of researchers in the field of electric vehicles have been devoted to the introduction of ways to increase 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 source for the applications of air conditioning, power-steering, heating systems… etc. therefore, the regenerative braking system have been proposed and pursued in order to achieve the previously stated requirements [8-15]

This paper is organized in the following manner; the brake by wire system lab setup configuration is illustrated in section2. Section 3 is concerned with the proposed brake by wire system modeling. Then simulation and validation of the proposed system is illustrated in section 4. Applying sliding mode control on the mathematical model using Matlab Simulink is proposed in section 5. Section 6 shows the validation of the sliding mode control between the practical lab setup results and the mathematical matlab simulink model results. Conclusion is stated in section 7.

II. The proposed brake by wire system lab setup configuration

A. *Mechanical labortory setup*

In this section the Electro-Mechanical Brake-by-wire experimental lab setup will be shown and the function of each part will also be described.

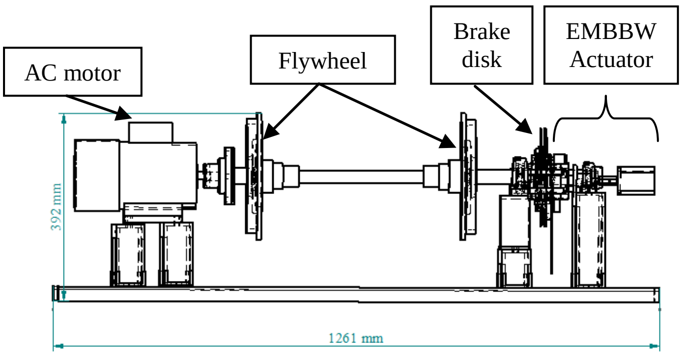

Figure.1 Mechanical laboratory setup schematic

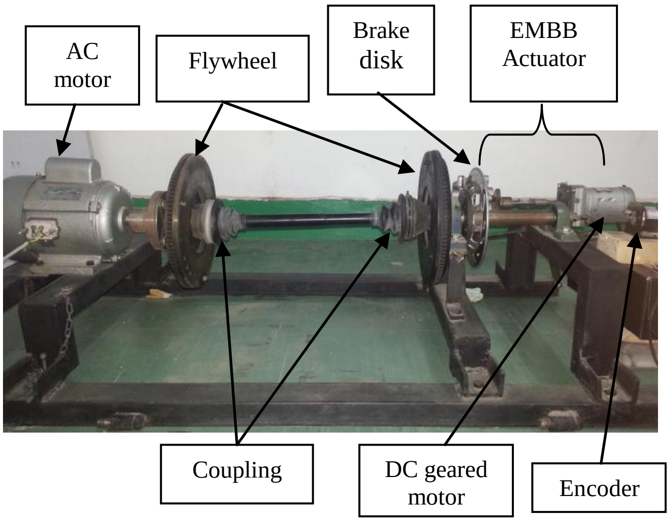

Figure.2 Mechanical laboratory setup

The proposed mechanical lab setup, as shown in figures 1, 2 consists of a one horse power AC induction motor (with a max. speed of 1500 rpm) used to drive the system. Two flywheels are used to store the rotational energy, which is also connected to a brake disc. Two couplings are connected face to face as shown to join the two flywheels allowing any degree of misalignment that could occur during rotation or vibration of the system. An Electro mechanical brake-by-wire actuator (EMBBW) is used to brake the system.

B. *Electro mechanical brake-by-wire actuator (EMBBW)*

Figure 3 illustrates the Electro-mechanical brake actuator used to brake the system.

A DC geared motor is used to rotate a screw nut mechanism. The screw is connected to the DC motor through a pin and both of them are fixed to the system chassis to lock linear movement.

Likewise, the nut is connected to a double pinned plate which by its own turn is connected to the two pistons of the caliper. The connections shown in figure 3 force these components to act as one part that moves linearly, while the pistons generate the force on the pads to break the system.

An encoder of high precision (250 pulses per revolution) and a programmable microcontroller (Arduino mega 2560) are used to measure the speed (RPM) of the system during the operation. This measurement is used afterwards to validate the simulation data extracted from Matlab Simulink model.

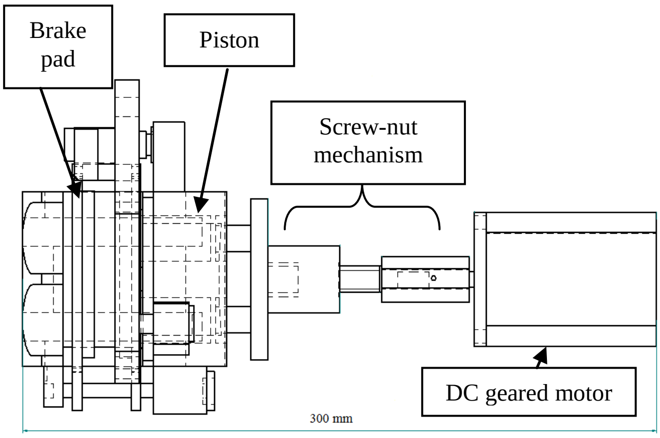

Figure.3 EMBBW Actuator

III. The proposed brake by wire system modeling

Figure 4 represents the schematic of the proposed brake by wire actuator.

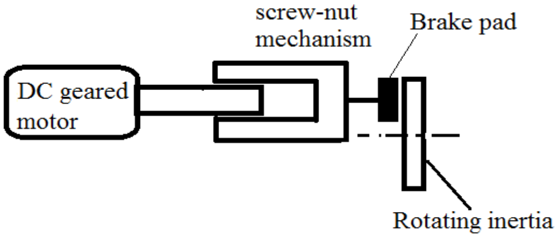

Figure.4 BBW system schematic

The DC motor electric and mechanical equation could be as shown below

$$V_m(t)=L_m\times I'_m+K_{em}\times\theta'_m(t)+R_m\times I_m(t) \qquad (1)$$

$$J_m\times\theta''_m(t)=K_{tm}\times I_m-C_m\times\theta'_m(t)-T_g(t) \qquad (2)$$

Where:

$V_m(t)$	Motor volt
L_m	Motor phase induction
R_m	Motor phase resistance
I_m	Motor phase current
K_{em}	Motor backemf constant
θ'_m	Motor angular velocity
J_m	Motor inertia
θ''_m	Motor angular acceleration
K_{tm}	Motor torque constant
C_m	Viscosity friction coefficient
T_g	Motor torque

$$Tg(t)=(F_{axial}(t)\times d_m[(\pi\times\mu_s\times d_m)+(p_s\times\cos\beta)])/(2[(\pi\times d_m\times\cos\beta)-(\mu_s\times p_s)]) \qquad (3)$$

$$T_g(t)=F_{axial}(t)\times\psi$$

$$F_{axial}(t)=(\theta_g(t))/(2\times\pi\times Ps\times K) \qquad (4)$$

Where:

F_{axial}	Power screw axial force
Θg	Output angular position of motor
Ps	Power screw thread pitch
Dm	Power screw thread mean diameter
Ms	Friction coefficient between power screw and nut
β	Power screw thread angle

$$T_b(t)=F_{axial}(t)\times\mu_p\times R_{mp}=(\theta g(t))/(2\times\pi)\times p_s\times\mu_p\times R_{mp}\times K \qquad (5)$$

Where:

T_b	Rotating disk braking torque
M_p	Brake pad rotor dynamic friction coefficient
R_{mp}	The mean radius of the brake pad rotor contact friction area

$$J_v\theta''v(t)+C_v\theta'_v(t)+T_b(t)=0 \qquad (6)$$

Where:

J_v	Rotating mass moment of inertia
C_v	Rotating inertia viscous damping coefficient
Θ_v	Rotating inertia angular displacement

IV. Proposed model simulation and validation for open loop

The DC motor parameters have been recognized using Matlab parameter estimation toolbox, Different voltage waveforms were fed to the motor. Inputs and their corresponding responses are recorded versus time, allowing them to act as inputs of the toolbox to start the estimation process and after several numbers of iterations an approximated and feasible parameters are obtained.

In this section, the proposed BBW mathematical model introduced in section 3 is experimentally simulated and validated. The lab setup presented in section 2 is used in the validation process. The objective of the validation process is to have creditable mathematical model that can be used efficiently to study and test the system and sliding mode control effect. Having a creditable mathematical model provides the ability of simulating the model and testing different types of operating conditions and system disturbances.

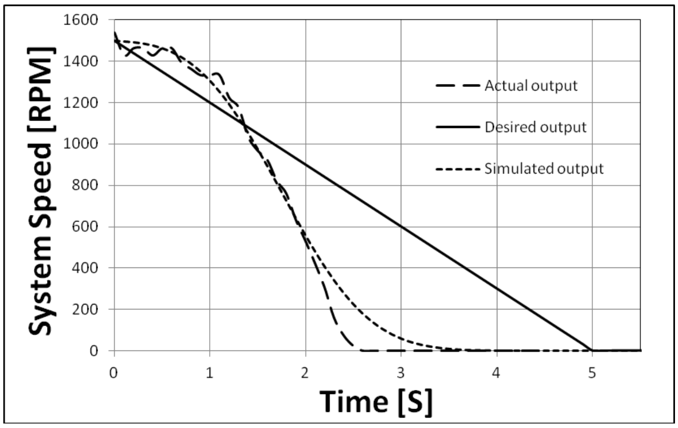

Figure.5 (Braking in 5 Sec 'open loop')

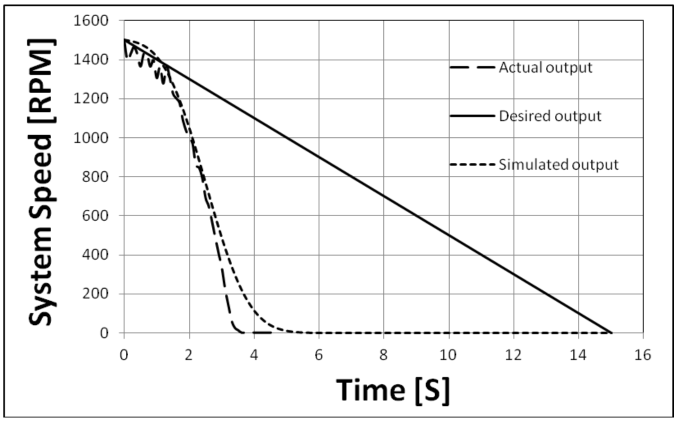

Figure.6 (Braking in 15 Sec 'open loop')

V. Applying sliding mode control on the proposed mathematical model

The major advantage of using the sliding mode in this case is the low sensitivity to plant parameter variations and disturbances which eliminates the necessity of exact modeling. Sliding mode control enables the decoupling of the overall system motion into independent partial components of lower dimension hence, reducing the complexity of feedback design.

This section investigates variable structure control (VSC) as a high-speed switched feedback control resulting in sliding mode. For example, the gains in each feedback path switch between two values according to a rule that depends on the value of the state each instant. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a pre-specified path in the state space and to maintain the plant's state trajectory on this path for subsequent time. When the plant state trajectory is above the path, a feedback path has one gain and a different gain if the trajectory drops below the path. This path defines the rule for proper switching. This path is also called a sliding path. Ideally, once intercepted, the switched control maintains the plant's state trajectory on the path for all subsequent time and the plant's state trajectory slides along this path.

This paper is concerned with maintaining the behavior of a first order system. The breaking RPM action shell tracks the desired RPM performance. The sliding mode path equation can be presented as follows:

$$\text{Tracked RPM} = \text{Max.RPM} - \text{Const.} \times \text{Time}$$

Where

Tracked RPM	RPM that the system shell follows
Max. RPM	Max starting RPM of the system
Const.	Slope of the line of the Tracked RPM
Time	Braking time

According to the results of the above equation the system trajectories run in opposite directions, which lead to the appearance of a sliding mode along this line.

$$\text{Control Action}\begin{cases}\text{Braking action,}\\ \quad \text{IF Actual RPM} > (\text{Tracked RPM} + \text{error})\\ \text{Releasing action,}\\ \quad \text{IF Actual RPM} < (\text{Tracked RPM} - \text{error})\end{cases}$$

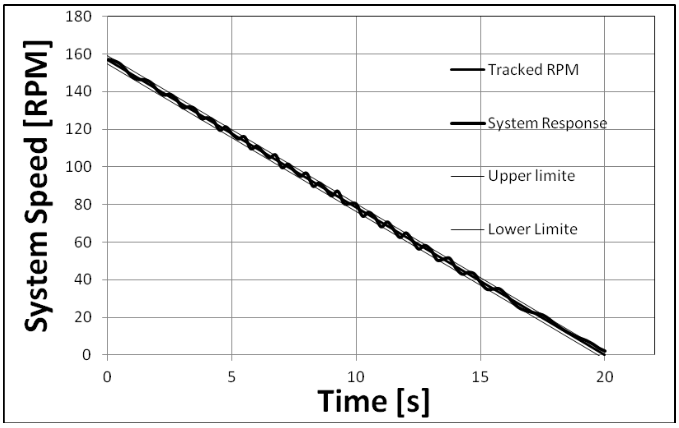

Figure.7 Simulated system response

VI. Model simulation and validation for sliding mode control

In this section, sliding mode control is applied to the system through a microcontroller (Arduino Mega 2560). An algorithm is developed to measure the system speed and determine upper and lower limits through the tracked and given RPM which is desired to stop at. All of the data is to be monitored using RS232 serial communication protocol.

Figures 9 to 12 show a comparison between sliding mode control data and simulated data against the tracked RPM (Desired performance of the system). As demonstrated by figures, the proposed sliding mode control strategy shows high performance and can actually track the desired RPM which validates its efficiency as a kind of control on such a system.

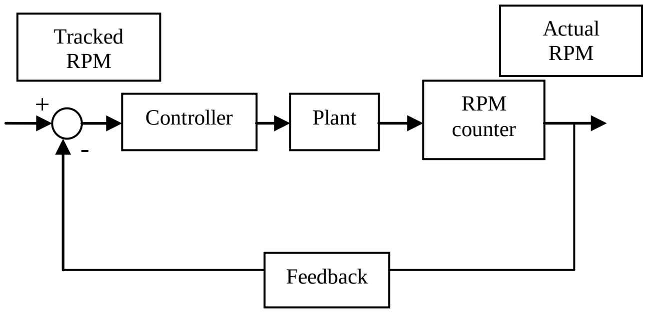

Figure.8 System block diagram

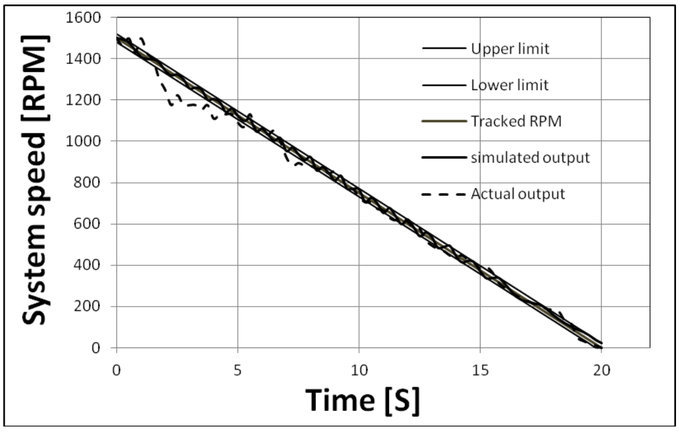

Figure.9 System response (Braking in 20 sec with a range ± 20 RPM)

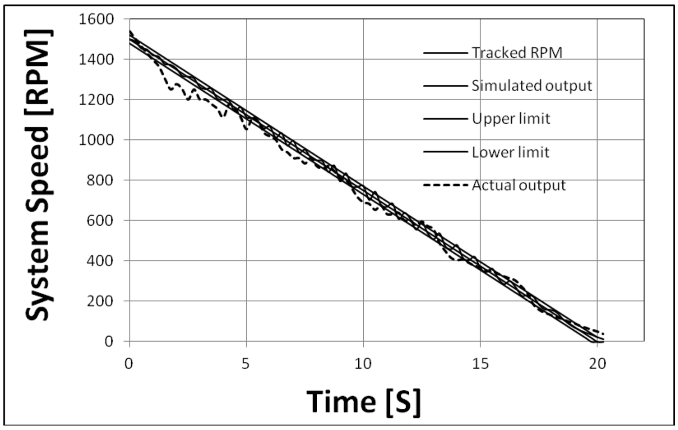

Figure.10 System response (Braking in 20 sec with a range ± 10 RPM)

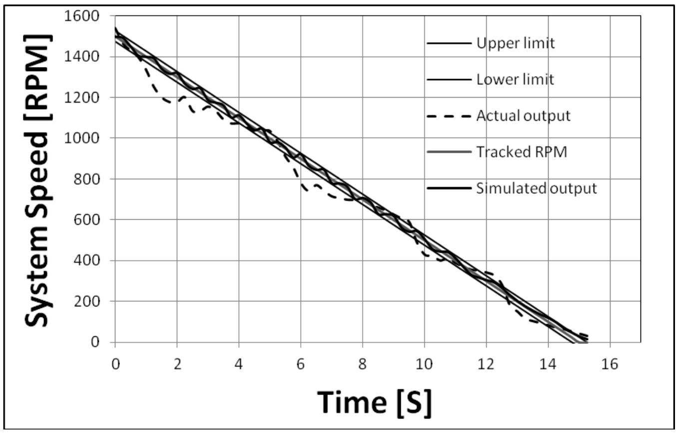

Figure.11 System response (Braking in 15 sec with a range ± 20 RPM)

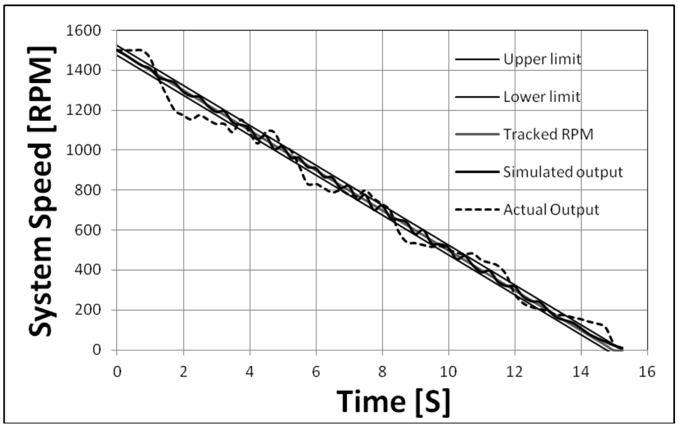

Figure.12 System response (Braking in 15 sec with a range ± 10 RPM)

VII. Conclusion

In the present paper a highly realistic mathematical model for BBW system is developed and validated experimentally in open loop mode on a specially developed lab setup. Then braking performance of a BBW system using sliding mode control strategy has been investigated. The sliding mode control strategy is applied to the mathematical model and the lab setup. The results of mathematical model and practical work are compared and presented in several figures. The developed controller shows a high performance in simulation. In practical tests the controller achieved the desired target with relatively small drift in breaking time by amount of 0.5%. The using of sliding mode controller shows a noticeable enhancement in braking performance is achieved with respect to the open loop control mode.

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