Intelligent Control of Electronic Wedge Brakes: A Fuzzy-SMC Approach with UKF-Based Friction Estimation

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Abstract— **An energy-efficient braking system that achieves high braking efficacy by utilising self-reinforcement is the Electronic Wedge Brake (EWB). Conversely, its vulnerability to fluctuations in the pad friction coefficient presents obstacles to the system's stability and robustness. The purpose of this paper is to investigate the performance of Fuzzy Sliding mode control (FSMC) technqiue to estimate and compensate the variations in the pad friction co-efficent and handle external disturbances. In addition, the system incorporates an Unscented Kalman Filter (UKF) to enhance the precision of the friction coefficient estimation, which allows for precise adaptive control adjustments. The control strategy proposed has been validated through extensive MATLAB/Simulink simulations, which have shown improved braking precision, enhanced robustness against friction coefficient variations, and superior performance in dynamic braking scenarios. The findings verify that the FSMC-based approach with UKF adaptation effectively mitigates the detrimental effects of friction variations, thereby enhancing the energy efficiency and stability of EWB systems.**

Keywords: Electronic Wedge Brake, Friction coefficient, Fuzzy, Sliding mode, Kalman Filter and Energy Efficiency

I. INTRODUCTION

The Electronic Wedge Brake (EWB) is a sophisticated brake-by-wire (BBW) system that utilises the self-reinforcement effect to accomplish highly energy-efficient braking [1]. EWB is a promising candidate for next-generation braking systems due to its ability to function within the standard 12V electrical architecture [2]. Siemens VDO, the original developer of EWB, reports that it utilises only 10 percent of the energy required by conventional hydraulic brakes and reduces the braking distance by 15 percent as a result of its rapid response characteristics. Consequently, EWB is universally recognised as one of the most promising BBW technologies, with ongoing research concentrating on the optimisation of wedge mechanisms to improve performance [3]. Nevertheless, the self-reinforcement effect, which is beneficial in terms of energy consumption, also introduces a high degree of sensitivity to parametric variations, particularly variance in the friction coefficient of the pad. Significant deviations in braking force, potential instability, and degraded performance can result from even minor variations in the pad-disc friction coefficient in EWB, which are amplified by the wedge mechanism [4]. To enhance robustness against system parameter variations, existing control strategies have primarily concentrated on PID-based cascade control [5] and PI-based state feedback control with parameter optimisation [6], despite the fact that EWB remains largely experimental. On the other hand, there has been a limited examination of adaptive control techniques that are specifically intended to account for real-time friction variations. A Fuzzy-based adaptation mechanism is integrated into a Sliding Mode Control (SMC) scheme in this paper to resolve these challenges. The FSMC structure substantially enhances tracking accuracy and reduces phase lag. In order to further reduce model uncertainties and disturbances, an adaptive fuzzy logic-based scheme is implemented to continuously estimate and compensate for friction variations. Additionally, a real-time estimation of the pad friction coefficient is implemented through the integration of an Unscented Kalman Filter (UKF)-based estimator. The adaptive approach not only improves robustness against friction fluctuations but also enables sensor-less clamp force estimation, thereby eradicating the necessity for dedicated force sensors and reducing system complexity and cost. In order to verify the proposed control framework, a series of simulations are conducted under varying friction conditions and external disturbances, illustrating substantial enhancements in braking performance, robustness, and stability. This research introduces an intelligent control solution that improves the practical feasibility of EWB systems for next-generation automotive braking applications by integrating Sliding Mode Control (SMC), Fuzzy Adaptation, and UKF-based Friction Estimation.

This paper consists of five sections such as one may find the background in section I. Section II shared the mathematical modelling whereas section III Shares the equations of proposed control techniques. One may find the results within Section IV. Section V concludes the work along with some future recommendations and provides further directions.

II. MATHEMATICAL MODELING

A typical Electronic Wedge Brake (EWB) system consists of a 12V DC motor responsible for generating the actuation force, a lead screw that converts the motor's rotational motion into linear displacement, and the brake assembly, which

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includes the wedge mechanism and the brake pad. Each of these subsystems is modeled individually and later integrated to develop a comprehensive dynamic model of the EWB system, as shown in Fig.[1] and adopted from [1].

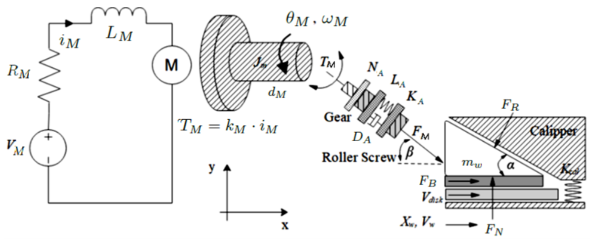

Fig. 1. Electronic Wedge Brake with a single motor variant

The DC motor is modeled using the following differential equations:

$$\dot{\omega}_m = -\frac{D_m}{J_m}\omega_m + \frac{K_t}{J_m}I_m - \frac{1}{J_m}T_l \tag{1}$$

$$\dot{I}_m = -\frac{K_e}{L_m}\omega_m - \frac{R_m}{L_m}I_m + \frac{1}{L_m}V_m \tag{2}$$

Lead Screw Dynamics: The lead screw force is modeled as:

$$F_m = K_a\left(\frac{\theta_m L_a N_a}{2\pi} - \frac{X_w}{\cos\beta}\right) + D_a\left(\frac{\omega_m L_a N_a}{2\pi} - \frac{V_w}{\cos\beta}\right) \tag{3}$$

The torque transmitted by the lead screw is given by:

$$T_{\text{screw}} = \frac{F_m L_a N_a}{2\pi\eta} \tag{4}$$

This torque is equivalent to the load torque from the motor's perspective:

$$T_l = T_{\text{screw}} \tag{5}$$

Wedge Mechanism Dynamics: The force balance equations in the x and y directions are written as:

$$F_m\cos\beta + \mu F_c - F_R\sin\alpha = M_w\ddot{V}_w \tag{6}$$

$$F_m\sin\beta + F_R\cos\alpha - F_c = M_w\ddot{V}_w\tan\alpha \tag{7}$$

Given the force relation:

$$F_c = K_{cal}X_w\tan\alpha \tag{8}$$

Combining the above and simplifying yields:

$$\dot{V}_w = \frac{F_m}{M_w(1+\tan^2\alpha)\cos\beta} + \frac{(\mu-\tan\alpha)K_{cal}\tan\alpha}{M_w(1+\tan^2\alpha)}X_w \tag{9}$$

State-Space Representation: The overall system dynamics can be represented in standard state-space form:

$$\dot{x} = Ax + Bu \tag{10}$$

$$y = Cx \tag{11}$$

with the state and output vectors defined as:

$$x = \begin{bmatrix} X_w & V_w & \theta_m & \omega_m & I_m \end{bmatrix}^T, \quad y = F_c$$

The system matrices are:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{a_1 a_4}{a_2} & -\frac{D_a a_4}{a_2} & \frac{K_a a_3}{a_2} & \frac{D_a a_3}{a_2} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_a a_3}{\eta J_m a_4} & \frac{D_a a_3}{\eta J_m a_4} & -\frac{K_a a_3^2}{\eta J_m} & -\frac{D_m + D_a a_3^2}{\eta J_m} & \frac{K_t}{J_m} \\ 0 & 0 & 0 & -\frac{K_e}{L_m} & -\frac{R_m}{L_m} \end{bmatrix} \tag{12}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{L_m} \end{bmatrix}^T \tag{13}$$

$$C = \begin{bmatrix} K_{cal}\tan\alpha & 0 & 0 & 0 & 0 \end{bmatrix} \tag{14}$$

Constants Used:

$$a_1 = K_{cal}\tan\alpha(\tan\alpha - \mu) \tag{15}$$

$$a_2 = M_w(1+\tan^2\alpha) \tag{16}$$

$$a_3 = \frac{L_a N_a}{2\pi} \tag{17}$$

$$a_4 = \cos\beta \tag{18}$$

where β is defined as:

$$\beta = \begin{cases} 0, & \text{for tangential motor force} \\ \alpha, & \text{for optimal motor force} \end{cases}$$

As per [9]-[10] Friction is modeled as a d_M viscous damping. The EWB model's performance and stability are affected by inherent non-linearities, notably in screw efficiency (varying significantly with driving/driven state), pad friction (speed and condition-dependent), wedge movement direction (especially at optimal actuation angles), and actuator time delay [11]-[13]. Ignoring these non-linearities by using a simplified linear model can lead to inaccurate predictions of EWB behavior, suboptimal control, instability under varying conditions, and ultimately compromise the safety and effectiveness of the braking system in real-world applications. Therefore, accurately accounting for these non-linearities is crucial for designing robust and reliable control strategies for Electronic Wedge Brakes [14]-[15].

III. Control Design

The control design for the Electronic Wedge Brake (EWB) system is presented in this section, with a particular emphasis on the performance evaluation of Sliding Mode Control (SMC) and Fuzzy Sliding Mode Control (FSMC). The purpose of these controls is to estimate and compensate for variations in the pad friction coefficient, as well as addressing external disturbances. The control system is further enhanced by the integration of the Unscented Kalman Filter (UKF) to improve the precision of the friction coefficient estimation, thereby facilitating more precise adaptive control adjustments.

TABLE I
LIST OF PARAMETERS FOR THE MOTOR MODEL

Symbol	Description
R_M	Motor resistance (in Ω)
L_M	Motor inductance (in H)
θ_M	Motor angle (in rad)
ω_M	Motor rate (in rad/s)
i_M	Motor current (in A)
u_M	Motor input voltage (in V)
J_M	Motor inertia (in Nm/rad/s^2)
k_M	Motor torque constant (in Nm/A)
d_M	Motor damping coefficient (in Nms/rad)
K_A	Axial stiffness (in N/m)
D_A	Axial damping coefficient (in Ns/m)

A. Sliding Mode Control (SMC)

Sliding mode Control (SMC) is an effective control method that is frequently implemented in systems [11-12] that are susceptible to disturbances and uncertainties. Stability and robustness are guaranteed by driving the system states to a predefined sliding surface and subsequently maintaining them on this surface. This is the objective of SMC. The system's state-space representation is defined as:

$$\dot{x} = Ax + Bu + Dd$$

$$y = Cx$$

$$u = -K \cdot \text{sgn}(s)$$

where x is the system state vector, u is the control input, d is the external disturbance, and K is the sliding mode control gain. The sliding surface s is designed as:

$$s = Cx$$

The control law drives the system toward the sliding surface and ensures that the trajectory remains on it once reached, despite any disturbances.

B. Fuzzy Sliding Mode Control (FSMC)

The fuzzy inference system within the FSMC utilizes a Mamdani-type controller with two inputs: the sliding surface s and its derivative $\dot{s}$, and one output: the adaptive control gain ΔK. The fuzzy logic controller employs a rule base structured around typical control heuristics. For instance, if both s and $\dot{s}$ are large, the gain is increased to ensure a stronger corrective action, whereas for small s and $\dot{s}$, the gain is reduced to minimize chattering. A representative subset of the fuzzy rules is as follows:

- **IF** s is Positive Large (PL) **AND** $\dot{s}$ is Positive Large (PL) **THEN** ΔK is High (H)
- **IF** s is Zero (Z) **AND** $\dot{s}$ is Zero (Z) **THEN** ΔK is Low (L)
- **IF** s is Negative Medium (NM) **AND** $\dot{s}$ is Positive Small (PS) **THEN** ΔK is Medium (M)

Seven linguistic variables were used for the inputs and outputs: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). The fuzzy rule base ensures that the control gain dynamically adjusts in real-time based on the system's tracking error and its rate, thereby enhancing the robustness and reducing chattering compared to conventional SMC. The final control input is then expressed as:

$$u = -(K + \Delta K) \cdot \text{sgn}(s) + \lambda \cdot \hat{\mu}$$

where ΔK is computed from the fuzzy inference system based on the current behavior of the sliding surface s.

C. Unscented Kalman Filter (UKF) for Friction Coefficient Estimation

The friction coefficient μ plays a crucial role in the braking system's performance. Variations in this coefficient can significantly affect the braking efficacy. To estimate and compensate for these variations, the Unscented Kalman Filter (UKF) is used to accurately estimate the friction coefficient in real-time. The UKF is preferred over other Kalman filters because of its ability to handle non-linearities, which are typical in friction estimation. The friction coefficient estimation can be represented by the following nonlinear dynamic model:

$$\mu = f(x, u) + \eta$$

where $f(x, u)$ is a nonlinear function sharing the friction dynamics whereas η denotes the process noise. The UKF provides the best estimate $\hat{\mu}$ by propagating the state and covariance through the non-linear system. The UKF algorithm focuses on two main key tasks:

1) **Prediction**: Utilise the system dynamics model to predict the subsequent state.
2) **Update**: Minimise the estimation error by updating the estimate in accordance with the new measurements.

$$u = -K \cdot \text{sgn}(s) + \lambda \cdot \hat{\mu}$$

The friction coefficient μ is then incorporated into the FSMC control law for real-time adaptation. Thus, after evaluating the related literature and mathematics behind traditional SMC, paper concludes that if fuzzy logic is integrated within SMC for our case, it will surely enhance the performance of EWB. This is the reason we have done simulations using FSMC Control design along with UKF for tackling the Friction coefficient estimation.

IV. RESULTS AND DISCUSSION

Simulation experiments were conducted to evaluate the performance of the controllers presented in the previous sections. For the controller design, the pad friction coefficient (μ_c) was set to a typical value of 0.35. The wedge angle was configured at 20°, and the screw efficiency (η) was assigned a value of 0.65, as mentioned in [9]. The desired settling time for the system response was targeted to be within the range of 0.2 to 0.25 seconds. A comparison between the controllers was performed, ensuring that they consumed the same input energy in the absence of modeling uncertainties, by configuring the control systems accordingly.

A. Simulation Results

The simulation model compares the proposed clamping force controller to a conventional sliding mode controller (SMC). The control algorithm is implemented in MATLAB. A look-up table [9] built from experimental data can simulate the power screw, a major source of nonlinearities in the EWB system. Our future research will cover this. Figure 2 exhibits model validation between simulation tool and derived model, while Figure 3 shows power screw efficiency fluctuation, which is about 4% of the nominal value at its minimum and maximum. Figure 4 shows the EWB system's step response and compares the fuzzy sliding mode controller to an SMC under various settings. Figures 5 compare SMC and FSMC controllers using predicted clamping force. Figure 6 compares the two controllers' clamping force signals. The fuzzy sliding mode controller with UKF outperforms the traditional SMC in both cases. Figure 6 shows the viability of fuzzy sliding mode control using UKF approach, which uses approximated clamping force.

B. Technical Discussion

The simulation results show that the Fuzzy Sliding Mode Controller (FSMC) with Unscented Kalman Filter (UKF) regulates the Electro-Mechanical Brake (EWB) system clamping force better than the SMC. The nonlinear power screw mechanism, a primary source of disturbances in EWB systems, makes the FSMC essential for robustness, precision, and disturbance rejection. By adjusting pad friction coefficient (c) to 0.35, wedge angle to 20°, and screw efficiency () to 0.65, the controller may achieve a settling time of 0.2 to 0.25 seconds, meeting the demands of high-performance braking systems. Comparing FSMC with SMC ensures that both controllers operate within the same energy constraints, making their efficacy evaluation fair. FSMC clamping force responses consistently outperform SMC clamping force responses, demonstrating its superior flexibility to system nonlinearities and external disturbances. The proposed control methods are supported by the look-up table model based on experimental data in [9], which efficiently estimates the power screw's nonlinear properties. FSMC and UKF improve state estimation precision, which is crucial for optimal braking efficacy in variable and changing operational conditions. These findings demonstrate that FSMC can be used in real brake systems to provide more accurate and robust control than SMC-based techniques.

V. CONCLUSIONS

The Fuzzy Sliding Mode Controller (FSMC) with Unscented Kalman Filter (UKF) is compared to the normal SMC for clamping force management in Electro-Mechanical Braking (EWB) systems. Transient and steady-state performance and power screw mechanism nonlinearities are better handled by FSMC than SMC in simulations. With c = 0.35, wedge angle = 20°, and screw efficiency = 0.65, the suggested controller achieves a settling time of 0.2 to 0.25 seconds. Fairly comparing both controllers under the same energy restrictions showed the FSMC's superior robustness and accuracy. FSMC integration with UKF improved state estimate and real-time braking disturbance and uncertainty adjustment. Experimental data shows that the look-up table model accurately estimates power screw nonlinearities, proving the control technique's reliability. Future research should include experimental datasets and refine the power screw model with adaptive modelling or machine

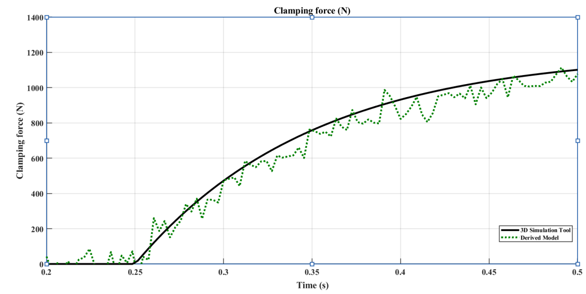

Fig. 2. Model Validation b/w Simulation tool and Derived model

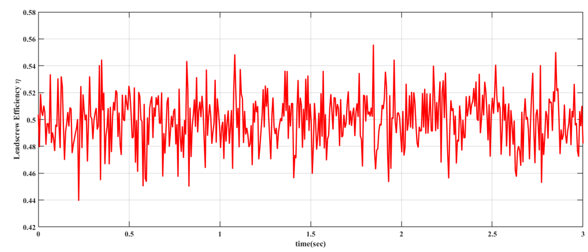

Fig. 3. Illustration of Power screw efficiency

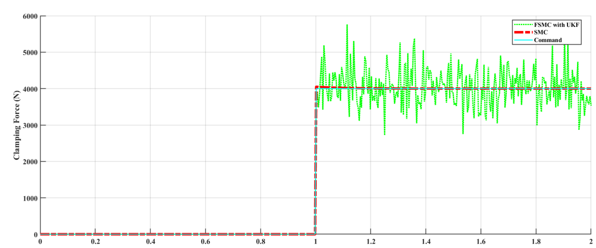

Fig. 4. Step response of EWB system: FSMC + UKF and SMC

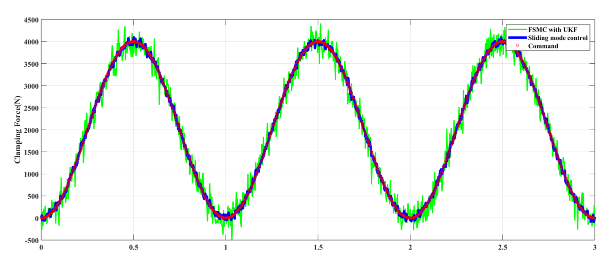

Fig. 5. Clamping force control with reference to estimated clamping force: FSMC with UKF and SMC

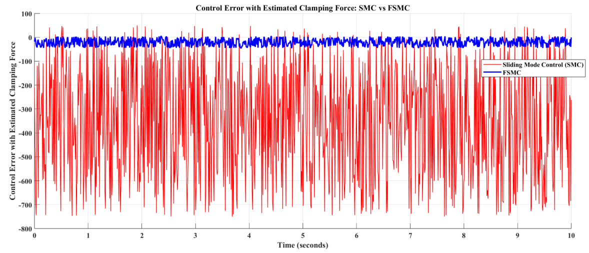

Fig. 6. Control error with reference to estimated clamping force: FSMC + UKF and SMC

learning to eliminate system nonlinearities. Particle filters and deep learning models increase real-time clamping force estimation, improving system performance in dynamic and uncertain environments. Next-generation intelligent braking systems will benefit from these control accuracy, dependability, and adaptability improvements. Our future task is real-time comparison validation.

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