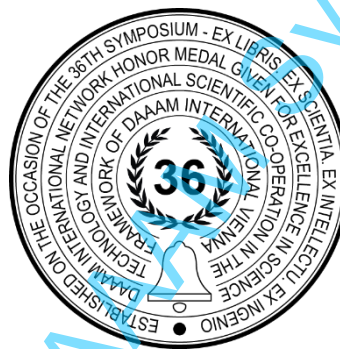


IMPACT OF FRICTION MODEL SELECTION ON THE DYNAMIC BEHAVIOUR OF AN ELECTRO HYDRAULIC BRAKE PRESSURE GENERATION UNIT

Zaid Al-Dailami, Simon Vojtech, Lukas Hubka & Jaroslav Hlava



This Publication has to be referred as: Al-Dailami, Z[aid]; Vojtech, S[imon]; Hubka, L[ukas] & Hlava, J[aroslav] (2026). Impact of Friction Model Selection on the Dynamic Behaviour of an Electro Hydraulic Brake Pressure Generation Unit, Proceedings of the 37th DAAAM International Symposium, pp.xxxx-xxxx, Z. Al-Dailami (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/37th.daaam.proceedings.xxx

Abstract

The Pressure Generation Unit (PGU) is the key actuator in an Electro Hydraulic Brake (EHB) system, where accurate friction modelling is essential for realistic pressure generation and reliable system simulation. This paper compares two friction modelling approaches for a physics-based PGU model: the Hyperbolic Tangent model and the dynamic LuGre model. The Hyperbolic Tangent model offers a simple and computationally efficient representation of friction, while the LuGre model is more complex and captures nonlinear friction effects such as hysteresis, pre-sliding displacement, and the Stribeck effect. Both models are implemented using equivalent formulations in Simulink and manually written C-code to enable a direct comparison under identical operating conditions. Their performance is evaluated by analysing load, plunger displacement, and plunger velocity responses, with the simulated plunger displacement also validated against experimental measurements. The results show that the LuGre model provides a more realistic representation of the PGU dynamics, with closer agreement to the measured plunger displacement, particularly during low-speed operation and motion reversal, while the Hyperbolic Tangent model remains an efficient alternative for applications where computational cost is a primary concern. In addition, the compiled C-code implementation enabled efficient integration into the complete EHB model and completed the simulation approximately three times faster, demonstrating its suitability for Software-in-the-Loop (SiL) and future real-time embedded automotive applications.

Keywords: Electro Hydraulic Brake; Pressure Generation Unit; LuGre Friction Model; Hyperbolic Tangent Friction Model; Software-in-the-Loop (SiL).

1. Introduction

Driven by the increasing demand for enhanced vehicle safety and efficiency, Brake-by-Wire (BBW) systems have emerged as a key technology in modern automotive braking. These systems replace, either partially or completely, the conventional mechanical linkage between the brake pedal and the wheel brakes with electronically controlled actuation.

Compared with conventional hydraulic braking systems, BBW technologies provide faster response, improved pressure modulation and seamless integration with advanced vehicle functions such as Anti-lock Braking Systems (ABS), Electronic Stability Control (ESC), Automatic Emergency Braking (AEB) and regenerative braking.[1] Among the different BBW architectures, Electro Hydraulic Braking (EHB) has grown as one of the most practical solutions because it combines the proven reliability of hydraulic braking with the flexibility and precision of electric actuation, making it well suited for modern and electric vehicles [2].

A key component of the EHB system is the Pressure Generation Unit (PGU), which is responsible for producing the hydraulic pressure required for brake actuation. As the actuator directly governs pressure generation, its dynamic behaviour has a substantial influence on braking performance, pressure tracking accuracy, and the overall stability of the braking system [3]. As a result, developing an accurate mathematical representation of the PGU is essential for controller design, system optimisation, and virtual validation prior to experimental testing.

One of the main challenges in modelling the PGU is the accurate representation of mechanical friction. Friction arises from the interaction of the moving components within the transmission mechanism and exhibits strongly nonlinear behaviour, particularly during low-speed motion, direction reversals, and transient operating conditions. These effects include stick-slip motion, hysteresis, and pre-sliding displacement, all of which can significantly influence pressure generation and actuator response. If such nonlinearities are not adequately captured, the simulation may fail to reproduce the behaviour of the physical system accurately, leading to reduced confidence in pressure prediction and control development [4]. Experimental studies have also shown that nonlinear friction effects, such as stick-slip behaviour and friction memory, can strongly influence the agreement between simulated and measured responses [5].

Various friction models have been proposed to represent these nonlinear characteristics. Simple static models, such as the Coulomb model and its continuous Hyperbolic Tangent approximation, are computationally efficient and straightforward to implement, making them attractive for real-time applications. However, they cannot accurately reproduce dynamic friction effects such as friction memory, hysteresis and pre-sliding displacement. Dynamic friction models, particularly the LuGre model, overcome these limitations by introducing an internal state that describes the average deformation of microscopic surface asperities, enabling realistic representation of stick-slip motion, the Stribeck effect and hysteresis under varying operating conditions [6],[7],[8]. Although the LuGre model generally provides higher simulation fidelity, its increased computational complexity may become a limitation for embedded real-time applications.

The increasing complexity of EHB systems has also changed the product development process, making Model-Based Design (MBD) the preferred approach for system development and validation. MBD enables engineers to evaluate system behaviour and optimise control strategies using executable mathematical models before hardware implementation [9]. Through the progressive validation stages of Model-in-the-Loop (MiL), Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL), potential design issues can be identified early, reducing development time, cost and dependence on physical prototypes [10]. Erler and Essers demonstrated a similar validation approach in which the same virtual model was used for both SiL and HiL testing [11]. In automotive braking, Simulink-based ABS models have also been validated experimentally, with HiL recognised as an important tool for testing electronic braking systems [12].

Although extensive research has been conducted on brake pressure control and friction compensation in EHB systems and numerous friction models have been proposed to represent nonlinear friction behaviour, limited attention has been given to comparing the influence of different friction models on the dynamic response of the PGU itself. Furthermore, few studies have investigated the trade-off between simulation accuracy and computational efficiency using equivalent implementations in both Simulink and embedded C code, which is essential for real-time automotive applications. Therefore, this paper presents a physics-based PGU model incorporating two friction modelling approaches: the Hyperbolic Tangent model and the dynamic LuGre model. Both models are implemented using equivalent formulations in Simulink and manually written C-code and evaluated under identical braking conditions. Their influence on friction force, hydraulic pressure generation and overall system behaviour is analysed, providing guidance for selecting an appropriate friction model for virtual validation and future real-time automotive BBW systems.

2. Pressure Generation Unit and Friction Modelling

PGU is the core electromechanical actuator of the EHB system, responsible for generating the hydraulic pressure required for brake actuation. It converts the rotational motion of the electric motor into the linear displacement of a plunger through a ball screw–ball nut mechanism. The dynamic behaviour of the PGU is governed by the interaction between the mechanical transmission, hydraulic forces, and friction acting on the moving components. Therefore, an accurate mechanical model is essential for evaluating the influence of different friction modelling approaches on the overall system response.

2.1 PGU Architecture

The mechanical model describes the behaviour of the plunger within the PGU. As illustrated in Figure 1, the ball screw is directly coupled to the plunger and converts the rotational motion of the electric motor into a linear displacement. The plunger separates the hydraulic circuit into two pressure chambers with different effective cross-sectional areas. During normal brake actuation, the motor drives the plunger forwards. In this operating mode, hydraulic pressure is generated in the large chamber, whose effective area is defined by the full cross-sectional area of the large plunger

diameter. The resulting hydraulic force acting on the plunger is therefore determined by the pressure in the large chamber and its corresponding effective area.

When the plunger reaches its maximum forward travel and additional brake pressure is required, the PGU switches to the reverse pressure-generation mode. The relevant hydraulic valves are actuated, and the motor reverses the direction of plunger motion. During the backward stroke, pressure is generated in the small chamber. The effective hydraulic area in this mode is the annular area formed by the difference between the cross-sectional areas of the large and small plunger diameters. The smaller effective area during the reverse stroke allows the PGU to generate additional hydraulic pressure while the plunger moves backwards. Since friction influences the plunger motion and the resulting pressure response in both operating modes, static friction, referred to as stiction, and sliding friction are included in the mechanical model.

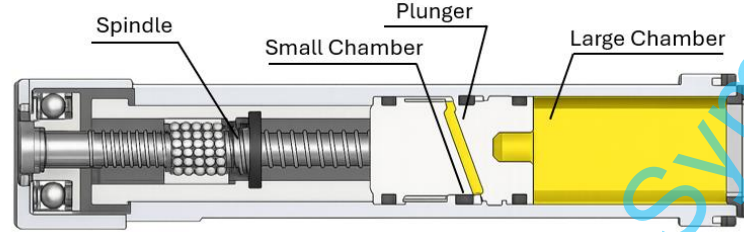


Fig. 1. Cross-sectional view of PGU

3.2 Mechanical Dynamics

The translational motion of the plunger is described by Newton's second law. It considers all significant forces acting on the moving assembly. These include the spindle driving force, hydraulic forces generated in the large and small chambers, friction, and the stiffness and damping forces generated at the mechanical end stops. The resulting equation of motion is:

$$M_{eq}\ddot{x}_{PGU} = F_{spindle} + F_{small} - F_{large} - F_{friction} - (F_{contactS} + F_{contactD}) \quad (1)$$

where M_{eq} denotes the equivalent moving mass of the motor and PGU assembly. The spindle force $F_{spindle}$ is generated by the ball screw mechanism and provides the driving force for the plunger. The hydraulic forces F_{large} and F_{small} correspond to the pressures acting on the effective areas of the large and small chambers, respectively. The friction force $F_{friction}$ represents the resistance to motion and is modelled using either the Hyperbolic Tangent or the LuGre friction model. Finally, $F_{contactS}$ and $F_{contactD}$ represent the stiffness and damping components of the end-stop contact force, preventing unrealistic motion beyond the mechanical travel limits.

3.3 Friction Modelling

To investigate the influence of friction representation on the dynamic response of the PGU, two friction models are implemented and compared: a Hyperbolic Tangent friction model and the LuGre dynamic friction model. In both cases, the friction force $F_{friction}$ replaces the corresponding term in equation 1.

Hyperbolic Tangent Friction Model

The Hyperbolic Tangent model provides a smooth approximation of Coulomb friction while eliminating the discontinuity at zero velocity. The hyperbolic tangent friction force is expressed as:

$$F_{friction} = F_{max} \tanh(kv) \quad (2)$$

where v is the spindle velocity, F_{max} is the maximum friction force, and k controls the transition steepness around zero velocity. Although computationally efficient and numerically robust, this model cannot reproduce pre-sliding displacement, hysteresis, or the Stribeck effect.

LuGre Friction Model

Unlike the Hyperbolic Tangent model, the LuGre model represents friction as a dynamic process by introducing an internal state variable that characterises the average deflection of the bristles at the contact interface. This enables the model to capture pre-sliding displacement, hysteresis, varying static friction, and the Stribeck effect. The steady-state friction characteristic is described by the Stribeck function:

$$g(v) = F_c + (F_s - F_c) e^{-\left(\frac{v}{v_s}\right)^2} \quad (3)$$

where F_c denotes the Coulomb friction level, F_s the static friction level, v_s the Stribeck velocity, and v is the plunger velocity.

The evolution of the internal bristle state is given by:

$$\dot{z} = v - |v| \sigma_0 \cdot \text{sat}\left(\frac{z}{g(v)}\right) \quad (4)$$

where z represents the average bristle deflection and σ_0 is the bristle stiffness.

The resulting LuGre friction force is calculated then as:

$$F_{\text{friction}} = \sigma_0 z + \sigma_2 v \quad (5)$$

In the implemented model, both the static and Coulomb friction levels are continuously adapted according to the hydraulic load acting on the plunger and the current operating mode of the PGU. This allows the model to reproduce load-dependent friction characteristics while preserving the dynamic behaviour described by the LuGre formulation.

The simulations that is performed in MATLAB/Simulink used the fixed-step ode3 Bogacki–Shampine solver with a step size of 100 μ s. The same solver settings, model parameters, initial conditions, and input profiles are used for both friction models to ensure a consistent comparison.

The experimental validation is carried out directly on the physical PGU, where the plunger displacement is measured using a displacement sensor under the same operating conditions as the simulation. This allows a direct comparison between the measured response and the behaviour predicted by the two friction models. The experimental signal naturally contains the measurement noise present in the test setup, and no additional noise is introduced into the simulation. For real-time implementation, a representative ECU control-cycle requirement of 1 ms is considered as the target execution limit for the compiled C-code. The LuGre parameters represent the combined friction behaviour of the PGU and account for variations in hydraulic load and direction of plunger motion. In this manner, the main friction effects of the different contact interfaces are represented through an equivalent friction model rather than by modelling each contact surface alone.

3. Results and discussion

This section presents the validation of the proposed friction modelling approach at both the component and system levels. First, the Hyperbolic Tangent and LuGre friction models are compared at PGU level to evaluate their influence on the actuator dynamics. Subsequently, the selected LuGre model is implemented as compiled C-code and integrated into the complete EHB system. The compiled C-code implementation is then compared with the pressure request signals from the ECU to verify the suitability of the model for SiL and future HiL applications.

2.2 Component-Level Validation

The Hyperbolic Tangent and LuGre friction models are compared at the PGU component level to evaluate the influence of friction model selection on the dynamic response of the EHB system. Both models are implemented in Simulink using their respective mathematical formulations, while all remaining model parameters and operating conditions are kept identical to ensure a consistent comparison. Experimental measurements of the plunger displacement are also included to validate the simulation results. Figure 2 presents the load, plunger displacement, and plunger velocity responses.

Both friction models accurately follow the requested load profile, with only minor differences under steady-state conditions. In one hand, the LuGre model provides smoother load tracking with reduced overshoot and fewer oscillations during transient operation, whereas the Hyperbolic Tangent model exhibits noticeable oscillations, particularly during motion reversal and rapid load changes.

The experimental plunger displacement shows that the LuGre model agrees more closely with the measured response throughout the operating cycle. Specifically, after the load is released, the experimental response returns smoothly without oscillations, which is accurately reproduced by the LuGre model. On the other hand, the Hyperbolic Tangent model exhibits overshoot and oscillations that are not observed experimentally. Similar behaviour is reflected in the plunger velocity, where the LuGre model produces smoother transitions, while the Hyperbolic Tangent model generates higher velocity peaks and oscillatory behaviour.

All in all, the results demonstrate that the LuGre model provides a more realistic representation of PGU dynamics by accounting for dynamic friction effects such as pre-sliding displacement, hysteresis, and friction memory. Therefore, it is better suited for high-fidelity EHB simulations, while the Hyperbolic Tangent model remains a simpler alternative with lower computational complexity.

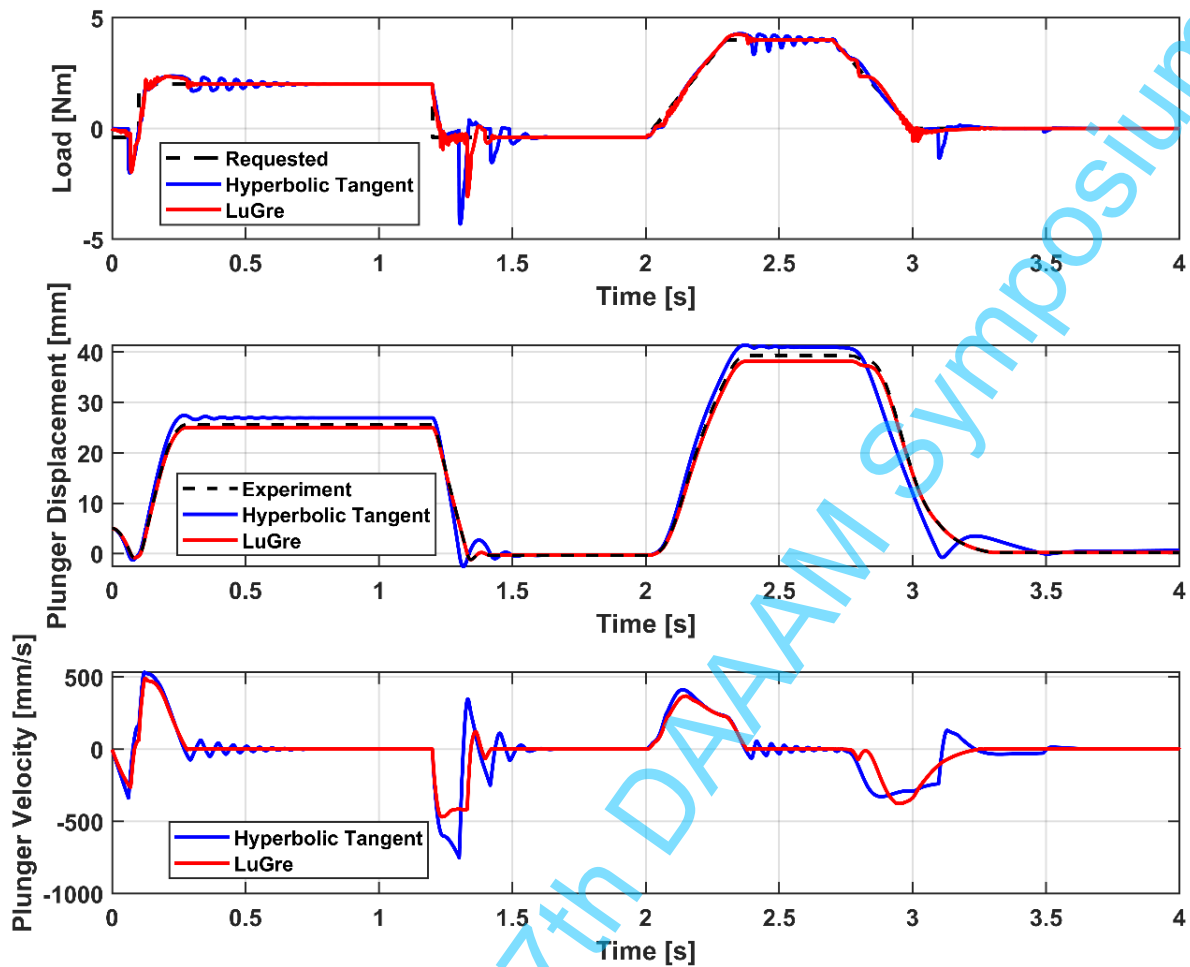


Fig. 2. Comparison of Hyperbolic Tangent and LuGre friction models

2.3 System-Level Validation

Following the component-level validation, the LuGre friction model is implemented as compiled C-code and integrated into the complete EHB system. This implementation enables deployment of the model to real-time hardware platforms for SiL and future HiL validation. The model is evaluated using brake pressure demand signals recorded from the ECU during representative braking manoeuvres. Figure 3 presents the requested and generated brake pressure responses for all four wheel calipers.

The compiled LuGre model follows the requested brake pressure profiles in all four brake channels. The overall pressure build-up and release characteristics are well reproduced, while small deviations are observed mainly during rapid transient phases. These differences are expected because the brake pressure is generated through the complete nonlinear EHB system, where actuator dynamics, hydraulic behaviour, and friction effects influence the response. Nevertheless, the generated pressures closely follow the requested profiles throughout the braking manoeuvres, demonstrating stable and consistent system behaviour.

The results confirm that the compiled LuGre friction model can be successfully integrated into the complete EHB model while preserving the desired dynamic response. In addition, the compiled C-code implementation executed approximately three times faster than the equivalent Simulink model, demonstrating its suitability for computationally efficient SiL, HiL, and future embedded real-time applications.

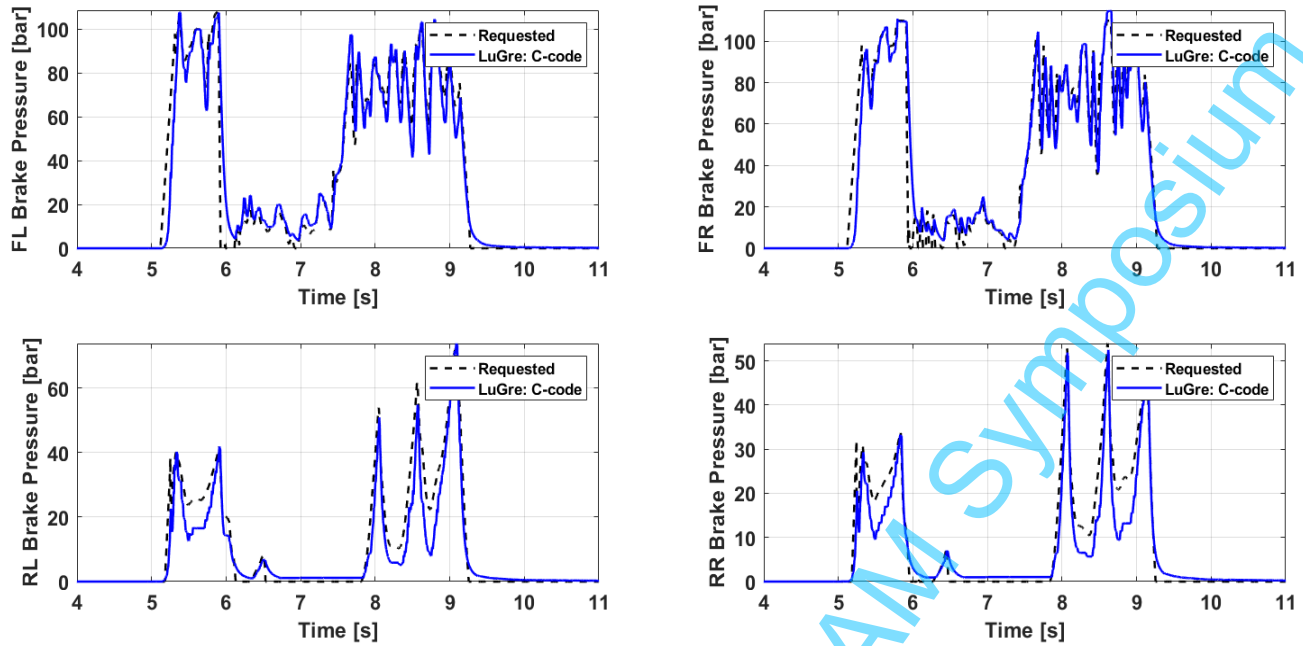


Fig. 3. System-level brake pressure response of the compiled C-code LuGre model

4. Conclusion

This paper presented a comparative evaluation of the Hyperbolic Tangent and LuGre friction models for the PGU of an EHB system. The comparison demonstrated that the LuGre friction model provides a smoother transient response, with reduced oscillations in load, plunger velocity, and plunger displacement owing to its ability to capture dynamic friction phenomena like pre-sliding displacement and hysteresis. On the other hand, the Hyperbolic Tangent model exhibited faster but more oscillatory behaviour while remaining computationally efficient. Based on these findings, the LuGre model is implemented as compiled C-code and integrated into the complete EHB system. The system-level validation showed excellent agreement between the compiled C-code implementations and pressure requests, confirming that the model can be translated into embedded code without significantly affecting its dynamic behaviour. Furthermore, the compiled C-code implementation completed the simulation approximately three times faster than the equivalent Simulink model, demonstrating its suitability for real-time execution and providing a reliable basis for SiL applications.

Future work will focus on deploying the compiled model on a HiL platform and evaluating its performance under a wider range of braking scenarios and operating conditions to further assess its robustness and real-time applicability.

5. Acknowledgments

This work was supported by the Student Grant Competition of the Technical University of Liberec under project No. SGS-2026-3594.

6. References

- [1] Li, C.; Zhuo, G.; Tang, C.; Xiong, L.; Tian, W.; Qiao, L.; Cheng, Y. & Duan, Y. (2023). A Review of Electro-Mechanical Brake (EMB) System: Structure, Control and Application. *Sustainability*, 15(5), 4514.
- [2] Liu, H.; Wei, L.; Liu, H.; Wu, J. & Li, L. (2022). Brake Pressure Estimation of the Integrated Braking System Considering Vehicle Dynamics. *Actuators*, 11(11), 329.
- [3] Han, W.; Xiong, L. & Yu, Z. (2019). Braking Pressure Control in Electro-Hydraulic Brake System Based on Pressure Estimation with Nonlinearities and Uncertainties. *Mechanical Systems and Signal Processing*, Vol. 131, 703–727.
- [4] Chen, Z.; Ding, R.; Zhou, Q. & Wang, R. (2026). Study on precise control of braking pressure in an electro-hydraulic brake system. *Journal of Vibration and Control*, in press. DOI: 10.1177/10775463261459083
- [5] Piscan, I.; Janssens, T. & Predincea, N. (2011). Experimental Validation of FEM for Frictional Contacts. *Proceedings of the 22nd DAAAM International Symposium*, Vienna, Austria.
- [6] Ren, Z.; Cui, Y.; Hui, W. & Xie, X. (2026). Dual-Layer Sliding Mode Motion Control of Piezoelectric Stick-Slip Actuator Based on Nonlinear Extended State Observer. *Smart Materials and Structures*, 35, 015055.
- [7] Márton, L. & Lantos, B. (2009). Control of Mechanical Systems with Stribeck Friction and Backlash. *Systems & Control Letters*, 58(2), 141–147.

- [8] Do, N. B.; Ferri, A. A. & Bauchau, O. A. (2007). Efficient Simulation of a Dynamic System with LuGre Friction. *Journal of Computational and Nonlinear Dynamics*, Vol. 2(4), 281–289.
- [9] Kelemen, M.; Virgala, I.; Kelemenová, T.; Miková, L.; Frankovský, P. & Lipták, T. (2013). Model Based Design and HIL Simulations. *American Journal of Mechanical Engineering*, 1(7), 276-281.
- [10] Shylla, D.; Jain, A.; Shah, P. & Sekhar, R. (2023). Model in Loop (MIL), Software in Loop (SIL) and Hardware in Loop (HIL) Testing in MBD. *Proceedings of the 2023 4th IEEE Global Conference for Advancement in Technology (GCAT)*, Bangalore, India, 1–6, DOI: 10.1109/GCAT59970.2023.10353323.
- [11] Erler, M. & Essers, M. (2012). Approach for Generation of Complete Virtual Machine Tools Based on a Unified Model Description. *Proceedings of the 23rd DAAAM International Symposium*, Vienna, Austria.
- [12] Beles, H.; Rus, A.; Dragomir, G.; Mitran, T.; Trusca, D. & Tolea, B. (2015). Researches Regarding the Continuous Improvement of the ABS (Anti-Lock Braking System) Operation for the Passenger Cars. *Proceedings of the 26th DAAAM International Symposium*, Vienna, Austria.

Working Paper of 37th DAAAM Symposium