Automated Modeling of an Electromagnet with Magnetorheological Fluid

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ABSTRACT

This article presents an automated system for the design, analysis, and optimization of Electromagnetic Systems (EMSs) using Magnetorheological (MR) fluids. The system integrates MATLAB with the Finite Element Method Magnetics (FEMM) environment to solve both direct and inverse design problems, optimize parameters, and visualize results through graphical and tabular representations. Featuring a user-friendly graphical interface, the system simplifies the design process by allowing engineers to select materials, input parameters, and generate dependency graphs for various device characteristics. Machine Learning (ML) algorithms are employed for parameter optimization, whereas finite element analysis ensures accurate magnetic field modeling. The results demonstrate the system's effectiveness in improving design efficiency and accuracy, with applications ranging from optimizing the velocity of movement of the MR fluid magnetic particles bridge front and the electromagnetic force acting on the MR fluid magnetic particles bridge front to visualizing magnetic field distributions. The proposed scalable and adaptable system is a valuable tool for engineers working on MR fluid-based devices. Future work may focus on extending its capabilities to include real-time control and advanced multiphysics simulations.

Keywords-electromagnetic system; automated system; magnetorheological fluid; optimal design

I. INTRODUCTION

The design of Magnetorheological (MR) fluid-based devices involves the integration of multiple physical phenomena, including Electromagnetic (EM), thermal, mechanical, and control systems. Engineers rely on specialized software tools to effectively model, simulate, optimize, and control these complex systems. For magnetic field modeling, widely used tools include ANSYS Maxwell, COMSOL Multiphysics, and Finite Element Method Magnetics (FEMM). The following is a review of recent studies that demonstrates how these software environments have been utilized to address challenges in MR device design.

A. Applications of COMSOL Multiphysics

COMSOL Multiphysics has been used extensively to model and optimize MR devices by analyzing magnetic fields, mechanical behavior, and multiphysics interactions. For instance, authors in [1] developed an energy-harvesting MR damper and optimized its magnetic field properties using finite element analysis. Authors in [2] employed COMSOL to improve torque transmission in an MR clutch by designing a new seal and analyzing fluid flow characteristics. Authors in [3] investigated the magnetic and mechanical behavior of an MR clutch with a Halbach array, using COMSOL to evaluate magnetic flux density and shear stress distributions. Similarly, authors in [4] developed a multiphysics coupling model for an MR damper, integrating electromagnetic and mechanical analyses to improve performance. Authors in [5] optimized a segmented Halbach array for MR brakes, leveraging COMSOL to model complex magnetic fields and improve braking torque. Other notable applications include investigating the impact of soft magnetic particles on MR gel clutches [6], analyzing circular sector pole head designs for multipole MR brakes [7], and verifying optimization algorithms for MR dampers [8]. In addition, authors in [9] simulated hybrid-mode MR drum brakes, and authors in [10] predicted the damping force characteristics of small-scale MR dampers to ensure accurate prototype fabrication.

B. Applications of Finite Element Method Magnetics

FEMM has proven instrumental in analyzing magnetic fields and optimizing material selection for MR devices. For example, authors in [11] conducted a magneto-static analysis for a 10-disk MR brake to improve magnetic field distribution and torque performance. Authors in [12] investigated the material properties and geometric dimensions for scaled MR brakes to maximize magnetic induction in the fluid gap. Authors in [13] designed a pressure relief valve using FEMM and determined the optimal parameters for efficient operation. Authors in [14] developed a lightweight four-rotor MR brake to improve the torque-to-weight ratio through magnetic flux density analysis. Furthermore, authors in [15] enhanced the damping properties of MR actuators for vehicle suspensions by achieving a uniform magnetic flux distribution. Authors in [16] optimized the structural parameters of MR brakes by evaluating the magnetic flux concentration to improve torque transmission.

C. Applications of ANSYS

ANSYS software has been extensively used to analyze and optimize MR devices, focusing on electromagnetic and thermal simulations. Authors in [17] integrated neural networks with ANSYS-APDL to optimize MR valve performance by predicting the magnetic flux density. Authors in [18] resolved the "block-up phenomenon" in MR dampers by optimizing the flow path diameter using ANSYS Maxwell. Authors in [19] analyzed the effects of piston material and fluid gap on MR dampers to improve the damping force. A vane-type MR brake for orthosis devices was designed in [20], by optimizing the torque characteristics. Additionally, authors in [21] developed a hybrid multi-plate MR clutch and conducted magnetic field analysis for high-performance operation. Magnetic flux density in MR dampers was maximized in [22], and key influencing factors were identified. Finally, multi-field simulations for MR brakes were conducted in [23] to ensure robust performance under thermal and structural stresses.

D. Applications of MATLAB

MATLAB has been widely used for control system development, optimization, and fault diagnosis in MR devices. For example, authors in [24] simulated MR brakes for automotive applications and calculated the braking torque at different stopping times. Authors in [25] designed semi-active suspensions for electric vehicles by implementing PID-controlled MR dampers to improve driving comfort. Authors in [26] used magnetorheological elastomers to mitigate delamination during drilling, reducing the thrust force by 45%. Image processing techniques in MATLAB were used in [27] for intelligent diagnosis of MR clutches, identifying faults such as disk eccentricity. MATLAB was co-simulated with ADAMS in [28] to develop adaptive control algorithms for MR dampers in knee prostheses. ADAMS software was used in [29] for parametric analysis of the MR strut. Torsional buckling in sandwich structures with MR fluid cores was analyzed in [30]. MATLAB was also integrated with COMSOL in [31] to optimize asymmetric MR dampers. The pressure drop performance of MR valves was improved in [32], and vibration control strategies for MR suspensions were simulated in [33]. Finally, authors in [34] developed multidimensional models for frame structures with MR dampers, demonstrating a significant reduction in seismic displacements.

E. Developing an Automated Modeling System

Based on the analysis presented, the following conclusions can be drawn. ANSYS excels at simulating electromagnetic effects, whereas COMSOL Multiphysics supports multiphysics coupling, enabling the analysis of thermal and mechanical interactions alongside electromagnetic phenomena. FEMM, a free and open-source tool, is particularly well suited for simpler 2D magnetic field modeling and prototyping. It is often integrated with MATLAB/Simulink to facilitate advanced simulations and mathematical modeling. Therefore, the development of efficient, user-friendly, and scalable automated systems for engineering modeling is essential. Such systems should integrate calculations and analyses into a unified framework. In this context, automation accelerates design iterations, optimizes parameters, and facilitates real-time control implementation using tools such as MATLAB and FEMM. This ensures scalability and adaptability for future applications.

This article focuses on the development of an automated system within the MATLAB environment for the optimal design of MR brakes by incorporating the FEMM environment. The proposed system integrates magnetic field modeling and optimization algorithms to efficiently address the complexities of MR fluid-based systems.

II. MATERIALS AND METHODS

The authors have developed mathematical models [35] for a group of braking devices with MR fluid [36, 37], shown in Figure 1, conducted a parametric analysis [38], and applied Machine Learning (ML) methods to optimize the model parameters [39, 40]. In this context, a hybrid mathematical model consisting of a system of equations incorporating both linear and nonlinear elements was developed, as given in (2) of [38]. It is assumed that the magnetic particles in the fluid are in the form of cubes and spheres.

The model enables the solution of both direct and inverse problems of the magnetic circuit [38]. Specifically, given the magnetic flux Φ, the dimensions of the Electromagnetic System (EMS), and the materials of the stator and rotor, the direct problem determines the magnetomotive force F. Conversely, if F is known, Φ can be calculated. During the solution process, additional parameters of the magnetic circuit are also determined, including the magnetic induction across different regions, magnetic field intensities, magnetic fluxes, and other key characteristics [38]. In [38], mathematical expressions were derived to determine the EM force P_E acting on the frontal surface of the magnetic particle bridge and the velocity v of the bridge front. A parametric analysis of the model was conducted, revealing the behavior of the parameters F, Φ, P_E, and v as functions of other system parameters [38]. Furthermore, the adequacy of the hybrid mathematical model has been demonstrated, confirming its alignment with the physical phenomena observed in the studied EMS.

(a)

(b)

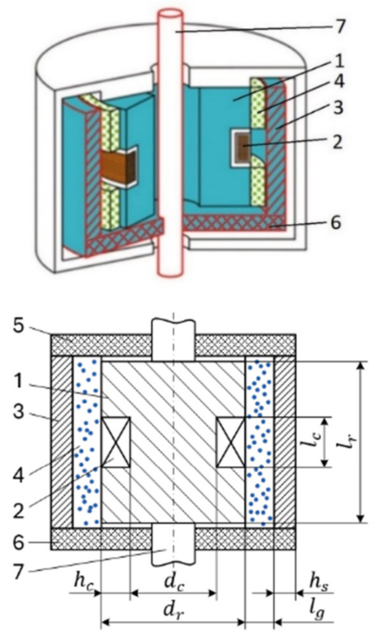

Fig. 1. MR fluid brake: (a) its block scheme, and (b) 1-ferromagnetic rotor; 2-control coil; 3-ferromagnetic stator; 4-magnetorheological fluid with magnetic particles; 5,6-non-magnetic cover; 7-shaft.

In [40], two single-objective optimization problems were formulated to address the optimization of MR brake parameters. The first problem aimed at maximizing the EM force (P_E) acting on the bridge front of the MR fluid's magnetic particles, for a given magnetomotive force (F) of the brake's control coil. The second problem sought to maximize the velocity (v) of the MR fluid magnetic particle bridge front for the same value of F. For both problems, the optimization variables included the structural dimensions d_r, h_s, h_c, l_r, l_c shown in Figure 1, within predefined value ranges, as well as the coil voltage U (12, 24, 48 V). To solve the formulated optimization problems using ML methods, inverse problems were solved for the given ranges of structural dimensions and control coil voltage, resulting in the creation of a database. Additionally, the control coil of the brake was designed for all cases, including the selection of the control coil winding conductor and the calculation of coil parameters such as heating temperature. Cases where the control coil temperature exceeded the allowable limit for the winding conductor, rendering the design non-operational, were also included in the database. The database was trained for both classification and prediction tasks. First, it was trained to determine the operational feasibility of the electromagnet for arbitrary values of d_r, h_s, h_c, l_r, l_c, and U. Subsequently, it was trained to predict the target function values of P_E and v. ML models from MATLAB's Classification Learner and Regression Learner tools were utilized for these classification and prediction tasks. Following the successful classification and prediction of P_E and v for arbitrary values of d_r, h_s, h_c, l_r, l_c, and U, as well as the determination of the electromagnet's operational status, a genetic algorithm was applied to the trained dataset to optimize the system parameters. In [40], the authors applied ML algorithms for the optimal design of another EMS - an electromagnet with a straight armature.

The results obtained in [35, 38, 40] have enabled the development of an automated system for designing EM devices with MR fluid, which is described in the next section of the article.

III. AUTOMATED MODELING AND OPTIMIZATION OF EMS WITH MR FLUID

The automated system enables the modeling of an EMS (brake) with MR fluid in accordance with specified conditions, allowing the selection of materials and the input of required parameter values. The automated modeling system has been implemented in the MATLAB environment with the integration of FEMM tools and consists of three main functional layers:

- A layer for data input and result output through a Graphical User Interface (GUI).
- A database (library of materials used).
- A core (solving module) responsible for performing all the necessary calculations.

The graphical interface is designed to facilitate interaction between the designer and the automated system. It is fully implemented using MATLAB's App Designer tool and UI Components functions. Upon launching the system, the main window shown in Figure 2 opens, where the designer can initiate the design process by clicking the "Start Design" button.

Fig. 2. Main window.

The materials to be used are selected from the opened window, as shown in Figure 3. To explore the material libraries, users can click the "View" button. These libraries are stored in Excel spreadsheets, ensuring convenient and structured data management.

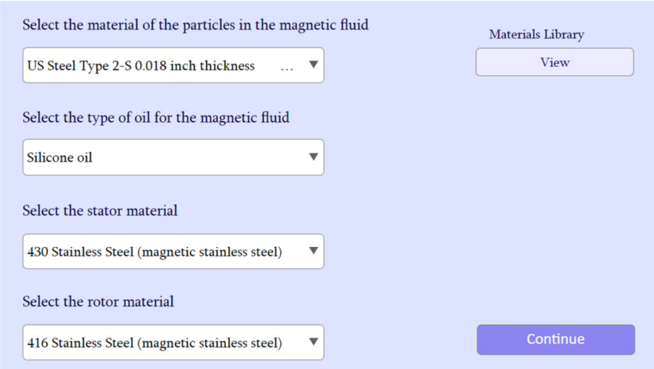

Fig. 3. Material selection window.

After clicking the "Continue" button, the input data window shown in Figure 4 opens, allowing the selection of the problem type to be solved.

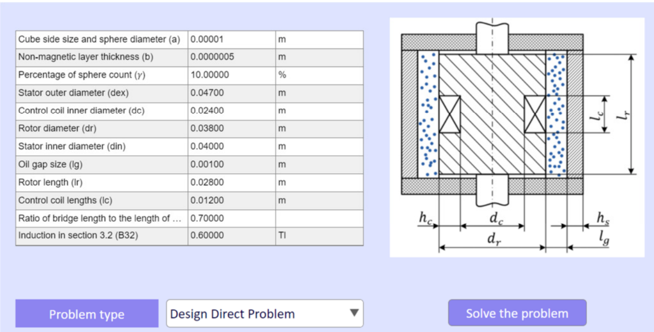

Fig. 4. Input data window.

The system provides five problem types:

1. Direct problem of EM brake design: Given the known dimensions, materials of the EMS, and the prescribed velocity v of the particle bridge front, the objective is to determine the electromagnetic force P_E required to maintain v. Additionally, the magnetic flux Φ is computed, and by solving the direct problem, the necessary magnetomotive force F of the control winding is determined to achieve the desired values of Φ, P_E, and v [35, 38].
2. Inverse problem of brake design: For given dimensions and materials of the EMS, as well as a given magnetomotive force F of the control winding, the inverse design problem involves determining the magnetic flux Φ, the electromagnetic force P_E, and ultimately the velocity v of the particle bridge front [35, 38].
3. Design of the control winding: Given the known supply voltage of the control winding, the ambient temperature, the system dimensions, and the required magnetomotive force F, the appropriate winding conductor (type and cross-sectional diameter) is selected. The number of windings' coil turns, the current, the current density, the electrical power, and the coil heating temperature are calculated. The latter parameter is particularly critical since exceeding the allowable heating temperature of the selected conductor renders the designed electromagnet non-operational from a thermal standpoint.
4. Optimization of key parameters of the EM brake: The optimization process considers key parameters of the EMS, particularly the velocity v of the particle bridge front (which ultimately influences the system's response time) and the electromagnetic force P_E acting on the front. Two optimization problems are solved to maximize the values of P_E and v [40].
5. Field analysis using the FEM environment: The electromagnetic field of the system is modeled using the finite element method. The obtained field distribution allows to measure the magnetic induction values, to determine the forces acting between the particles, and to perform a detailed analysis of the magnetic field distribution. Based on this analysis, the magnetic circuit of the system is constructed or refined. This step is crucial because the hybrid mathematical model mentioned above is derived from the equivalent circuit of the magnetic system. The accuracy of this circuit directly affects the precision of the hybrid model.

(a)

(b)

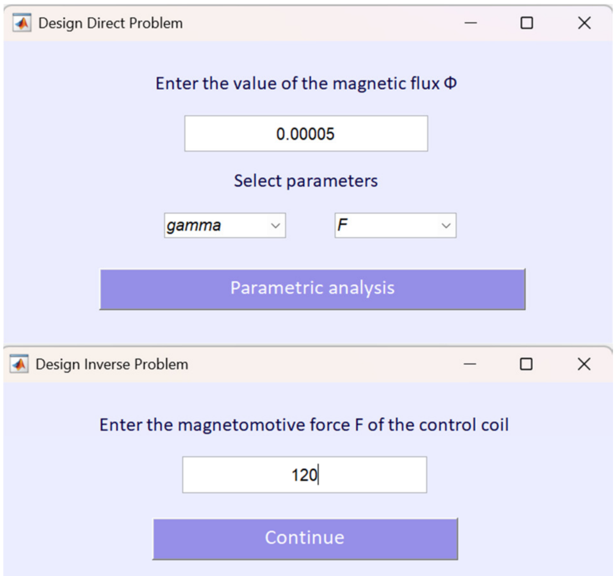

Fig. 5. Additional windows required for design: (a) window for the direct problem, and (b) window for the inverse problem.

After selecting the problem type, we click on the "Solve the problem" button and a new window opens, as shown in Figure 5. The results of solving the inverse design problem and the winding design are displayed in tabular form in Figure 6. Figure 7 presents a window that allows users to visualize parameter interactions [38], helping them to understand how different parameters influence the results. The combination of graphical and tabular representations allows users to view both formats simultaneously, which can increase the efficiency of the analysis.

(a)

(b)

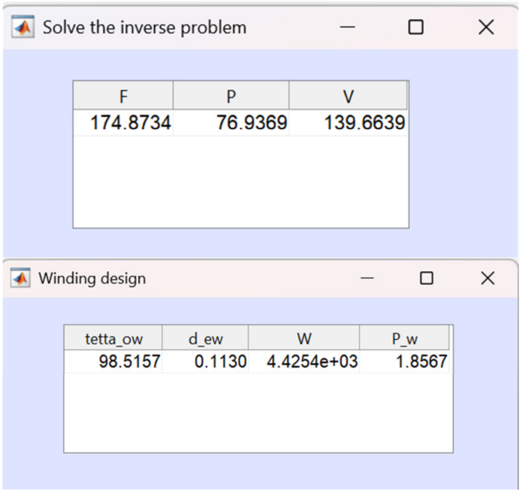

Fig. 6. Results windows: (a) results of solving the inverse design problem, and (b) results of the winding design.

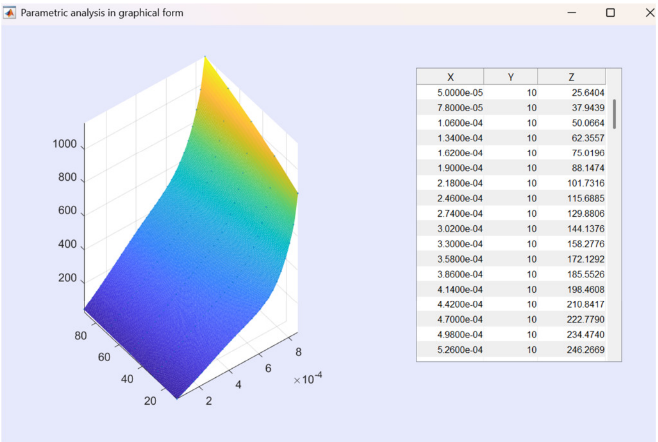

Fig. 7. Window for visualization of parametric analysis results

The developed system enables optimal design, significantly improving the efficiency and accuracy of the design process. As shown in Figure 8, the users can select the objective by which they want to optimize the problem. The system offers optimization using several methods, which can be selected from a drop-down menu.

Clicking the "Continue" button starts the optimal design process [40], and the results of the solution are displayed in the form of corresponding graphs, as shown in Figure 9.

By clicking the "Field research using FEMM environment" button, the modeling of the magnetic field of the magnetorheological fluid-based EMS is initiated using the finite element numerical method via the FEMM environment. The magnetic field images shown in Figure 10 are obtained, the magnetic induction values are measured in different parts of the system, and the electromagnetic forces acting on the magnetic particles of the magnetorheological fluid, as well as the velocities of these particles, are calculated.

(a)

(b)

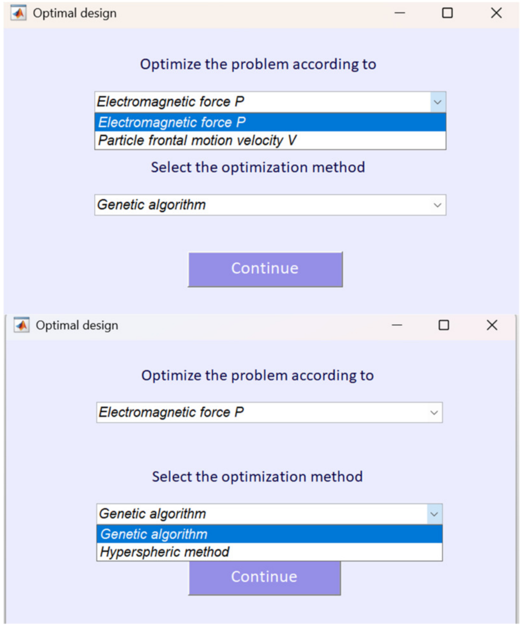

Fig. 8. Windows for selecting: (a) the optimization objective, and (b) the methods.

(a)

(b)

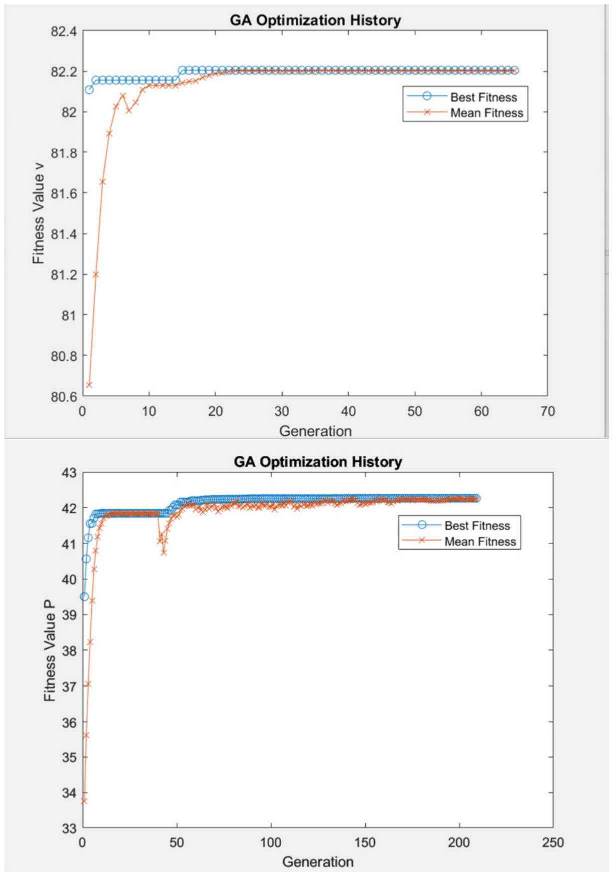

Fig. 9. Optimization results: (a) based on the velocity of the bridge front, and (b) based on the electromagnetic force.

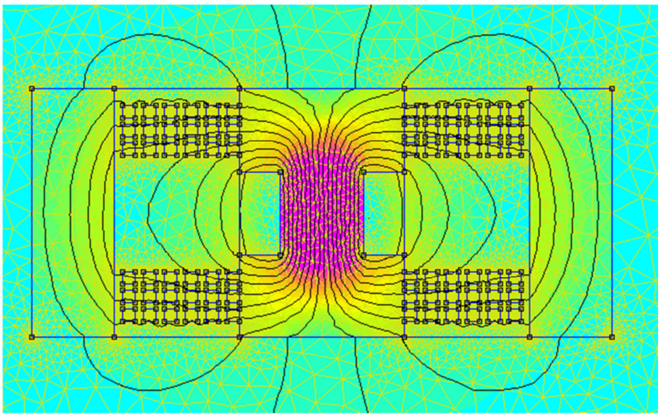

Fig. 10. Magnetic field image obtained through numerical modeling for a control winding current density of j=60 A/mm^2.

IV. RESULTS AND DISCUSSION

The key achievements of the presented automated modeling system are as follows:

- System performance and efficiency: By integrating MATLAB with the FEMM environment, the developed system efficiently solved both direct and inverse design problems, reducing the time required for design iterations. The GUI provided an intuitive platform for engineers to input parameters, select materials, and visualize results, enhancing the overall usability of the system.
- Parametric analysis: One of the key features of the system is its ability to perform parametric analysis and generate 3D functional dependencies between selected variables. As shown in Figure 7, the system allows users to visualize how different parameters influence the results through graphs. This capability is particularly useful for understanding complex interactions between variables, such as the relationship between P_E and v under varying structural dimensions and control coil voltages. The combination of graphical and tabular representations enables users to analyze multiple parameters simultaneously, improving the efficiency of the design process.
- Optimization results: The system successfully optimized key parameters of MR brakes, such as P_E and v, using ML algorithms. The optimization process considered various structural dimensions and control winding voltages, ensuring that the designs met operational constraints, such as temperature limits. The results showed that the system could generate optimal designs with improved performance, as evidenced by the dependency graphs presented in Figure 9.
- Magnetic field analysis: The integration of FEMM enabled accurate modeling of the magnetic field distribution within MR devices. Figure 10 illustrates the magnetic field images obtained through numerical modeling for a control winding current density of j=60 A/mm^2. The system measured magnetic induction values across different regions of the device and calculated the electromagnetic forces acting on the MR fluid particles, providing valuable insights into the system's behavior.
- User feedback and practical applications: Preliminary feedback from users indicated that the system's GUI and automated features significantly streamlined the design process. The system's adaptability to various MR fluid-based applications, such as brakes, dampers, and clutches, makes it a versatile tool for engineers. Future work could focus on expanding the system's capabilities to include real-time control and advanced multiphysics simulations.

V. CONCLUSION

In this study, an automated system for modeling Electromagnetic Systems (EMSs) with Magnetorheological (MR) fluid has been developed by integrating MATLAB and Finite Element Method Magnetics (FEMM) environments. The system is based on a hybrid mathematical model developed by the authors for solving both direct and inverse design problems, and provides parametric analysis of the models to visualize and investigate functional dependencies between selected parameters in graphical and tabular form, and optimization algorithms for maximizing key parameters such as the electromagnetic force (P_E) and the velocity of movement of the MR fluid magnetic particles bridge front (v). During the optimization process, the system also utilizes databases generated by the developed automated system and trained using Machine Learning (ML) algorithms. In addition, the system enables accurate modeling of the magnetic field distribution of EMSs. The novelty of the system lies in:

- Efficiency: Automation significantly reduces the time needed for design iterations and parameter optimization.
- Accuracy: The integration of optimization algorithms and finite element analysis ensures precise modeling and optimization of MR devices.
- User-friendliness: The Graphical User Interface (GUI) simplifies the design process, making it accessible to engineers with varying levels of expertise.
- Scalability: The system is adaptable to a broad range of MR fluid-based applications, from brakes to dampers and clutches.

The results obtained from the system, including optimized designs and magnetic field visualizations, demonstrate its effectiveness in improving the performance of MR devices. Future developments could focus on expanding the system's capabilities to include additional multiphysics simulations and integrating real-time control algorithms for dynamic applications.

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