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Force Validation in a Reluctance Coilgun: A Comparative Study Using Mathematical and Modelling, FEMM 4.2, Ansys Maxwell 2D & Ansys Maxwell 3D Simulations

Hiren M. Patel[1,*],
Department of Electrical Engineering,
Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda,
Vadodara. Gujarat, INDIA-390001
Email: hiren.m.patel-eed@msubaroda.ac.in
Jagrut J. Gadit[2]
Department of Electrical Engineering,
Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda,
Vadodara. Gujarat, INDIA-390001

Abstract:

Accurately predicting the force acting on a projectile in a reluctance coilgun is essential for optimizing coil design, current input, and overall system performance. This study compares three different methods for estimating force in a single-stage reluctance coilgun: a simplified analytical model using lumped parameters, two-dimensional finite element simulations with FEMM 4.2, and advanced 2D and 3D simulations using ANSYS Maxwell. In order to facilitate an equitable comparison, we employed a consistent coilgun design, material characteristics, and excitation parameters throughout all methodologies. The analytical model, based on simplified electromagnetic equations, predicted a force of 894.64 N, while the FEMM 2D simulation gave 778.62 N. ANSYS Maxwell simulations offered more refined results, with the 2D model predicting 761.78 N and the 3D model yielding 735.06 N. Our results show that analytical models tend to overestimate force significantly because they assume linear material behavior and uniform magnetic fields. Conversely, finite element methodologies incorporate magnetic characteristics, spatial field fluctuations, and geometric considerations, resulting in enhanced precision in predictions. This research highlights how modeling dimensionality and methodology critically affect force predictions. We identified a clear trade-off between computational speed and accuracy: analytical models work well for early design stages, 2D simulations balance accuracy with computational cost, and 3D simulations provide the highest accuracy for final validation. These findings offer practical guidance for choosing the right modeling approach in coilgun design and establish a reliable framework for force characterization in electromagnetic launcher systems.

Keywords: Electromagnetic launcher, force on a projectile, finite element analysis, magnetostatic, velocity analysis, efficiency analysis

1. INTRODUCTION

Electromagnetic launch systems have consistently attracted rigorous academic scrutiny as promising substitutes for conventional chemical propulsion mechanisms, owing to their inherent benefits such as enhanced controllability, reliable repeatability, the absence of propellant requirements, and reduced mechanical wear [1]-[3]. Among the diverse range of electromagnetic accelerators, coilguns -also referred to as electromagnetic launchers that employ solenoidal coils—offer significant advantages owing to their operational independence from sliding electrical contacts as well as their ability to operate with relatively straightforward mechanical configurations [4][5]. Coilguns are principally classified into induction coilguns and reluctance coilguns, distinguished by the electromagnetic interaction principle that enables the acceleration of projectiles [6]. In a reluctance coilgun, a ferromagnetic projectile is propelled as a consequence of the magnetic force generated from spatial gradients in magnetic energy upon the application of a current pulse to a solenoid [7].

The operational mechanism of a reluctance coilgun is fundamentally straightforward while also being analytically complex [8]. When an electric current flows through an excitation coil, a powerful magnetic field is established along the axis of the coil. A ferromagnetic projectile positioned near the entrance of the coil experiences a force that attracts it toward the region of increased magnetic field strength, generally oriented toward the axial center of the coil [9][10]. This force is commonly termed the reluctance force and arises from the magnetic system's inherent inclination to minimize its total reluctance by attracting high-permeability materials into regions characterized by intense magnetic flux. Accurate forecasting of this axial electromagnetic force as a function of the projectile's position and the coil current is pivotal to the design of coilguns, as it directly affects projectile acceleration, pulse timing, energy efficiency, and ultimately the maximum attainable exit velocity [10][11].Despite its seemingly straightforward nature, the force–position–current correlation within a reluctance coilgun exhibits significant nonlinearity [6][8]. Numerous elements contribute to this nonlinearity, such as the magnetic saturation of the projectile material, pronounced fringing fields at both the coil's entrance and exit, time-varying currents, eddy currents within conductive components, and three-dimensional geometric influences [12]. Moreover, the force reverses direction once the projectile passes the magnetic center of the coil, a phenomenon known as “suck-back,” which can significantly reduce launcher efficiency if the current is not switched off at an optimal instant [8][12][13]. Consequently, reliable force characterization across the entire projectile stroke is a prerequisite for optimal timing strategies and energy-efficient design [7].The definition of force fundamentally influences the dynamic characteristics of the projectile, consequently impacting factors such as acceleration, exit velocity, efficiency, and the holistic performance of the entire system [6][10]. In real-world applications, the force is variable rather than constant, exhibiting significant fluctuations in relation to the projectile's position, coil current, magnetic saturation, and the geometric configuration [9][13-15]. This spatial and temporal variability makes analytical prediction nontrivial, particularly when nonlinear material properties and fringing effects are significant. Therefore, the dependable modeling of force profiles throughout the projectile stroke is critical for enhancing coil geometry, synchronizing current pulse timing, and maximizing energy transfer efficiency [11][16].

Historically, analytical or lumped-parameter models have been widely used as the first step in reluctance coilgun analysis [17]. These models are typically derived from magnetic circuit theory or magnetic co-energy formulations, where the electromagnetic force is expressed as the partial derivative of stored magnetic energy with respect to projectile displacement at constant current [14][15][17]. Such models provide exceptional physical insight and outstanding computational efficiency, making them highly appealing for early-stage design and parametric studies [2][18][19]. However, they consistently depend on straightforward assumptions, including uniform flux distribution, minimal leakage and fringing, linear magnetic materials, and one-dimensional field variation [17]. As a result, analytical models often provide only approximate overestimated force predictions and may deviate significantly from real behaviour, particularly in regimes where magnetic saturation and geometric complexities dominate [16].To overcome these limitations, finite element method (FEM) -based numerical simulations have become the standard approach for detailed electromagnetic analysis of coilguns and related actuators [9]-[13]. Finite Element Method (FEM)-based approaches decisively enable the attainment of spatially resolved solutions to Maxwell’s equations, unequivocally allowing the integration of nonlinear material properties, complex geometrical designs, and practical boundary conditions [11][13]. Two-dimensional axisymmetric FEM formulations are highly regarded in the realm of reluctance coilguns because they offer an exceptional balance of accuracy and computational efficiency. Open-source software such as FEMM 4.2 has been extensively used in academic and educational research for simulating solenoids, actuators, and magnetic launchers, providing magnetostatic and time-harmonic solutions with nonlinear materials and scripting support for parametric sweeps [11][13].

While 2D axisymmetric simulations can capture many essential characteristics of reluctance coilguns, they inherently neglect three-dimensional effects such as end fringing asymmetry, nonuniform current distribution, and deviations from perfect axial symmetry present in practical designs [7][16]. Commercial multiphysics platforms such as ANSYS Maxwell address these shortcomings by offering both 2D and full 3D electromagnetic solvers, including transient formulations that can account for time-dependent currents, motion, and eddy current effects [13][16]. ANSYS Maxwell further provides multiple force computation techniques, such as the virtual work method and Maxwell stress tensor approach, each with distinct numerical characteristics and sensitivity to meshing and solver settings [9][14][17].

Despite the availability of these modelling tools, there remains a notable gap in the literature concerning systematic, quantitative comparisons between analytical force models, 2D axisymmetric FEM simulations, and full 3D transient FEM solutions for reluctance coilguns under identical geometric and excitation conditions [17]. Many published studies focus on a single modelling approach or present experimental validation without critically examining the discrepancies arising from modelling assumptions and dimensional constraints [3][6][13]. Consequently, design engineers and researchers are often presented with insufficient direction regarding the anticipated accuracy, constraints, and computational considerations linked to each modelling technique, especially during the shift from conceptual design to high-fidelity optimization or multistage launcher development [5].Inspired by this identified deficiency, the current research embarks on an exhaustive comparative analysis of methodologies for force characterization pertaining to a single-stage reluctance coilgun. Three distinct approaches are examined: (i) a lumped-parameter analytical model based on magnetic co-energy [14][17]; (ii) two-dimensional axisymmetric finite element simulations using FEMM 4.2 [11][13]; and (iii) transient 2D and 3D simulations in ANSYS Maxwell employing both virtual work and Maxwell stress tensor -based force evaluation [9][16]. By maintaining consistent geometry, material properties, and excitation parameters across all experimental models, this research powerfully clarifies the impact of modeling assumptions and dimensionality on the expected electromagnetic force.The primary objective of this work is to evaluate and contrast the accuracy, robustness, and computational efficiency of these three modelling approaches in predicting the axial force acting on a ferromagnetic projectile over its complete stroke [10][17]. A focused examination is conducted to elucidate the roots of variances among the methodologies, encompassing phenomena such as magnetic saturation influences, fringing field effects, sensitivity to mesh configurations, and the formulation of solvers [16]. Alongside static force–position characteristics, we assertively delve into the impact of force prediction n errors on timing strategy and design optimization [7][8].

This investigation aspires to furnish substantive guidance for coilgun developers and scholars, transcending mere comparison. By correlating model fidelity with computational cost and predictive reliability, the paper outlines when simplified analytical models are sufficient, when 2D axisymmetric FEM simulations provide an optimal balance, and when full 3D transient analysis becomes indispensable. Furthermore, a reproducible modelling workflow is presented to facilitate laboratory validation and enable extension of the proposed methodology to multistage reluctance coilgun systems [4][5].

A further significant contribution of this research is the development of a systematic and reproducible protocol for the characterization of forces generated by coilguns [11][13]. This encompasses well-defined protocols for geometry specification, material characterization, meshing approaches, and force extraction methodologies across various simulation platforms [9]. Such a workflow is essential for ensuring consistency and repeatability, particularly in research and laboratory environments where validation against experimental data is required [3][6][13].

In addition to the comparative analysis of modeling methodologies, the present investigation integrates an uncertainty assessment aimed at quantifying the sensitivity of force predictions to critical parameters, including mesh granularity, material characteristics, and numerical differentiation within analytical frameworks [16][17]. This particular dimension is often overlooked and not given the attention it rightfully deserves; nevertheless, it is of paramount importance for gaining a thorough understanding of the reliability and resilience of the results generated through simulation processes. By clearly identifying and explaining the primary origins of errors that may arise during these simulations, this study provides significant and practical insights that can be utilized to improve the precision of models and reduce the levels of uncertainty encountered in real-world scenarios [17].

The findings and results that have been derived from this comprehensive study carry significant and direct implications that are critically relevant for the intricate processes involved in the design and subsequent optimization of reluctance coilguns, as referenced in sources [2] and [11]. For early-stage design, analytical models may suffice for rapid parameter sweeps and conceptual understanding [17][19]. However, as the design progresses toward implementation, more accurate methods such as FEMM or ANSYS become necessary to capture nonlinear and geometric effects [11][13]. The comparative analyses delineated in this manuscript facilitate the formulation of distinct criteria for the selection of the most suitable modeling methodology, contingent upon the prerequisites of accuracy, the availability of computational resources, and the overarching design objectives [17].Ultimately, the methodologies and conclusions elucidated herein are not confined to single-stage systems; rather, they can be extrapolated to multistage coilgun architectures, where the precision of force predictions becomes increasingly paramount due to the complexities arising from inter-stage interactions and timing constraints [4][5]. Consequently, the reproducible framework and analytical methodology established in this study furnish a robust foundation for subsequent inquiries into electromagnetic launch systems, encompassing optimization, control mechanisms, and empirical validation [1][7][18].

In summary, this scholarly manuscript aims to bridge the existing gap that has been identified between fundamental analytical modeling techniques and the sophisticated, high-precision numerical simulations by providing an extensive and methodical assessment of the various methodologies employed for force characterization specifically within the context of reluctance coilguns, as referenced in source number 17. This initiative, it provides both practical insights for design and a methodological framework that facilitates accurate, efficient, and scalable modeling of electromagnetic acceleration systems [1].

2. LITERATURE REVIEW

The field of research focused on reluctance coilguns and the mechanisms associated with electromagnetic launching technologies has experienced significant and noteworthy progress over the past several decades, integrating a wide variety of contributions that encompass not only analytical modeling but also the application of finite element analysis, robust empirical validation techniques, and comprehensive methodologies aimed at optimizing system performance to achieve enhanced efficiency and effectiveness in practical implementations.

a. Early analytical and circuit-based modeling

Early work on coilgun modeling focused on lumped parameter and circuit-based approaches. Researcher [20] developed one of the foundational capacitor-driven coilgun models, integrating circuit equations with projectile motion dynamics. Similarly, Krishnan and Sudhoff proposed electromechanical formulations combining inductance variation and Newtonian motion.

Energy-based methods using magnetic co-energy became widely adopted for force estimation. Research endeavors such as [20][21] conceptualized force as the spatial derivative of accumulated magnetic energy, thereby presenting a method that is computationally efficient. Nonetheless, it is important to note that the majority of these theoretical models fundamentally assume a linear relationship inherent within magnetic materials, while simultaneously failing to take into account the significant and often detrimental phenomenon known as flux leakage, which can lead to inaccuracies and inefficiencies in practical applications.

Magnetic equivalent circuit (MEC) methodologies advanced the traditional lumped models by integrating nonlinear reluctance pathways [22]. These techniques provided enhanced precision while simultaneously preserving a relatively low computational expense.

b. *Energy-based force modelling approaches*

Advanced analytical models introduced nonlinear magnetic behaviour, including saturation effects. Research in [23][24] incorporated B–H curve nonlinearity into inductance estimation, significantly improving force prediction accuracy.

Dynamic models combining electromagnetic and mechanical domains were also proposed. For example, the research conducted by [25][26] introduced sophisticated coupled differential equation models that meticulously account for both transient current behavior as well as the dynamics of projectile motion, thereby providing a comprehensive framework for analysis. These advanced models significantly underscored the critical importance of accurately estimating the inductance gradient, revealing how even minor discrepancies can lead to substantial variations in the predictions of force exerted in such systems.

c. *Finite element analysis using FEMM*

Finite element analysis, commonly referred to as FEA, has been extensively utilized within the realm of IEEE research endeavors to effectively tackle and mitigate the various limitations and restrictions that are often associated with traditional analytical models. FEMM-based simulations provide accurate field distribution and force estimation under nonlinear conditions.

Several works utilized 2D axisymmetric FEMM models to compute electromagnetic force using virtual work and Maxwell stress tensor methods [4][13]. These studies demonstrated improved agreement with experimental results compared to analytical approaches.

Hybrid modelling approaches combining FEMM with MATLAB/Simulink were proposed in [27], enabling system-level simulation of coilgun dynamics. These models allowed optimization of coil parameters and firing sequences.

However, FEMM's limitations, particularly its 2D axisymmetric assumption, were noted in [28], where discrepancies arose due to unmodeled 3D effects.

d. *High-fidelity simulation using ANSYS Maxwell*

High-fidelity simulations using ANSYS Maxwell have been widely reported in IEEE literature for accurate electromagnetic analysis.

Studies in [5][29] employed 2D and 3D transient simulations to model coilgun behaviour, including eddy currents and nonlinear materials. These works demonstrated that 3D models provide more accurate force predictions, especially near coil edges.

Force computation methods such as Maxwell stress tensor and virtual work were compared in [30], showing consistency under fine mesh conditions but divergence under coarse discretization.

The comprehensive analysis that was performed in reference [3] meticulously scrutinized the intricate effects that various configurations of projectiles and the architectural design of coils exert on performance metrics, employing the advanced simulation capabilities of ANSYS, which effectively underscored the critical importance of meticulous geometric refinement as a pivotal factor in significantly improving the overall operational efficiency and effectiveness of the system under investigation.

e. *Multi-stage coilgun Systems*

Research into multi-stage coilguns has been undertaken to achieve higher speeds and improved efficiency. IEEE studies [31][32][33] demonstrated that proper timing and synchronization of multiple coils significantly enhance acceleration.

These works highlighted challenges such as:

- Switching delays [28]
- Energy losses [34]
- Inter-stage coupling [35]

f. *Optimization Techniques*

Optimization methods have been widely applied in coilgun design.

Genetic algorithms and evolutionary optimization were used in [23][35] to optimize coil parameters and firing sequences. These methods investigated have resulted in enhanced efficiency and speed relative to manual calibration.

Alternative investigations have placed a significant emphasis on the exploration and analysis of geometric optimization techniques as well as advanced control methodologies, as referenced in source [36], thereby highlighting the crucial importance and value of cohesive design paradigms that seamlessly integrate these two areas of focus to enhance overall system performance and effectiveness.

g. *Experimental Validation*

Experimental validation remains critical for verifying models. Studies in [4][13][31] compared simulation results with measured projectile velocities and force profiles.

Although methodologies grounded in the Finite Element Method (FEM) demonstrated a commendable level of concordance, analytical frameworks frequently produced inflated force estimations as a result of reductive assumptions.

h. *Identified Research Gaps*

From the reviewed literature, the following gaps are identified:

- Lack of direct comparison between analytical, FEMM, and ANSYS methods
- Insufficient focus on uncertainty quantification
- Need for standardized modelling workflows

The literature demonstrates that:

- Analytical models are fast but less accurate [20][21]
- FEMM provides a balance between accuracy and efficiency [4][13][27]
- ANSYS Maxwell offers high accuracy at a higher computational cost [5][29]

However, a unified comparative framework is missing, which motivates the present study.

3. THEORETICAL BACKGROUND

The operational mechanisms of a reluctance coilgun are fundamentally governed by electromagnetic energy conversion, where electrical energy in a conductive coil transforms into the kinetic energy of a ferromagnetic projectile, necessitating a thorough comprehension of magnetic field distribution, energy storage, inductance variations, and electromechanical interactions, which this section articulates through a theoretical framework that integrates analytical models with commonly utilized numerical simulation concepts.

a. *Principle of reluctance force*

A reluctance coilgun operates on the principle that ferromagnetic materials are drawn to areas of lower magnetic reluctance or higher magnetic intensity; when electric current flows through a solenoid, it creates a magnetic field that magnetizes the projectile, and the interaction between this magnetization and the magnetic field gradient produces a net force that accelerates the projectile toward the coil's center.

The system inherently progresses towards a state where magnetic energy is at its minimum, thereby facilitating the movement of the projectile into areas of enhanced magnetic coupling. The force is therefore inherently position-dependent and varies nonlinearly along the projectile stroke.

b. *Magnetic energy and co-energy formulation*

The predominant analytical methodology employed for the computation of forces within reluctance systems is fundamentally predicated upon the principles of magnetic energy and co-energy [20][21]. For a current-controlled system, the electromagnetic force can be derived from the magnetic co-energy W′, defined as:

$$F(x) = \frac{\partial W'(x, I)}{\partial x} \tag{1}$$

For linear magnetic systems, the co-energy is equal to the stored magnetic energy and can be expressed as:

$$W'(x, I) = \frac{1}{2} L\,(x) I^2 \tag{2}$$

Substituting into the force expression yields [20]:

$$F(x) = \frac{1}{2} I^2 \frac{dL(x)}{dx} \tag{3}$$

This formulation highlights that the force is proportional to the square of the current and the spatial gradient of inductance. It forms the basis of most lumped parameter models used in early-stage design [24][25].

However, this formulation presupposes:

- Linear characteristics of magnetic materials
- Insignificant hysteresis effects
- The nonexistence of eddy currents

In empirical applications, these presuppositions are frequently contravened, resulting in inconsistencies between theoretical predictions and observed experimental outcomes [13].

c. *Position-Dependent Inductance*

A crucial factor in force estimation is the position-dependent inductance L(x), which increases as the ferromagnetic projectile moves through the coil, enhancing the system's magnetic permeability and consequently raising inductance. This variation is nonlinear and depends on:

- Projectile geometry and material properties
- Coil dimensions and number of turns
- Magnetic saturation effects

Analytical estimation of L(x) is challenging due to complex flux paths and fringing fields. Simplified formulations that are predicated on solenoid inductance frequently do not adequately encapsulate these phenomena. As a result, computational techniques or inductance profiles derived from empirical experimentation are commonly employed [26][27].

d. *Nonlinear magnetic behaviour and saturation*

Ferromagnetic substances demonstrate nonlinear B-H relationships, indicating that permeability is variable and diminishes as the substance nears magnetic saturation. This has a significant impact on force generation [23][24].

At diminished magnitudes of magnetic fields, the substance exhibits heightened permeability, which culminates in strong magnetic coupling and improved inductance. Conversely, as the magnetic field intensity increases, the substance attains a saturation threshold, thereby limiting any additional enhancement in flux density. This phenomenon consequently diminishes the rate at which inductance changes with spatial position, leading to a reduction in the force forecasted by linear models.Integrating nonlinear B-H curves into the analytical framework is vital for the precise prediction of force. Neglecting saturation effects can lead to substantial overestimations of force, particularly near the coil center where magnetic fields are strongest, as evidenced by empirical research [5].

e. *Electromechanical Coupling*

The coilgun operates as a coupled electromechanical system, where electrical and mechanical dynamics interdependently affect one another. The governing equations can be expressed as:

Electrical Equation:

$$V = RI + \frac{d\lambda}{dt} \tag{4}$$

Where $\lambda = L(x)I$ is the flux linkage.

Mechanical equation:

$$m\frac{d^2y}{dx^2} = F(x, I) \tag{5}$$

These equations are coupled through the position-dependent inductance $\boldsymbol{L(x)}$. As the projectile progresses, fluctuations in inductance affect current dynamics, thereby impacting the resultant force.

Dynamic models that address these interrelated equations yield a more accurate depiction of coilgun functionality in contrast to static force computations [25][26].

They are particularly important for predicting projectile velocity and optimizing switching timing.

f. *Force computation using Maxwell stress tensor*

In finite element analysis simulations, the Maxwell stress tensor (MST) is often employed to compute electromagnetic forces by integrating the stress tensor over a closed surface surrounding the projectile[30].

The general form of the Maxwell stress tensor in magnetostatics is:

$$T = \frac{1}{\mu_0}\left(BB - \frac{1}{2}B^2 I\right) \tag{6}$$

The force is then obtained by :

$$F = \oint_s T \cdot ds \tag{7}$$

This approach is widely used in FEM-based tools such as FEMM and ANSYS Maxwell due to its accuracy and applicability to complex geometries [5][13][29]. However, it demonstrates significant sensitivity to mesh quality and requires careful selection of integration surfaces.

g. *Virtual work method*

An alternative numerical method for force computation is the principle of virtual work, closely linked to the energy-based approach [30]. In this methodology, the force is determined by assessing the variation in magnetic energy resultant from a minor virtual displacement of the projectile.The virtual work method is highly advantageous in finite element simulations as it eliminates the need for direct calculation of field gradients. It is generally more stable than the Maxwell stress tensor method, especially in coarse meshes.

Both MST and virtual work methods are implemented in FEMM and ANSYS, and their comparative performance has been studied extensively in the literature [30].

h. *Effects of eddy currents*

Under transient operational conditions with rapidly changing currents, eddy currents arise in the conductive projectile, generating opposing magnetic fields per Lenz's law, which subsequently reduces the net force acting on the projectile [33].

Eddy currents also contribute to:

- Energy losses (Joule heating) [34]
- Reduced efficiency [37]
- Delay in magnetic field penetration [5]

Accurate modelling of eddy currents requires transient electromagnetic simulation, typically available in high-fidelity tools like ANSYS Maxwell [5][29]. Analytical frameworks often overlook these effects, leading to a bloated evaluation of efficacy.

i. *Fringing fields and end effects*

Fringing fields emerge at the margins of the coil, where magnetic flux lines radiate outward instead of being confined within the core. These phenomena are particularly accentuated in the vicinity of the coil's entry and exit points, where the gradients of force demonstrate significant steepness [38].

2D axisymmetric models partially capture fringing effects but fail to account for:

- Asymmetry in winding
- Finite coil length
- Edge irregularities

3D simulations provide a more accurate representation of these phenomena, which explains the improved accuracy of ANSYS-based models compared to FEMM [5][28][29].

j. *Limitations of Analytical Models*

While analytical models are valuable for quick estimation and conceptual understanding, they suffer from several limitations:

- Linear Material Assumption: neglects saturation [23][24]
- Simplified Geometry : ignores fringing and 3D effects [28][38]
- No Eddy Currents: neglects transient losses [33]
- Approximate Inductance: difficult to model accurately [26][27][29]
- These limitations motivate the use of finite element methods for detailed analysis [4][5][13].

The conceptual framework that serves as the foundation for the operation and design of reluctance coilguns is, at its core, intricately rooted in the fundamental principles governing the conversion of electromagnetic energy into kinetic energy, as well as the dynamic changes in inductance that occur in relation to the positional variations of the components within the system. Analytical methods employing co-energy principles enable force estimation but require simplifications that reduce precision; in contrast, numerical techniques like FEMM and ANSYS Maxwell improve this theoretical framework by accounting for nonlinear materials, complex geometries, and transient behaviors.

A thorough comprehension of these theoretical constructs is imperative for elucidating discrepancies that may arise among various modeling methodologies and for the advancement of precise and dependable coilgun designs.

4. METHODOLOGY

The methodology adopted in this study focuses on a systematic and comparative evaluation of electromagnetic force prediction in a single-stage reluctance coilgun using analytical and numerical modelling approaches. Three distinct techniques are employed: (i) a lumped-parameter analytical model, (ii) two-dimensional (2D) finite element simulation using FEMM 4.2, and (iii) high-fidelity simulations using ANSYS Maxwell in both 2D and three-dimensional (3D) configurations. To ensure consistency and reliability in comparative analyses, identical geometric parameters, material properties, and excitation conditions are retained across all modeling approaches.

a. *Coilgun geometry and design parameters*

A comprehensive analysis is conducted in this research regarding a cylindrical configuration of a single-stage reluctance coilgun, which serves as the primary focus of the study. This sophisticated system is composed of a solenoidal excitation coil that generates a magnetic field and a ferromagnetic projectile that has been meticulously positioned along the central axis to ensure optimal performance. The geometry that has been meticulously chosen not only enhances the potential for analytical simplification but also ensures a high degree of compatibility with axisymmetric finite element modeling techniques, thus facilitating a more in-depth examination of the system's characteristics.

The coil possesses an inner diameter of 5 cm, an outer diameter of 6 cm, and an axial length of 5 cm. It is constructed with 150 turns of 18 AWG copper wire. The excitation is delivered as a high-current pulse, exhibiting a peak current of 710 A. This current magnitude is characteristic of capacitor-driven pulsed power systems typically employed in laboratory-scale coilguns, as illustrated in figure 1.

The projectile is characterized by a cylindrical geometry, with a length of 5 cm and a diameter of 4 cm. It is postulated to be fabricated from a soft ferromagnetic material displaying a relative permeability of 1000. This elevated permeability guarantees robust magnetic coupling with the coil field, thereby facilitating efficient acceleration owing to the reluctance force.

The distance of air that exists between the projectile and the inner surface of the coil is considered to be negligible in size, which not only enhances the linkage of magnetic flux but also concurrently presents a vulnerability to the phenomenon known as fringing effects. These geometric and material parameters have been meticulously selected to accurately represent a realistic yet computationally manageable coilgun system.

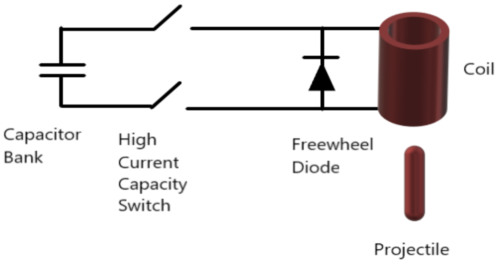

Figure 1. Schematic Diagram of Reluctance Coilgun.

b. *Analytical modelling approach*

The analytical framework is predicated upon a streamlined electromagnetic formulation extrapolated from the principles of magnetic energy and co-energy. The force exerted on the projectile is articulated as a function of coil current, the number of turns, magnetic permeability, and the effective cross-sectional area of the projectile.

This methodology presupposes a quasi-static magnetic field and a uniform flux distribution throughout the coil region. The derivation disregards higher-order phenomena such as flux leakage, fringing fields, and nonlinear magnetic saturation. Furthermore, the variation in inductance relative to the projectile's position is approximated, and the magnetic field is considered as one-dimensional along the axis of the coil.

Force experienced by the projectile is given by,

$$F = \frac{(NI)^2 \; x \; \mu_0 \; x \; a}{2 \; x \; g^2} \text{ Newtons} \tag{8}$$

Where,

N = Number of turns of the coil
I = Current passing through the coil (Ampere)
μ0 = Permeability of free space (Henry/m)
a = πr^2 = Area of the projectile (sq.m)
r = radius of the projectile (meters)
g = gap spacing between projectile and coil (meters)

The force is calculated using a closed-form expression (equation 8), which enables rapid evaluation without the need for iterative numerical computation. Employing the specified design parameters, the analytical framework forecasts a force magnitude of 894.64 N.

Although this approach is computationally efficient and advantageous for initial design and parametric investigations, its precision is constrained by the simplifying assumptions employed. Specifically, the exclusion of nonlinear B–H attributes and spatial field variances leads to an exaggeration of the electromagnetic force.

c. *FEMM 4.2 simulation methodology :*

To enhance precision, finite element assessment is conducted utilizing FEMM 4.2, an open-source electromagnetic simulation instrument. The geometric arrangement of the coilgun is modeled within a two-dimensional axisymmetric environment, employing the intrinsic cylindrical symmetry of the system to alleviate computational intricacy.

(i) Geometry and Material Definition: The geometric configuration of the coil and projectile is delineated in accordance with the parameters previously articulated. The simulation domain includes the coil, projectile, and surrounding air. Appropriate boundary conditions are established to accurately represent the magnetic field.Nonlinear magnetic properties are incorporated using the specific B–H curves of the projectile material. This methodology enables the simulation to accurately capture saturation phenomena, which are imperative for realistic predictions of force.

(ii) Meshing strategy: A finite element mesh is carefully created within the computational domain, with increased density in regions of high field gradients, especially near the air gap and projectile edges. Proper mesh refinement is essential for accurately calculating electromagnetic forces, especially when using field-based methods like the Maxwell Stress Tensor.

(iii) Excitation and solver settings: The coil excitation is characterized as a current source of 710 A. A magnetostatic solver is utilized under steady-state current assumptions. Although transient phenomena are not directly modeled in FEMM, the magnetostatic solution provides a reasonable approximation for instantaneous force evaluation.

(iv) Force computation: The electromagnetic force exerted on the projectile is determined through the application of the Maxwell Stress Tensor (MST) methodology. This process entails the integration of the stress tensor over a closed contour that encompasses the projectile. The force computed utilizing FEMM is quantified at 778.62 N.Field geometry in FEMM, its mesh formation and magnetic field distribution are as shown in figure 2, 3 and 4, respectively.

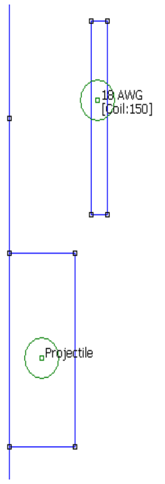

Figure 2. RCG Geometry in FEMM

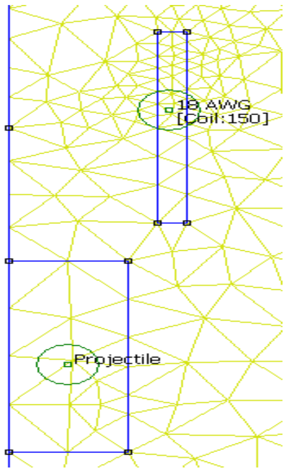

Figure 3. Mesh Formation.

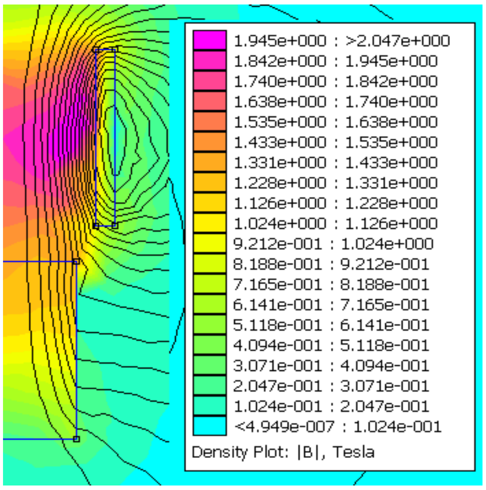

Figure 4. Magnetic Field Plot.

d. *ANSYS Maxwell simulation methodology :* Simulations are performed using ANSYS Maxwell to improve modelling fidelity.

(i) 2D axisymmetric simulation: The 2D model in ANSYS Maxwell follows a similar axisymmetric formulation as FEMM but benefits from advanced solver algorithms and improved material modelling capabilities.

The geometry and material properties are defined identically to those used in FEMM. An enhanced mesh is produced autonomously, employing adaptive meshing techniques to augment solution precision in key areas.

Here, the geometry in Ansys Maxwell 2D and its magnetic field distribution are shown in figures 5 and 6, respectively.

The electromagnetic force is calculated using established methods, such as virtual work and the Maxwell stress tensor. The calculated force is 761.78 N, marginally lower than the FEMM result, reflecting enhanced numerical accuracy.

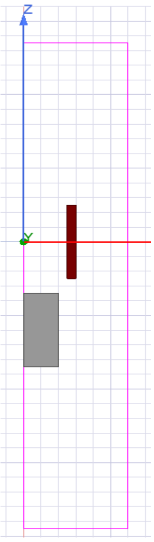

Figure 5. Geometry in Ansys Maxwell 2D

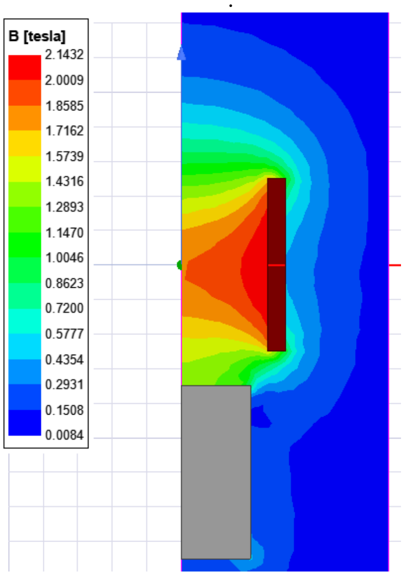

Figure 6. Magnetic Field Plot in Ansys Maxwell 2D.

(ii) 3D simulation: A full 3D model is developed to capture spatial effects that cannot be represented in 2D simulations. This includes:

- End effects due to finite coil length
- Asymmetry in magnetic field distribution
- Flux leakage in radial and axial directions

Geometry and Meshing

The complete 3D geometry of the coil and projectile is constructed. A volumetric mesh is constructed, exhibiting enhanced resolution in areas anticipated to exhibit significant magnetic gradients.

Here, the geometry in Ansys Maxwell 3D and its magnetic field distribution are shown in figures 7 and 8, respectively.

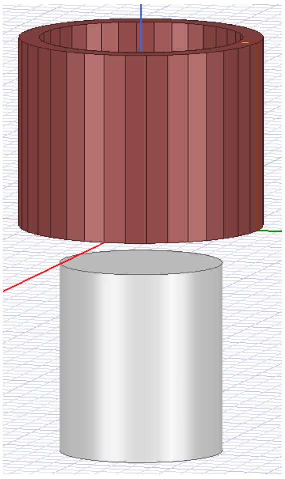

Figure 7. Geometry in Ansys Maxwell 3D.

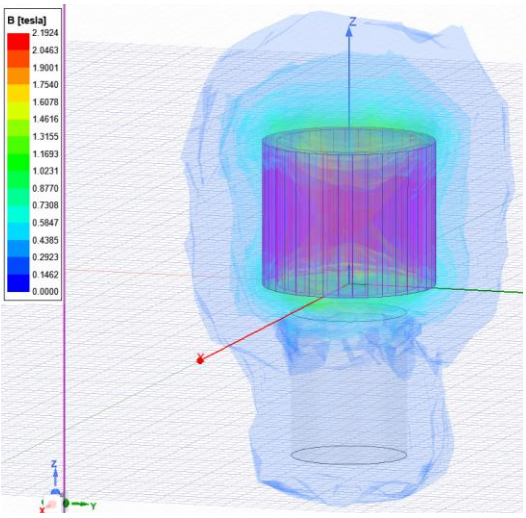

Figure 8. Magnetic Field Plot in Ansys Maxwell 3D.

Transient Simulation Setup: Unlike the 2D models, the 3D simulation can incorporate transient effects, including time-varying currents and eddy currents. Nevertheless, to ensure alignment with alternative methodologies, the examination centers on the instantaneous force experienced during peak current scenarios, specifically under steady state conditions.

Force Evaluation: The force is computed using advanced numerical techniques available in ANSYS Maxwell, ensuring accurate integration over complex 3D field distributions. The resulting force is 735.06 N, which is the lowest among all methods and is considered the most realistic.

e. Comparative Framework and Validation Strategy

A key aspect of the methodology is the establishment of a consistent comparative framework. All models employ uniform:

- Geometric parameters
- Material characteristics
- Excitation criteria

This guarantees that variations in outcomes are attributable exclusively to modelling assumptions and computational techniques as opposed to discrepancies in input data.

Additionally, care is taken to minimize numerical errors by:

- Using refined meshes
- Applying appropriate boundary conditions
- Verifying solver convergence

Although experimental validation is beyond the scope of this study, the methodology is designed to be reproducible and extendable for future experimental comparison.

f. Uncertainty and sensitivity considerations

To enhance reliability, the methodology considers potential sources of uncertainty, including:

- Mesh density and discretization errors
- Material property variations
- Numerical integration errors in force computation

Sensitivity to these factors is minimized through careful modelling practices, but their influence is acknowledged as a limitation, particularly in high-field regions where saturation occurs.

This methodology provides a framework for comparing analytical and numerical methods, highlighting their advantages, limitations, and significance in coilgun design.

5. RESULTS AND DISCUSSION

The results obtained from analytical modelling, FEMM 4.2 simulation, and ANSYS Maxwell (2D and 3D) simulations provide a comprehensive basis for evaluating the accuracy and applicability of different force prediction techniques in a reluctance coilgun. Through the preservation of uniform geometry, consistent material characteristics, and equivalent excitation conditions throughout all methodologies, the discrepancies in outcomes may be unequivocally ascribed to modeling assumptions, numerical formulations, and dimensional accuracy.

The computed electromagnetic forces are summarized as follows:

- Analytical Model method, the force is 894.64 Newton
- FEMM 4.2 (2D) method, the force is 778.62 Newton
- ANSYS Maxwell (2D) method, the force is 761.68 Newton
- ANSYS Maxwell (3D) method, the force is 735.06 Newton

These results reveal a clear trend: the predicted force decreases progressively as the modelling approach becomes more sophisticated and physically representative.

a. *Comparison of analytical and numerical results*

The analytical model yields the highest force value of 894.64 N. When compared to the most accurate 3D simulation result (735.06 N), this represents an overestimation of approximately 21.7%. This divergence stems from the assumptions within the analytical framework.

The model assumes a uniform magnetic field and linear material responses. However, the magnetic field in the coilgun is notably non-uniform, particularly near coil edges and air gaps. Moreover, ferromagnetic materials exhibit nonlinear B-H characteristics, leading to saturation at high field intensities. The framework neglects these aspects, resulting in an overestimation of force.

Conversely, the FEMM 4.2 simulation markedly mitigates this discrepancy, forecasting a force of 778.62 N. This denotes a decrease of approximately 13% relative to the analytical prediction. The improved accuracy is attributed to the integration of nonlinear material characteristics and a spatially detailed magnetic field distribution. However, FEMM remains reliant on a two-dimensional axisymmetric model, limiting its ability to effectively depict actual three-dimensional scenarios.

The ANSYS Maxwell 2D simulation produces a slightly lower force value of 761.78 N. The difference between FEMM and ANSYS 2D results, though relatively small (approximately 2.2%), highlights the influence of solver algorithms, meshing strategies, and numerical precision. ANSYS Maxwell employs more advanced adaptive meshing and solver techniques, which may contribute to improved accuracy.

The 3D simulation in ANSYS Maxwell yields the lowest force value of 735.06 N, which is considered the most realistic estimate. The reduction in force compared to 2D simulations underscores the importance of three-dimensional effects that are otherwise neglected.

b. *Influence of dimensionality*

This investigation highlights the impact of dimensionality on force prediction accuracy. The transition from one-dimensional to three-dimensional models enhances physical realism.

In two-dimensional axisymmetric models, symmetry is assumed about the central axis.

While this assumption simplifies computation, it neglects several important phenomena, including:

- Asymmetry in coil winding
- Finite coil length effects
- Radial flux leakage

The three-dimensional model elucidates these phenomena by delineating the comprehensive spatial distribution of the magnetic field. Boundary effects at the coil ends significantly reduce the magnetic coupling with the projectile. Such phenomena result in a reduced net force in comparison to two-dimensional predictions.

The findings illustrate that even in geometrically uncomplicated systems, three-dimensional modeling can yield significantly divergent and more precise outcomes. This is vital for the precise design and enhancement of electromagnetic launch systems.

c. *Role of magnetic saturation*

Magnetic saturation significantly affects force prediction accuracy. During high-current conditions, like the 710 A excitation used here, the ferromagnetic projectile approaches saturation. Saturation reduces relative permeability, limiting further increases in magnetic flux density.

Analytical models typically assume constant permeability, leading to overestimated inductance and its spatial gradient. Since electromagnetic force relates to the inductance change with position, this results in exaggerated force values.

Both FEMM and ANSYS simulations utilize nonlinear B-H curves to accurately represent saturation effects. This serves as a principal rationale for the numerical results consistently exhibiting lower and more realistic values compared to analytical forecasts.

d. *Effect of fringing fields and flux leakage*

Fringing fields occur at the coil's edges, causing magnetic flux lines to extend outward and reduce effective linkage with the projectile, thereby decreasing electromagnetic force.

Analytical models typically ignore fringing effects, leading to overly optimistic force predictions. FEMM 2D simulations can somewhat address fringing through spatial field solutions, yet they remain limited by the assumption of axisymmetry, affecting their accuracy.

The 3D ANSYS model furnishes a comprehensive depiction of fringing and flux leakage phenomena. The findings reveal a significant reduction in force near the coil's entrance and exit. This explains the differences noted between 2D and 3D simulation results.

e. *Numerical Method Considerations*

The selection of a force computation methodology significantly affects the resultant outcomes. In simulations grounded in the Finite Element Method (FEM), the computation of electromagnetic forces is generally executed through either the Maxwell Stress Tensor (MST) approach or the principle of virtual work.

The MST approach necessitates the integration of electromagnetic stresses across a closed surface encompassing the projectile. Although this approach is widely utilized, it demonstrates a susceptibility to the caliber of the mesh and the choice of the integration surface. Inadequate refinement of the mesh may lead to numerical inconsistencies.

ANSYS Maxwell provides both MST and virtual work methods, offering greater flexibility and reliability. The use of adaptive meshing and advanced solvers further enhances accuracy. This may explain the slight differences observed between FEMM and ANSYS 2D results.

f. *Computational efficiency and practical implications*

A clear trade-off emerges between computational efficiency and modelling accuracy:

- The analytical model is extremely fast and suitable for initial design exploration.
- FEMM 2D offers a good balance between accuracy and computational cost, making it ideal for parametric studies.
- ANSYS 2D provides improved accuracy with moderate computational effort.
- ANSYS 3D delivers the highest accuracy but requires significant computational resources and time.

For the effective design of coilguns, this trade-off assumes significant importance. Initial phases of the design process may utilize analytical models to investigate a broad spectrum of parameters. As the configuration advances, it is crucial to apply FEM-oriented techniques to improve forecasting precision and refine overall performance.

g. Implications for coilgun performance

The precise prediction of force is paramount for the accurate determination of projectile acceleration, velocity, and the overall efficiency of the system. An overestimation of force, as evidenced in analytical models, can result in erroneous timing of current switching, which may produce phenomena such as “suck-back,” wherein the projectile experiences deceleration subsequent to traversing the coil's center.

The more precise force profiles derived from three-dimensional simulations facilitate enhanced optimization of pulse timing and coil design. This aspect is particularly critical in multi-stage coilguns, where the synchronization among stages is of utmost importance.

h. Summary of findings

The comparative analysis highlights several key findings:

- Analytical models significantly overestimate force due to simplifying assumptions.
- FEMM 2D provides improved accuracy but is limited by axisymmetric assumptions.
- ANSYS 2D offers further refinement with better numerical methods.
- ANSYS 3D provides the most realistic results by capturing full spatial effects.

Overall, the study demonstrates that modelling fidelity has a direct and significant impact on force prediction. The selection of modeling methodology should consequently be directed by the necessary degree of precision and accessible computational assets.

6. CONCLUSION

This study presents a systematic and comparative investigation of electromagnetic force prediction in a single-stage reluctance coilgun using three different modelling approaches: analytical formulation, 2D finite element simulation using FEMM 4.2, and high-fidelity 2D and 3D simulations using ANSYS Maxwell. By preserving consistent geometrical configurations, material characteristics, and excitation parameters throughout all methodologies, the analysis yields a comprehensive insight into the manner in which modeling assumptions and computational techniques affect force estimation. The results demonstrate that the analytical model significantly overestimates the electromagnetic force, predicting a value of 894.64 N, compared to 735.06 N obtained from the 3D ANSYS simulation. This divergence of approximately 20–22% underscores the constraints inherent in simplified analytical methodologies, particularly their inadequacy in accommodating nonlinear magnetic phenomena, fringing fields, and flux leakage. While analytical models retain their utility for swift estimations and conceptual comprehension, their relevance is constrained in contexts necessitating elevated precision. Finite element modeling implemented through FEMM 4.2 yields a significant enhancement in predictive accuracy. By incorporating nonlinear material properties and spatial field distribution, FEMM alleviates the exaggerations commonly found in analytical models. Nevertheless, the fundamental assumption of axisymmetry curtails its capacity to capture three-dimensional phenomena such as end fringing and asymmetrical flux distribution. Consequently, the forecasts derived from FEMM, although more advanced than those from the analytical model, still deviate from the most precise values. The simulations conducted via ANSYS Maxwell further augment the analytical framework. The two-dimensional model affords enhanced numerical precision and improved management of nonlinearities in comparison to FEMM, whereas the three-dimensional model delivers the most exhaustive representation of the electromagnetic system. The three-dimensional simulation effectively encapsulates critical phenomena including end effects, flux leakage, and non-uniform magnetic field distribution, thereby facilitating the most precise force predictions. This substantiates the claim that three-dimensional modeling is essential for the precise design and enhancement of coilgun systems, especially when operating under elevated current circumstances where nonlinear phenomena are prominent. A significant and noteworthy outcome of this comprehensive investigation is the clear identification and understanding of a distinct trade-off that exists between the realms of computational efficiency and the precision of modeling accuracy, which is critical for informed decision-making. Analytical models, which are inherently characterized by their remarkable computational economy and efficiency, are widely regarded as highly suitable and appropriate for conducting preliminary design evaluations and conducting thorough parametric investigations that may inform further design iterations. In contrast, the two-dimensional simulations conducted using the Finite Element Method Magnetics (FEMM) achieve a practical and effective equilibrium that balances the demands of accuracy with the associated computational costs, thereby rendering them particularly well-suited for the critical intermediate phases of the design process where such considerations are paramount. ANSYS two-dimensional simulations afford additional refinement, while ANSYS three-dimensional simulations, despite their computational demands, are crucial for conclusive design validation and precision analysis. The findings further underscore the critical importance of accurately predicting the force exerted in order to significantly enhance the overall performance of coilguns in various applications. Any discrepancies or inaccuracies in the estimation of this force can lead to improper timing in the switching of electrical currents, which ultimately results in a notable decrease in operational efficiency and may also lead to detrimental effects, such as a reduction in projectile velocity caused by the phenomenon known as magnetic "suck-back." Therefore, it is absolutely imperative that comprehensive and reliable modeling techniques are employed to facilitate the optimization process for coil design, current profiles, and the strategic timing of switching mechanisms, ensuring peak performance in practical implementations. Such meticulous attention to detail in the predictive modeling will not only enhance the functionality of coilguns but will also contribute significantly to advancing the field of electromagnetic propulsion technologies. This study establishes a reproducible framework for coilgun analysis, including parameter definitions and evaluation metrics. The framework can be expanded to complex systems like multi-stage coilguns, where precise force prediction is crucial. Future research may focus on integrating transient electromechanical coupling, eddy current effects, and experimental validation to strengthen model reliability, alongside employing optimization techniques like genetic algorithms and machine learning with high-fidelity simulations for improved performance. In summary, this research conveys substantial understandings regarding the benefits and drawbacks of diverse modeling techniques for reluctance coilgun evaluation. It provides practical recommendations for the choice of appropriate methods predicated on design requirements, thus promoting the progression of effective, precise, and scalable electromagnetic launch systems.

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