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Research TEE

Novel Structure of Driving Coil to Improve the Performance of Reluctance Type Electromagnetic Launcher

Hiren M. Patel[1,*], Jagrut J. Gadit[2]

Abstract

An electromagnetic launcher has established itself as a system with great potential against the traditional propulsion system in power systems, industry, space, and defense-based applications. The performance of these launchers is represented by the force exerted on the projectile of the launching system. The better the force better the impact of the projectile. The present field of research aims to the improvement of reluctance coilgun type electromagnetic launchers based on the novel structure of driving coils of excitation circuits compared to conventional cylindrical structures. Two approaches are investigated in this research: tapered- and curvature-conical coil structures. Also, the performance of the projectile structures based on these approaches is studied. The outstanding and distinct performance of the proposed driving coil structures is noticed in terms of force on the projectile. The electromagnetic launcher system is considered based on the electromagnetic effect observed in 2-D finite element analysis-based simulations.

Keywords: Electromagnetic launcher, reluctance coilgun, finite element analysis, driving coils, projectile, force analysis

INTRODUCTION

An electromagnetic launcher is an efficient system compared to conventional chemical launchers that suffer from heating, aging, and pollution problems. In addition, successive launches are difficult for these launchers.

Railgun, coilgun, and Thomson coil-based launchers are popularly used for power systems, industry, space, and defense applications. A coilgun is the most suitable for successive and long-distance launch applications compared to others.

Reluctance coilguns are widely used in electromagnetic launchers because they are very simple in structure and trigger circuit design. In addition, its acceleration is higher than that of the induction type [1–7].

Paper Structure

This substantial research aimed to enhance the force performance of reluctance-type electromagnetic launchers.

Introduction

An electromagnetic launcher (EML) is preferred over conventional liquid-based launchers because

***Author for Correspondence**
Hiren M. Patel
E-mail: yatindaraji@gmail.com

[1]Research Scholar, Department of Electrical Engineering, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India
[2]Associate Professor, Department of Electrical Engineering, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

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it overcomes the drawbacks of traditional systems. Additionally, the coilgun type of electromagnetic launcher offers better performance for long-distance applications compared to other launchers. Extensive prior research has been conducted to assess the performance of EMLs. To achieve superior performance with a reluctance coilgun-type EML, it is crucial to design the driving coils, projectile, and switching circuit properly. This research focuses on the improved design of the driving coil, which serves as the excitation mechanism for the EML.

Objectives

The superior performance of the reluctance coilgun-type electromagnetic launcher is anticipated based on the force experienced by the projectile, which indicates a higher impact of the EML. Utilizing novel driving coil structures, such as tapered and curvature-conical coil designs, is expected to yield greater force.

Methods

The magnitude of force experienced by the projectile must be increased to achieve a higher impact with the EML. Tapered and curvature-conical coil structures in the driving coils enhance the force performance. A 2-dimensional (2-D) finite element analysis-based simulation is conducted to evaluate the electromagnetic effects and determine the force exerted on the projectile.

Results

Simulations were conducted for tapered and curvature-conical coil structures used for excitation and generating electromagnetic force on the projectile. Both normal and reverse directions of these tapered and curvature-conical coil structures were simulated, and the magnitude of force on the projectile was measured in each case. A similar case study was performed for the projectile structure. Finally, a comparative analysis was carried out against the base case, i.e., the conventional cylindrical structure of the EML, to evaluate force performance.

Conclusions

This extensive work concludes that electromagnetic launchers (EMLs) with tapered and curvature-conical coil structures for driving coils exhibit improved force values compared to the conventional cylindrical design. Conversely, these tapered and curvature-conical coils' reversed configurations show lower force values than the cylindrical base case. Additionally, the tapered and curvature-conical projectile structures also demonstrated lower force values compared to the base case. The research identified that the optimal configuration is achieved when driving coils with a curvature shape in the normal direction are used, as this configuration results in the highest force value and therefore the greatest impact.

OBJECTIVES

The main objective of this research is to obtain superior performance of reluctance type electromagnetic launcher with the help of novel structure of driving coil of EML. The higher the force on the projectile, the higher the impact. Therefore, force is considered as the evaluation parameter in this study to satisfy the objective. The novel structure of the EML, that is, tapered and curved structures with inner and outer conical coils in the normal and reverse directions, has been studied in this extensive work to obtain the distinct performance of a reluctance-type EML. In addition, projectiles with tapered- and curvature-conical structures in the normal and reversed directions were considered for force evaluation.

METHODS

The electromagnetic launcher under consideration is a reluctance coilgun type. A simple capacitor-driven EML is considered. Such EMLs consist of three major design components: driving coils, projectiles, and triggering circuits. This is a capacitor-driven circuit. It can be represented as a simple resistor (resistor-inductor) series circuit, which is supplied by the charged capacitor (C), so it becomes an R-L-C series discharging circuit, as shown in Figure 1.

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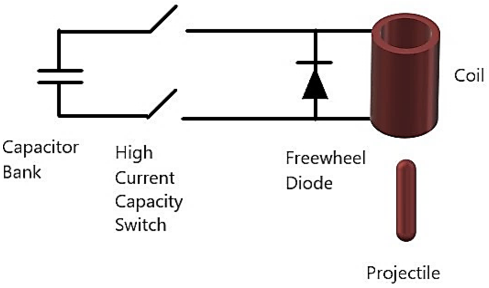

Figure 1. Block diagram of reluctance type EML.

Here, the capacitor is initially charged by an external source, and then the switch with a high current-carrying capacity connects the capacitor to the driving coil of the EML. Therefore, a transient current is created, which is responsible for the electromagnetic thrust on the projectile. Owing to the reluctance principle, the projectile accelerates. The holding torque on the projectile is prevented because the freewheeling diode and projectile are further accelerated [8–13].

Projectile experiences the electromagnetic force which is given by the analytical formula:

$$Force\,F=\frac{(X\,x\,Y)^2\,x\,c\,x\,D}{2\,x\,E^2}F=\frac{(¿)^2\,x\,\mu_0\,x\,a}{2\,x\,g^2}$$
$$F=\frac{(¿)^2\,x\,\mu_0\,x\,a}{2\,x\,g^2}F=\frac{(¿)^2\,x\,\mu_0\,x\,a}{2\,x\,g^2}\ \text{Newtons} \quad (1)$$

Where,
X = Number of turns of the coil
Y = Peak value of current passing through the coil (Ampere)
C = Permeability of free space (Henry/m)
D = Area of the projectile (sq.m) with circular cross-section
E = Gap spacing between projectile and coil (meters)

Here, the electromagnetic structure was analyzed and simulated using the finite element analysis-based tool “FEMM 4.2”. It is a 2-D and single physics-based software package. The problem under consideration in this study involves only one physics, that is, the electromagnetic effect, and there are no difficulties in simulating such problems. In addition, the basic structure under consideration is cylindrical, and the proposed novel structures are symmetric about one axis along the z-axis in the problem, which is an axisymmetric problem.

Finite element analysis is used to analyze the electromagnetic problem. First, it will discretize the entire domain under study and find the vector potential “A”. Then, the magnetic flux density “B” is a function of A, given by:

$$\nabla\,X\,A\;=\;B \quad (2)$$

For two-dimensional analysis, the energy of an element per unit depth is

$$W_e\;=\;\iint\frac{B^2}{2\mu}dx\,dy \quad (3)$$

Where e indicates the quantity of element and μ is permeability.
Force on the element is

$$F_e\;=\;-\frac{\partial W_e}{\partial x} \quad (4)$$

The total force is determined as the combined effect of all elements using Eqs. (2–4) [14–17].

The design parameters of the simulations are listed in Tables 1–3. The base case simulation is obtained as shown in Figures 2 and 3.

Table 1. Design parameters of the projectile.

Design parameter of projectile	Value	Unit
Length	5	cm
Diameter	1	cm
Relative permeability	1000	-

Table 2. Design parameters of the coil.

Design parameter of coil	Value	Unit
Coil length	8	cm
Inner diameter	3	cm
Outer diameter	6	cm
Number of turns	1000	Turns
Maximum current passing through the coil	700	Ampere
Wire (copper)	18	AWG

Table 3. Other parameters for simulations.

Other simulation parameters	Value	Unit
Airgap between the coil and the projectile	1	cm
Air cushion (0–100) to (0, 100)	3	cm
Max. arc angle (for coil)	10	Degree
Max. arc angle (for projectile)	05	Degree
Axisymmetric problem	-	-

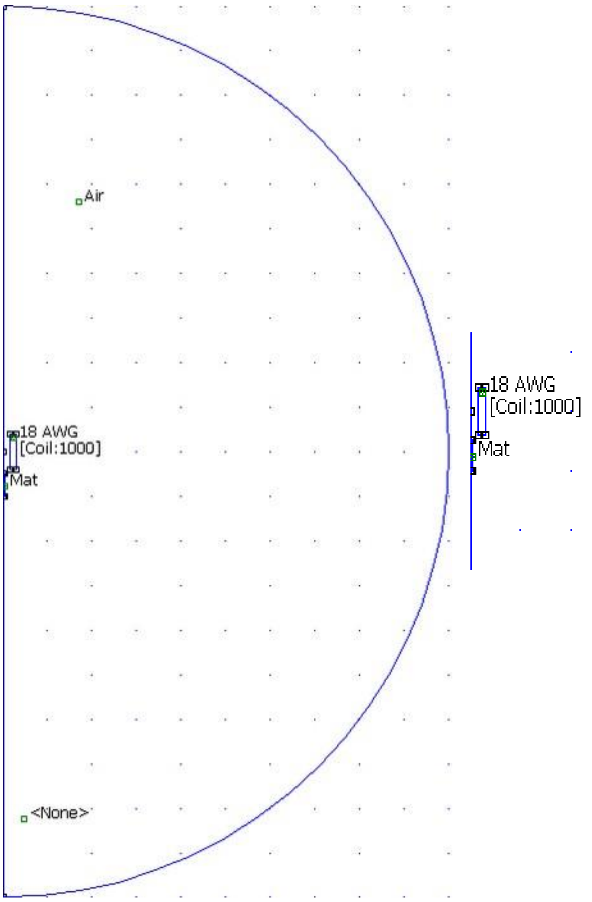

Figure 2. Geometry of EML in FEMM 4.2.

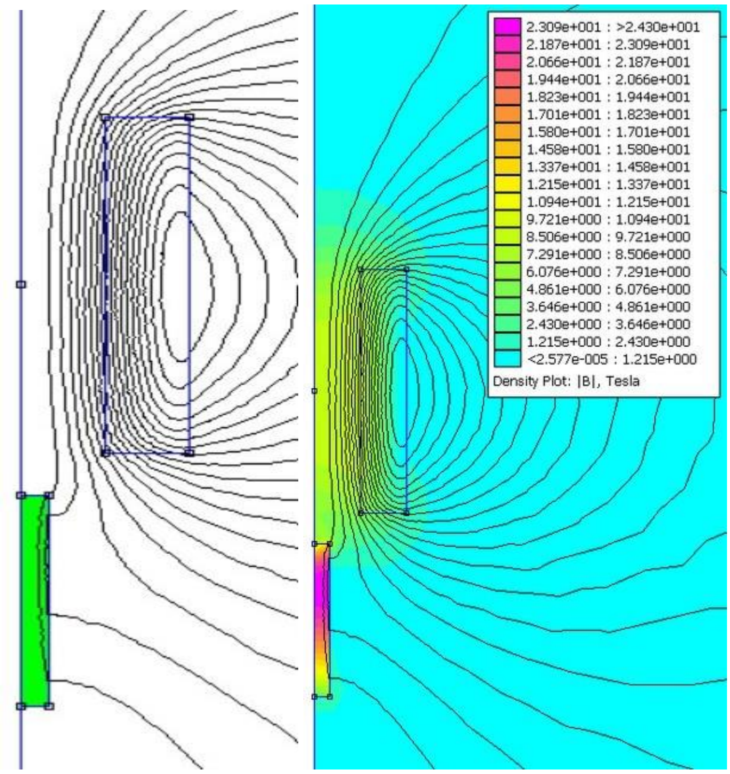

Figure 3. FEM-based simulation with electromagnetic field distribution of EML in FEMM 4.2 [18–20].

The force obtained through simulation is 3426.96 N.

RESULTS

Different case studies are considered as shown in Table 4.

Case 1: The base case exhibited a force on a projectile of 3426.96 Newton.

Case 2: Coil–Inner Conical Tapered–Normal.

As shown in Figure 4(a), a coil with an inner conical tapered structure in the normal direction was simulated, and the force experienced by the projectile was 6158. 59 N. It is electromagnetic field (EMF) distribution is shown in Figure 4(b).

Table 4. Different case study.

Case no.	Structure details
1	Base Case
2	Coil–Inner Conical Tapered–Normal
3	Coil–Inner Conical Tapered–Reversed
4	Coil–Inner Conical Curvature–Normal
5	Coil–Inner Conical Curvature–Reversed
6	Coil–Outer Conical Tapered–Normal
7	Coil–Outer Conical Tapered–Reversed
8	Coil–Outer Conical Curvature–Normal
9	Coil–Outer Conical Curvature–Reversed
10	Projectile–Tapered–Normal
11	Projectile–Tapered–Reversed
12	Projectile–Curvature–Normal
13	Projectile–Curvature–Reversed

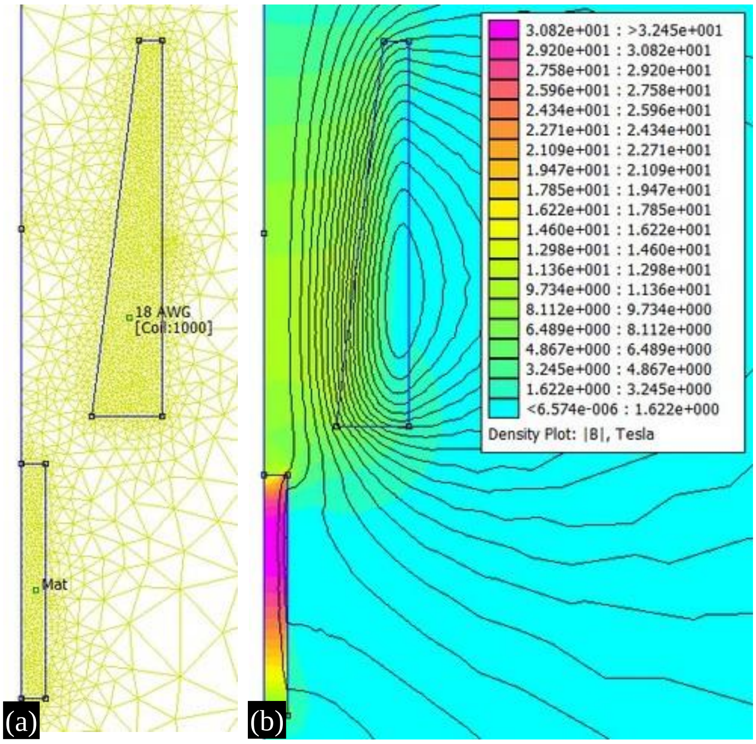

Figure 4. Simulation of case 2; (a) structure, (b) electromagnetic field simulation.

Case 3: Coil–Inner Conical Tapered–Reversed.

As shown in Figure 5(a), a coil with an inner conical tapered structure in the reversed direction was simulated, and the force experienced by the projectile was 2242.83 N. The EMF simulation is shown in Figure 5(b).

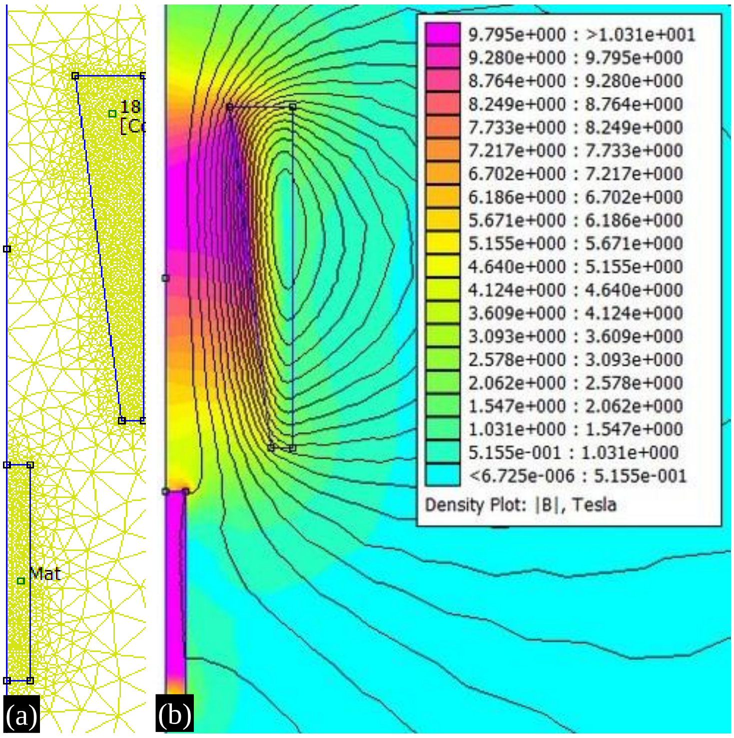

Figure 5. Simulation of case 3; (a) structure, (b) electromagnetic field simulation.

Case 4: Coil–Inner Conical Curvature–Normal.

As shown in Figure 6(a), a coil with an inner conical curvature structure in the normal direction is simulated, and its EMF distribution is shown in Figure 6(b). The force on the projectile is 7094.42 N.

Case 5: Coil–Inner Conical Curvature–Reversed.

As shown in Figure 7(a), a coil with an inner conical curvature structure in the reverse direction was simulated, and its EMF distribution is shown in Figure 7(b). The force on the projectile is 2293.89 N.

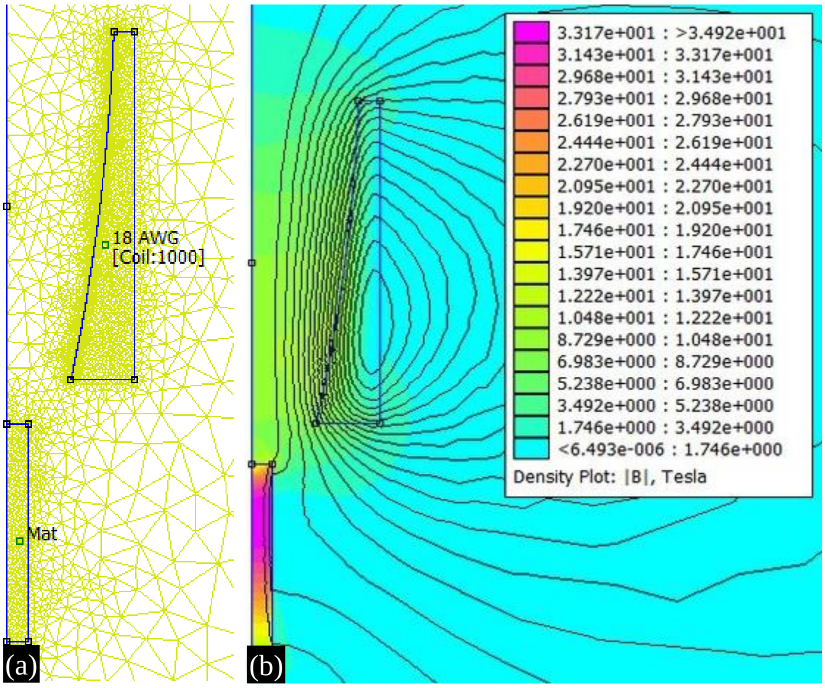

Figure 6. Simulation of case 4; (a) structure, (b) electromagnetic field simulation.

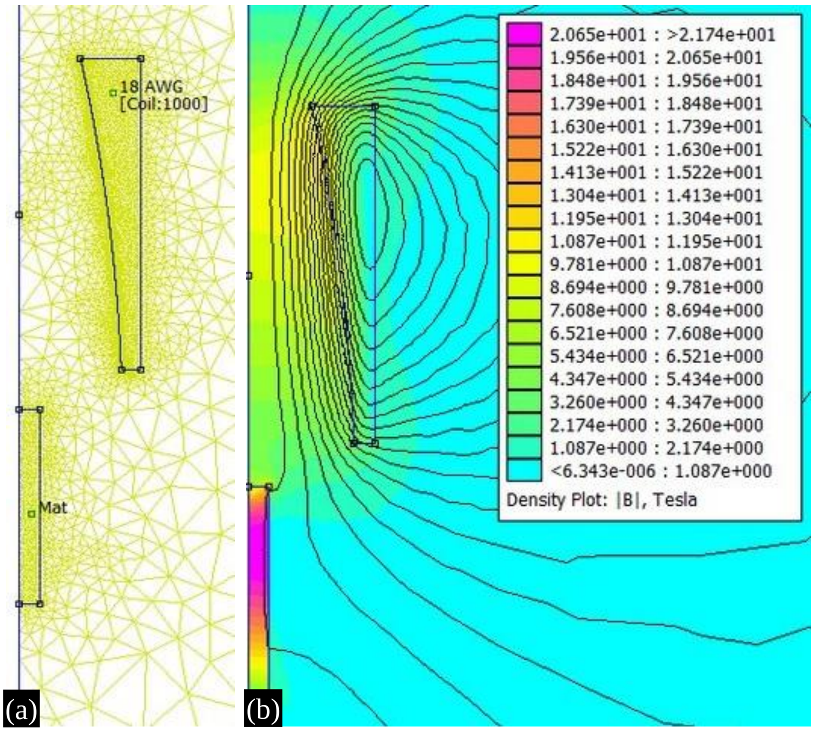

Figure 7. Simulation of case 5; (a) structure, (b) electromagnetic field simulation.

Case 6: Coil–Outer Conical Tapered–Normal.

As shown in Figure 8(a), a coil with an outer conical tapered structure in the normal direction is simulated, and its EMF distribution is shown in Figure 8(b). The force on the projectile is 5051.71 N.

Case 7: Coil–Outer Conical Tapered–Reversed.

As shown in Figure 9(a), a coil with an outer conical tapered structure in the reversed direction is simulated, and its EMF distribution is shown in Figure 9(b). The force on the projectile is 1359.44 N.

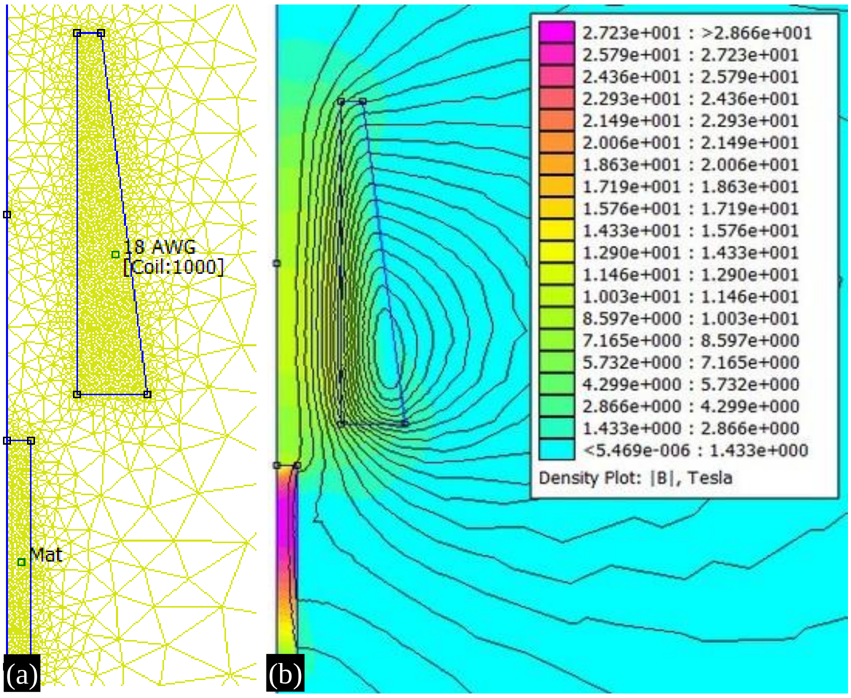

Figure 8. Simulation of case 6; (a) structure, (b) electromagnetic field simulation.

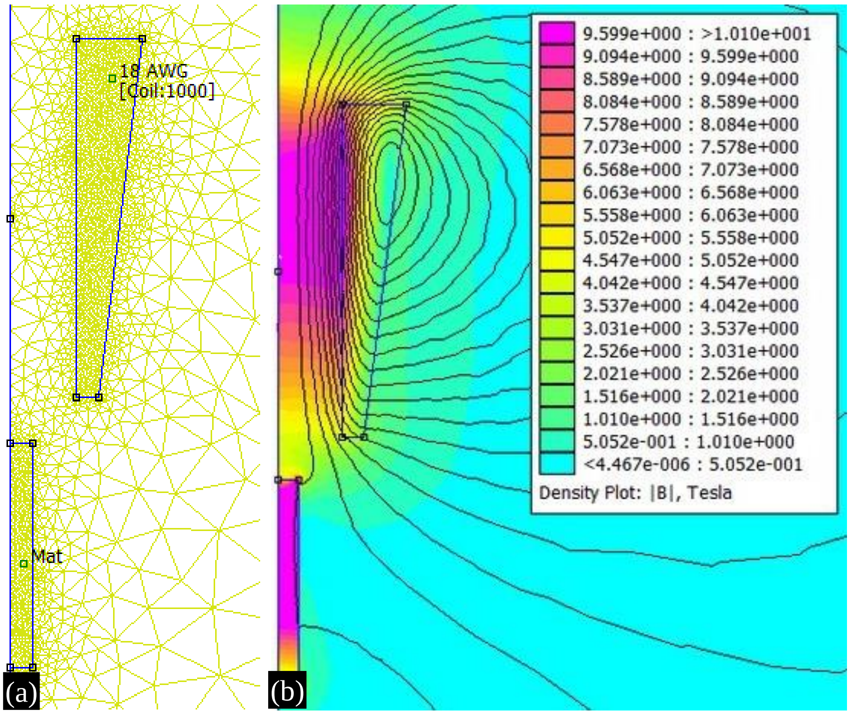

Figure 9. Simulation of case 7; (a) structure, (b) electromagnetic field simulation.

Case 8: Coil–Outer Conical Curvature–Normal.

As shown in Figure 10(a), a coil with an outer conical curvature structure in the normal direction was simulated along with the EMF distribution, as shown in Figure 10(b), and the force on the projectile was 5526.01 N.

Case 9: Coil–Outer Conical Curvature–Reversed.

As shown in Figure 11(a), a coil with an outer conical curvature structure in the reversed direction was simulated along with the EMF distribution, as shown in Figure 11(b), and the force on the projectile was 1269.68 N.

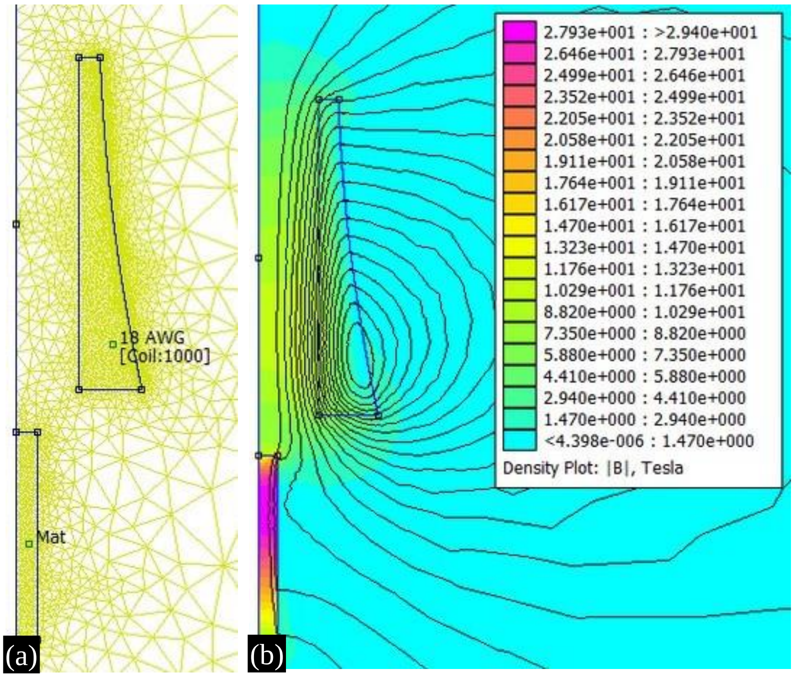

Figure 10. Simulation of case 8; (a) structure, (b) electromagnetic field simulation.

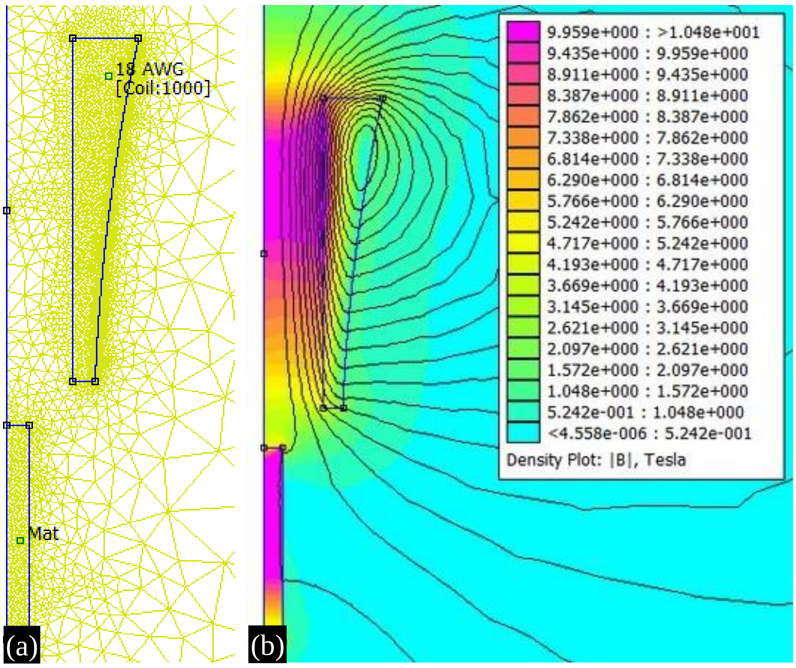

Figure 11. Simulation of case 9; (a) structure, (b) electromagnetic field simulation.

Case 10: Projectile–Tapered–Normal.

As shown in Figure 12(a), a projectile with an outer conical tapered structure in the normal direction is simulated along with the EMF distribution, as shown in Figure 12(b), and the force on the projectile is 2370.29 N.

Case 11: Projectile–Tapered–Reversed.

As shown in Figure 13(a), a projectile with an outer conical tapered structure in the reversed direction was simulated along with the EMF distribution, as shown in Figure 13(b), and the force on the projectile was 3026.37 N.

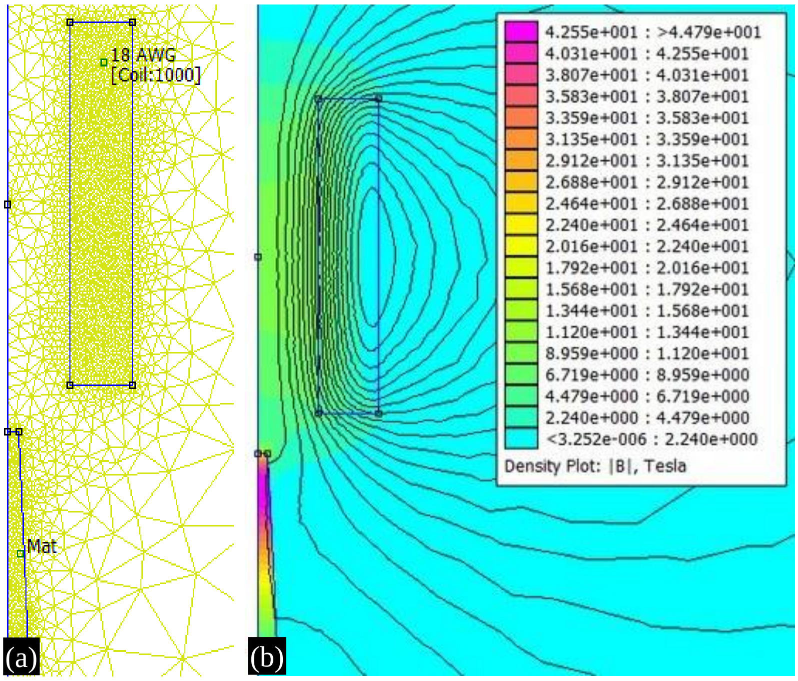

Figure 12. Simulation of case 10; (a) structure, (b) electromagnetic field simulation.

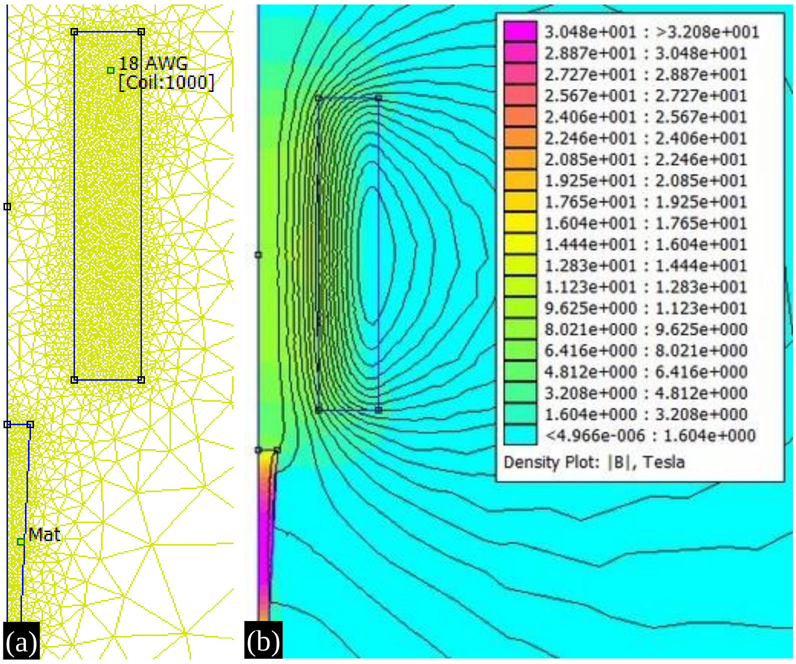

Figure 13. Simulation of case 11; (a) structure, (b) electromagnetic field simulation.

Case 12: Projectile–Curvature–Normal.

As shown in Figure 14(a), a projectile with an outer conical curvature structure in the normal direction was simulated, and the EMF distribution is shown in Figure 14(b). Also, the force on a projectile is 2328.64 N.

Case 13: Projectile–Curvature–Reversed.

As shown in Figure 15(a), a projectile with an outer conical curvature structure in the reversed direction was simulated, and the EMF distribution is shown in Figure 15(b) Also, the force on a projectile is 3019.9 N.

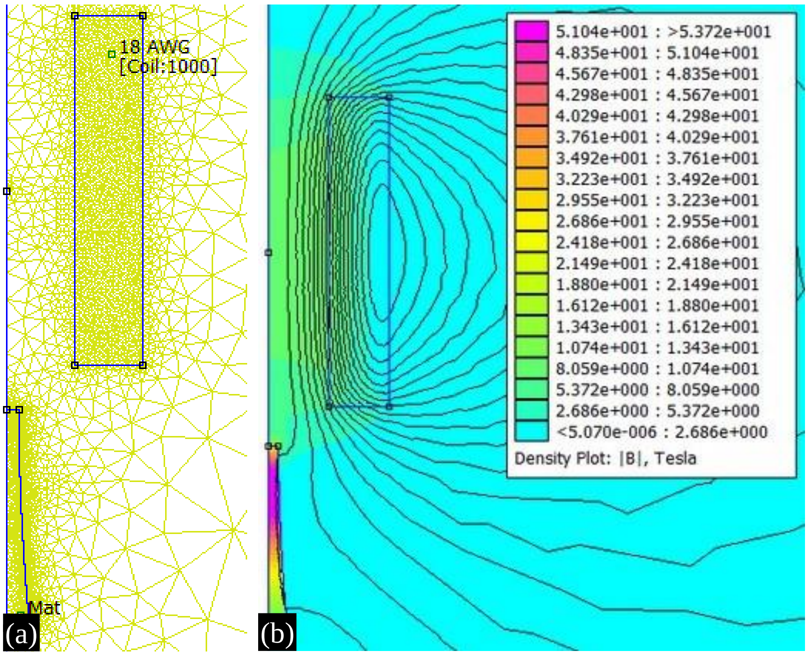

Figure 14. Simulation of case 12; (a) structure, (b) electromagnetic field simulation.

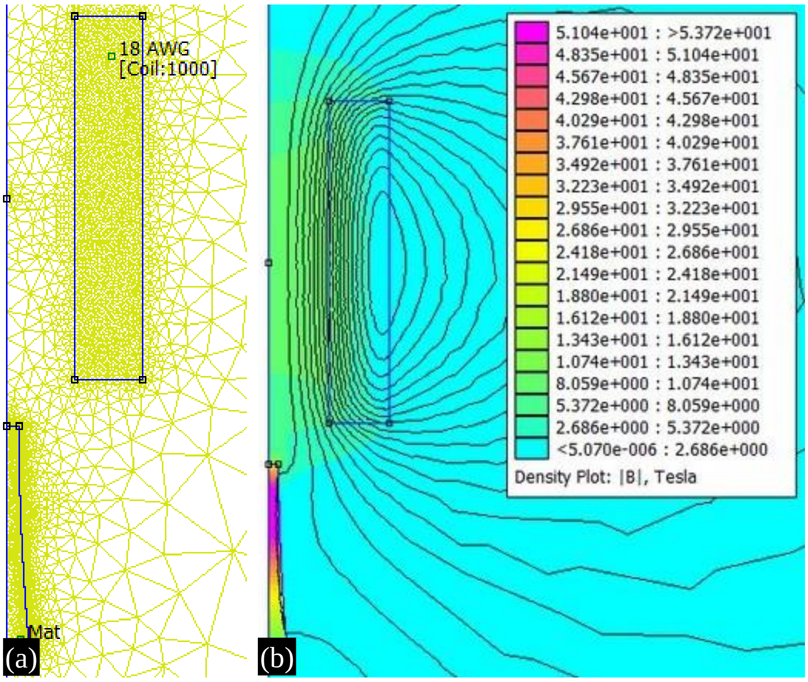

Figure 15. Simulation of case 13; (a) structure, (b) electromagnetic field simulation.

Table 5. Comparison of different cases.

Case no.	Structure details	Force (Newton)
9	Coil–Outer Conical Curvature–Reversed	1269.68
7	Coil–Outer Conical Tapered–Reversed	1359.44
3	Coil–Inner Conical Tapered–Reversed	2242.83
5	Coil–Inner Conical Curvature–Reversed	2293.89
12	Projectile–Curvature–Normal	2328.64
10	Projectile–Tapered–Normal	2370.29
13	Projectile–Curvature–Reversed	3019.9
11	Projectile–Tapered–Reversed	3026.37
1	Base Case	3426.96
6	Coil–Outer Conical Tapered–Normal	5051.71
8	Coil–Outer Conical Curvature–Normal	5526.01
2	Coil–Inner Conical Tapered–Normal	6158.59
4	Coil–Inner Conical Curvature–Normal	7094.42

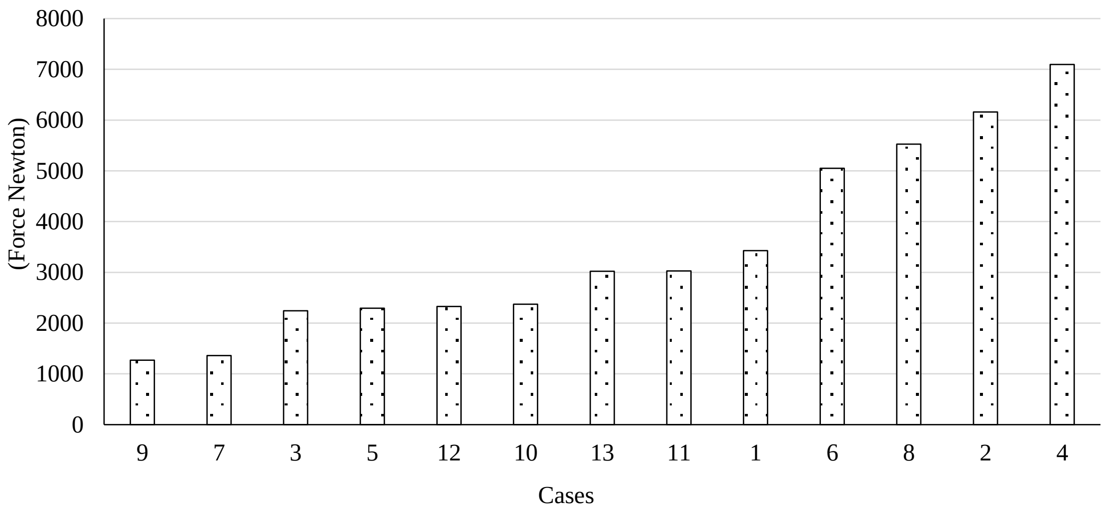

Figure 16. Comparative analysis of all cases in Table 5.

Table 5 presents a comparison of various structural cases. Figure 16 displays the comparative analysis in graphical form. The study reveals that a driving coil structure with an inner conical curvature in the normal direction provides the highest force. This configuration shows a remarkable improvement over the base case, with the force being more than double that of the base case.

CONCLUSION

From this extensive study of the novel structure of driving coils, that is, tapered- and curvature-conical coils and projectiles, force analysis was obtained outstandingly and distinctly. In addition, important conclusions were drawn from the evaluation of this study. The driving coil's inner conical tapered and curved structure in the normal direction has higher forces compared to the base case and other cases. In addition, the normal direction of the outer conical in the case of tapered and curved structures has higher forces than the base case and other cases, except for that of the inner conical in normal directions. Solid projectiles are considered with outer conical curvature and tapered structures, where the reverse direction shows better performance than the normal direction. In addition, these projectile cases had a lower force than that of the base case.

The conical coil with inner and outer tapered and curved structures with reversed direction structures exhibits lower forces compared to the base and other cases. Among these, the driving coil with an outer conical curvature in the reverse direction shows the least force. Higher forces on the projectile indicate a higher impact on the EML and its superiority. This remarkable conclusion lays the foundation for shape optimization of the driving coils and projectile structures to achieve superior performance of the projectile of the reluctance type EML.

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