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Lorentz Force Visualization Using an Electromagnetic Swing Through a STEM–Engineering Design Process for Middle School Electromagnetism Learning

Hanum Rachma Putri[1], Eka Cahya Prima[1*], Amaira Utami[1]

[1] *Department of Science Education, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudi No. 229, Isola, Bandung, 40154, Indonesia*

Corresponding author. Email:ekacahyaprima@upi.edu

ABSTRACT

The pedagogy of physics education, particularly in electromagnetism, often relies on lecture-centric approaches that offer minimal experiential learning opportunities, thereby complicating students' comprehension of abstract concepts. The innovative aspect of this research resides in the design and application of a tactile Lorentz force visualization instrument, specifically an electromagnetic swing, within the framework of STEM-based Engineering Design Process (EDP) learning. This study aims to explore the efficacy of a STEM-oriented Engineering Design Process (EDP) that uses the electromagnetic swing as a hands-on learning tool to enhance students' understanding of the Lorentz force. The research employs an experimental practicum approach with a STEM emphasis, integrated with the Engineering Design Process (EDP), targeting 8th-grade students in junior high school. Findings reveal that the STEM-based Engineering Design Process (EDP) was successfully executed, enabling students to engage in inquiry, imaginative thinking, planning, creation, and iterative improvement. Data from the practicum indicate that increasing the number of coil turns resulted in a corresponding increase in the swing's frequency per minute, consistent with the principles of the Lorentz force and the magnetic field of a solenoid. This study demonstrates that a practicum grounded in the STEM–Engineering Design Process (EDP) is effective in helping students visualize the Lorentz force, as an increase in coil turns correspondingly enhanced the swing motion, thereby showcasing students' understanding of the interplay between electric current, magnetic fields, and force.

Keywords: Lorentz Force; Electromagnetism; Middle School; Magnetic Swing.

I. INTRODUCTION

Electromagnetism is a fundamental area of physics that significantly impacts daily life, as seen in the functioning of domestic appliances, transportation systems, and communication devices such as radios, smartphones, and computers. Its implications extend to sophisticated medical imaging methods such as Magnetic Resonance Imaging (MRI), industrial machinery, and renewable energy production, underscoring the pivotal role of electromagnetic principles in contemporary society. As a principal discipline within physics, electromagnetism underscores the need to understand the natural laws that govern both physical phenomena and technological advancements [1]. More generally, physics serves as the foundational science underlying all scientific disciplines, endeavoring to elucidate the essential principles that govern the natural world. This field encompasses the examination of phenomena occurring across a variety of scales, from elementary particles, atoms, and molecules to complex systems such as living organisms, advanced technologies, and extensive structures including planets, stars, galaxies, and the universe itself [2].

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Physics is introduced at the early stages of secondary education to establish a robust conceptual foundation enabling students to grasp complex scientific concepts, among which electromagnetism is acknowledged as one of the most abstract yet crucial subjects. In Indonesia, junior high school physics is implemented through the Merdeka Curriculum, which prioritizes not only conceptual understanding of science but also the development of scientific process skills. Within this curriculum framework, electromagnetism is formally incorporated in Phase D (Grade IX) as part of the structured content progression. Despite their fundamental importance in physics education, the abstract nature of electromagnetic concepts frequently poses learning challenges for students, underscoring the need for instructional strategies that foster active learning and meaningful engagement. Consistent with this requirement, the Merdeka Curriculum advocates exploring both educators' and students' potential and innovation to enhance the quality of classroom learning [3], [4].

In pursuit of enhancing physics education, the STEM (Science, Technology, Engineering, and Mathematics) pedagogical approach offers a promising framework for instructional improvement. STEM serves as a link between educational environments and real-world contexts, enabling students to connect theoretical concepts to practical applications [5]. STEM-oriented instruction may be applied through various pedagogical models, including cooperative learning, Problem-Based Learning (PBL), and Project-Based Learning (PjBL), all of which facilitate active and meaningful learning experiences [6]. The fundamental principle underlying STEM education is the integration of science, technology, engineering, and mathematics into a coherent contextually grounded learning framework that mirrors authentic problem-solving processes [7]. Furthermore, STEM education has emerged as one of the most widely adopted instructional methodologies globally, with significant growth and influence across a range of scientific fields [8], [9].

Despite these advancements, many educators continue to rely on traditional, lecture-based instructional methods, which hinder student engagement and comprehension. Research indicates that conventional pedagogical practices characterized by limited student participation tend to be repetitive and insufficiently effective in cultivating deep conceptual understanding. Additionally, it has been reported that student attention declines after approximately 15-20 minutes of uninterrupted lecturing [10]. Consequently, physics education, particularly in conceptual domains such as electromagnetism, which require profound comprehension, can substantially benefit from experiential and laboratory-based learning methodologies.

The hands-on learning model empowers students to engage directly with scientific phenomena, thereby fostering a stronger connection between theoretical knowledge and practical application. Through experimental activities and observational learning, students can cultivate a deeper understanding of abstract physics concepts, including the interplay between electricity and magnetism [1]. Empirical evidence substantiates the efficacy of this approach, as hands-on laboratory experiences have been demonstrated to significantly enhance students' conceptual understanding and practical skills [11]. Furthermore, the integration of experimental activities with project-based learning has been shown to increase student engagement and improve learning outcomes, underscoring the instructional value of active learning environments [12]. These findings underscore the vital role of experiential learning in facilitating students' knowledge construction through direct exploration.

To further enhance the benefits of hands-on learning, incorporating the Engineering Design Process (EDP) into STEM education has been shown to foster creativity, critical thinking, and problem-solving skills. The EDP offers a systematic framework that guides learners through stages such as problem identification, solution planning, testing, evaluation, and iterative improvement. The prototyping and redesign process is associated with high levels of cognitive engagement among both educators and learners [13], while iterative evaluation encourages deeper analytical reasoning [14]. Notwithstanding these benefits, the technology and engineering components of STEM education remain underrepresented at the secondary school level, thereby constraining opportunities for interdisciplinary learning and authentic problem-solving experiences [15].

Scholarly literature underscores the significance of integrating engineering design principles into instructional practices to facilitate authentic and interdisciplinary learning experiences. The inclusion of engineering design in educational contexts has been shown to forge meaningful connections among STEM disciplines and promote real-world problem-solving [16], [17]. The combination of design processes and experimental activities empowers students to apply STEM knowledge more effectively to real-world situations and enhances their ability to transfer learning beyond the classroom [18]. Evidence from design-based learning tasks, such as constructing a paper bridge under specific load constraints, illustrates that students can coherently integrate mathematical reasoning with physical principles [19]. Furthermore, integrating the Engineering Design

Process (EDP) into instructional frameworks has been found to improve students' problem-solving capabilities and deepen their conceptual understanding in science [20]. Curriculum redesign initiatives that integrate engineering design with backward design methodologies have also yielded significant improvements in students' conceptual mastery and engagement, particularly concerning electromagnetism topics [21].

When applied specifically to the domain of electromagnetism education, the STEM–Engineering Design Process (EDP) framework provides a robust methodology for enhancing students' conceptual understanding. Electromagnetism, which involves the interplay between electricity and magnetism, represents a fundamental yet abstract component of physics education [1]. The depth of conceptual understanding within this area is significantly contingent on students' capacity to comprehend the concept of fields, which is integral to knowledge construction in electromagnetism [22]. Nonetheless, because electromagnetic fields are inherently invisible, students often struggle to visualize and conceptualize electromagnetic phenomena, thereby impeding meaningful learning experiences.

Despite the promising prospects inherent in STEM-oriented pedagogies and the Engineering Design Process (EDP), there remains a dearth of research focused on methods for visualizing and interacting with electromagnetic phenomena through STEM–EDP-driven projects. In Indonesian educational institutions, traditional, teacher-centered pedagogical strategies continue to prevail in physics instruction, with discussion and lecture-based methodologies being the predominant instructional practices. Such methods offer limited opportunities for hands-on engagement and student-centered learning, which have been shown to adversely impact students' involvement and educational outcomes in physics classrooms [23-25]. Consequently, students frequently possess insufficient opportunities to observe physical phenomena directly and to build conceptual understanding through significant learning experiences. The novelty of this study is to bridge this gap by developing and implementing a hands-on visualization tool for the Lorentz force, in the form of an electromagnetic swing, specifically crafted within a STEM-based Engineering Design Process (EDP) framework for middle school education. The objective of this study is to examine how the execution of a magnetic swing experiment, situated within a STEM-focused Engineering Design Process (EDP) framework, can facilitate students in cultivating a more profound understanding of electromagnetism concepts, particularly the Lorentz force, through experiential investigation.

II. METHOD

This research employs an experiment-based practicum learning approach integrating a STEM framework with the Engineering Design Process (EDP), specifically focusing on magnetism content delivered to eighth-grade students at the junior high school level. The practicum methodology invites students to engage in activities, conducting experiments to validate or examine a theory learned, thereby fostering a scientific attitude and providing a more precise comprehension than mere verbal instruction, which proves beneficial for practical applications in everyday life [26].

This research is grounded in the Lorentz force concept, which governs the force experienced by a current-carrying conductor in a magnetic field and serves as an essential foundation for understanding electromagnetic induction [27]. The Lorentz force is expressed by

$$F = ILB \qquad (1)$$

where F is the magnetic force, I is the electric current, L is the effective length of the conductor in the magnetic field, and B is the magnetic field strength [28].

The Engineering Design Process (EDP) is a structured problem-solving framework that emphasizes creativity and systematic thinking in the development of innovative products or solutions [29]. The integration of the EDP model within Student Worksheets enriches the application of science, technology, engineering, and mathematics (STEM) principles in educational activities [30]. The model typically comprises five sequential stages: ask, imagine, plan, create, and improve [31]. Figure 1 elucidates the stages of the Engineering Design Process.

Fig. 1 The Stages of The Engineering Design Process

The learning activities associated with each stage of the Engineering Design Process in this study are outlined in Table 1.

Table 1. Learning Activity in Each Stages of The Engineering Design Process

STEM-EDP Stages	Activities
Ask	Students identify the engineering problem and constraints by defining the goal of creating a fast and smooth magnetic swing and recognizing conditions needed for safe and free motion (e.g., stability, distance, safety rules).
Imagine	Students brainstorm possible solutions by proposing strategies to make the swing move faster, predicting how design choices (coil turns, structure, alignment) affect motion, and anticipating potential construction difficulties and material use.
Plan	Students select the best solution by developing a detailed construction plan, listing materials, determining coil turns, drawing the design, and outlining step-by-step procedures that meet all given requirements.
Create	Students build the magnetic swing by following their plan and conduct initial testing to observe swing speed, smoothness, and stability while completing the construction checklist.
Improve	Students evaluate what works and what does not, redesign their swing to improve performance, and conduct repeated testing to determine whether the motion becomes faster, smoother, and more stable.

The targeted learning outcomes aligned with the Merdeka Curriculum adopted by the school are summarized in Table 2.

Table 2. Learning Outcomes

	Learning Outcomes (CP)
Science comprehension	Students are able to construct simple electrical circuits and understand magnetic and electrical phenomena to solve challenges or problems encountered in everyday life.
Science Process Skill	Students plan and carry out operational steps based on correct references to answer questions. In their investigations, students use various types of variables to prove their predictions.

The experimental variables, including the independent, dependent, and control variables of the magnetic swing experiment, are outlined in Table 3.

Table 3. Experiment Variables

Variables	Details
Independent	Number of coil turns in the electromagnet
Dependent	Number of swings or swings frequency in one minute
Control	Power supply voltage, distance between coil and magnet, type of coil

The practicum is focusing on the sub-chapter of magnetism, electromagnetism. This practicum is carried out for 3-4 lesson hours, or about 80-160 minutes, with 2 groups of 5-6 students each. This research aims to study the relationship between electric current and magnetic field in an electromagnet and to determine how varying the number of coil turns affects the electromagnet's strength. The tools and materials that were used in this practicum are shown in Figure 2 and Table 3.

(a) (b)

Fig. 2 (a) Materials that were used for practicum and (b) tools that were used for practicum (Source: google.com)

Table 3. Tools and materials for practicum

Tools name	Amount	Materials name	Amount
1. 1 set Multimeter	1 pieces	1. Copper Wire	2 meter
2. Crocodile clip wire	2 pieces	2. Cardboard 30x30 cm	1 pieces
3. Disc Magnet	1 pieces	3. Glue stick	2 pieces
4. Scissors	1 pieces	4. Sandpaper	1 pieces
5. Power supply	1 pieces	5. Ice cream stick	4 pieces
6. Glue gun	1 pieces	6. Double tape	1 pieces
7. Cutter	1 pieces		

Figure 3 illustrates the experimental setup of the magnetic swing apparatus used to demonstrate the Lorentz force.

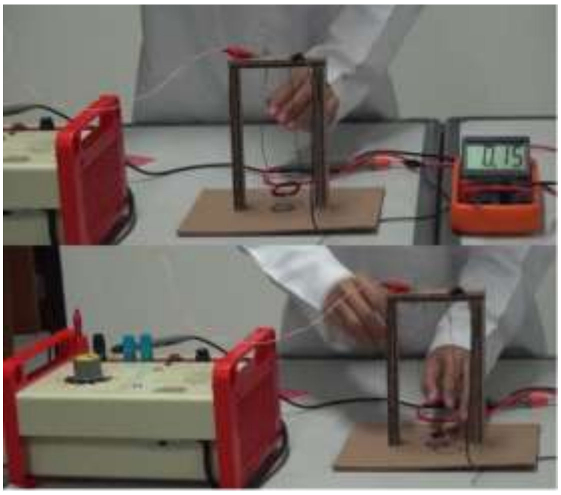


Fig. 3 Experimental setup of the magnetic swing

The following procedural steps, as illustrated in Figure 4, were carried out to construct and test the magnetic swing to investigate the effect of coil turns on electromagnet strength.

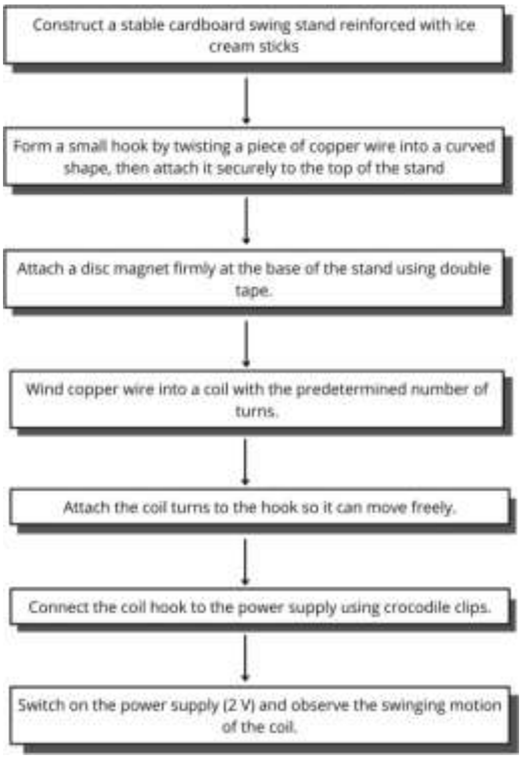


Fig. 4 The Flowchart's Procedures of The Magnetic Swing Experiment

The results of the observation process are recorded in the student worksheet provided by the teacher. This study uses a STEM-EDP-based worksheet that guides students through the stages of thinking, designing, creating, testing, redesigning, and retesting. A worksheet in education is a set of printed or digital sheets containing instructions, tasks, exercises, or questions designed to help students learn, practice, and apply knowledge independently or in groups [32]. The worksheet used in this research consists of a main page (cover), precaution notes, learning objectives, an introduction to the experiment, instructions, project requirements, and the sequential STEM–EDP components. While completing the practicum, each group is given time to discuss and answer the worksheet questions based on their design decisions and interpretations of the magnetic swing experiment.

III. RESULTS AND DISCUSSION

This section delineates the outcomes of the magnetic swing practicum and presents a comprehensive analysis of student interactions with the stages of the STEM-Engineering Design Process (STEM-EDP) and their interpretation of the experiment aimed at visualizing the Lorentz force using the magnetic swing.

The initial phase of the STEM-Engineering Design Process commenced with the Ask phase, during which participants from both groups exhibited the capability to identify pertinent problems and constraints associated with the design and functionality of the magnetic swing. Students recognized the challenge as *'creating a smooth and stable swinging motion,'* while the constraint was delineated as '*the hook attached to the swing must be aligned with the swing string to ensure smooth and stable motion*.' The identification of problems and the development of solutions are essential elements of engineering design learning, as they direct learners in articulating challenges and ascertaining viable solution pathways [20]. At this juncture, students articulated the fundamental engineering challenge and acknowledged the requisite scientific and mathematical concepts vital for devising effective solutions. This process is particularly significant in the context of science education, as it aids in bridging the gap between engineering obstacles and the underlying principles of physics, which encompass the interplay between electric current, magnetic fields, and force [33].

Further examination of students' responses reveals that they did not solely concentrate on the assembly of the apparatus but also deliberated various factors influencing system performance, such as motion smoothness, stability, and component compatibility. These contemplations signify an emerging comprehension of mechanical constraints, including friction at the pivot point and material flexibility, both of which can substantially impact the efficacy of the Lorentz force in facilitating consistent oscillatory movement. While some students prioritized performance-related criteria, others underscored construction-oriented challenges; both perspectives are congruent with the objectives of the Ask stage, which necessitates that learners delineate problems and acknowledge constraints prior to solution development [31]. Through a nuanced understanding of the problem context, students are better equipped to comprehend scientific concepts and employ them to elucidate and address practical challenges [34]. Furthermore, participation in engineering design–oriented activities exposes students to the iterative and exploratory nature of engineering, thereby nurturing creativity and promoting a multiplicity of perspectives in the formulation of practical solutions [35].

The second phase of the STEM-Engineering Design Process is characterized as the Imagine stage, wherein students from both groups showcased their capacity to generate and assess potential solutions aimed at enhancing the performance of the magnetic swing through the integration of scientific concepts with engineering design parameters. Students proposed potential solutions, including '*ensuring the hook moves smoothly*' and '*increasing the number of wire coils*,' as strategies to attain faster and more stable motion. They evaluated these potential solutions by '*adjusting the alignment between the swing and the magnet to achieve smooth, fast, and stable motion, as well as regulating the electric current flowing through the swing*.' These proposals illustrate the students' grasp of the correlation between coil turns, electric current, and magnetic force in engendering effective motion in accordance with the Lorentz force. Additionally, students' responses indicate their aptitude in linking engineering design decisions with foundational physics principles. Considerations related to friction, alignment, and current regulation exhibit an awareness of mechanical and electrical constraints that influence system performance. Anticipation of possible design challenges such as instability and misalignment suggests an evolution of evaluative thinking and feasibility analysis within the Imagine stage. Collectively, these findings underscore substantial student engagement in the generation, evaluation, and selection of design strategies, in harmony with previous research emphasizing the significance of the Imagine stage in cultivating scientific problem-solving skills [20].

The third phase, termed the Plan stage within the STEM–Engineering Design Process, observed students exhibiting varying degrees of proficiency in converting their conceptualized solutions into organized and actionable strategies. Overall, students demonstrated a grasp of the methodical arrangement of design concepts into procedural tasks, which included the preparation of the framework, the formation of the wire coil, the positioning of the magnet, and the provision of electric current. This reflects the synthesis of scientific principles with engineering methodologies. Furthermore, they successfully identified appropriate tools and materials for constructing the magnetic swing, evidencing an awareness of resource management, material suitability, and considerations related to precision and safety. The hand-drawn design sketches illustrated in Figure 5 exemplify how students conceptualized the structural and spatial dimensions of the magnetic swing during this planning phase. The sketch by Group 1 depicts a flat base platform, suggesting the use of paper and indicating a more simplistic approach to structural support, whereas Group 2's design showcases a base that exhibits discernible thickness and internal space, implying the use of cardboard and a more thorough consideration of stability and durability. Additionally, Group 2 displays superior spatial organization of the framework and the suspended components, which may enhance system balance and operational efficacy. Despite these structural variances, both groups failed to detail the distance between the coil and the magnet, as well as the number of coil turns—critical parameters that influence magnetic interaction. Regarding procedural planning, Group 2 provided both detailed and sequential procedures alongside clear visual representations, while Group 1 did not supply thorough step-by-step procedures nor effectively communicate their design through their drawings. Nonetheless, these responses signify substantive engagement in the Plan stage, with students exhibiting developing competence in procedural planning, material selection, and design visualization within the STEM–EDP framework. Consistent with previous research, the application of scientific knowledge to practical scenarios, such as the planning and design of a technical product, can enhance students' capacity to comprehend and address science-related challenges, underscoring the importance of the planning phase in promoting integrated STEM competencies. [36], [37].

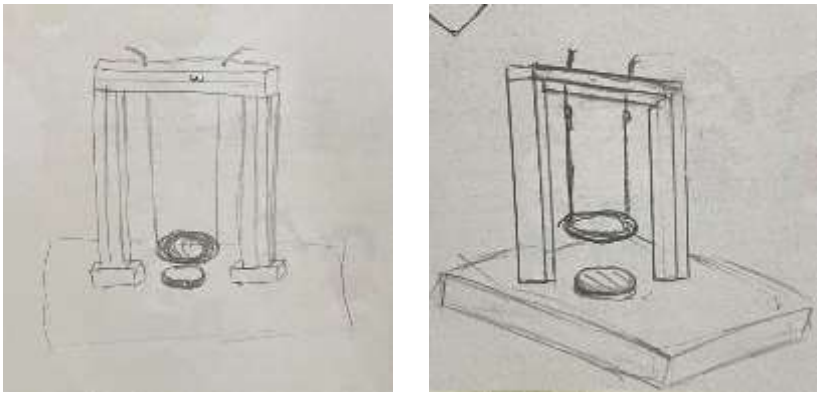

(a) (b)

Fig. 5 (a) The students' hand-drawn design of the magnetic swing of group 1 and (b) the students' hand-drawn design of the magnetic swing of group 2

The fourth stage of the STEM-Engineering Design Process was designated as the Create stage, during which both groups adhered to their respective plans to fabricate magnetic swing prototypes, as depicted in Figure 6. These prototypes served as tangible manifestations of the students' ideations and functioned as instruments for testing and assessing the feasibility, functionality, and efficiency of the proposed solutions. Throughout the construction phase, students were guided by predefined project specifications encompassing structural requirements, component arrangement, and performance criteria. By assembling the supporting frame, suspension system, copper wire coil, magnet, and electrical connections, students transmuted abstract design concepts into a physical system intended to exemplify the Lorentz force through the interplay between electric current and a magnetic field. This hands-on construction process facilitated students' visualization of their designs, assessment of compliance with project requirements, and transformation of conceptual ideas into real-world applications, which constitutes a fundamental aspect of engineering learning experiences [35].


(a) (b)

Fig. 4 The students' product of magnetic swing of group 1 and group 2

During the Improve stage of the STEM–Engineering Design Process, modifications were implemented based on the outcomes of the preliminary testing phase. Following revisions to the electrical connections and overall configuration, all groups successfully completed the practicum. However, during the retesting phase, one group displayed a swinging motion that was not consistently smooth, indicating that while the primary functional issues had been rectified, minor mechanical factors such as friction, alignment, or balance continued to influence the system's performance. The quantitative data gathered during this practicum included (1) the number of coil turns employed by each group and (2) the total number of swings produced by the magnetic swing within a one-minute interval. The results signify clear distinctions not only in oscillation frequency but also in amplitude and stability of the swings. Group 1, which incorporated 35 coil turns, achieved a production rate of 115 swings per minute, characterized by wider and smoother oscillations. In contrast, Group 2, utilizing 25 coil turns, generated 151 swings per minute but exhibited narrower and faster oscillations that were less stable. Figure 5 provides a comparative analysis of coil turns and the corresponding swing frequency for each group.

The assessment of the project requirements was conducted using a teacher-completed checklist to ensure that students followed the given instructions. Table 4 presents the assessment of Group 1's magnetic swing project requirements, while Table 5 presents the assessment of Group 2's magnetic swing project requirements.

Table 4. Assessment of Group 1 Magnetic Swing Project Requirements

No.	Requirements	Yes	No
1.	The swing is built on a base platform.	✓	
2.	There are two pillars, each 15 cm tall and 2 cm wide. There is a roof pillar (10 cm × 2 cm) connecting the pillars.	✓	
3.	The pillars are reinforced with ice cream sticks inside.	✓	
4.	There are hooks attached so the coil can swing freely.	✓	
5.	The coil diameter is similar to the magnet diameter.	✓	
6.	The distance between coil and magnet is exactly 2 cm.	✓	
7.	The swing moves continuously without abrupt stopping after the current is applied.		✗
8.	The motion is smooth and unobstructed by the pole, wires, or hook.		✗
9.	The swing oscillates consistently in a forward–backward direction.		✗
10.	The final product is neat and creatively designed.	✓	

The results in Table 4 indicate that Group 1 satisfactorily fulfilled the majority of the structural and design requirements for the magnetic swing, encompassing the base platform, pillar dimensions, reinforcement, hook installation, compatibility between coil and magnet diameters, and maintenance of a fixed distance between the coil and magnet. These outcomes suggest that students exhibited a commendable performance in constructing the physical structure and adhering to the designated design specifications. Nevertheless, the swing did not satisfy several motion-related performance criteria, as it failed to maintain continuous motion, encountered obstructions, and did not oscillate consistently in a back-and-forth direction. This indicates that while the structural design was satisfactory, challenges persisted in minimizing friction, ensuring appropriate alignment, and achieving stable dynamic motion influenced by the Lorentz force.

Table 5. Assessment of Group 2 Magnetic Swing Project Requirements

No.	Requirements	Yes	No
1.	The swing is built on a base platform.	✓	
2.	There are two pillars, each 15 cm tall and 2 cm wide. There is a roof pillar (10 cm × 2 cm) connecting the pillars.	✓	
3.	The pillars are reinforced with ice cream sticks inside.	✓	
4.	There are hooks attached so the coil can swing freely.	✓	
5.	The coil diameter is similar to the magnet diameter.	✓	
6.	The distance between coil and magnet is exactly 2 cm.	✓	
7.	The swing moves continuously without abrupt stopping after the current is applied.		✗
8.	The motion is smooth and unobstructed by the pole, wires, or hook.		✗
9.	The swing oscillates consistently in a forward–backward direction.		✗
10.	The final product is neat and creatively designed.		✗

Table 5 reveals that Group 2 succeeded in meeting the majority of the fundamental construction requirements, including the base platform, pillar configuration, reinforcement, hook installation, and coil-magnet alignment. Similar to Group 1, the fixed distance between the coil and magnet was effectively maintained, showcasing compliance with design constraints. However, Group 2 did not fulfill all motion performance criteria, as the swing did not move in a continuous manner, displayed obstructed motion, lacked consistent forward-backward oscillation, and demonstrated lower levels of neatness and creativity in the final product. These findings indicate that while students managed to assemble the apparatus, they encountered greater difficulties in optimizing motion stability, alignment, and current regulation, underscoring the complexity of translating conceptual comprehension into effective functional performance.

Despite meeting numerous structural and design requirements outlined in Tables 4 and 5, functional testing of the prototypes uncovered a common issue across both groups. During the testing phase, electric current did not flow through the circuit, resulting in the absence of observable swing motion and magnetic interaction. This outcome suggests that complications pertaining to circuit continuity, wire connections, or power supply configuration impeded the system from operating as intended. Although the initial testing yielded unsatisfactory results, the Create stage proved vital as a learning phase within the STEM–EDP framework, enabling students to identify fundamental flaws in the electrical components of their designs. Facilitating students' experiences of failure is crucial in engineering education, as substantial learning occurs when learners reflect on errors, analyze the causes of failure, and make revisions to their solutions accordingly [37]. Rigorous testing and analysis also empower students to recognize which components necessitate refinement to enhance design effectiveness [38], thereby accentuating the significance of iterative testing as a basis for troubleshooting and redesign in subsequent stages.

The Improve stage of the STEM–Engineering Design Process involved implementing modifications derived from the findings of the initial testing. After amending the electrical connections and optimizing the overall setup, the electric current was successfully enabled to flow through the circuit, facilitating the magnetic swing to operate as planned and allowing all groups to conclude the practicum with success. While all groups adhered to the required criteria, one group exhibited swinging motion that was not consistently smooth during the retesting phase, indicating that although primary electrical concerns had been resolved, minor mechanical factors such as friction, alignment, or balance continued to impede system performance.

These findings underscore the significance of the Improve stage as an iterative process through which students refine both the electrical and mechanical dimensions of their designs. By addressing circuit-related failures and assessing persistent motion inconsistencies, students demonstrated their understanding that effective engineering solutions necessitate ongoing testing, analysis, and refinement. As articulated by the NGSS, "The engineering design process begins by asking questions, making observations, and gathering information about a situation people wish to change. Students then propose a solution, build and test a prototype, and refine the design based on the results of testing" [39]. This stage reinforced a deeper conceptual understanding of the interplay between electric current, magnetic fields, and force, while emphasizing the importance of troubleshooting and optimization in engineering problem-solving. Furthermore, the NGSS highlights that "engineering design is iterative, meaning that engineers often revisit and revise their designs based on insights gained from testing" [39], further emphasizing the value of addressing both electrical and mechanical enhancements within educational contexts.

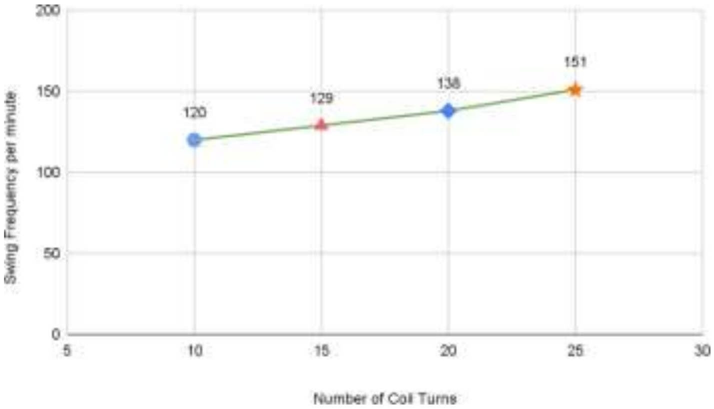


Fig. 7 Comparison of Coil Turns and Swing Frequency

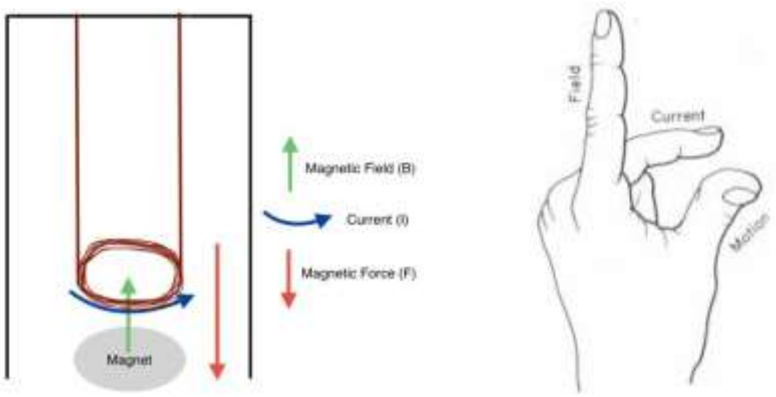
The graph illustrates a positive correlation between the quantity of coil turns and swing frequency. As the number of turns is increased from 10 to 25, the swing frequency correspondingly rises from 120 to 151 swings per minute. This pattern indicates that coils with a greater number of turns generate more substantial electromagnetic effects, thereby enhancing the motion of the swing. The observed increase suggests that augmenting the number of coil turns intensifies the magnetic field, resulting in an increased magnetic force acting on the magnet and consequently stimulating faster oscillatory motion. The relatively uniform and near-linear escalation in frequency indicates that, within the studied parameters, the system consistently responds to variations in coil turns without experiencing abrupt saturation effects.

The data reveals that an increase in the number of coil turns fortifies the magnetic field created by the electromagnet, which enhances the magnetic force imposed on the system. The magnetic (Lorentz) force acting on a current-carrying conductor situated in a magnetic field is articulated by Equation (1).

In this study, the magnetic field is produced by a coil that functions as a short solenoid. The magnetic field inside a solenoid is given by

$$B = \mu_0 \frac{N}{l} I \qquad (2)$$

where μ_0 is the permeability of free space, N is the number of coil turns, l is the solenoid length, and I is the electric current [15]. In an electromagnet, the magnetic field strength is proportional to the number of coil turns ($B \propto N$). Therefore, increasing the number of turns increases B, which directly leads to a larger magnetic force acting on the magnet and conductor system. This increased force enhances the acceleration of the swing, resulting in higher oscillation frequencies. To further support conceptual understanding, a left-hand rule diagram is included to illustrate the relationship between current direction, magnetic field direction, and the resulting Lorentz force that determines the direction of the swing's motion. The direction of the Lorentz force is determined using Fleming's left-hand rule, as illustrated in Figure 8.



(a) (b)

Fig.8 (a) The direction of the fleming's rule in magnetic swing and (b) the direction of the fleming's left hand rule

The figure demonstrates the application of the Lorentz force in a magnetic swing experiment, where a current-carrying coil is situated within the magnetic field produced by a permanent magnet. When an electric current (I) traverses the coil within the magnetic field (B), a magnetic force (F) acts upon the wire, causing the coil to either move or oscillate. Using the left-hand rule, the direction of the Lorentz force is illustrated, with the thumb indicating the direction of the magnetic force, the index finger denoting the direction of the magnetic field, and the middle finger representing the direction of the electric current. The interaction between the electric current and the magnetic field produces a force that displaces the coil from its original position. Reversing the current direction alters the magnetic force's direction, resulting in an inverse oscillation of the coil. This occurrence exemplifies that the Lorentz force emerges from the interaction between electric current and magnetic field, consistent with Equation (1), and can be directly observed in the oscillatory motion of the magnetic swing experiment.

Overall, the magnetic swing experiment effectively visualizes the Lorentz force, supported by a representation of the left-hand rule that aids students in comprehending the interplay between current direction, magnetic field orientation, and the consequent force acting on the system.

IV. CONCLUSION

This study illustrates that the magnetic swing practicum effectively facilitates students in visualizing the Lorentz force while actively engaging with all phases of the STEM-Engineering Design Process (EDP). Throughout the learning activity, students were able to identify challenges and constraints, generate and assess design concepts, construct magnetic swing prototypes, and refine their designs based on testing outcomes. The findings indicate that an increase in the number of coil turns resulted in a more pronounced swing motion, as evidenced by measurable changes in swing behavior, indicating that both coil turns and swing motion were quantitatively analyzed. These outcomes reflect the students' evolving understanding of the connection between electric current, magnetic fields, and force. In light of these findings, it is advised that future implementations place heightened emphasis on quantitative analysis by explicitly linking experimental observations to the concept of Lorentz force. Guiding students to systematically gauge and analyze variables such as electric current, effective conductor length, and magnetic field strength would facilitate a clearer quantitative interpretation of swing behavior, encompassing variations in frequency, amplitude, and stability. Enhancing this quantitative dimension may further bolster students' capacity to interrelate mathematical representations with observable electromagnetic phenomena, thereby deepening their conceptual understanding of electromagnetism within a STEM-EDP framework.

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