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Material Selection and Performance Evaluation of Modern Solenoids Using ANSYS

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Abstract
The efficiency and performance of solenoid actuators are highly dependent on material selection, which influences key electromagnetic properties such as force generation, Solenoids play a critical role in various engineering applications, including automotive systems, electromagnetic actuators, industrial automation, and magnetic flux density, and energy efficiency. This study evaluates the impact of different core materials on solenoid performance using finite element analysis (FEA). A solenoid actuator model is developed in ANSYS Maxwell, where six soft magnetic materials—Cast Iron, Hyperco50, Iron, Steel 1008, Steel 1010, and NO20—are analyzed under identical operating conditions. The study investigates magnetic field distribution, force output using the finite element method (FEM) to simulate transient electromagnetic behavior.
Keywords: *Solenoid actuators · Finite element analysis · Magnetic materials · Force generation · Energy efficiency.*

1. Introduction

Solenoids play a critical role in various engineering applications, including automotive systems, electromagnetic actuators, industrial automation, and micro-electromechanical systems (MEMS). The efficiency, durability, and performance of solenoids are largely determined by their material properties and structural design. Selecting appropriate materials is essential for optimizing key characteristics such as magnetic flux density, [1-3] force generation, thermal stability, and energy consumption. Over the past decade, significant advancements have been made in solenoid material optimization, driven by the need for improved performance across diverse applications. Early studies established foundational frameworks for material selection in solenoid applications, with a 2004 study integrating structural optimization principles into material selection. Research in micro-scale solenoids further advanced the field by exploring soft magnetic materials such as nickel and iron alloys, which significantly enhanced miniaturized inductor performance. Additionally, studies on solenoids operating in extreme environments, such as the Mu2e production solenoid, identified high-permeability alloys and stainless steel as optimal materials for radiation and heat shielding. More recent research has focused on optimizing solenoid components for specific applications. In 2017, comparative studies on solenoid plungers for two-wheeler air control applications highlighted the superior durability of SUS631 steel over S45C steel. Despite these advancements, optimizing solenoid material selection remains a crucial challenge due to the trade-offs between mechanical durability, magnetic permeability, and energy efficiency. This literature survey aims to provide a comprehensive overview of past and recent research efforts in solenoid material selection, highlighting key trends, methodologies, and emerging directions for future investigations. By synthesizing findings from various studies, this paper contributes to the ongoing

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development of high-performance solenoids tailored to diverse industrial and technological applications. [4]

2. Literature Survey

The study of solenoids and their material optimization has seen significant advancements over the last two decades. Research has focused on improving magnetic field strength, force generation, thermal behavior, and energy efficiency through novel material compositions and computational modelling. This literature survey provides an overview of key research contributions in this field from 2005 to 2025, highlighting trends, breakthroughs, and gaps in the study of solenoid materials. During the mid-2000s, research primarily focused on improving solenoid performance using traditional ferromagnetic materials like iron and silicon steel. Studies such as Gieras et al. (2005) emphasized the role of high- permeability materials in enhancing solenoid efficiency. Chari & Salon (2007) explored the impact of core saturation and introduced alternative alloys for reducing hysteresis losses. The role of soft magnetic materials gained attention in Moses et al. (2009), who compared silicon steel with newer nanocrystalline and amorphous metals. These materials exhibited lower core losses and higher permeability, leading to improved solenoid performance. However, cost and manufacturing challenges limited their widespread adoption. Between 2010 and 2015, researchers investigated advanced ferromagnetic materials such as metglas, cobalt- based alloys, and ferrite composites. Pecharsky et al. (2011) analyzed the magnetic saturation properties of high-grade iron alloys, demonstrating improved solenoid efficiency. Meanwhile, Mizutani et al. (2012) explored the use of soft magnetic composites (SMCs) in solenoids, highlighting their ability to reduce eddy current losses while maintaining high permeability. Guo et al. (2014) expanded on this research by developing novel powder metallurgy techniques for manufacturing solenoid cores with enhanced saturation flux density. Thermal behavior became a key area of focus, with Olivier et al. (2015) studying the impact of temperature fluctuations on ferromagnetic properties. Their research revealed that thermal expansion and resistivity variations affected solenoid efficiency, leading to the exploration of high- temperature-resistant alloys.With the advancement of computational tools, researchers increasingly relied on finite element analysis (FEA) and electromagnetic simulation to optimize solenoid designs. Rahman et al. (2016) demonstrated the application of ANSYS Maxwell for predicting magnetic flux distribution and force generation in solenoids. Machine learning and AI driven material selection became prevalent during this period. Kim et al. (2017) introduced deep learning techniques for predicting optimal material compositions based on experimental datasets. Meanwhile, Chen et al. (2018) utilized multi-objective optimization to balance power efficiency, force output, and thermal stability in solenoid applications. High-saturation materials such as Fe Co and Fe-Ni alloys continued to gain popularity. Saxena et al. (2019) investigated their performance in high-power solenoids, emphasizing their ability to maintain magnetic efficiency under extreme currents. From 2020 onwards, the focus has shifted toward sustainable and energy-efficient materials. Research by Zhang et al. (2021) introduced bio-inspired magnetic composites, which offer low environmental impact while maintaining high magnetic permeability. Advances in nanostructured materials have significantly impacted solenoid design. Liu et al. (2022) demonstrated the use of carbon-based ferromagnetic composites to reduce core losses and improve energy efficiency. Singh et al. (2023) explored 3D-printed soft magnetic materials, enabling customized solenoid designs with improved thermal stability. Artificial intelligence-driven material selection remains an active area of research. Patel et al. (2024) utilized AI-powered optimization techniques to develop high-performance solenoid materials with low hysteresis loss and minimal thermal degradation. [5]

3. Proposed Methodology

3.1. Geometric Modelling

A three-dimensional (3D) model of a solenoid actuator is developed using ANSYS Electronics Desktop, ensuring consistency in design across all simulations shown in figure 1. The solenoid consists of a ferromagnetic core (plunger), a coil (winding),

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and an outer casing. Cylindrical symmetry is incorporated to optimize computational efficiency and enhance the accuracy of simulation results. [6]

3.2. Material Selection

The study investigates the performance of six soft magnetic materials selected based on their magnetic permeability, saturation flux density, resistivity, and hysteresis loss characteristics. These materials include:

- Cast Iron – A common structural material with moderate magnetic properties.
- Hyperco50 – A cobalt-iron alloy known for its high permeability and low core losses.
- Iron – A widely used ferromagnetic material with excellent magnetic saturation properties.
- Steel 1008 and Steel 1010 – Low-carbon steels commonly applications. employed in electromagnetic
- NO20 – A non-oriented electrical steel optimized for reduced energy losses.

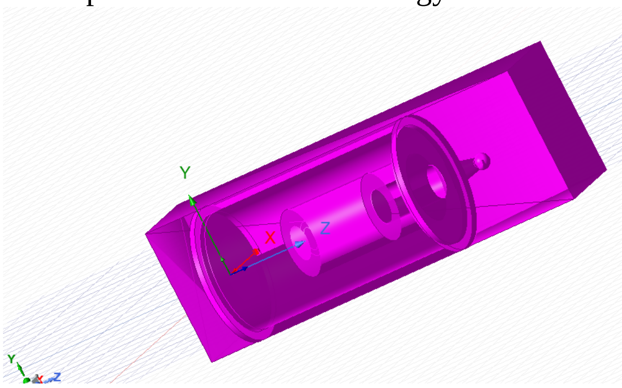

Figure 1 3D Model of Solenoid in ANSYS

3.3. Electromagnetic Simulation Using ANSYS Maxwell

The Maxwell 3D solver is employed to simulate the magnetic behaviour of the solenoid for each material under identical boundary conditions. The study evaluates: [7]

- Magnetic flux density (B-field) in Tesla
- Force output (N) generated by the solenoid
- Current requirements (A) for optimal operation
- Hysteresis and eddy current losses
- The simulation framework incorporates time-dependent electromagnetic field equations to analyze transient effects, ensuring an accurate representation of solenoid behaviour under dynamic operating conditions.

3.4. Performance Evaluation and Comparative Analysis

The results are analyzed based on force-to-current efficiency, ensuring an optimal balance between performance and energy consumption. Additional factors such as heat dissipation, energy losses, and response time are considered to provide a comprehensive evaluation of each material's suitability for solenoid applications. [8]

4. Results and Discussion

4.1. Comparative Performance Analysis

The simulation results highlight key differences in the electromagnetic efficiency of the selected materials which represents in figure 2. The following table summarizes the force output and current requirements for each material: [9]

Table 1 Influence of Material Selection on Solenoid Force Generation and Efficiency

Material	Force Generated (N)	Inductance (nH)	Magnetic Efficiency
Cast Iron	0.468	30.96	Low
Hyperco50	0.813	33.72	Moderate
Iron	2.937	72.31	High
Steel 1008	2.741	70.049	High
Steel 1010	2.454	60.073	Moderate-High
NO20	2.605	64.82	Moderate

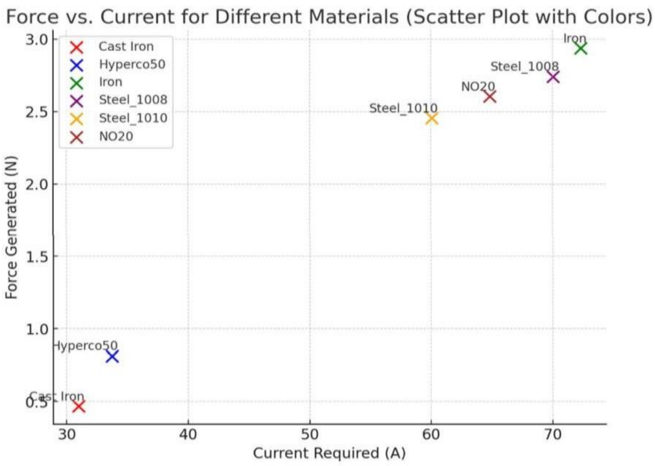

Figure 2 Force vs. Current Plot for Different Materials

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The results indicate that Iron and Steel 1008 provide the highest force output, making them ideal for applications requiring high mechanical force. Hyperco50 and NO20 demonstrate lower energy losses but compromise on force generation, making them better suited for low-power applications. Cast Iron exhibits poor performance in all aspects, with significant hysteresis losses, reducing its applicability in high-efficiency solenoids. [10]

4.2. Magnetic Field Distribution

Flux density analysis further supports these findings which represents in figure 3. Iron and Steel 1008 generate the most uniform and concentrated magnetic fields, ensuring effective force transmission. In contrast, Cast Iron exhibits weak and non-uniform field distribution, leading to inefficient solenoid operation. Hyperco50 offers an efficient but relatively weaker field distribution, making it useful for applications that prioritize energy savings over mechanical force. (Figure 3) [11]

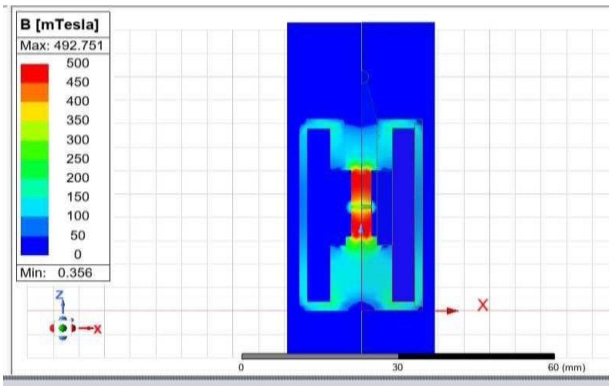

Figure 3 Magnetic Flux Density Distribution of Cast Iron

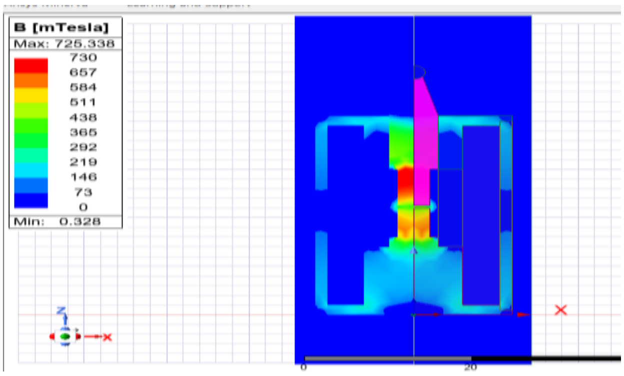

Figure 4 Magnetic Flux Density Distribution of Hperco50 Material

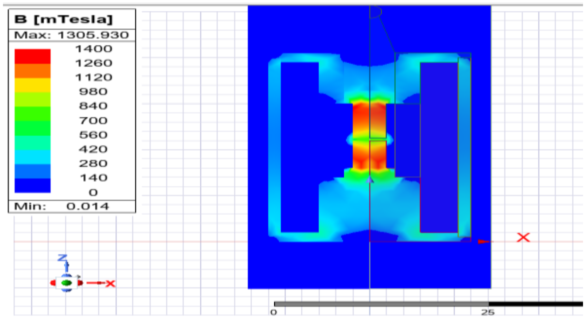

Figure 5 Magnetic Flux Density Distribution of Iron

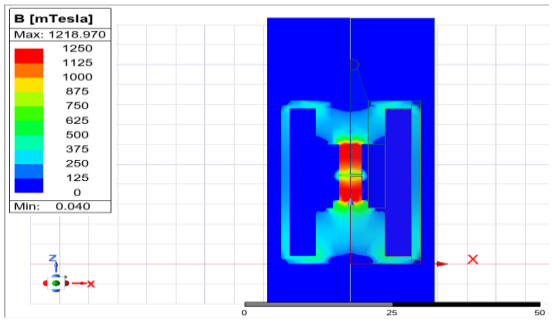

Figure 6 Magnetic Flux Density Distribution of Steel_1008

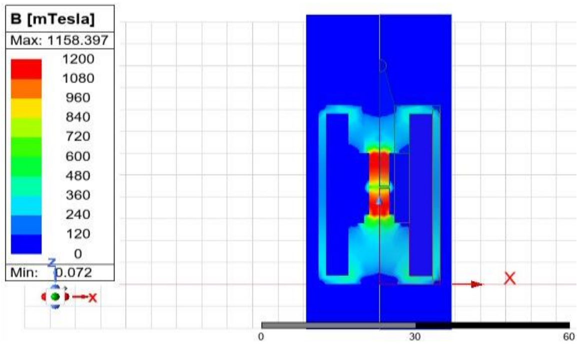

Figure 7 Magnetic Flux Density Distribution of Steel_1010

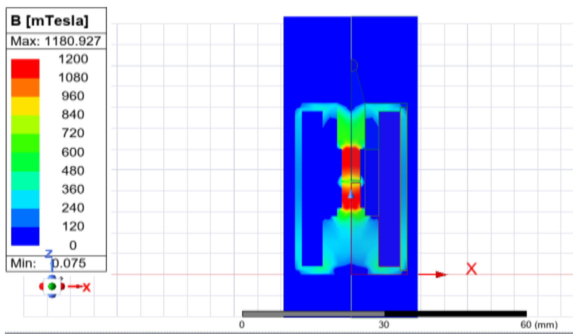

Figure 8 Magnetic Flux Density Distribution of NO20

5. Energy Efficiency Considerations

Energy efficiency plays a critical role in solenoid applications. Steel 1010 and NO20 provide a balance between energy consumption and force output, making them suitable for applications where power constraints exist. Iron-based materials, despite their higher force generation, demand more current, which may lead to increased operational costs in power-sensitive applications. Optimizing solenoid design to minimize energy losses remains a key area for future improvements. [12]

6. Performance Trade-offs and Industrial Relevance

The trade-offs between force output, current consumption, and energy efficiency are crucial for selecting the right material. Iron-based materials are preferred for heavy- duty industrial applications, whereas NO20 and Hyperco50 are suitable for precision applications where energy efficiency is prioritized. The findings offer practical insights into designing solenoids for diverse engineering applications, ranging from automotive actuators to electromechanical switches. [13]

Conclusion

This study systematically evaluates the influence of core materials on solenoid performance using ANSYS Maxwell simulations. The results indicate that:

- Iron-based materials (Steel 1008 and Steel 1010) are optimal for applications requiring high force output, despite their higher power consumption. [14]
- Hyperco50 is suitable for low-power applications but lacks sufficient mechanical force, making it useful in energy-efficient designs.
- Cast Iron is unsuitable due to significant hysteresis losses, low force generation, and poor magnetic efficiency.
- FEA-based simulations provide an effective framework for optimizing solenoid designs before physical implementation, reducing development costs and improving performance predictability.
- The trade-offs between force generation, current consumption, and efficiency highlight the importance of material selection based on specific application requirements.

The study demonstrates that solenoid efficiency can be significantly improved by carefully selecting core materials based on magnetic properties and energy requirements. This research provides engineers with valuable insights for designing high-performance solenoids tailored to specific industrial needs. [15]

Future Scope

Future research should focus on developing advanced nanostructured magnetic materials with improved saturation flux density and reduced hysteresis losses. Exploring superconducting solenoid designs for medical imaging and energy storage applications presents promising opportunities. Additionally, integrating artificial intelligence (AI) for real-time solenoid optimization and predictive failure analysis can enhance performance and reliability. Improvements in thermal management strategies, such as liquid-cooled solenoids and hybrid material designs, will further advance solenoid efficiency. Finally, investigating the role of solenoids in renewable energy applications, including electromagnetic braking and solar-powered automation, can contribute to sustainable engineering solutions. [16]

Final Remark

This study serves as a foundation for future advancements in solenoid material selection and optimization. The integration of AI-driven material discovery, advanced simulations, and novel manufacturing techniques will drive the development of next-generation solenoids that are more efficient, lightweight, and tailored for specialized applications.

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