

Multi-objective DOE-Optimization of a Rectangular Structured Linear Actuator Based on Taguchi Method

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This paper introduces an innovative rectangular structured linear oscillating machine (LOM) featuring an innovative arrangement of permanent magnets (PMs) which are positioned on the mover. A Sinusoidal Magnet Arrangement (SMA) is chosen to minimize PM materials while ensuring the performance parameter, in terms of electromagnetic force (EM), remains unaffected. The main focus of the design is to reduce the cogging force and enhance the electromagnetic force to the PM mass ratio. The optimization is accomplished by utilizing design-of-experiment (DOE) optimization for a linear actuator, along with the finite element method (FEM) and the Taguchi method. A multi-objective optimization approach is employed to refine the parameters of the linear actuator, focusing on the maximum force, the force-to-PM-weight ratio, and minimizing cogging force. By identifying the most effective parameters, an appropriate case with high sensitivity and accuracy is selected. The output parameters, like electromagnetic force and stroke of the proposed design and optimization approach, result very well while the design is a simply structured due utilization of a rectangular structured core part. The proposed design significantly reduces the cogging force to an exceptionally low level, enhancing performance and reliability.

Index Terms— Sinusoidal magnet arrangement, rectangular structure, cogging force reduction, Taguchi method of optimization

I. INTRODUCTION

The first optimized linear actuator [1] was developed by utilizing DOE and response surface method (RSM) techniques. This approach helped verify the effectiveness of the initial design and enhanced its performance characteristics, including output power and compactness. Following this [2], space mapping, and manifold mapping optimization were implemented for linear actuators. While a Maxwell stress tensor analysis has been applied to the linear actuator, it tends to increase calculation time due to the complexity and nonlinearity of the equations involved [3]. The Taguchi method has been established as the most effective optimization technique for assessing influential parameters. Recently, research has shown that multi-objective optimization can efficiently identify the key factors affecting electric machines in a short amount of time [4], [5], [6].

The main purpose of this paper is to design an optimized linear actuator. The focus is on reducing costs and enhancing the electromagnetic performance of the linear actuator, making it suitable for implementation in conventional actuator structures. The key contributions of this paper include a novel topology that introduces a SMA in the mover for the first time. A new technique of optimization is adopted to optimize the performance. This technique aims to achieve multi-objective optimization, addressing factors such as maximum force, improving the force-to-permanent magnet weight ratio, and minimizing cogging force, all using the Taguchi method. The highlights of this report are as follows:

- 1) The proposal features a linear actuator with an SMA, focusing on low cost and minimum PM material utilization.
- 2) DOE optimization utilizing the Taguchi method identifies influential parameters efficiently.
- 3) The optimization process adopts a multi-objective approach for a comprehensive outcome.

II. DESIGN AND OPERATING PRINCIPLE

Fig. 1 presents a benchmark mark design of the proposed SMA design of the actuator, included to illustrate its significance. The proposed SMA design of the actuator shown in Fig. 2, delivers an identical electromagnetic force while utilizing 50 percent of the PM materials.

Investigated SMA design includes a C-shaped stator core with a rectangular structure. Coils are wound around both legs of the C-shaped stator core as shown in Fig. 2. The currents in the coils are set to flow in opposite directions, which makes the flux to add and enter to rotor core. This setup is also adopted for the coils of another stator. Mover is composed of core materials and PMs which are placed in a sinusoidal pattern.

The proposed SMA design operates using single-phase alternating current (AC). During one half-cycle of the AC, the mover adjusts its position to one extreme, providing the least reluctant path for the magnetic flux. During the remaining half cycle of the AC, the mover shifts to the opposite extreme. By maintaining a continuous supply of alternating current (AC), the mover experiences a linear oscillatory electromagnetic force.

III. MULTI-OBJECTIVE DOE /OPTIMIZATION METHOD

The Taguchi method, a DOE technique, is being applied for the first time to identify effective parameters in linear actuator characteristics. Known for its effectiveness in optimizing electrical machines, the method uses fractional factorial experiments arranged in an "Orthogonal Array." This structure ensures an even distribution of parameter levels across columns and symmetrical combinations for each pair of columns. While the Taguchi method yields optimization results, they may not always be optimal. Increasing the levels of each variable can improve accuracy, but it can also be inefficient and time-consuming. The main goal of this approach is to pinpoint the effective parameters. To comprehensively evaluate the

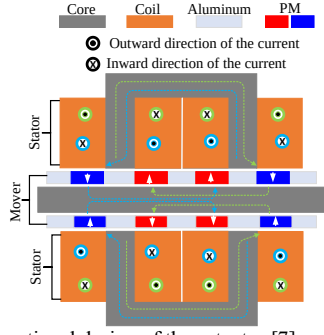


Fig. 1. Conventional design of the actuator [7].

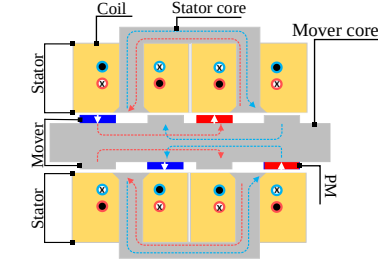


Fig. 2. Proposed SMA design of the actuator.

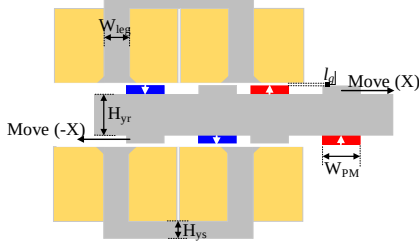


Fig. 3. Optimization parameters of the Proposed SMA design of the actuator.

optimization effect of the linear actuator, the overall process is divided into three levels. The structural parameters of both the stator and rotor (shown in Fig. 3) are optimized independently using an improved iterative Taguchi method combined with sensitivity analysis, as illustrated in Fig. 4.

IV. PERFORMANCE RESULTS OF THE SMA TOPOLOGY

Fig. 5 and Fig. 6 show the cogging force and Electromagnetic force of the conventional design of the actuator and proposed SMA, actuators, respectively. In the optimized SMA model, the maximum force decreased by 2.53% compared to the initial model and by 5.39% compared to the conventional model. Additionally, the cogging force is reduced in the optimized SMA model, with a decrease of 82.06% compared to the initial model and 92.4% compared to the conventional model. Additionally, the proposed SMA design utilizes around 50% PM materials compared to the conventional design of the actuator.

V. CONCLUSION

The LOM's rectangular structure and sinusoidal arrangement have halved magnet costs compared to traditional designs. Using the Taguchi DOE optimization strategy, key parameters were targeted across three layers. The optimized LOM shows over 80% reduction in cogging force and 50% cost savings of the PMs due to comprehensive multi-objective optimization.

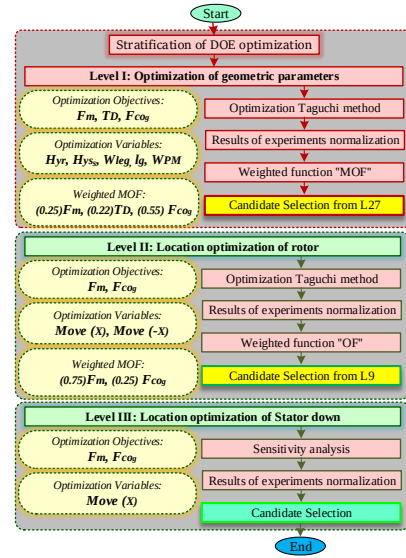


Fig. 4. Flowchart of multi-objective stratification of DOE optimization.

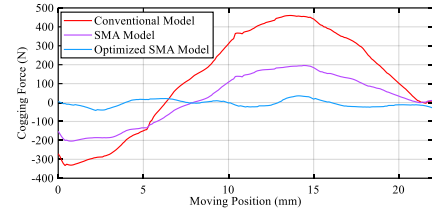


Fig. 5. The cogging force of the linear actuators after completing the optimization process.

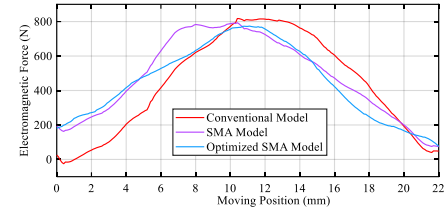


Fig. 6. The Electromagnetic force of the linear actuators after completing the optimization process.

REFERENCES

- [1] D. J. Lee, K. S. Woo, N. C. Park, and Y. P. Park, "Design and optimization of a linear actuator for subminiature optical storage devices," *IEEE Trans Magn*, vol. 41, no. 2, 2005.
- [2] D. Echeverría, D. Lahaye, L. Encica, E. A. Lomonova, P. W. Hemker, and A. J. A. Vandenput, "Manifold-mapping optimization applied to linear actuator design," *IEEE Trans Magn*, vol. 42, no. 4, 2006.
- [3] J. Lee, E. M. Dede, D. Banerjee, and H. Iizuka, "Magnetic force enhancement in a linear actuator by air-gap magnetic field distribution optimization and design," *Finite Elements in Analysis and Design*, vol. 58, 2012.
- [4] Z. Xing, X. Wang, W. Zhao, X. Li, L. Xiong, and X. Zhang, "Optimization Design of Interior Permanent Magnet Synchronous Motor With U-Shaped Rotor for Low-Level Torque Ripple and Electromagnetic Vibration," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 1, 2024.
- [5] Z. Shi, X. Sun, Y. Cai, and Z. Yang, "Robust Design Optimization of a Five-Phase PM Hub Motor for Fault-Tolerant Operation Based on Taguchi Method," *IEEE Transactions on Energy Conversion*, vol. 35, no. 4, 2020.
- [6] J. He, G. Li, R. Zhou, and Q. Wang, "Optimization of Permanent-Magnet Spherical Motor Based on Taguchi Method," *IEEE Trans Magn*, vol. 56, no. 2, 2020.
- [7] M. Jawad, H. Yu, Z. Ahmad, B. Ullah, and B. Alghamdi, "Design Optimization and Resonance Analysis of Rectangular Structured Moving Magnet Linear Actuator," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3272898.