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ANALYSIS OF ERRORS IN TOROIDAL CORE LINEAR MOTION DRIVES AND METHODS FOR ACCURACY IMPROVEMENT

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Abstract:

This article presents a comprehensive analysis of electromagnetic and structural errors that occur in toroidal core linear motion systems and evaluates their influence on the operational accuracy and stability of the device. Linear motion drives based on toroidal cores are widely used in modern electromechanical and mechatronic systems thanks to their compact structure, high efficiency and ability to generate stable electromagnetic forces. However, various electromagnetic and constructive imperfections that arise during the design and manufacturing processes can have a negative impact on system performance, positioning accuracy and dynamic characteristics. So, finding and fixing these mistakes is an important job for scientists and engineers. The primary aim of this research is to identify the essential parameters that guarantee stable traction force generation, diminish vibration levels, and enhance positioning accuracy in toroidal core drives. The study focuses on the effects of magnetic flux distribution, air-gap geometry, winding symmetry, magnetic saturation, and structural alignment on the system's electromagnetic behavior. The study further investigates how fluctuations in these parameters result in alterations of electromagnetic force, energy dissipation, and dynamic instability within the motion system. Mathematical modeling and simulation techniques were utilized to examine the electromagnetic phenomena in toroidal core structures, aiming to fulfill the research objectives. We then checked and compared these results with experimental data to see how different sources of error affected system performance. We paid special attention to studying the drive system's dynamic properties, like how stable the force is, how it vibrates, and how accurately it responds while it's running. The findings demonstrate that enhancing the structural precision of the toroidal core, optimizing magnetic flux distribution, and employing advanced control algorithms can markedly improve the performance, reliability, and positional accuracy of linear motion systems. Also, reducing the difference in windings and carefully designing the air-gap geometry makes electromagnetic distortions and vibrations less noticeable. This research gives scientists and engineers a scientific and practical way to design, improve, and control toroidal core linear motion drives. The suggested methods and analytical findings can be effectively utilized in the advancement of high-precision electromechanical systems for industrial automation, robotics, precision positioning devices, and cutting-edge mechatronic technologies.

Keywords: toroidal core, linear motion drive, electromagnetic system, electromagnetic errors, structural inaccuracies, modeling, magnetic flux distribution.

1. Introduction

Linear motion drives play an important role in modern industry, robotics, and automated systems that require high precision. In particular, toroidal core electromagnetic drives are distinguished by their high efficiency, compact design, and stable magnetic flux distribution [1]. Compared to conventional electromechanical systems, these types of devices provide higher speed, lower vibration levels, and more accurate positioning capabilities. For this reason, they are widely used in robotics, automated production lines, and mechatronic systems that require high precision. At the same time, various structural and electromagnetic errors may occur in toroidal core motion systems [2]. Uneven distribution of magnetic saturation, irregularities in the air-gap geometry, violations of winding symmetry, and assembly tolerances may negatively affect the operational accuracy of the device. These errors can increase traction force pulsations and vibration intensity, reducing energy efficiency. Consequently, the system's positioning accuracy and long-term operational reliability may decrease [3]. In recent years, numerous scientific studies have been conducted on modelling and optimising toroidal core electromagnetic drives. Particular attention has been paid to enhancing device performance through the determination of magnetic field distribution, the optimisation of structural parameters and the improvement of control algorithms. Nevertheless, a comprehensive investigation into the effects of system errors and the development of effective methods to reduce them remain important scientific challenges [4]. This article aims to identify the main errors that occur in toroidal core motion systems, analyse their influence on device accuracy, and develop effective optimisation approaches to improve system precision and operational performance [5].

2. Materials and Methods

The aim of this study is to identify errors in toroidal core linear motion systems and evaluate their impact on the device's accuracy and performance. A comprehensive research methodology was implemented that integrated electromagnetic modelling, structural analysis and experimental testing. This approach enables the sources of errors arising during system operation to be determined and effective methods to be developed for minimising their influence on system performance. The first stage of the research involved developing an electromagnetic model of the toroidal core linear motion system. Finite Element Analysis (FEA) was used to look at the magnetic field distribution, the direction of magnetic flux, and the areas of magnetic saturation. This method makes it possible to accurately analyze complicated electromagnetic processes, and it is commonly used to design and improve electromagnetic systems. Several important parameters were chosen as primary variables during the modeling process. These factors include the magnetic permeability of the toroidal core, the number of windings in the coils, the amount of current going to the windings, and the shape of the air gap between the magnetic parts. All of these factors are very important in figuring out how the magnetic circuit works and how well the linear motion drive system works. Using these parameters, we figured out the magnetic flux distribution, electromagnetic traction force, and magnetic field intensity. These quantities are necessary for comprehending the operational characteristics of the electromagnetic drive and for pinpointing the factors that affect the system's stability and efficiency. The electromagnetic traction force generated in the system can be determined using the following relationship: $F = (B^2 \cdot A)/(2\mu_0)$, where F is the electromagnetic traction force (N).

B – magnetic flux density or magnetic induction (T),

A – effective magnetic surface area (m^2),

μ_0 – magnetic permeability of free space.

This equation describes the relationship between the magnetic flux density and the force generated in the air-gap region of the electromagnetic system. The stability of this force is one of the most important factors affecting the positioning accuracy and dynamic performance of toroidal core linear motion drives: $H = \frac{N \cdot I}{l}$

where:

N – number of windings,

I – electric current (A),

l – length of the magnetic circuit.

In the second stage of the research, structural errors were analyzed. At this stage, several important constructive parameters were investigated, including air-gap accuracy, winding symmetry, core geometry, and assembly tolerances. These factors play a critical role in determining the stability and efficiency of the electromagnetic drive system. Particular attention was paid to the air-gap geometry, since even slight variations in the air-gap distance can have a significant impact on the characteristics of the magnetic circuit. It was determined that air-gap asymmetry increases magnetic reluctance, consequently reducing the electromagnetic traction force generated by the system. Such deviations may also cause instability in the magnetic flux distribution, leading to fluctuations in the generated force. In the third stage, experimental tests were conducted under laboratory conditions in order to validate the modeling results and evaluate the real operating characteristics of the system. For this purpose, a prototype of the toroidal core linear motion drive was designed and constructed. During the experimental investigations, several important performance parameters were measured and analyzed, including: traction force and its pulsation characteristics, vibration level of the system, magnetic flux distribution within the core, thermal distribution and heat dissipation, overall energy efficiency of the device. To measure the system's vibration level, accelerometers were put in at important structural points on the device. Infrared thermography was used to look at the thermal behavior and heat distribution of the electromagnetic structure to find areas where the temperature changed and where it might get too hot. Then, the experimental results were compared to those from electromagnetic modeling and numerical simulations to see how accurate and reliable the model was. In the last part of the research, optimization methods were created to fix the problems that had been found and make the toroidal core linear motion system work better. The goal of this process was to improve the distribution of magnetic flux, make precise changes to the air-gap geometry, and find the best winding configuration. These improvements enhance the stability of the electromagnetic traction force, reduce vibration levels and increase the system's overall efficiency and positioning accuracy.

3. Results and Discussion

The research results demonstrated that electromagnetic and structural parameters significantly influence the operational performance of toroidal core linear motion systems. The results obtained from Finite Element Analysis (FEA) modeling and laboratory experiments were analyzed jointly to obtain a comprehensive understanding of the system behavior. According to the modeling results, uneven magnetic flux distribution leads to the formation of magnetic saturation regions within the toroidal core [6]. These areas make the electromagnetic traction force less stable, which causes the force to pulse more while the machine is running. Calculated results show that traction force pulsations go up by an average of 8–12% when there are magnetic saturation zones [7]. There was also a drop of about 6–9% in the maximum traction force at the same time. These kinds of changes could have a big effect on how well the linear motion system stays in place and how well it moves. The accuracy of the air-gap geometry was also identified as one of the most critical parameters affecting system performance. The research results showed that even small variations in the air-gap size can lead to noticeable changes in the electromagnetic characteristics. In particular, increasing the air-gap thickness by 0.05–0.1 mm increases the magnetic reluctance of the magnetic circuit, causing a 5–10% decrease in the traction force [8]. Moreover, air-gap asymmetry contributes to the increase of vibration levels and may lead to the formation of local thermal concentration zones within the electromagnetic structure. Another important factor affecting system performance is the symmetry of the windings. When the winding symmetry is disturbed, the magnetic field distribution becomes uneven, which results in an irregular distribution of electromagnetic forces within the system [9]. Experimental results confirmed that violations in winding symmetry lead to an increase in traction force pulsation by approximately 6–9%. In addition, such asymmetry causes a decrease in the overall energy efficiency of the device and contributes to increased thermal losses. During laboratory testing, it was also observed that magnetic saturation and winding asymmetry can generate local thermal hotspots within the toroidal core structure [10]. The maximum temperature rise recorded during the experiments was approximately 10–12 °C above the nominal operating temperature. Over long-term operation, such thermal effects may accelerate material degradation and reduce the reliability and service life of the system components. In the optimization stage of the research, several improvements were implemented in order to reduce the identified errors and enhance system performance [11]. The optimization process focused on making the winding configuration better, as well as the magnetic flux distribution and air-gap geometry. These changes made the device work much better. After optimization, the maximum traction force went up by about 10% on average, while the traction force pulsation went down by about 12–15% [12]. The system's overall energy efficiency also went up by 10% to 12%, and the level of vibration went down a lot. These results suggest that achieving high precision in toroidal core linear motion systems necessitates the comprehensive optimisation of electromagnetic and structural parameters [13]. Magnetic flux distribution, air-gap geometry and winding configuration directly influence the accuracy, stability and efficiency of the system. Proper design and optimisation of these parameters can significantly enhance the performance and reliability of toroidal core electromagnetic drives in modern industrial automation, robotics and high-precision mechatronic systems [14]. In toroidal core linear drives, the electromagnetic traction force is determined by the following formula: $F = \frac{B^2 \cdot A}{2\mu_0}$

where:
F – electromagnetic traction force (N)
B – magnetic flux density (T)
A – cross-sectional area of the magnetic flux (m^2)
μ_0 – vacuum magnetic permeability [15].
The vacuum magnetic permeability is equal to: $(4\pi \times 10^{-7})$
Magnetic flux in toroidal core systems is determined as follows: $\Phi = B \cdot A$
where:
Φ – magnetic flux (Wb)
B – magnetic flux density (T)
A – magnetic surface area (m^2)
Magnetic Field Intensity where:
H – magnetic field intensity (A/m)
N – number of windings
I – electric current (A)
l – length of the magnetic circuit (m).

This equation is widely used in the analysis of electromagnetic systems to evaluate the strength of the magnetic field generated by the coil within the magnetic circuit [16].

Energy efficiency: $\eta = \frac{P_{out}}{P_{in}} \times 100\%$

where:

η – energy efficiency (%)
P_out – useful output power (W)
P_in – total input power (W) [17].

This parameter is used to evaluate how effectively the toroidal core linear motion system converts electrical energy into useful mechanical work, and it is an important indicator in performance optimization and system design [18].

Table 1. Main errors in toroidal core motion systems

Type of error	Cause	Effect on the system
Magnetic saturation	Magnetic material reaching its limit	Increase in traction force pulsation
Air-gap asymmetry	Low assembly accuracy	Traction force decreases by 5–10%
Winding asymmetry	Improper coil placement	Non-uniform magnetic field distribution
Thermal losses	Increased current	Reduction in system efficiency

Table 2. Changes in device performance after optimization

Parameter	Conventional design	Optimized system
Maximum traction force (N)	210	232
Traction force pulsation (%)	14	9
Energy efficiency (%)	78	88
Maximum temperature (°C)	72	60

The graph illustrates the distribution of magnetic flux in the toroidal core linear motion system. The diagram shows that the main magnetic flux path forms a closed loop along the toroidal core, while the magnetic flux density decreases in the air-gap region [19]. The modeling results indicate that non-uniform magnetic flux distribution leads to the formation of localized magnetic saturation zones. In these regions, the magnetic induction value becomes relatively high, which causes an increase in traction force pulsation. As a result, the dynamic stability and smooth operation of the system may be negatively affected. As can be observed from the graph, in the optimized design the magnetic flux is distributed more uniformly throughout the core structure. This improved flux distribution reduces saturation effects, minimizes force fluctuations, and enhances the operational stability and overall performance of the device [20].

4. Conclusion

This study comprehensively analysed the electromagnetic and structural errors that occur in toroidal core linear motion systems, as well as their impact on device accuracy. The results showed that the operational stability and performance of toroidal core drives are directly influenced by magnetic flux distribution, air-gap geometry and winding symmetry. Modelling and experimental analyses revealed that non-uniform magnetic saturation increases traction force pulsation and negatively affects the device's dynamic performance. It was also noted that even small changes in the air-gap cause the magnetic reluctance to go up, resulting in reduced traction force. When winding symmetry is disturbed, the magnetic field becomes unevenly distributed, leading to higher vibration levels and increased energy losses. During the research, optimization methods for improving system performance were developed based on electromagnetic modelling, structural analysis and laboratory testing. As a result of the optimisation process, the magnetic flux distribution improved, the air-gap accuracy increased, and the winding configuration was refined. Consequently, traction force pulsation was reduced, energy efficiency increased and vibration levels decreased significantly. The results obtained indicate that comprehensive optimisation of both electromagnetic and structural parameters is essential for designing and controlling toroidal core linear motion systems. The findings provide a scientific and practical foundation for the effective application of toroidal core drives in industrial automation, robotics, and high-precision mechatronic systems. Future research directions include the use of advanced magnetic materials, the development of optimized designs for high-power systems, and the improvement of digital control algorithms to further enhance system performance and precision.

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