A Comprehensive Review of the Longitudinal End Effects in Linear Motors

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Abstract

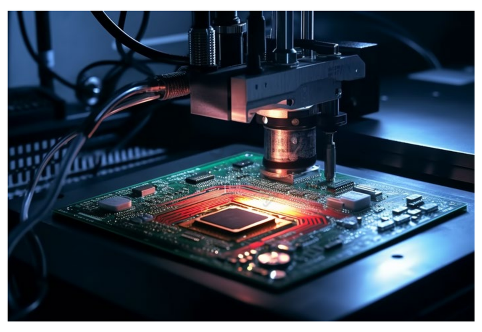
Due to the end effects of linear motors, the thrust fluctuation increases significantly and the dynamic response performance decreases. This results in reduced operational stability and control efficiency. Here, several main longitudinal end effects are analyzed, and their consequences are discussed. Subsequently, the modeling methods for end effects are explored. Finally, some typical mitigation are shown. Through this paper, researchers can gain a comprehensive understanding of the longitudinal end effects of linear motors.

Introduction

linear motors

VS.

rotary motors



Linear motors are fundamental to critical systems like semiconductor lithography and maglev transport for their advantages.

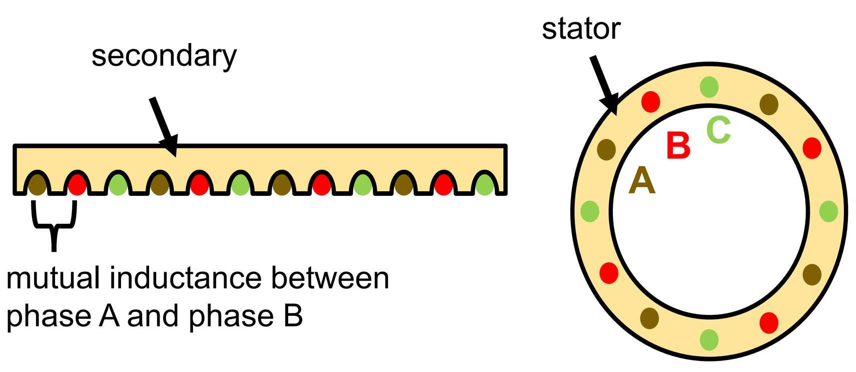
- High precision
- High speed
- Low mechanical loss

Their inherent end effect is a primary cause of thrust ripple and positioning inaccuracy. In-depth research on this effect is key to improve their speed, precision, and energy efficiency.

Causes and effects

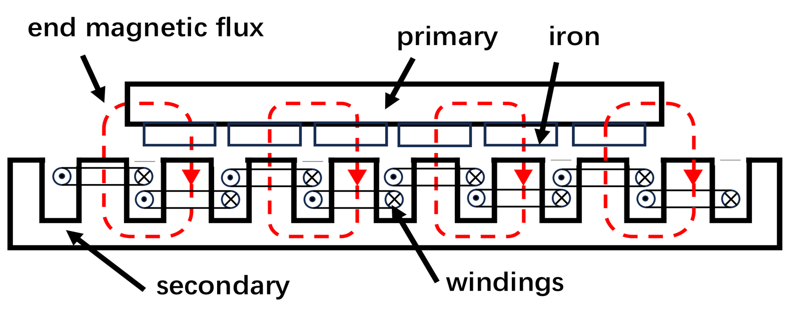
- Phase unbalance

Unbalanced phase mutual inductance at the terminals compared to the central region.



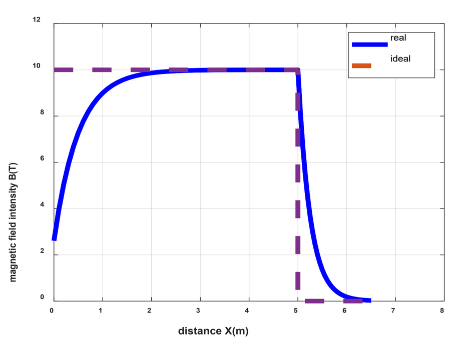
- End magnetic flux

The magnetic field lines at both ends traverse a longer air path, resulting to weaker end magnetic flux.



- Electrical transient

position	Middle(X=1~4)	End(X=5)
magnetic field	stable	abrupt
induce current	no	yes
induced magnetic field	no	Lag the original magnetic field

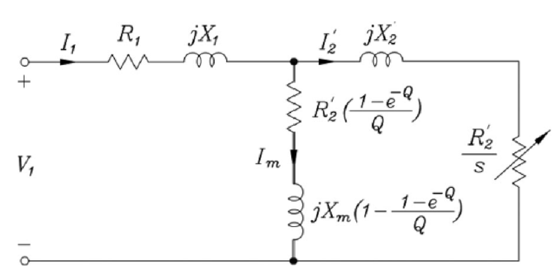


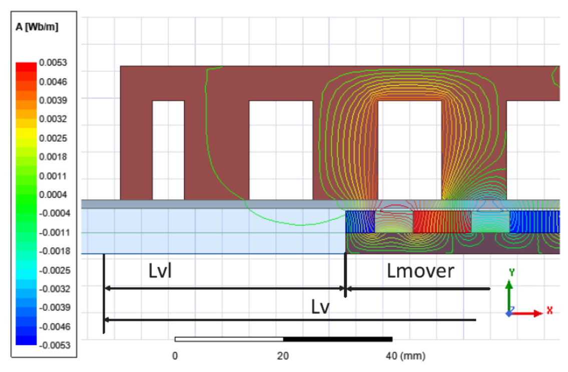
abrupt magnetic field ➡ induce current ➡ induced magnetic field

Conclusion

Despite advantages over rotary motors in high-precision and high-speed applications, linear motors suffer from longitudinal end effects that cause significant thrust fluctuations. This paper analyzes these effects, discusses their consequences, and explores modeling methods. Finally, typical mitigation techniques are presented. The study provides a comprehensive understanding, supporting improved design and control strategies.

Analysis methods





Analytical modelling

- Equivalent Circuit Method
- Analytical Field Method
- Harmonic Analysis Method
- Magnetomotive Force-Permeance Method

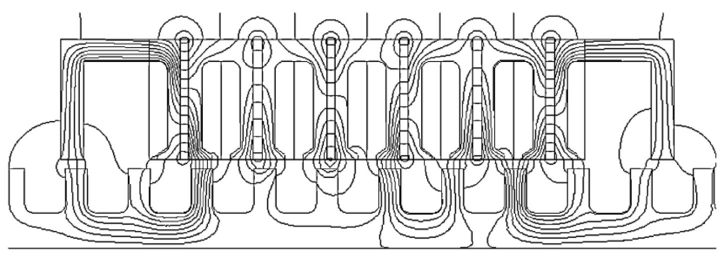
Numerical modelling

- Finite Element Method
- Boundary Element Method
- Finite Difference Method
- Finite Volume Method

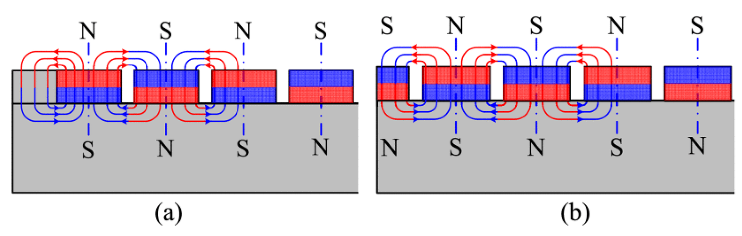
Mitigation

- Geometric optimization

Weaken the influence of end effects by designing the physical shape and size of the motor's primary and secondary components.



Extending the secondary plate

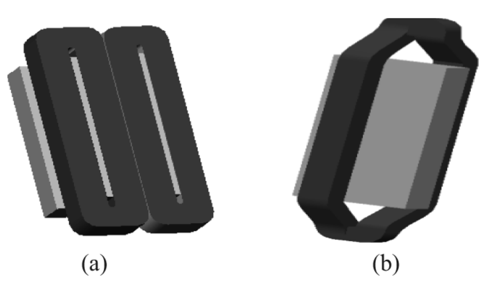


(a) Adding an iron block (b) Adding a mirror PM

Auxiliary end teeth/edge ends

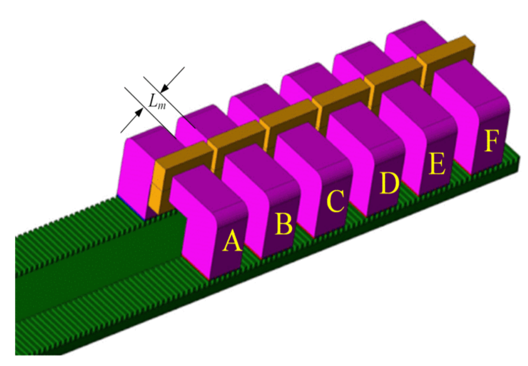
- Modification of electromagnetic structure

Use innovative materials, topological arrangements, or winding excitation schemes to counteract end effects.



(a) Concentrated windings
(b) Distributed ring windings

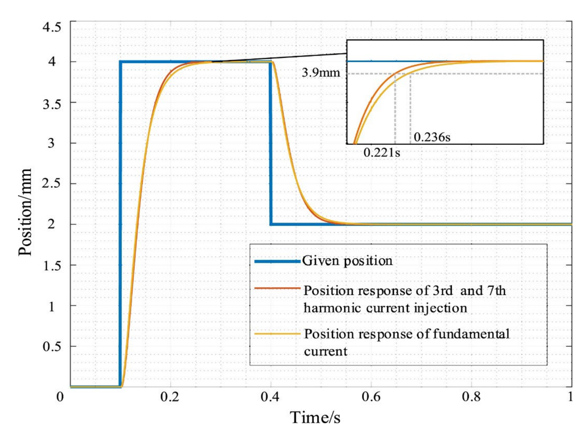
Change the winding configuration



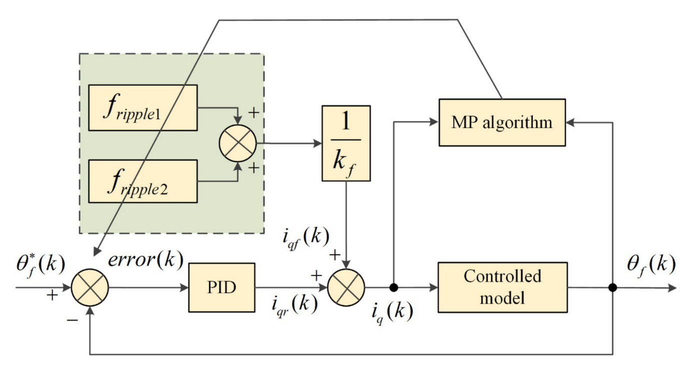
Divided into short primaries

- Electronic compensation

An active control strategy that real-time adjust the voltage or current waveform applied to the motor windings.



Harmonic current injection



Feedforward compensation of thrust ripple with matching pursuit algorithm