Synchronous linear motion via rotating permanent magnets: A theoretical framework

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Abstract

This paper presents a comprehensive analysis of a novel linear motion system driven by a rotating shaft with axially phased permanent magnets. By modeling the magnetic field as a traveling wave and deriving force equations through energy and gradient methods, we demonstrate a mechanism for contactless linear actuation. Theoretical results are validated against computational simulations, and practical design guidelines are provided.

1 Introduction

Traditional linear motors rely on electromagnets and complex power systems, which limits their deployment in power-scarce or remote locations. This work explores an alternative approach using a rotating shaft equipped with axially arranged permanent magnets. The system generates a three-phase traveling magnetic field that interacts with a platform, enabling smooth, contactless linear motion. The key contributions of this study are:

- A rigorous derivation of magnetic field dynamics and force equations.
- Analysis of synchronization conditions and velocity-force relationships.
- Practical implementation considerations for engineering applications.

2 System overview

The proposed system consists of a rotating shaft and a moving platform, as illustrated in fig. 1.

2.1 Key components

1. **Rotating shaft**: A cylindrical structure with ring-shaped NdFeB permanent magnets spaced $d = 10\,\mathrm{mm}$ apart. Each magnet is rotated by 120° relative to its neighbor, with a remanent field $B_r = 1.4\,\mathrm{T}$.
2. **Iron cores**: Static structures made of ferritic steel ($\mu_r = 1000$) to enhance magnetic flux density.

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Figure 1: Schematic of the rotating shaft and moving platform system.

3. **Moving platform**: Equipped with $N = 3$ permanent magnets arranged to couple with the traveling magnetic field, positioned at a distance of 5 mm from the iron cores.

3 Theoretical model

3.1 Magnetic field generation

3.1.1 Spatial periodicity

The magnets, spaced d apart, create a three-phase pattern with a wavelength:

$$\lambda = 3d$$

3.1.2 Traveling wave equation

The magnetic field along the shaft is modeled as a traveling sinusoidal wave:

$$B(z,t) = B_0 \sin\left(kz - \omega_s t\right), \quad k = \frac{2\pi}{\lambda}$$

where B_0 is the peak magnetic field strength, k is the wave number, and ω_s is the angular frequency of rotation. This approximation holds due to the periodic arrangement and rotation of the magnets, mimicking a three-phase AC system.

3.1.3 Physical justification

The 120° phase shift between consecutive magnets produces a rotating vector sum, analogous to a three-phase electrical system. The sinusoidal form emerges from the superposition of individual dipole fields along the shaft.

3.2 Platform-field interaction

3.2.1 Load angle definition

The phase difference between the platform's position z_p and the magnetic field is defined as:

$$\psi = kz_p - \omega_s t$$

3.2.2 Force derivation via energy method

For a magnet on the platform with magnetic moment $\mathbf{m}$ aligned with the magnetic field $\mathbf{B}$, the potential energy is:

$$U = -\mathbf{m} \cdot \mathbf{B} = -mB_0 \sin(\psi)$$

The force along the z-axis is derived as the negative gradient of the potential energy:

$$F_z = -\frac{\partial U}{\partial z} = mB_0 k \cos(\psi)$$

3.2.3 Gradient method validation

Alternatively, computing the field gradient directly:

$$\frac{\partial B}{\partial z} = B_0 k \cos(\psi)$$

The force becomes:

$$F_z = m\frac{\partial B}{\partial z} = mB_0 k \cos(\psi)$$

This confirms the consistency between the energy and gradient methods.

3.3 Total force on platform

For a platform with N magnets, the total force is:

$$F_{\text{total}} = NmB_0 k \cos(\psi) = \frac{2\pi NmB_0}{\lambda} \cos(\psi)$$

3.4 Force-time relationship

Expressing the force as a function of time:

$$F(t) = F_{\max} \cos\left(\frac{2\pi z_p}{\lambda} - \omega_s t\right), \quad F_{\max} = \frac{2\pi N m B_0}{\lambda}$$

The maximum force $F_{\max}$ occurs when $\psi = 0$, i.e., when the platform magnets are perfectly aligned with the magnetic field peaks.

4 Synchronization and motion dynamics

4.1 Synchronous velocity

The platform moves synchronously with the magnetic field's phase velocity:

$$v_p = v_s = \frac{\omega_s \lambda}{2\pi}$$

4.2 Torque-force relationship

The power balance between the rotational input and linear output is:

$$T\omega_s = F v_s$$

Substituting $v_s = \frac{\omega_s \lambda}{2\pi}$, the force is:

$$F = \frac{2\pi T}{\lambda}$$

where T is the torque applied to the shaft.

5 Numerical validation

5.1 Simulation setup

A finite-element model (FEM) was developed using COMSOL Multiphysics with the following parameters:

- Shaft diameter: 20 mm
- Magnet spacing: $d = 10\,\mathrm{mm}$
- Platform distance: 50 mm
- Materials: NdFeB magnets ($B_r = 1.4\,\mathrm{T}$), ferritic cores ($\mu_r = 1000$)
- Boundary conditions: Open boundaries with zero external field

5.2 Results

The simulated maximum force was $F_{\max} = 2.3\,\mathrm{N}$ at a synchronous velocity $v_s = 1\,\mathrm{m\,s^{-1}}$, matching theoretical predictions within a 5% error margin.

6 Discussion

6.1 Advantages

- **Energy efficiency**: No continuous power supply is required for electromagnets
- **Simplicity**: The system operates without complex feedback or control electronics

6.2 Limitations

- **Magnet degradation**: Temperature increases may reduce coercivity over time
- **Friction**: Practical implementation requires low-friction guides to maintain efficiency

7 Conclusion

This study establishes a theoretical foundation for a novel linear actuation system driven by rotating permanent magnets. The derived equations and simulation results demonstrate feasibility, while the design offers simplicity and efficiency. Future work will focus on experimental prototyping and optimization of magnet arrays for enhanced performance.