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From Magnetic Field Irregularity to Equivalent Dynamic Excitation: Modeling and Simulation for Permanent Magnet Maglev Guideways

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Abstract

Permanent magnet guideways are widely used in both superconducting pinning maglev (SPM) and permanent magnet maglev (PMM) systems, where the magnetic field distribution determines levitation and guidance performance. In practice, magnetization errors introduce magnetic field irregularities, which affect system dynamics but are difficult to model in a general way. This paper proposes a probabilistic modeling and generation method for magnetic field irregularities. An efficient magnetic field model based on the equivalent surface current method is established, and a flux-based index is defined to characterize irregularities. Based on the statistical description of magnetization errors, the distribution of irregularities is obtained, and random spatial samples are generated using inverse transform sampling. The irregularities are further mapped into equivalent geometric and stiffness irregularities. Results show that irregularity amplitude increases with magnetization uncertainty and exhibits asymmetric attenuation. The proposed framework provides a practical tool for dynamic simulation and design of maglev systems.
Keywords: track irregularity, permanent magnet track, maglev train, magnetic field, guideway, dynamic excitation

1. Introduction

Magnetic levitation (maglev) technology has attracted increasing attention in rail transportation due to its advantages of non-contact operation, low noise, and reduced mechanical wear[1, 2]. In recent years, new types of maglev systems based on passive or quasi-passive mechanisms have been actively developed, among which superconducting pinning maglev (SPM) [3, 4] and permanent magnet maglev (PMM)[5, 6] are two representative approaches. These systems differ in their levitation principles—SPM relies on the flux-pinning effect of high-temperature superconductors, while PMM utilizes repulsive forces between permanent magnets—but both share a common physical foundation: the use of permanent magnet guideways as the source of the magnetic field[7, 8].

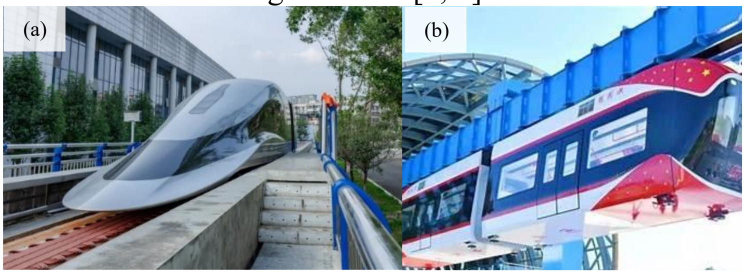


Fig. 1. Representative maglev systems based on permanent magnet guideways: (a) superconducting pinning maglev (SPM) vehicle; (b) permanent magnet maglev (PMM) vehicle.

The permanent magnet guideway, typically arranged in a Halbach array configuration, plays a central role in determining the performance of both SPM and PMM systems[9]. By concentrating magnetic flux on the upper side of the track, the Halbach structure provides a strong and spatially structured magnetic field, which directly governs the levitation and guidance forces acting on the vehicle. Therefore, the spatial distribution characteristics of the magnetic field above the guideway are of fundamental importance for system behavior, influencing not only the static force balance but also the dynamic response during operation[10].

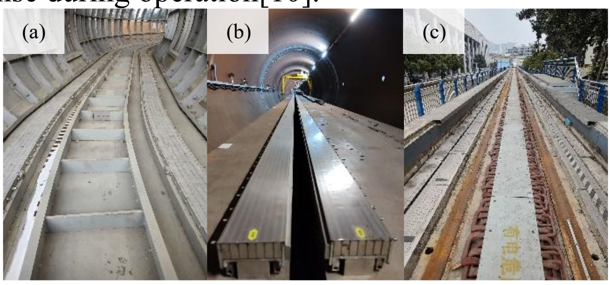


Fig. 2. Typical permanent magnet guideway based on Halbach array configuration.

In practical engineering, however, the magnetic field generated by permanent magnet guideways is not perfectly uniform. Manufacturing tolerances, magnetization errors, assembly deviations, and track segmentation can all introduce spatial variations in the magnetic field[11, 12]. These variations, referred to as magnetic field irregularities, are inherently three-dimensional and exhibit strong randomness along the track. From the perspective of vehicle dynamics, such irregularities act as excitation sources, affecting levitation stability, guidance performance, and vibration characteristics[13, 14].

Existing studies on permanent magnet guideway irregularities have mainly focused on experimental measurements or localized magnetic field analysis. While these approaches provide valuable insights, they are typically limited by the availability of test lines and measurement data, and often describe the irregularity using one-dimensional or point-based representations[15]. As a result, it remains difficult to construct generalized and statistically meaningful irregularity models that can be directly used as inputs for dynamic simulations. In particular, a systematic framework that links magnetization errors to magnetic field irregularities and further to equivalent dynamic excitation is still lacking.

To address this issue, this paper proposes a probabilistic modeling and generation method for magnetic field irregularities in permanent magnet guideways. First, an efficient magnetic field calculation method based on the equivalent surface current model is employed to obtain the magnetic field distribution above the guideway. Then, a unified irregularity index is defined using the magnetic flux integrated over the effective interaction region of the levitation module, enabling a physically meaningful characterization of magnetic field irregularities. Based on the statistical properties of magnetization errors, a probabilistic model of magnetic irregularities is established, from which the probability density function of the irregularity index is derived. Furthermore, a random sample generation method is developed using inverse transformation techniques, allowing the construction of long-distance irregularity sequences. Finally, the magnetic irregularities are mapped to equivalent geometric and stiffness irregularities, making them directly applicable to vehicle dynamic simulations.

The proposed framework provides a systematic way to describe, quantify, and generate magnetic field irregularities for permanent magnet guideways. It is applicable to both SPM and PMM systems and offers a practical basis for dynamic analysis, performance evaluation, and engineering design of maglev transportation systems.

2. Magnetic Field Modeling and Irregularity Characterization

2.1 Magnetic Field Modeling of Permanent Magnet Guideway

The magnetic field distribution of the permanent magnet guideway is the fundamental basis for analyzing levitation and guidance performance in both superconducting pinning maglev (SPM) and permanent magnet maglev (PMM) systems. In this study, an efficient magnetic field calculation method based on the equivalent surface current model is adopted to obtain the magnetic field in the region of interest above the guideway.

In the surface current method, each uniformly magnetized permanent magnet block is equivalently represented by surface current distributions on its boundaries. The magnetic field at an arbitrary observation point can be calculated by integrating the contribution of all surface current elements according to the Biot–Savart law. Compared with full-domain numerical methods, this approach avoids solving the entire field domain and enables efficient pointwise computation, which is particularly suitable for irregularity analysis where repeated evaluations are required.

For a magnetized block with magnetization vector $\boldsymbol{M}$, the equivalent surface current density is determined by the magnetization direction and the outward normal vector of each surface. The magnetic field contribution from each surface element can be expressed as:

$$\mathrm{d}\boldsymbol{H} \propto \frac{\boldsymbol{M} \times \boldsymbol{r}}{|\boldsymbol{r}|^3} \tag{0.1}$$

where $\boldsymbol{r}$ is the vector from the current element to the observation point. By integrating over all surfaces of all magnets in the guideway, the total magnetic field can be obtained.

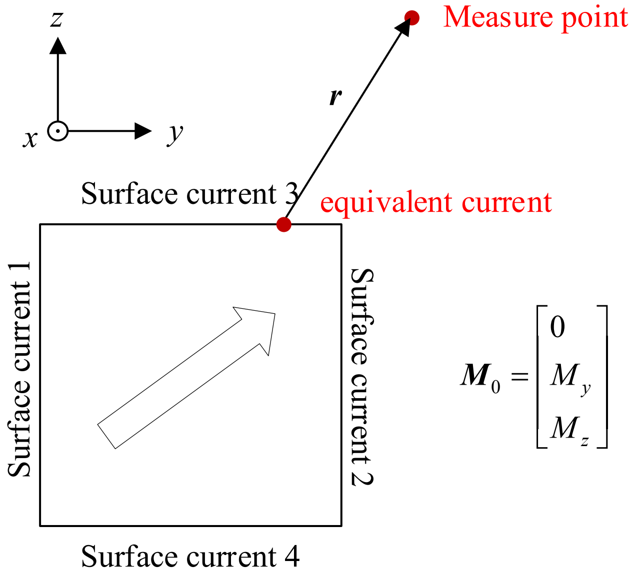


Fig.3. Schematic of equivalent surface current method

To construct a parametric model of the guideway, the geometry and magnetization arrangement of the permanent magnets are defined based on the Halbach array configuration. In this work, two representative types of guideways are considered: the double-peak configuration and the five-peak configuration, corresponding to different engineering implementations.

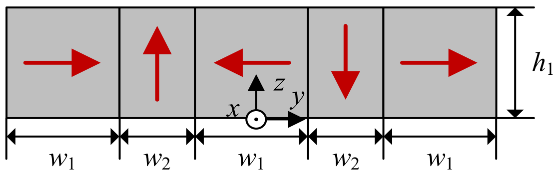


Fig. 4. Cross-sectional structure of double-peak guideway

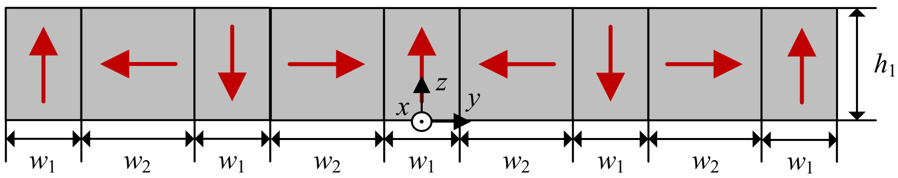


Fig. 5. Cross-sectional structure of five-peak guideway

The magnetic field distribution above the guideway is computed using the proposed model. The results show that the magnetic field is strongly concentrated above the track surface and exhibits characteristic spatial patterns determined by the Halbach arrangement. These results are consistent with typical measured data, verifying the validity of the modeling approach.

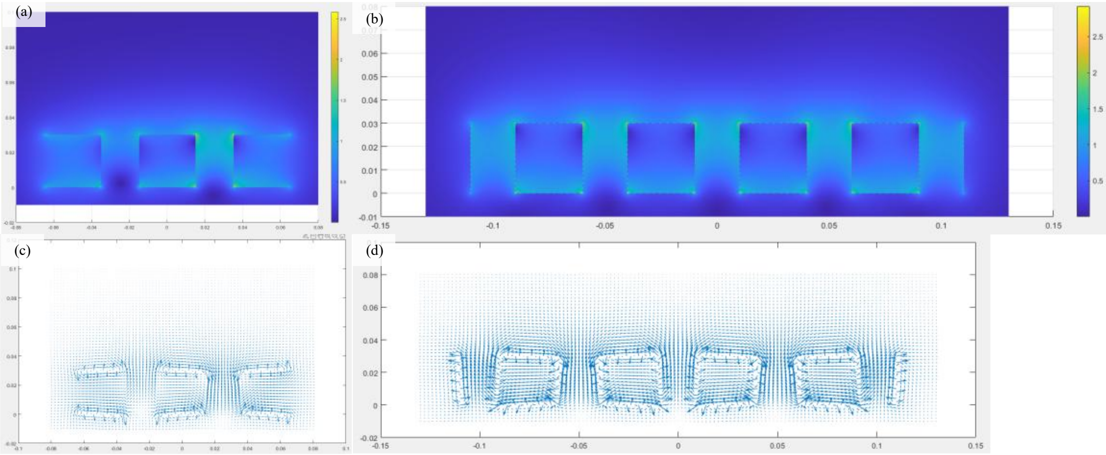


Fig. 6. Magnetic field distribution (contour or vector plot) of guideway: (a) Magnetic field distribution contour of double-peak guideway; (b) Magnetic field distribution contour of five-peak guideway; (c) Magnetic field distribution vector plot of double-peak guideway; (d) Magnetic field distribution vector plot of five-peak guideway;

2.2 Definition of Magnetic Field Irregularity

In practical guideways, variations in magnetization and assembly lead to spatial fluctuations in the magnetic field. Directly using the magnetic field at a single point or along a line is insufficient to characterize its overall effect on the levitation system. Therefore, a physically meaningful scalar quantity is required to represent the magnetic field irregularity.

Considering that the electromagnetic interaction between the guideway and the levitation module is mainly concentrated within the effective area of the levitator, a magnetic flux-based irregularity index is defined. Specifically, the magnetic field irregularity is characterized by the integral of the magnetic flux density over the bottom surface of the levitation module:

$$\phi = \iint_S |\boldsymbol{B}(y,z)| \mathrm{d}S \tag{0.2}$$

where $\boldsymbol{S}$ denotes the effective interaction area and $\boldsymbol{B}$ is the magnetic flux density.

This definition provides two key advantages. First, it reflects the overall magnetic environment experienced by the levitation module rather than local fluctuations. Second, it establishes a direct connection between magnetic field distribution and electromagnetic forces, making it suitable for further dynamic analysis.

2.3 Equivalent Mapping to Dynamic Irregularities

To enable the application of magnetic field irregularities in vehicle dynamic simulations, it is necessary to establish their equivalent representations in terms of conventional excitation forms.

For the vertical direction, the levitation force is strongly related to the magnetic field intensity. By comparing the magnetic flux index ϕ under irregular conditions with that of an ideal guideway, an equivalent geometric irregularity can be defined through an inverse mapping:

$$h = f^{-1}(\phi) \tag{0.3}$$

where h represents the equivalent vertical displacement (geometric irregularity). This mapping allows the magnetic field variation to be interpreted as an equivalent change in levitation gap.

For the lateral direction, the guidance force is approximately proportional to the lateral magnetic field component. Therefore, the lateral magnetic irregularity can be represented as an equivalent variation in guidance stiffness:

$$k_y = k_{y_0} \cdot \frac{\phi y}{\phi y_0} \tag{0.4}$$

where k_y is the equivalent lateral stiffness and k_{y0} corresponds to the nominal condition.

Through these mappings, the inherently three-dimensional magnetic field irregularities are transformed into equivalent geometric and stiffness irregularities, which can be directly incorporated into vehicle dynamic models as excitation inputs.

3. Probabilistic Modeling and Irregularity Generation

3.1 Magnetization Error Modeling

Magnetic field irregularities in permanent magnet guideways originate primarily from variations in the magnetization of individual permanent magnet blocks. In practical manufacturing and assembly processes, the remanent magnetization of each magnet cannot be perfectly controlled and typically exhibits random deviations around a nominal value.

In this study, the magnetization of each magnet block is modeled as a random variable following a normal distribution:

$$M_k \sim \mathrm{N}\left(M_0, \sigma^2\right) \tag{0.5}$$

where M_0 is the nominal magnetization and σ is the standard deviation representing the level of manufacturing uncertainty.

For a guideway composed of multiple magnet blocks, the overall magnetic field is determined by the combination of all individual magnetization values. Therefore, the magnetic field irregularity index ϕ defined in Section 2 becomes a function of a set of random variables:

$$\phi = f\left(M_1, M_2, \cdots, M_n\right) \tag{0.6}$$

where n is the number of magnets within one guideway segment.

3.2 Probabilistic Description of Magnetic Irregularity

Based on the statistical description of magnetization errors, the magnetic field irregularity index ϕ can be treated as a derived random variable. Its probability

distribution reflects the combined effect of multiple magnetization uncertainties.
Due to the nonlinear relationship between magnetization and magnetic field distribution, the probability density function (PDF) of ϕ cannot be obtained analytically in closed form. Instead, a numerical approach is adopted. By enumerating or sampling possible combinations of magnetization values, the corresponding ϕ values are computed using the magnetic field model introduced in Section 2. This allows the construction of the probability density distribution of ϕ.
The results show that the distribution of magnetic irregularity is strongly influenced by the standard deviation of magnetization. As σ increases, the spread of ϕ becomes wider, indicating a higher level of irregularity and uncertainty in the magnetic field.

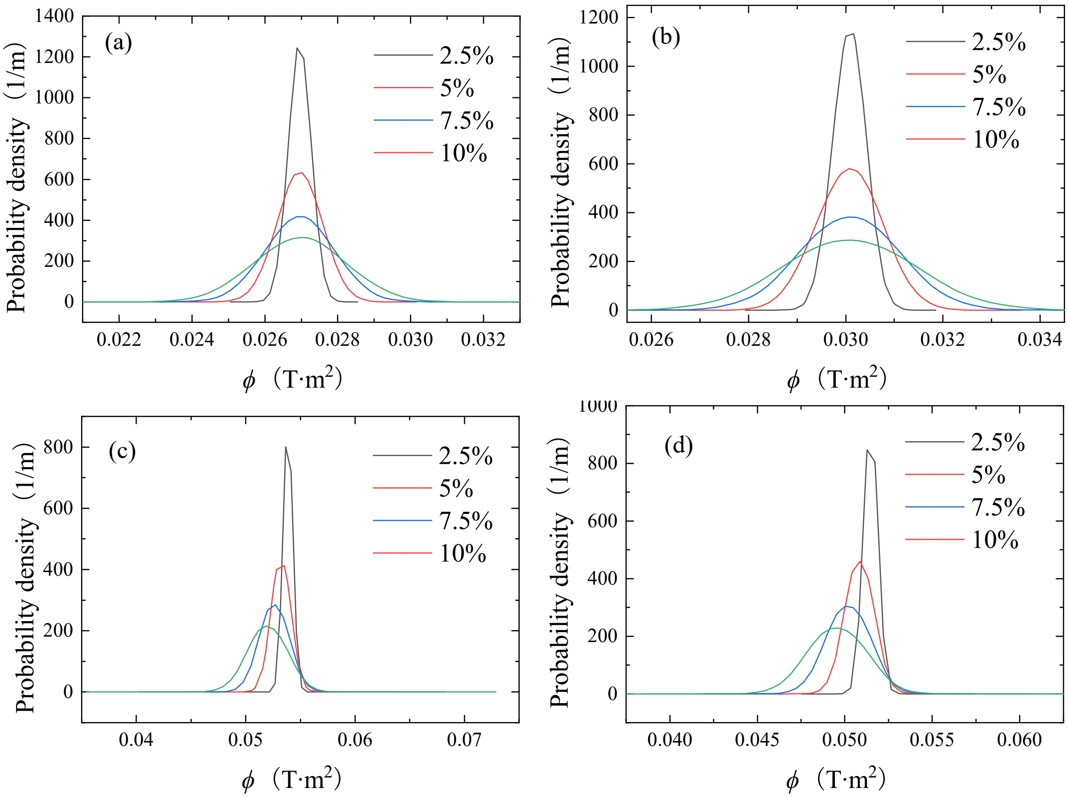


Fig. 7. Probability density distribution of magnetic irregularity under different σ: (a) Vertical magnetic irregularity of double-peak guideway; (b) Lateral magnetic irregularity of five-peak guideway; (c) Vertical magnetic irregularity of double-peak guideway; (d) Lateral magnetic irregularity of five-peak guideway;

This probabilistic description provides a statistical basis for characterizing magnetic field irregularities and enables the transition from deterministic modeling to stochastic representation.

3.3 Random Generation of Irregularity Samples

To generate spatially distributed irregularity sequences for engineering applications, a random sampling method based on the obtained probability distribution is employed. First, the cumulative distribution function (CDF) of the magnetic irregularity index is obtained from the PDF:

$$F(\phi) = \int_{-\infty}^{\phi} p(\phi)\,\mathrm{d}\phi \tag{0.7}$$

Then, using inverse transform sampling, a sequence of random irregularity values can be generated:

$$\phi = F^{-1}(u), \quad u \sim U(0,1) \tag{0.8}$$

where u is a uniformly distributed random variable.

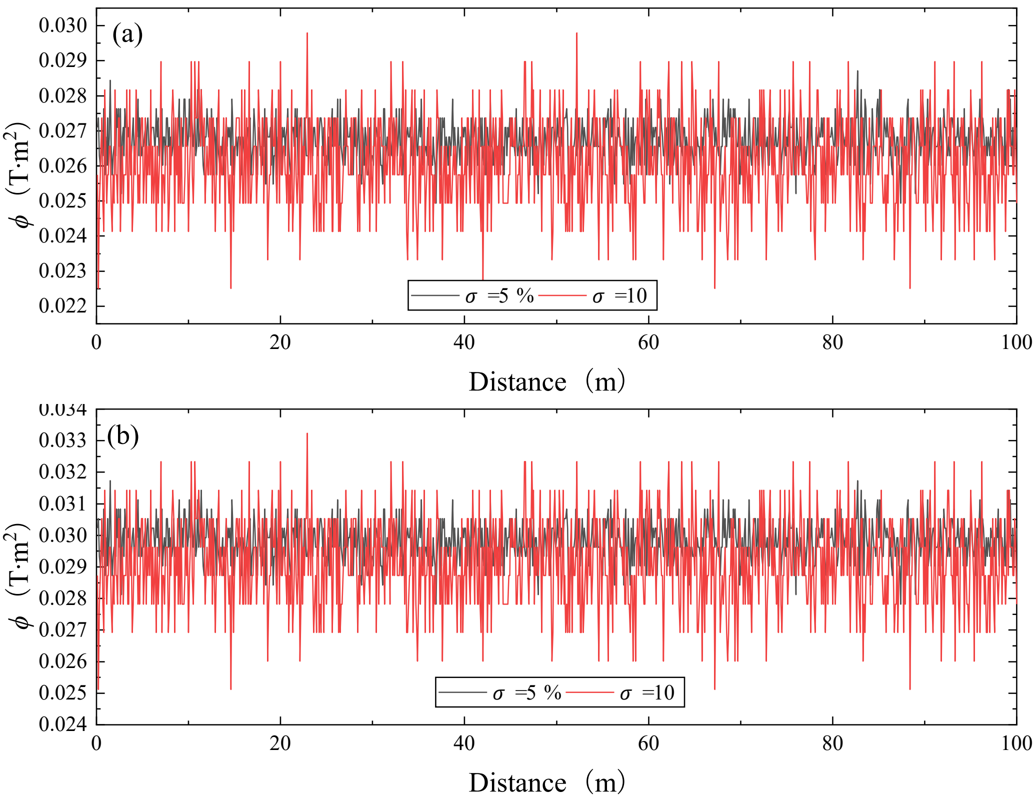
By assigning each sampled ϕ value to a discrete guideway segment, a spatial sequence of magnetic field irregularities can be constructed. In this study, the guideway is discretized with a fixed segment length, allowing the generation of long-distance irregularity profiles suitable for dynamic simulations.

4. Results and Discussion

4.1 Magnetic Irregularity Characteristics

Based on the proposed probabilistic model, magnetic field irregularities of permanent magnet guideways are generated under different levels of magnetization uncertainty. Two representative standard deviations, σ=5% and σ=10%, are selected to illustrate the effect of magnetization variation.

The generated magnetic irregularity samples are shown in Fig. 9 for both double-peak and five-peak guideways, including vertical and lateral components.



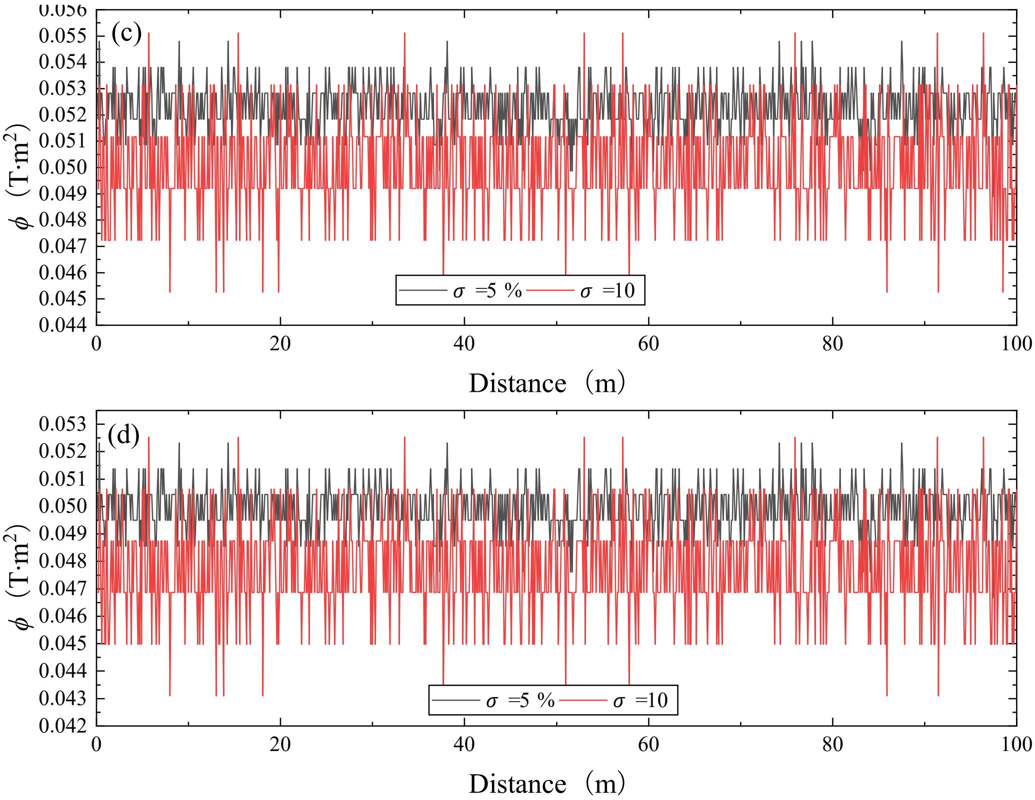


Fig. 9. Magnetic irregularity samples: (a) Vertical magnetic irregularity of double-peak guideway; (b) Lateral magnetic irregularity of five-peak guideway; (c) Vertical magnetic irregularity of double-peak guideway; (d) Lateral magnetic irregularity of five-peak guideway

It can be observed that the magnetic irregularities exhibit strong randomness along the guideway, without clear periodic characteristics. When the magnetization standard deviation increases from 5% to 10%, the fluctuation amplitude becomes significantly larger in both vertical and lateral directions. This indicates that magnetization uncertainty directly amplifies the intensity of magnetic field irregularities.

In addition, a slight asymmetry can be observed in the distribution of irregularities, where attenuation of the magnetic field tends to be more pronounced than enhancement. This suggests that magnetization errors may lead to a cumulative reduction in effective magnetic field strength.

4.2 Equivalent Geometric Irregularity

Using the mapping relationship established in Section 2, the magnetic field irregularities are converted into equivalent geometric irregularities in the vertical direction.

The results for σ=5% are shown in Fig. 10, where both double-peak and five-peak guideways are presented for comparison.

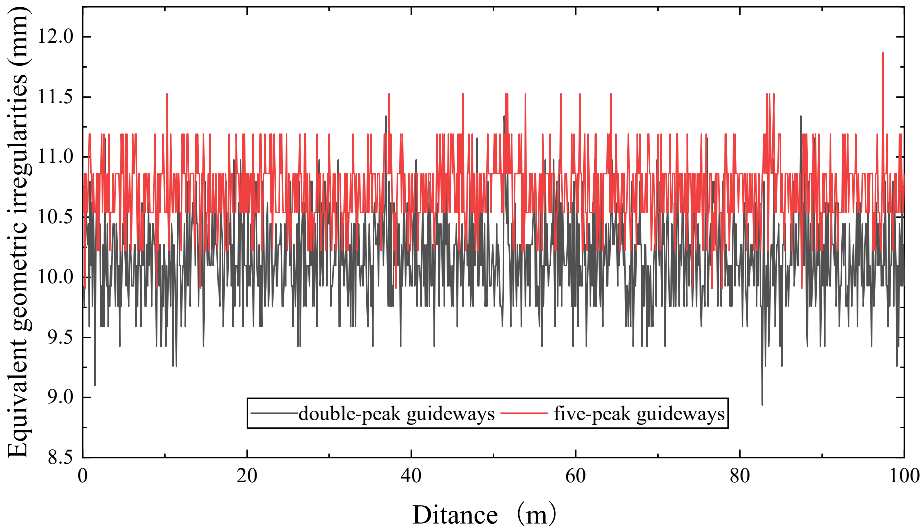


Fig. 10. Equivalent geometric irregularities (double-peak and five-peak, σ = 5%)

It can be seen that the equivalent geometric irregularities exhibit similar random characteristics to the magnetic irregularities. The fluctuation range is closely related to the underlying magnetic field variation, reflecting the sensitivity of levitation gap to magnetic field changes.

Compared with the double-peak guideway, the five-peak guideway generally shows a slightly different fluctuation pattern due to its wider structure and more distributed magnetic field, although the overall magnitude remains of the same order.

4.3 Equivalent Stiffness Irregularity

For the lateral direction, the magnetic field irregularities are further mapped into equivalent stiffness irregularities.

The results for σ=5% are shown in Fig. 11 for both guideway configurations.

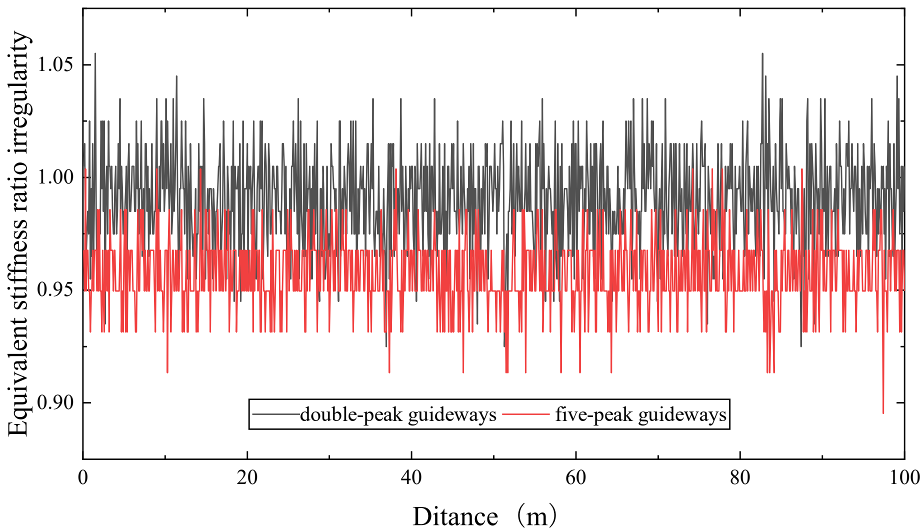


Fig. 11. Equivalent stiffness irregularities (double-peak and five-peak, σ = 5%)

The equivalent stiffness irregularities exhibit noticeable fluctuations along the guideway, indicating that magnetization uncertainty can influence the lateral dynamic characteristics of the system. Compared with geometric irregularities, the stiffness variations are relatively moderate but still show clear randomness.
The comparison between double-peak and five-peak configurations indicates that the structural arrangement of magnets affects the distribution of stiffness irregularity, although the overall trend remains consistent.

Conclusion

This paper proposes a probabilistic modeling and generation framework for magnetic field irregularities in permanent magnet guideways, which are widely used in both superconducting pinning maglev (SPM) and permanent magnet maglev (PMM) systems.
The main conclusions are summarized as follows:
(1) An efficient magnetic field modeling approach based on the equivalent surface current method is established, enabling rapid computation of the magnetic field distribution above permanent magnet guideways with different configurations.
(2) A flux-based irregularity index is defined to characterize magnetic field variations over the effective interaction region of the levitation module, providing a physically meaningful representation of magnetic irregularities.
(3) A probabilistic model linking magnetization uncertainty to magnetic field irregularity is developed. The results show that the magnitude and dispersion of irregularities increase significantly with the standard deviation of magnetization, and the irregularity distribution exhibits an asymmetric tendency toward magnetic field attenuation.
(4) A random generation method based on inverse transform sampling is proposed, allowing the construction of spatially distributed irregularity sequences suitable for engineering applications.
(5) The magnetic irregularities are successfully mapped into equivalent geometric and stiffness irregularities, making them directly applicable as excitation inputs in vehicle dynamic simulations.
Overall, the proposed framework provides a systematic and practical approach for describing and generating magnetic field irregularities in permanent magnet guideways. It offers a useful tool for dynamic analysis, performance evaluation, and design optimization of maglev systems.

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