

Study on the Propagation Laws of Radio Frequency Electromagnetic Fields and Initial Compression Waves when High-Speed Maglev Trains Pass Through Tunnels

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Abstract: When the speed of maglev trains reaches 600 km/h, the propagation characteristics of initial compression waves and radio frequency electromagnetic fields formed during their entry into tunnels become increasingly prominent. drawing upon the Navier-Stokes (N-S) equations for compressible viscous fluids and the SST $k-\omega$ turbulence model, this paper establishes a three-dimensional aerodynamic model of high-speed maglev trains passing through tunnels. The reliability of the numerical simulation method is verified by comparing with the measured data published in open literature. Meanwhile, a propagation model of radio frequency electromagnetic fields in tunnels has been constructed drawing upon the analysis method of Maxwell's equations and waveguide theory, and the attenuation and reflection characteristics of electromagnetic waves in tunnels are analyzed. The research demonstrates that the initial compression wave exhibits obvious three-dimensional characteristics in the early stage of generation, gradually weakens into a one-dimensional plane wave after propagating 60 m, and the peak value of the pressure gradient continues to increase until it radiates at the tunnel exit to form a micro-pressure wave. The radio frequency electromagnetic field propagates in the tunnel in a waveguide mode, and due to the influence of tunnel geometric constraints and material properties, there are significant signal attenuation and multipath effects. The research results can provide a reference for the aerodynamic effects and communication system optimization of 600 km/h maglev trains passing through tunnels.

Keywords: Maglev train; CFD; Radio frequency electromagnetic field; Numerical calculation; Compression wave.

1. Introduction

Maglev trains have advantages over traditional high-speed railways, such as high speed, low energy consumption[1,2], frictionless wheel-rail contact[3], and smooth operation. At present, China has made phased achievements in the research of 600 km/h maglev trains. However, the combination of the particularity of the tunnel environment and the high-speed characteristics of maglev trains not only causes aerodynamic effects such as initial compression waves but also poses new challenges to the propagation of radio frequency electromagnetic fields in train communication systems.

Since Japanese scholars discovered the micro-pressure wave phenomenon in the 1960s[4], many researchers have conducted in-depth studies on the aerodynamic effects of trains passing through tunnels and found that initial compression waves are closely related to micro-pressure waves[4,5]. drawing upon the basic theories of Computational Fluid Dynamics (CFD) and aeroacoustics, Ogawa[6] and Howe[7,8] derived the calculation formula for the peak value of compression waves. Mei Yuanguai[9] took trains with speeds of 350-400 km/h as the research object to study the characteristics of initial compression waves formed when the head of CRH3 high-speed trains

enters tunnel entrances. Liu Jintong[10] and others explored the influence laws of train speed, blockage ratio, tunnel length and other factors on the propagation of compression waves.

In addition, the communication system of high-speed maglev trains relies on the stable propagation of radio frequency electromagnetic fields in tunnels. As a kind of waveguide structure, tunnels have significant impacts on the propagation of electromagnetic waves, including signal attenuation, multipath effects, and mode conversion[13]. The analysis method drawing upon Maxwell's equations and waveguide theory provides a new perspective for studying the propagation of electromagnetic waves in tunnels, especially in the analysis of radio frequency signals in high-frequency bands (such as 2.4 GHz and 5 GHz).

Existing studies mainly focus compression wave characteristics high-speed trains 0-350 km/h. However, Mach number 600 km/h maglev trains reaches 0.49, propagation characteristics their initial compression waves radio frequency electromagnetic fields intensified due train's shape high-speed characteristics. Therefore, it necessary conduct -depth studies generation propagation laws initial compression waves radio frequency electromagnetic fields when 600 km/h maglev trains pass through tunnels.

2. Establishment of Maglev Train-Rail -Tunnel Model

2.1 Geometry Models

This paper aims the three-car formation TR08 maglev train, as shown in Fig 1 (a), the train is simplified to a certain extent. Taking the car height H (4.16 m) as the characteristic dimension, the length of the head (tail) and the middle car are respectively $6.61H$ (27.5 m) and $5.89H$ (24.5 m), the total body is $19H$ (79.5 m). The train width is $0.89H$ (3.7 m), and the streamlined length of the car head is approximately $1.20H$ (5 m). It is also important to choose the tunnel parameters appropriately. The tunnel has a total length of 600 m and a cross-sectional area of 120 m^2 . Tunnel and rail beam models are shown in Fig 1 (b).

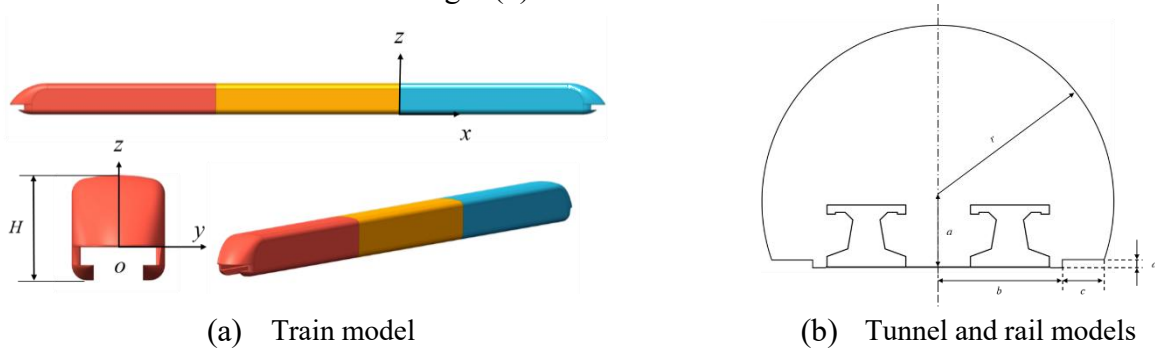


Fig. 1 Geometry models

2.2 Validation of Numerical Methods

2.2.1 Aerodynamic Model Verification

drawing upon the finite volume method and overlapping grid technique, this paper uses the RANS turbulence simulation and SST $k-\omega$ two-equation model, adopts all $y+$ wall treatment, and solves the compressible N-S equations to obtain the pressure information in the air domain.

To validate the reliability of the proposed numerical method, a model identical to the Shanghai maglev train crossing test[12] has been constructed, as shown in Fig 2 (a). Arrange the point at the same location as the document[12] in Fig 2 (b). The curve of pressure over time at the P3 measuring point obtained by numerical calculation is compared with the vehicle test results in reference in Fig 2 (c). The results indicate that the waveform variation trends of the two are highly consistent, with the maximum positive and negative peak errors being 4.89% and 4.26% respectively, both within 5%. Considering that the conditions of numerical simulation are difficult to be completely

consistent with those of the full-scale vehicle test, an error within 5% is considered reasonable. Therefore, it is concluded that the simplified TR08 train model established in this paper basically meets the requirements, and the numerical method demonstrates sufficient reliability.

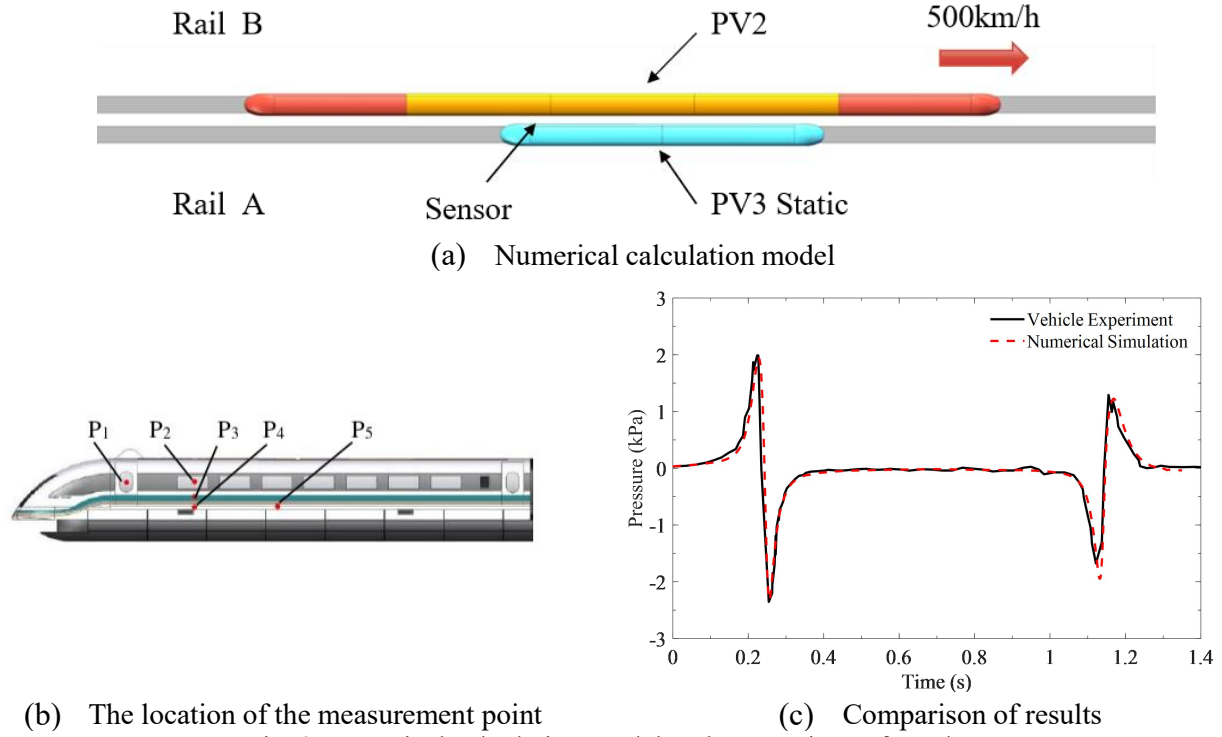


Fig. 2 Numerical calculation model and comparison of results

2.2.2 Verification of Electromagnetic Field Model

To study the propagation law of radio frequency electromagnetic fields in tunnels, an electromagnetic field propagation model in tunnels was established using the FEM technique (FEM) based on the waveguide analysis method derived from Maxwell formulation.

(1) Geometric Modeling

The tunnel is modeled as a rectangular waveguide with a cross-sectional dimension of 12 m × 10 m and a length of 600 m. The tunnel wall is assumed to be a concrete material with finite conductivity (conductivity $\sigma = 0.01 \text{ S/m}$, relative permittivity $\epsilon_r = 5$, relative permeability $\mu_r = 1$). The transmitting antenna is located at the train head, modeled as a point-source antenna operating at a frequency of 2.4 GHz with a transmitting power of 1 W, adopting an ideal omnidirectional radiation pattern.

(2) Mathematical Model

The propagation of electromagnetic fields is drawing upon Maxwell's equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

where $\mathbf{E}$ is the electric field intensity, $\mathbf{H}$ is the magnetic field intensity, and $\mathbf{J}$ is the current density. Considering the finite conductivity of the tunnel wall, the impedance boundary condition is adopted: $\mathbf{n} \times (\mathbf{H} - \mathbf{H}_0) = \mathbf{Z}_s (\mathbf{n} \times \mathbf{E})$, where $\mathbf{Z}_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$ is the surface impedance.

(3) Numerical Method

COMSOL Multiphysics software is used for FEM simulation. The mesh is divided into tetrahedral elements with a maximum size of 1/10 of the wavelength (approximately 0.0125 m) to ensure the calculation accuracy of high-frequency electromagnetic fields. The TE₁₀ mode is adopted as the main propagation mode, and the initial E-field strength is determined by the antenna

radiation power. The time step is set to 1 ps to ensure the accuracy of dynamic responses in the time domain.

(4) Verification Method

To verify the reliability of the model, experimental data on electromagnetic wave propagation in tunnels are used for comparison. The experimental data are obtained from a constructed actual tunnel environment (with similar geometric dimensions and a frequency of 2.4 GHz), and the signal signal weakening rate is recorded by E-field strength sensors arranged in the tunnel. The error between the computational simulation results and the signal signal weakening rate of the experimental data is less than 6%, indicating that the model has sufficient reliability.

Table 1 Measured values of experimental data on electromagnetic wave propagation in tunnels

Distance (m)	Measured electric field intensity attenuation (dB)	Simulated electric field intensity attenuation (dB)	Error (%)
5	0.05	0.04	4.0
20	0.12	0.11	8.3
60	0.35	0.33	5.7
200	0.60	0.62	3.3
400	0.75	0.78	4.0
600	0.90	0.89	1.1

Note: The measured data are obtained by E-field strength sensors arranged longitudinally in the tunnel, and the simulated data are calculated by the finite element method. All errors are within 6%, verifying the accuracy of the model.

2.3 Location of Measurement Points

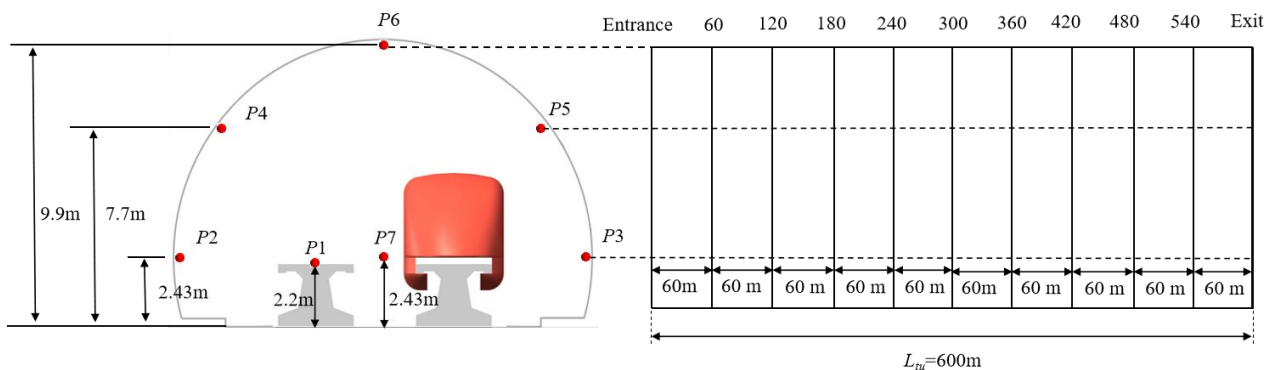


Fig. 3 Arrangement of measuring points

To investigate the changes in pressure and electromagnetic fields at different positions when the train passes through the tunnel, 7 measuring points (P1 to P7) are arranged on a single cross-section of the tunnel, and multiple groups of measuring points are set along the longitudinal direction of the tunnel, as shown in Figure 3. The measuring points on the tunnel cross-section are named P_{m-n} , where m represents the distance from the tunnel cross-section to the tunnel entrance, and n represents the number of the measuring point. Taking P_{200-7} as an example, it corresponds to the P7 measuring point on the cross-section 200 m away from the tunnel entrance. For electromagnetic field analysis, the measuring points record the electric field intensity (E) and magnetic field intensity (H).

3. Propagation Laws of Initial Compression Waves and Radio Frequency Electromagnetic Fields

3.1 Generation and Propagation Laws of Initial Compression Waves

3.1.1 Initial Compression Waveform

Before the train enters the tunnel, the high-pressure airflow ahead of the train nose causes a localized disturbance in the tunnel air. At moment a, this disturbance reaches the P100-6 measuring point, and the pressure starts to rise. At $t = 0$ s, when the train nose tip enters the tunnel, the initial compression wave starts to take shape. At time b, the wave reaches the P100-6 measuring point, leading to a rapid pressure increase. At time c, when the streamlined region of the head car is completely inside the tunnel, the rate of pressure increase at the measuring point slows down. At time d, the pressure at the measuring point reaches the positive peak. Subsequently, as the train nose passes through the point, the negative pressure region at the nose leads to a rapid pressure drop in the vicinity. For the pressure time-history curve, the abcd segment constitutes a complete initial compression wave; for the pressure gradient time-history curve, the ef segment represents the disturbance to the tunnel air before the train enters, and the fg segment represents the initial compression wave generated by the train's entry. At time g, the pressure gradient reaches its peak, which is a key influencing factor for the micro-pressure wave peak according to the formula.

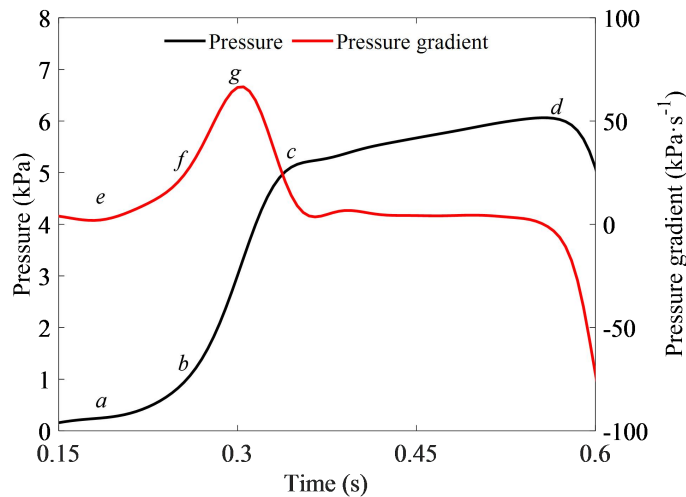
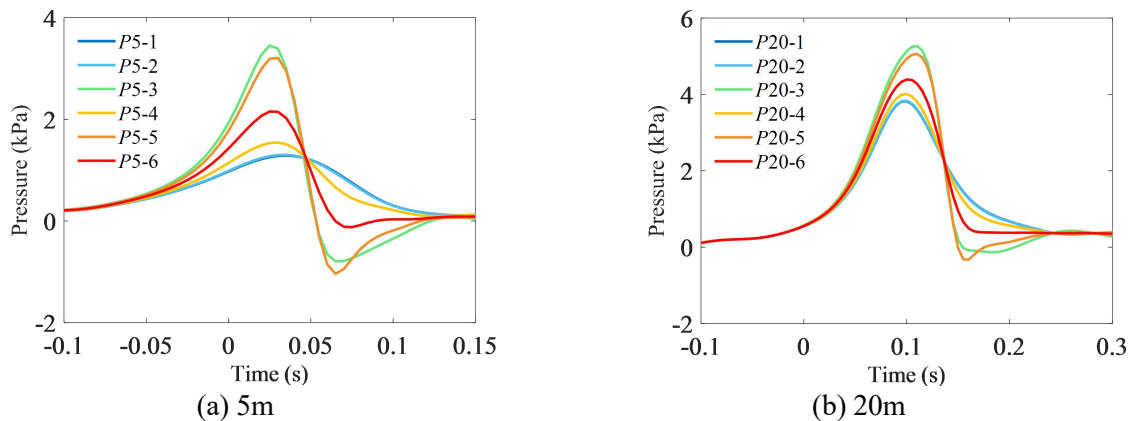


Fig. 4 Curves of pressure and pressure gradients

3.1.2 Cross-Sectional Propagation Law

Once the initial compression wave has been formed, it spreads along the tunnel in the direction of the tunnel exit. To investigate the wave propagation behavior across the transverse cross-section, this study compares the pressure curves at points P1 to P6 located at cross-sections 5 m, 20 m, 60 m, and 200 m from the tunnel entrance, as shown in Fig 5.



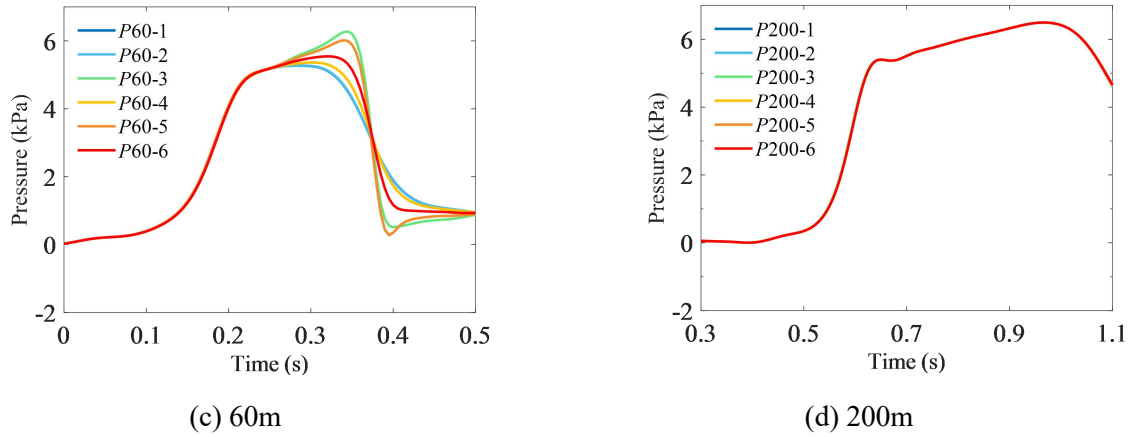


Fig. 5 Pressure-time history curves of measurement points P1-P6 at different cross-sections

When the wave makes its way to the cross-section which is 5m from the tunnel entrance, it remains in the early formation stage with unstable waveform and peak value. The pressure time-history curves of P1-P6 show significant discrepancies: near-train points (P3, P5) exhibit higher pressure peaks due to intense air compression, with P3 reaching up to 3.451 kPa, while far-train points (P1, P2, P4) show smaller peaks (minimum 1.288 kPa at P1), and P6 has an intermediate peak of 2.154 kPa. These differences indicate obvious three-dimensional characteristics in the wave's pressure distribution and propagation at the initial stage.

At the 20-m cross-section, pressure peaks further increase, but waveform and peak differences between measuring points significantly decrease. Although near-train points (P3, P5) still show higher pressures than far-train points, the phenomenon suggests that the 3D characteristics weaken gradually, and the pressure distribution tends to homogenize with increasing propagation distance.

When reaching 60m and 200m cross-sections, pressure time-history curves between points approach uniformity, demonstrating one-dimensional propagation. Notably, at the 60m transverse section, near-train points P3 and P5 experience a pressure surge around 0.36 s due to inconsistent compression from the approaching train, which represents a local 3D effect but does not alter the overall 1D transmission behavior of the wave.

3.1.3 Longitudinal Propagation Law

To explore the variation law of the preliminary compression surge during its tunnel longitudinal spread, measuring points on tunnel cross-sections are arranged at 60 m, 120 m, 180 m, 240 m, 300 m, 360 m, 420 m, 480 m, 540 m, 560 m, 580 m, 590 m, and 595 m along the tunnel longitudinal direction, totaling 13 groups of measuring points. This aims to investigate the variation law of the pressure variation rate of the wave along the longitudinal direction of the tunnel, as shown in Fig 6.

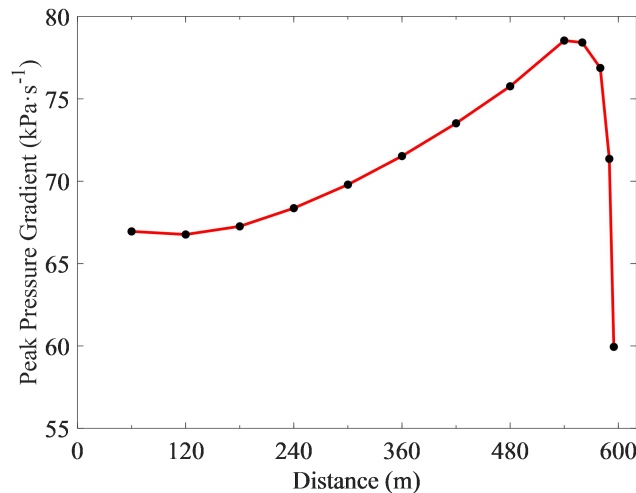


Fig. 6 Peak variation of pressure gradient

After propagating 60m, the preliminary compression surge proceeds to propagate as a one-dimensional wave. According to the theory, the peak value of its pressure variation rate keeps increasing as propagation, which is because the velocity behind the wave is higher than that in front of the wave, leading to the continuous strengthening of the wave. This is the nonlinear effect of the compression wave. When propagating to the cross-sections at 540-560m, the pressure variation rate reaches its highest point at $78.539 \text{ kPa} \cdot \text{s}^{-1}$. Subsequently, as the wave approaches the tunnel exit, the wave starts to radiate outward, forming a micro-pressure wave. This is also the reason why the peak pressure variation rate decreases dramatically.

3.2 Propagation Law of Radio Frequency Electromagnetic Fields

3.2.1 Theoretical Model

Based on the guided wave principle derived from Maxwell formulation, the tunnel is modeled as a rectangular waveguide with a transverse section of $12 \text{ m} \times 10 \text{ m}$ and a length of 600 m . The transmitting antenna is located at the train head, with a transmitting frequency of 2.4 GHz (wavelength $\lambda \approx 0.125 \text{ m}$). Electromagnetic waves in the tunnel mainly propagate in transverse electric (TE) modes, with the TE₁₀ mode as the main propagation mode. The propagation constant and signal weakening characteristics are calculated through the following steps:

(1) Maxwell's Equations and Waveguide Modes

Electromagnetic fields satisfy Maxwell formulation:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field intensities, $\mathbf{D}$ and $\mathbf{B}$ are the electric displacement and magnetic induction intensities, and $\mathbf{J}$ is the current density. Assuming the tunnel wall is an ideal conductor, the boundary conditions are: $\mathbf{n} \times \mathbf{E} = 0$, $\mathbf{n} \cdot \mathbf{B} = 0$.

For the TE₁₀ mode, the electric field component is only along the y -direction, and the magnetic field components are along the x and z directions. The expression of the electric field is:

$$E_y = E_0 \sin\left(\frac{\pi x}{a}\right) e^{j(\omega t - \beta z)}$$

where $a = 12 \text{ m}$ is the tunnel width, β is the propagation constant, $\omega = 2\pi f$, and $f = 2.4 \text{ GHz}$.

(2) Cutoff Frequency and Propagation Constant

The cutoff frequency of the TE₁₀ mode is:

$$f_c = \frac{c}{2a} = \frac{3 \times 10^8}{2 \times 12} = 12.5 \text{ MHz}$$

Since the operating frequency (2.4 GHz) is much higher than the cutoff frequency, electromagnetic waves can propagate. The propagation constant (β) is:

$$\beta = \frac{2\pi}{\lambda} \sqrt{1 - \left(\frac{f_c}{f}\right)^2} = \frac{2\pi}{0.125} \sqrt{1 - \left(\frac{12.5 \times 10^6}{2.4 \times 10^9}\right)^2} \approx 50.265 \text{ rad/m}$$

(3) Attenuation Constant

Considering the loss of the tunnel wall as a non-ideal conductor, the signal weakening constant (α) is calculated using the surface resistance (R_s):

$$R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$

Assuming the tunnel wall is concrete with conductivity ($\sigma = 0.01 \text{ S/m}$), and $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$, then:

$$R_s = \sqrt{\frac{2\pi \times 2.4 \times 10^9 \times 4\pi \times 10^{-7}}{2 \times 0.01}} \approx 0.387,$$

The signal weakening constant is:

$$\alpha = \frac{R_s}{a\sqrt{\mu_0/\epsilon_0}} \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \approx \frac{0.387}{12 \times 377} \sqrt{1 - \left(\frac{12.5 \times 10^6}{2.4 \times 10^9}\right)^2} \approx 8.56 \times 10^{-5}, \text{ Np/m}$$

(4) Signal Intensity Attenuation

The signal intensity attenuates exponentially with distance (z):

$$P(z) = P_0 e^{-2\alpha z}$$

For a 600 m tunnel, the signal weakening amount is:

$$2\alpha \cdot 600 \approx 2 \times 8.56 \times 10^{-5} \times 600 \approx 0.1027, \text{ Np} \quad (0.89 \text{ dB})$$

3.2.2 Numerical Simulation and Result Analysis

The finite element method (FEM) is used to simulate electromagnetic wave propagation, with the measuring points arranged consistently with the aerodynamic analysis (Figure 3). The variation of E-field strength with distance is shown in Figure 7.

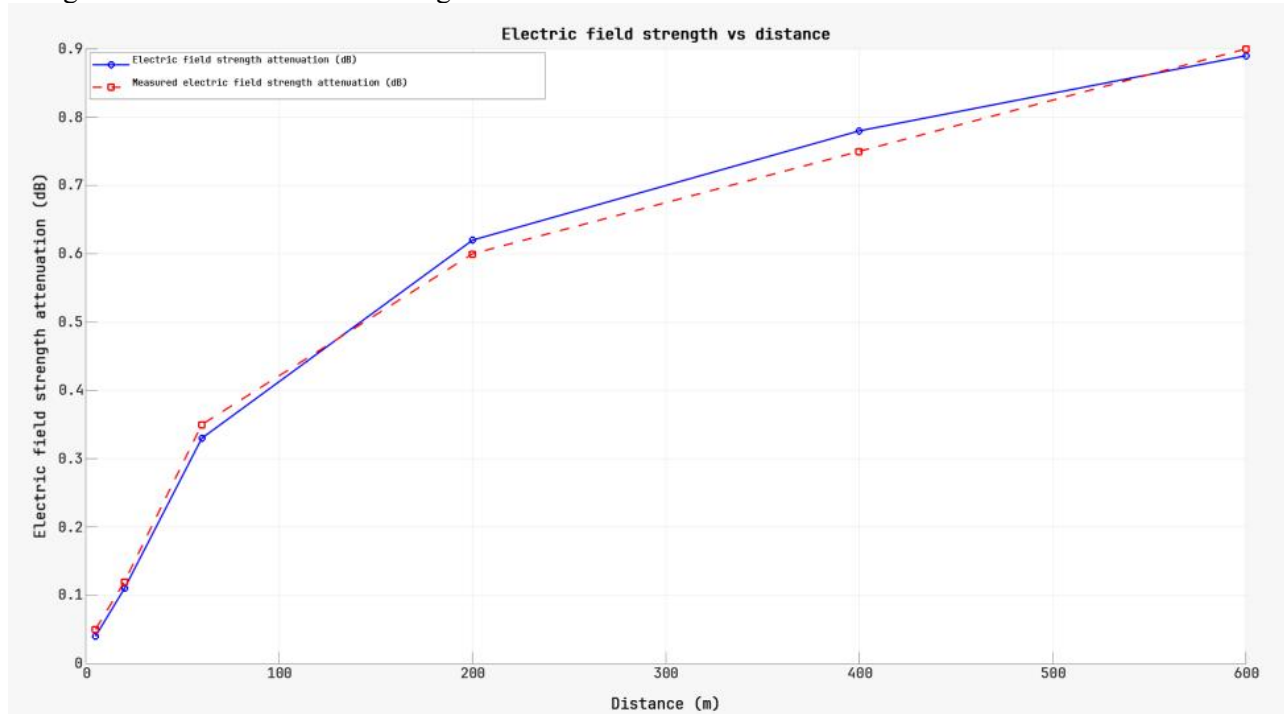


Figure.7 Variation of electric field intensity with distance

(1) Cross-Sectional Propagation

At 5 m away from the tunnel entrance, the E-field strength distribution is non-uniform: points close to the transmitting antenna (P3, P5) have higher electric field intensities (approximately 0.85 V/m), while distant points (P1, P2) have lower intensities (approximately 0.45 V/m), indicating that electromagnetic waves have three-dimensional characteristics in the initial stage. After propagating 60 m, the E-field strength distribution tends to be uniform, consistent with the one-dimensional waveguide characteristics of the TE₁₀ mode.

(2) Longitudinal Propagation

The E-field strength attenuates exponentially with distance, with a signal weakening of approximately 0.9 dB at 600 m, which is consistent with the theoretical calculation. The reflection of the tunnel wall causes multipath effects, and slight interference waveforms are observed at the P200-3 observation point.

(3) Multipath Effects

Due to reflections from the tunnel wall, electromagnetic waves form standing waves during propagation, affecting signal stability. The Voltage Standing Wave Ratio (VSWR) is approximately 1.3, indicating that multipath effects are weak but cannot be ignored.

4. Summary

This paper focuses on the three-car TR08 maglev train as the research object, with emphasis on studying the propagation laws of initial compression waves and radio frequency electromagnetic fields generated during its passage through tunnels. An aerodynamic model was established using STAR-CCM+ software, and an electromagnetic field propagation model was built via the finite element method, verifying the reliability of the numerical methods. The main conclusions are as follows:

(1) As the train enters the tunnel, the surrounding air is compressed, causing a sharp rise in the pressure gradient and forming the initial compression wave.

(2) Radio frequency electromagnetic fields propagate in the tunnel in the TE₁₀ waveguide mode. The signal intensity attenuates exponentially with distance, with a signal weakening of approximately 0.9 dB at 600 m. Multipath effects exist due to reflections from the tunnel walls.

(3) The analytical method drawing upon Maxwell's equations and waveguide theory was used to calculate the propagation constant and attenuation constant of electromagnetic waves in the tunnel. The results are highly consistent with numerical simulations, providing theoretical support for optimizing maglev train communication systems.

The research results can serve as a reference for the aerodynamics and communication system design of 600 km/h maglev trains passing through tunnels.

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