Unsteady Aerodynamic Performance of a Maglev Train: The Effect of the Ground Condition

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In this study, the influence of the ground effect on unsteady aerodynamic performance of maglev train was numerically investigated with an IDDES method. Firstly, the flow field structures in different ground conditions, especially at the tail of the train, are compared in detail. In addition, combined with the flow field structure, the time-average and instantaneous slipstream under different ground conditions were compared to analyse the reasons for the influence of ground conditions on slipstream. Finally, the aerodynamic differences of trains under different ground conditions are compared, and the influence of ground effect on the aerodynamic performance of maglev trains is summarized. This study is of great significance for understanding the flow field around maglev train under different ground conditions. The conclusions we draw can provide valuable references for the development of standards for evaluating the slipstream around the maglev train.
Abstract
The effect of the ground condition on unsteady aerodynamic performance of maglev train was numerically investigated with an IDDES (Improved Delayed Detached Eddy Simulation) method. The accuracy of the numerical method has been validated by wind tunnel experiments. The flow structure, slipstream and aerodynamic force around the train under stationary and moving ground conditions were compared. Compared with the stationary ground condition, the vortex structure under the condition of moving ground generated by the wake region is narrower and higher because of the track. Near the nose point of the head and tail vehicles, the peak value of slipstream under the condition of moving ground is slightly higher than that under stationary ground. In the wake area, the effect of the main vortex structure on both sides of the tail vehicle and the track makes the vortex structure in the wake area stronger than that under moving ground, the slipstream peak is larger and the locus thereof is further forward. Under the two ground conditions, the vortex structure is periodically shed from both sides of the train into the wake area, and the shedding frequency of the main vortex under the moving ground condition is lower than that under the stationary ground condition. Moving ground can increase the resistance of the maglev train, reduce the lift of the maglev train, and decrease the standard deviation of the maglev train’s aerodynamic force.

Key words: IDDES; Maglev train; Ground effect; Slipstream; Wake flow.

1. Introduction

In recent years, some breakthroughs have been made in maglev rail transit technology. Maglev trains have become the high-technology transportation mode leading modern rail transit development. Maglev train is a new type of high-speed transportation system, which adopts the suspension, guidance and propulsion technology without contact and abrasion. It has the advantages of low energy consumption, small environmental impact and low noise pollution, etc. [1],[2]. Magnetic levitation trains are similar in appearance to high-speed trains, and they are all elongated objects running on tracks. However, maglev trains are elevated in line and have small rail gap. In actual operation, there is relative motion between train and ground (track), which is difficult to be simulated in wind tunnel tests.

When running, the motion around the train includes the relative motion between the train and the air, as well as the relative motion between the stationary ground (track) and the train. Full-size testing is undoubtedly the most reliable method of assessment of maglev trains, because the full-size test perfectly reflects the actual operation of the train, however, in the case of train aerodynamics, full scale tests is complicated [3]. Full-scale testing is heavily dependent on the environment, and often requires a lot of testing to obtain reliable results. Another alternative technology is the scaled-down dynamic model test system, which is increasingly popular due to its low cost and simplicity compared to full-size field measurements [4]. According to CEN (2013) [5], a scaled-down test is recommended for train design. Bell et al. evaluated a scaled motion model technique for analysing slipstream of high-speed train in order to check TSI compliance during the high-speed train design [6].

Another method to study the aerodynamic performance of the train is wind tunnel test, which uses a fixed train model to simulate the relative motion of the train and the incoming wind by giving the velocity inlet conditions. Weise et al. conducted wind tunnel tests to analyse specific areas of slipstream and near-wake of HST trains. Their flow visualization found two typical flow patterns, separation vortexes and vortex shedding, that could alternate near the train's wake, depending on the geometry of the train's tail [7]. Bell et al. correlated the peak value of the slipstream velocity spectrum with the reverse rotating vortex moving outward from the tail of the high-speed train, quantified the near-wake characteristics and determined the cause of slipstream. It is found that the near wake area of the train is periodically unstable, which may be caused by the periodic vortex shedding from the side and top surface of the train [8],[9]. Obviously, the relative motion of the train and the ground is not considered in the stationary model wind tunnel experiment. In aerodynamic measurements, ground effect will produce results and is difficult to eliminate. Although there are some new technologies, such as the installation of moving ground and suction devices from the floor at the bottom of the train, it is found that the ground effect can be effectively reduced or even eliminated [10]. However, due to the high cost and complex operation of these technologies, their applications are limited.

With the introduction of unsteady numerical methods and turbulence models, computational fluid dynamics
(CFD) has become a very effective tool for studying train aerodynamic performance. CFD can overcome the limitations of actual wind tunnel tests. For example, the moving ground can be easily simulated, and the complex flow structure around the train can be effectively calculated and visualized, which helps us understand the internal mechanism of relevant problems [11]. Previous studies on aerodynamic performance have used CFD method in many studies [12]. Xia used the IDDES method to study the influence of the ground on the flow field structure around the high-speed train, and compared the influence of the difference in train wind distribution between stationary ground and moving ground conditions [13]. Based on three different wheel and ground boundary conditions, Zhang et al. studied the aerodynamic performance of high-speed trains under the conditions of moving ground and wheel rotation (MG&RW), and analysed the aerodynamic, unsteady and time-averaged flow fields around high-speed trains [14]. Chen et al. studied the influence of the head length on the aerodynamic performance of the train by using the improved delay-separated eddy simulation (IDDES) method, and compared the time-averaged structure and instantaneous near-wake structure as well as the associated slip velocity distribution under the three nose lengths [15]. Huang studied the air dynamics performance of the maglev train under different operating scenarios by comparing, and found the position where the surface pressure of the train changes significantly and the value of the train wind [16].

Based on the above discussion, there are few studies on the aerodynamic performance of maglev trains at home and abroad, and most of the studies on the aerodynamic performance of trains focus on high-speed trains. Although the maglev train and the high-speed train are similar in appearance, they are both long and thin objects running close to the ground, but the gap between the maglev train and the track is small, only about 10mm. During the operation of the train, the ground and track will interfere with the flow field structure around the train. Therefore, the aerodynamic load of the train is affected. The interference of different ground conditions on the maglev train may be very different from that of the high-speed train. The aerodynamic load may also be very different, so considering the influence of ground effects, it is necessary to study the influence of the unsteady aerodynamic characteristics of the maglev train. This paper takes maglev train as the model and uses IDDES method to compare the unsteady aerodynamic performance of maglev train under stationary ground (SG) and moving ground (MG). In order to fully understand the influence of ground effect, this paper will analyse the airflow distribution, wake structure and train aerodynamic force around maglev train.

2. Methods

2.1. Geometry model

In order to be consistent with the wind tunnel test, the geometric model is a two-coaches maglev train with a scale of 1:16. The dimensions of the train model are as follows: The length is 2.006 m (L), the width is 0.177 m (W), the height is 0.24 m (H), and the cross-sectional area is 0.036 m$^2$ (Fig.1.). The rail gap is defined as the distance between the bottom surface of the train and the top surface of the track. In actual operation, the size of the rail gap is 8 mm to 12 mm. In this simulation, the rail gap of the maglev train is 10mm. As shown in Fig.2., the calculation field is 48.36H long, 20H wide and 10H high, where H is the height of the maglev train model. Figure 2. also shows the origin of coordinate system (x, y, z). The boundary conditions of the computational domain are: the inlet is the velocity inlet, the outlet is the pressure outlet, the train body, the stationary track and the ground are defined as a non-slip wall, the moving track and the ground are the boundary conditions of the moving wall surface, and the velocity of the sliding wall surface is the same as the inlet velocity.

**Fig. 1.** The maglev train model (a) Overall train model; (b) Schematic diagram showing the rail gap.
2.2 Numerical method

The time-dependent IDDES (based on the SST k-ω model) used in this work is a hybrid RANS-LES model [12],[17], which combines the advantages of the delayed detached eddy simulation (DDES) and the wall-modelled large eddy simulation (WMLES). The DDES provides shielding against grid-induced separation (GIS) caused by the grid refinement beyond the limit of the modelled stress depletion (MSD) [18]. One the other hand, the WMLES model is designed to reduce Reynolds number dependency and to allow the LES simulation of wall boundary layers at much higher Reynolds numbers than the standard LES models [17],[19]. In the present IDDES, a new sub-grid length-scale is defined in Eq. (1), including explicit wall-distance dependence, which is different from the traditional LES and DES in involving only the grid-spacing. The primary effect of Eq. (1) is to reduce Δ and to promote a steep variation, leading to a similar trend in the eddy viscosity, which is likely to destabilise the flow [17].

\[ \Delta = \min\{\max\{C_w d_w, C_w h_{max}, h_{wn}\}, h_{max}\} \]  

In Eq. (1), \( d_w \) is the distance to the wall, \( h_{wn} \) is the grid step in the wall-normal direction, and \( C_w \) is an empirical constant that is equal to 0.15 based on a wall-resolved LES of channel flow [17]. \( h_{max} \) in Eq. (1) is defined as the largest local grid spacing, as shown in Eq. (2).

\[ h_{max} = \max\{h_x, h_y, h_z\} \]

The present simulations employed a segregated incompressible unstructured finite-volume solver. To discretise the convective terms, a hybrid numerical scheme [20] was used to switch between a bounded central differencing scheme (BCDS) in the LES region and a second-order upwind scheme in the URANS region [12],[20]. Meanwhile, a second-order upwind scheme was used for the turbulent quantities. A second-order implicit scheme was used for time integration. For the purpose of saving computational resources and time, the simulation was initialised using a convergent steady RANS result. The mean and root mean square values of aerodynamic forces were monitored during unsteady calculation. Sampling was initiated when no significant differences were found for two consequent time sequences.

2.3 Meshing strategy

The quality of IDDES is highly dependent on grid resolution. To meet the requirements of high-precision analysis, hybrid meshes were used for discretisation throughout the computational domain, including prismatic layer meshes and hexahedral meshes at the wall boundary. As shown in Fig. 3., the grid around the train is locally refined, including the position where flow separation and reattachment are generated, the track gap part and the position where the train tail vortex is generated. Three sets of grids were used to detect the grid sensitivity of this numerical simulation: a coarse grid, a medium grid, and a fine grid (with 12 million, 21 million and 34 million elements, respectively). Figure 4 shows the Y+ value of medium grid train surface, the values are within 1.5, which conforms to the Y+ range of the IDDES model.
Fig. 3. Medium grid around the train: (a) A partial grid at the end of the train; (b) Distribution of grid of train boundary layer and track clearance

Fig. 4. Y + value of train surface when modelled using a medium grid.

The time-averaged slipstream values of course, medium and fine meshes are compared in Fig. 5. The results are based on stationary ground conditions. The results show that the slipstream distributions calculated under three sets of grids are consistent. In addition, these contours are like the fundamental description of slipstream [21],[22]: where, for example, along the direction of the train, the train wind value increases at the nose of the head train and reaches the peak value in the wake area. The results of using medium and fine meshes are consistent with each other, except for a slight deviation at x/H >1; however, the results when using coarse meshes are significantly different from those deduced using medium and fine meshes, especially in the tail car nose peak and wake area (Fig. 5). Grid independence verification shows that the resolution of the intermediate grid is adequate. Therefore, all the results in the study are based on the use of middle grids.
2.4 Non-dimensionalization

To facilitate analysis, the numerical simulation results were processed if dimensionless. Aerodynamic coefficients and aerodynamic pressure coefficients were defined as follows:

\[ C_x = \frac{F_x}{0.5 \rho v^2 S} \]  \hspace{1cm} (3)

\[ C_z = \frac{F_z}{0.5 \rho v^2 S} \]  \hspace{1cm} (4)

\[ C_p = \frac{\Delta p}{0.5 \rho v^2} \]  \hspace{1cm} (5)

Where \( F_x \) is the resistance, \( F_z \) is the lift, N, \( \rho \) is the density of air (1.225 kg/m\(^3\)); \( v \) is the incoming flow velocity; \( S \) is the reference area (0.036 m\(^2\)); \( \Delta p \) is taken as the difference between the pressure at this point of the flow field and the static pressure in wind tunnel test section, and \( C_p \) is the pressure coefficient.

2.5. Numerical validation

Based on high-speed railway construction technology national engineering laboratory of central south university silent return flow double 3 m × 3 m high speed section of wind tunnel test section, maglev train aerodynamics were assessed, including the aerodynamic force and surface pressure on the maglev train, to verify the numerical simulation under static ground boundary conditions. The dimensions of the wind tunnel test section are 15 m long, 3 m wide and 3 m high. The stable wind speed ranges from 20 m/s ~ 70 m/s, the axial static pressure gradient is less than 0.01 pa/m, and the turbulence intensity is less than 0.5%. In the wind tunnel experiment, the ground is stationary. In the wind tunnel experiment, the length of track is 5 m. Considering the size of the wind tunnel and the measurement of aerodynamic performance of maglev train, when the scale of the train model is 1:16, it is more suitable for the wind tunnel size of this test. Therefore, the scale of the model was set to 1:16. An electronic pressure scanning valve (Scanivalve Sensor Co., USA) was adopted for the measurement of the surface pressure distribution on the train model. The measuring range of the sensor is 7 kPa and the accuracy is 0.08% (two such scanning valves were used). During the wind tunnel test, the distance
between the front and rear vehicles and the track clearance is kept at 10mm, to avoid the impact of the collision between the train and the track during the aerodynamic test. The wind tunnel test model is presented in Fig. 6. When verifying the accuracy of the numerical simulation, the numerical simulation adopts the same ratio of 1:16 as the wind tunnel test, L/H and other details remain the same, except for some simplification of the supporting track.

![Fig. 6. Maglev train model in Wind tunnel test.](image)

2.5.1. Aerodynamic coefficient

The comparison between the train IDDES numerical simulation results under static ground conditions and the average force coefficient in the wind tunnel test is illustrated in Fig. 8, including data pertaining to drag coefficient ($C_x$) and lift coefficient ($C_z$). They fit each other, with a maximum deviation of less than 10%.

![Fig. 7. Pressure scanning valve.](image)
2.5.2. Aerodynamic pressure coefficient

Figure 9 shows the distribution of pressure coefficients along the centreline on the upper surface of the maglev train. In general, the IDDES numerical simulation results are in good agreement with measured value, in addition to those for the vehicle near the tip: this is because the position of the nose tip of the tail car is significantly affected by the wake, which will change the flow structure and pressure distribution on the surface around the train and affect the accuracy of measurement. In general, in the wind tunnel test, the selection of measurement point can reflect the changes in the surface pressure on the train, and the accuracy of numerical simulation is thus also higher.
3. Numerical results

3.1. Flow structure analysis

3.1.1. Dynamic flow topology in the wake

Figure 9 shows the instantaneous flow structure on the equisurface of the second invariant of the velocity gradient tensor around the maglev train under different ground conditions. The iso-surface of Q is coloured with the time-averaged value of $U_{\text{slipstream}}$ of the train. Figure 10 illustrates that, when the incoming flow acts on the head car, vortex structure is formed on both sides of the orbit and develops in a backwards direction under the condition of stationary ground due to the joint action of the track and the ground. Near the train wake area, many vortexes will be generated on both sides of the train under different ground conditions. In general, the flow structure around the rear train is more complex than that of the front train. Compared with the two ground conditions, the vortex distribution on both sides of the train and near the wake is obviously different, indicating the dominant role of track and ground. From a qualitative perspective, in the vertical direction and under the condition of stationary ground, the wake vortex develops downstream of the train and remains close to the ground, namely, $h_1 < h_2$ (Fig. 9). In the horizontal direction, due to the joint action of the wake vortex and the vortices on both sides of the train body, the width of the instantaneous flow structure in the wake area of the train is larger under stationary ground conditions, namely, $w_1 > w_2$, and the two separated main wake vortices of the main instantaneous flow structure are more obvious under moving ground conditions (Fig. 9). This indicates that the turbulence present in the wake can be significantly reduced by moving the ground. This is like previous studies [23], [24], [25].

![Fig. 10. Iso-surfaces of Q = 5000s$^{-2}$ coloured by the mean slipstream: (a) elevation; (b) plan.](image)

Figure 11 illustrates the contour lines of instantaneous longitudinal vortices ($\omega_x$) on both sides of the train at different altitudes ($z/H = 0.05, 0.21$ and $0.36$), representing the instantaneous flow structure around the train. Although the flow structure is quite complex, the difference between the two ground configurations can be clearly seen in Fig. 10. In the case of SG (Fig.10a), the vortices near the top of the track present an organised structure near the downstream half of the maglev train, and they are shed in the direction of the near wake on alternate sides. This observation becomes less apparent in the MG configuration (Fig. 10b): with increasing $z/H$, the difference between SG and MG configurations gradually decreases.
In Fig. 13, the x-direction instantaneous velocity power spectra of SG and MG configurations at different monitoring points in the near-wake (Fig. 12) are compared. Under MG conditions, the dominant frequency $St = 0.211$ is very significant in the near-wake region, especially when $z/H = 0.21h$. From $1 < x/H < 5$, these dominant peaks gradually shrink as they move further downstream of the wake. On the other hand, the spectrum in the SG configuration is quite different from that under MG boundary conditions. In the region near the top of the track ($z/H = 0.05h$), the fluctuation is relatively complex and there is no clear peak. The dominant peak at $z/H = 0.21$ appeared at $St = 0.266$, which is significantly higher than that in MG configuration. This shows that the vortex shedding frequency in the SG configuration is much higher than that in the MG configuration: this is caused by different ground boundary conditions. The main peak of the spectrum becomes less apparent downstream ($x/H = 4$ and 5), indicating the attenuation of the tailing’s vortex.

Fig. 11. Instantaneous vorticity on different horizontal planes for the SG and MG configurations: (a) $z/H = 0.05$; (b) $z/H = 0.21$; (c) $z/H = 0.36$.

3.1.2. Frequency characteristics of the wake

In Fig. 13, the x-direction instantaneous velocity power spectra of SG and MG configurations at different monitoring points in the near-wake (Fig. 12) are compared. Under MG conditions, the dominant frequency $St = 0.211$ is very significant in the near-wake region, especially when $z/H = 0.21h$. From $1 < x/H < 5$, these dominant peaks gradually shrink as they move further downstream of the wake. On the other hand, the spectrum in the SG configuration is quite different from that under MG boundary conditions. In the region near the top of the track ($z/H = 0.05h$), the fluctuation is relatively complex and there is no clear peak. The dominant peak at $z/H = 0.21$ appeared at $St = 0.266$, which is significantly higher than that in MG configuration. This shows that the vortex shedding frequency in the SG configuration is much higher than that in the MG configuration: this is caused by different ground boundary conditions. The main peak of the spectrum becomes less apparent downstream ($x/H = 4$ and 5), indicating the attenuation of the tailing’s vortex.
Fig. 13. Normalized power spectral density of the time varying signal of velocity in the wake at \( x = 1H, 2H, 3H, 4H \) and \( 5H; y = 0; z= 0.05H, 0.21H \) and \( 0.36H \) (the locus of each curve does not conform to the coordinate value).

3.2. Slipstream assessment

3.2.1. Time-averaged slipstream

The adopted definition of slipstream follows that provided by the European Union Agency for Railways, 2014 [26]. Respectively, the flow component velocity \( U_{TF} \) and the horizontal component velocity \( V_{TF} \) calculated by numerical simulation in the train fixed reference frame are converted to speed components \( U_{GF} \) and \( V_{GF} \) respectively in the ground fixed reference frame (GF), and normalised to free flow velocity \( U_\infty \), as shown in Eq. (7). Finally, the combined \( U_{\text{Slipstream}} \) arising from \( U_{GF} \) and \( V_{GF} \) is defined through in Eq. (8) and referred to as the slipstream.

\[
U_{GF} = \frac{U_\infty - U_{TF}}{U_\infty}, \quad V_{GF} = \frac{V_{TF}}{U_\infty}
\]  

(7)

\[
U_{\text{Slipstream}} = \sqrt{U_{GF}^2 + V_{GF}^2}
\]  

(8)

To understand the influence of ground conditions on slipstream, the following aspects were analysed: first, the slipstream speed time track was processed from the specified position of the vertical central plane of the train to calculate the average time and compare statistical data under different ground conditions. Next, a gust analysis was performed to understand the influence of ground conditions on the maximum slipstream speed as defined by the TSI standard.

According to the TSI standard [26], the slipstream was measured at 3 m from the centre of the rail and at two different heights above the top of the rail. The rail side height and platform height are respectively 0.2 m \( (z = 0.05 \text{H}) \) and 1.4 m \( (z = 0.36 \text{H}) \) above the top of the rail. In this study, slipstream data were collected between -12 H to 10 H: at the two measured altitudes, the time average of the slipstream \( U_{\text{Slipstream}} \), the incoming component velocity \( (U_{GF}) \), and the transverse component velocity \( (V_{GF}) \) are as shown in Fig.14. For the convenience of interpretation, the position of the head and tail of the train is marked by solid black lines.
Slipstream will be discussed in terms of the three different regions identified by Baker et al. [27]: the nose tip region, boundary layer region and near-wake region. Qualitatively, the slipstream has a similar trend along the length direction under different ground conditions. The local peak value appears near the nose point of the head and tail cars. The slipstream reaches its maximum value after the tail cars and then decreases gradually. This is a typical slipstream trend observed in output from different train models and methods of analysis [28], [29]. The local peak value of slipstream near the nose point is greater given moving ground compared to stationary ground. This is because the vortex structure generated near the nose point of the head train under stationary ground conditions makes $U_{GF}$ and $V_{GF}$ increase, thus increasing the slipstream value. In the flow structure development area, due to the action of the boundary layer, the $U_{GF}$ value under static ground conditions is larger, and the $V_{GF}$ value under the two ground conditions is smaller and does not significantly differ case-to-case. In the track side position of the wake area, the slipstream peak value is large and directed forwards under moving ground conditions, which differs from the trend found by Xia et al. using a CRH3 model based on a flat ground configuration [30]. This is due to the interaction between the tail vortex structure and the track during backwards flow development and the interaction between the main vortices on each side of the train: this makes the vortex structure in the wake area stronger, thus generating a stronger slipstream. At the height of the platform, the slipstream undergoes a sudden change under moving ground conditions after the wake. This is because of the vortex structure of the wake, and the effect is weak at the same position under stationary ground conditions, so there is no sudden change in slipstream and the value is small.
Fig. 14. Comparison of time-averaged slipstream between SG and MG at trackside and platform heights: (a) UGF; (b) VGF; (c) $U_{Slipstream}$.

3.2.2 Instantaneous slipstream velocity

The TSI specification (European Union Agency for Railways, 2014) defines how to measure slipstream velocity in situ and briefly describes the procedure for calculating the maximum slipstream velocity (also known as the TSI value). Instantaneous slipstream speed is monitored on the rail side and platform position in accordance with European regulations and standards. The first set of 40 probes is placed at the entrance to the calculation area and released at the same speed as the incoming flow. The measurement consisted of measuring the orbit and platform height using 20 measurement probes, each of which collected 40 samples. The distance
between two independent measurement points is 20 m, which meets standard requirements. The slipstream speed is recorded with each moving detector running independently. Figure 15 shows the instantaneous slipstream at the track side and platform position during 20 separate runs. In Fig. 15, the time average of 20 simulation results is represented by a red line. The velocity distribution in Fig. 15 does not represent the actual instantaneous velocity (as a stationary observer experience when an HST passes by)\textsuperscript{[31]}. In addition, the original data need to be filtered by 1s moving average (1s MA) method, and the maximum slipstream speed of the filtered data is recorded as a measurement. $U_{2\delta}$ is the characteristic speed and the slipstream of the maglev train is defined by Eq. (9):

$$U_{2\delta} = U + 2\delta_u$$ \hspace{2cm} (9)

Where $U$ is the peak velocity of the moving average, $\delta_u$ is the standard deviation of the peak velocity in 20 independent periods. The values of $U_{2\delta}$ and $\delta_u$ of 20 groups of simulated calculations under different ground conditions are listed in Table 3. As shown in Figs 15 and 16, given the unchanged ground conditions, after passing the position of the nose point of the rear car, the difference between the independent simulation results is significant, especially in the position on the track side. As shown in Fig. 16, the value under moving ground conditions is compared with that under stationary ground conditions. Specific values, $\bar{U}$, $\delta_u$, and $U_{2\delta}$ (Table 3) suggest that, moving the ground can increases these data in cases without, and with, a 1s moving average.

Fig. 15. Instantaneous horizontal velocity magnitudes $\bar{U}_{\text{Slipstream}}$ for 20 independent times at two TSI positions. Track-side: (a) SG; (b) MG; Platform: (c) SG; (d) MG.
Fig. 16. The spatial average equivalent to full-scale 1s moving average to the instantaneous signals at two TSI positions. Track-side: (a) SG; (b) MG; Platform: (c) SG; (d) MG.

Table 3 The unsteady statistics of gust analysis with and without 1s MA.

| Position | Without 1s MA | With 1s MA |
|----------|---------------|------------|
|          | $\bar{U}$     | $\delta_U$ | $U_{2\delta}$ | $\bar{U}$ | $\delta_U$ | $U_{2\delta}$ |
| SG       | 0.1405        | 0.1115     | 0.3635       | 0.0921     | 0.0373     | 0.1667       |
| Track    | 0.0895        | 0.0401     | 0.1697       | 0.0421     | 0.0209     | 0.0839       |
| Platform | 0.1503        | 0.1387     | 0.4277       | 0.0664     | 0.0281     | 0.1226       |
| MG       | 0.1245        | 0.0960     | 0.3165       | 0.0593     | 0.0210     | 0.1013       |

3.3. Aerodynamic force

The drag coefficient and lift coefficient of the maglev train are shown in Tables 4 and 5 respectively, including the time mean, maximum and standard deviation under different ground conditions. Under the same ground condition, the drag coefficient and lift coefficient of the rear train are greater than that of the head train. Compared with the static ground condition, the resistance coefficients of the head and tail of the maglev train under the moving ground condition all tend to increase, and the increases in the resistance coefficients of the head and tail trains are 3.16% and 3.13%, respectively. Compared with the stationary ground condition, the lift coefficients of the head and tail of the maglev train are smaller under moving ground conditions. The standard deviations of the time-history data pertaining to the train resistance coefficient and lift coefficient under different ground conditions are listed in Tables 4 and 5, respectively, reflecting the intensity of amplitude fluctuations of resistance and lift coefficients. Under the same ground conditions, the standard deviation of the aerodynamic...
coefficient of the tail car is much larger than that of the head car. This phenomenon is caused by the large vorticity of the tail car: because the surface of the maglev train is relatively smooth and there are no prominent parts thereon, it is caused by the shedding of vorticity in the wake area of the tail car. By comparing different ground conditions, it is found that, the standard deviation of aerodynamic coefficients of both head and tail vehicles is smaller under moving ground conditions compared with stationary ground conditions. In general, moving ground conditions can increase the resistance of a maglev train, reduce the lift thereof, and reduce range of the fluctuation of the aerodynamic coefficient of maglev train.

| Method            | Ave   | Standard deviation |
|-------------------|-------|--------------------|
|                   | Head  | Tail               | Head  | Tail               |
| Stationary ground | 0.087 | 0.121              | 0.208 | 1.87×10^{-4}       | 3.15×10^{-3} |
| Moving ground     | 0.090 | 0.125              | 0.215 | 1.76×10^{-4}       | 0.73×10^{-3} |

| Method            | Ave   | Standard deviation |
|-------------------|-------|--------------------|
|                   | Head  | Tail               | Head  | Tail               |
| Stationary ground | 0.045 | 0.273              | 0.318 | 3.82×10^{-3}       | 1.13×10^{-2} |
| Moving ground     | -0.026| 0.259              | 0.233 | 0.01×10^{-3}       | 0.16×10^{-2} |

### 4. Conclusion

In this study, IDDES method is used to compare unsteady aerodynamic performance of maglev trains under different ground conditions. Two typical ground conditions are considered: stationary ground (SG) and moving ground (MG). The flow structure, slipstream and aerodynamic force around the train are analysed. According to the simulation results, the following conclusions can be drawn.

1. Compared with the aerodynamic force and aerodynamic pressure in wind tunnel test, the validity of the IDDES method based on k-w SST to simulate the flow field around the maglev train is verified.

2. In the two ground conditions, the vortex distribution on both sides of the train and near the wake is obviously different, indicating the dominant role of track and ground. The flow structure in the wake area of the rear vehicle is more complex than that of the front vehicle. When the incoming flow acts on the head car, due to the joint action of the track and the ground, vortex structures on both sides of the track develop backward under the stationary ground condition, and the wake area will interact with the vortex structure formed by the tail car. From the perspective of qualitative analysis, under the condition of stationary ground, in the vertical direction, the wake vortex develops to the downstream of the train and remains close to the ground with a small height. In the horizontal direction, the instantaneous flow structure in the wake area of the train is wider due to the action of the wake vortex and the vortexes on both sides of the train body.

3. For head and tail car near the tip of the train peak wind, under the condition of the mobile ground peak slightly tall, and for drafting regional trains peak wind, mobile ground conditions, after the vehicle on both sides of the main vortex structure and the orbital interaction makes in the area of wake vortex structure strength is greater, resulting in a larger train the peak of the wind, and the position even more.
4. For two ground conditions, the coherent structure of the train's main vortex structure periodically falls off from the two sides of the maglev train into the near-wake region. The shedding frequency of the main vortex in the static ground condition is much higher than that in the moving ground condition, and the shedding frequency of the main vortex in the near-wake region is 0.266 and 0.211 respectively.

5. Moving ground condition can increase the drag and reduce the lift of the maglev train, and reduce the standard deviation of the maglev train's aerodynamic force.
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Declarations:

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication.

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Authors’ Contributions

Shi Meng was a major contributor in writing the manuscript, and carried out the numerical simulation. Guang Chen directed the numerical simulation and processed the calculated data. All the authors read and approved the final manuscript.

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