Aerodynamic Analysis of Pressure Wave of High-Speed Maglev Vehicle Crossing: Modeling and Calculation

Dinggang Gao 1,2, Fei Ni 2,* , Guobin Lin 2, Shihui Luo 1 and Wen Ji 2

1 Traction Power State Key Laboratory, Southwest Jiaotong University, Chengdu 610031, China; 12138@tongji.edu.cn (D.G.); shluo@swjtu.cn (S.L.)
2 Maglev Transportation Engineering R&D Center, Tongji University, Shanghai 201306, China; 12154@tongji.edu.cn (G.L.); 12191@tongji.edu.cn (W.J.)

* Correspondence: fei.ni@tongji.edu.cn; Tel.: +21-6958-0338

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Abstract: When two maglev trains travel in opposite directions on two adjacent tracks, train crossing is inevitable. Especially when both trains run at full speed, the pressure wave formed by each other will have a significant impact on the structure of the vehicle. Therefore, it is important to understand the pressure distribution on the body surface during the crossing to mitigate impact of the pressure wave. In this work, numerical simulation techniques are employed to reveal the nature of pressure wave during train crossing. Firstly, the aerodynamic load calculation model and the pressure wave calculation model are established, based on the turbulence model and flow field control equation. Secondly, the governing equations are discretized together with determined corresponding boundary conditions, which leads to an effective numerical analysis method. Finally, the corresponding aerodynamic analysis is carried out for the high-speed maglev test vehicle running at speed 500 km/h on the open-air line. The simulation results reveal that the spot which sustains the most pressure fluctuation is at the widest part of the vehicle during the train crossing. This forms valuable insights on the aerodynamic nature of high-speed maglev train and provides necessary inputs to the structural design of the vehicle.

Keywords: high-speed maglev; vehicle crossing; computational fluid dynamics; air flow field; pressure wave

1. Introduction

At present, the operation speed of high-speed railway has been greatly improved compared with the conventional high-speed railways that rely on wheel drives. Using wheel–rail interaction to ensure stable operation, the speed of conventional high-speed railway has a certain upper limit, which is determined by the wheel drive system. On this basis, the maglev railway can theoretically reach higher speed with the same input power because it avoids the friction caused by wheel–rail contact. However, the inevitable train crossing during operation will induce pressure wave that can have large transient impact on the train body and thereafter, its operation safety. Therefore, many experts have carried out relevant research on train aerodynamics and have made a lot of valuable scientific research results.

Air flow field is the main cause of aerodynamic force generated by train movement. Professor Baker C, University of Birmingham, UK, fundamentally describes the nature of the flow field around the train [1–3]. On this basis, the generation mechanism of cross wind and pulsating wind and their influence on the train power system are studied. Soper et al. [4–6] studied the model scale of the flow around the train and measured the air flow characteristics and aerodynamic behavior at the rear of the train.
Krajnovic et al. [7–9], at Chalmers University of Technology in Sweden, first used the large eddy simulation method to analyze and discuss the aerodynamic stability of trains. Combined with large eddy numerical analysis and wind tunnel test, the feasibility of this method in analyzing the external flow field of trains is verified. The method is used to systematically study the train running state under the influence of cross wind.

Niu et al. [10–12], at Central South University, China, studied the aerodynamic characteristics of high-speed trains in the atmospheric boundary layer based on wind tunnel tests. The three-dimensional unsteady compressible Reynolds mean Navier–Stokes equation and k-ε turbulence model are used to obtain the pressure waves on the train surface at unequal speed intersection. The results are in good agreement with experimental measurements. At the same time, the effects of high-speed train reconnection on the aerodynamic performance of open-line operation, crosswind operation, open-line intersection, tunnel passing, and tunnel intersection are studied.

Yan and Yang [13] used k-ε turbulence model to simulate the crossing of high-speed trains in tunnels, analyzed the variation and distribution of the surface pressure of trains, and evaluated the comfort in the train cabin. Xi et al. [14] and Mao et al. [15] simulated the aerodynamic characteristics of 3-8 marshalled trains running at speed 350 km/h under different speeds of cross wind. The dimensionless relationship between resistance coefficient and formation number of the train was established to study the pressure wave amplitude during high-speed train crossing.

In this paper, a new train mode which is characterized by magnetic levitation, elevated and high-speed, is studied for the first time, which can provide a basis for engineering applications and train safety analysis. On the basis of the turbulence model and the flow field control equation, the aerodynamic load calculation model and the pressure wave calculation model are established as the numerical calculation method in use. On this basis, the aerodynamic behavior of the high-speed maglev vehicle is calculated and analyzed in detail. In addition, the corresponding aerodynamic analysis is carried out for the high-speed maglev test vehicle running at speed 500 km/h on the open line, with the results of induced pressure analyzed and discussed. Because the direct impact of air flow field on train body strength structure and running speed, it is of great value to study the air flow field at such a high speed, quantitatively.

2. Theoretical Background

To investigate the aerodynamic force on the train, the pressure distribution on the train surface needs to be obtained by solving the flow field around the train at first. Then, the aerodynamic force of the train can be obtained by integrating the product of pressure and area along the whole train surface.

2.1. Navier–Stokes System

The research results of air characteristics of a TR08 maglev train [16] show that the air flow around the maglev train is a typical three-dimensional, viscous, compressible, unsteady, and turbulent flow field. According to the laws of mass conservation, momentum conservation, energy conservation, and ideal gas equation of state, the control equation describing the external flow field of the maglev train can be characterized by the following Equations [16]:

(1) Continuity equation derived from conservation of mass:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0
\]  

(2) Momentum equation derived from momentum conservation:

\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}
\]
(3) Energy equation derived from energy conservation:

$$\frac{(\rho e)}{\partial t} + \partial \left(\rho u_j h\right) \partial x_j = \text{div}(k \text{grad}T) + \partial (u_i \tau_{ij}) \partial x_j$$

(3)

(4) The equation of state based on ideal gas assumption:

$$P = \rho RT$$

(4)

where $u_i (i = 1, 2, 3)$ is the velocity component; $\mu$ is the dynamic viscous coefficient; $P$ is the pressure, $\rho$ is the fluid density; $e$ is the internal energy; $R$ is the molar gas constant; $\tau_{ij} = 2\mu s_{ij} - (2/3)\mu(\partial u_i / \partial x_i) \delta_{ij}$ is the viscous stress tensor; and $\delta_{ij}$ is the Kronecker function.

In addition, $s_{ij}$ and $h$ are defined as follows:

$$s_{ij} = [(\partial u_i / \partial x_j) + (\partial u_j / \partial x_i)]/2; h = e + (1/2)(u^2 + v^2 + w^2) + (P/\rho).$$

Equations (1)–(4) constitute the basic governing equation for solving the external flow field of a Maglev train. In theory, the velocity field, pressure field, and temperature field around the maglev train can be completely determined by the above equations, together with the boundary conditions and initial conditions specified in solving the problem.

However, turbulence is a highly complex, random, unsteady, three-dimensional, swirling flow. The chaotic trajectory of particles, the fluctuation of velocity and pressure in turbulence, and the strong transport phenomena in adjacent regions make it very difficult to study the regularity of turbulent motion. For many years, besides the in-depth theoretical analysis of turbulence phenomena, fluid mechanics scientists have been seeking to solve turbulence problems by solving Navier–Stokes (N-S) equations with numerical methods and have developed the corresponding turbulence flow field simulation method [17].

2.2. Turbulent Mean Motion Equation

Turbulent flow is a highly random fluid motion. The characteristic quantities of various flows in turbulent motion show random fluctuations in time and space. Because of the randomness of turbulent motion, statistical averaging method is usually used in engineering to obtain the statistical average values and other statistical characteristics of various physical quantities in turbulence. However, due to the complexity of the basic turbulence unit, the basic equation of turbulence probability density has not yet been found, whereas the time and volume mean values are relatively easy to determine by experiments. According to ergodic hypothesis, the average values obtained by the three average methods are equal. Therefore, the time-average method can be used instead of the probability-average method, which is also a commonly used method in the discussion of turbulence.

The instantaneous value $A$ of turbulent motion parameters is expressed as the sum of the time-averaged value $\bar{A}$ and the fluctuation term $A'$:

$$A = \bar{A} + A'$$

(5)

The instantaneous value represented by Equation (5) is equal to the sum of the time mean and the fluctuation value. This relation is substituted for the basic equations of viscous fluid dynamics. Each of them belongs to any time in a certain time interval to find the time mean, then the whole equation system can be averaged by time. By using properties of time mean and fluctuation value, the basic differential equations of turbulence can be obtained. For incompressible flows:
(1) Continuity equation
\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_j} = 0 \] (6)

(2) Momentum equation
\[ \rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -\frac{\partial p}{\partial x_i} \nabla \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial}{\partial x_j} (-\rho \bar{u}_i' \bar{u}_j') \] (7)

(3) Energy equation
\[ \rho \frac{\partial \theta}{\partial t} + \rho \frac{\partial}{\partial x_j} (h \bar{u}_j) = \text{div}(k \nabla \theta) + \frac{\partial}{\partial x_j} (u_i \tau_{ij}) - \frac{\partial}{\partial x_j} (h' \bar{u}_j') \] (8)

It can be seen from (6)–(8) that the continuity equation of the mean turbulent motion of incompressible fluid has the same form as of the instantaneous motion, while the momentum equation only adds \( \rho \bar{u}_i' \bar{u}_j' / \partial x_j \), in which \( -\rho \bar{u}_i' \bar{u}_j' \) (i, j = 1, 2, 3) is the Reynolds stress.

For compressible flows, the weighted average of mass can be used as what follows:

(1) Continuity equation
\[ \frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_j) = 0 \] (9)

(2) Momentum equation
\[ \frac{\partial}{\partial t} (\bar{\rho} \bar{u}_i) + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} \nabla \frac{\partial \bar{\tau}_{ij}}{\partial x_j} + \frac{\partial}{\partial x_j} (-\bar{\rho} \bar{u}_i' \bar{u}_j') \] (10)

(3) Momentum equation
\[ \frac{\partial}{\partial t} (\bar{\rho} \bar{u}_i) + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_i \bar{u}_j) = \text{div}(k \nabla \theta) + \frac{\partial}{\partial x_j} (u_i \tau_{ij}) - \frac{\partial}{\partial x_j} (-\bar{h} \bar{u}_j') \] (11)

where
\[ \bar{u}_i' \bar{u}_j' = \bar{u}_i'' \bar{u}_j'' - \frac{\rho'}{\bar{\rho}} \bar{u}_i'' \bar{u}_j'' - \bar{u}_i'' \bar{u}_j'' \]

Although there are some differences between mass-weighted averaging and time-averaged methods for compressible flows, according to Morkovin hypothesis, compressibility has little effect on turbulence structure when Mach number is less than 5. The mean motion of compressible turbulence can be well predicted by combining the mass weighted average equation with the incompressible Reynolds stress model. Therefore, for the turbulence mean equation of compressible fluid of Equations (6)–(8), the weighted mean of mass and time mean are not distinguished.

2.3. Turbulence Model

After introducing the Boussinesq hypothesis, the key to calculate turbulent flow is how to determine \( \mu_t \), which is called turbulent viscous coefficient. As a function of spatial coordinates, it depends on the flow state rather than physical parameters.

On this basis, the relationship between \( A \) and turbulence time-averaged parameters, namely turbulence model, has been developed. According to the number of differential equations, it can be divided into zero-equation model, one-equation model, and two-equation model. In this paper, the \( k-\epsilon \) two-equation model is used for correlation analysis, according to references [10–12].
The \(k-\varepsilon\) two-equation model\,[18]\ introduced two physical quantities: turbulent kinetic energy \(k\) and turbulent energy dissipation rate \(\varepsilon\). \(k\) and \(\varepsilon\) are defined by the following formula:

\[
k = \frac{1}{2}u_i' u_i'
\]

\[
\varepsilon = \nu \frac{\partial u_i'}{\partial x_k} \frac{\partial u_i'}{\partial x_k}
\]

where \(\nu\) is the kinematic viscous coefficient.

According to the instantaneous value of turbulence and the average energy Equation (3), the turbulent fluctuation equation can be obtained, and then \(k\) and \(\varepsilon\) can be calculated through Equations (14) and (15), respectively.

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] + S_k \tag{14}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma\varepsilon}) \frac{\partial \varepsilon}{\partial x_j} \right] + S_\varepsilon \tag{15}
\]

where the source terms include,

\[
S_k = P_k - D_k, \quad P_k = \tau^{(i)}_{ij} (\partial u_i / \partial x_j), \quad S_\varepsilon = P_\varepsilon - D_\varepsilon, \quad P_\varepsilon = C_{\varepsilon 1} (\varepsilon / k) \tau^{(i)}_{ij} (\partial u_i / \partial x_j),
\]

and the dissipative terms read as,

\[
D_k = \rho \varepsilon, \quad D_\varepsilon = C_{\varepsilon 2} \rho (\varepsilon^2 / k).
\]

According to dimension analysis and other methods, \(\mu_t\) can be obtained based on (16).

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \tag{16}
\]

In addition, there are several coefficients in the above formulas, which are recommended by Patanka and Spalding\,[19]\ in Table 1 as follows:

| Coefficient | \(\sigma_t\) | \(\sigma_k\) | \(\sigma_\varepsilon\) | \(C_{\varepsilon 1}\) | \(C_{\varepsilon 2}\) | \(C_\mu\) |
|-------------|--------------|--------------|----------------------|------------------|------------------|---------|
| Value       | 0.9          | 1.0          | 1.3                  | 1.44             | 1.92             | 0.09    |

2.4. Computation Model of Pressure Wave during Train Crossing

Train crossing is a complex physical process. The flow field around the train is not only related to time, but also to the relative position between the two trains. In that case, moving mesh technology is needed, and the corresponding flow field control equation must also include the effect of mesh movement by air motion. The flow field control equation should be written as follows:

\[
\frac{\partial (\rho \varphi)}{\partial t} + \text{div} \left[ \rho \varphi (U - U_g) \right] = \text{div} (\Gamma \phi \text{grad} \varphi) + S_\varphi \tag{17}
\]

where \(U_g\) is the velocity of the interface of the control body; \(\varphi\) is a parameter in the flow field; \(U\) is the velocity; \(S_\varphi\) is the generalized source term; \(\Gamma \phi\) is the generalized diffusion coefficient.

The corresponding governing equations can be obtained by taking different values of \(\varphi\), \(S_\varphi\), and \(\Gamma \phi\), respectively. For example, when \(\varphi = 1\), \(\Gamma = 0\), \(S_\varphi = 0\), (17) becomes a continuity equation; when
\( \varphi = u, v, w \) (17) becomes a momentum equation; when \( \varphi = c \), (17) is an energy equation and heat conduction equation, and so forth.

Note that, the solution of (17) can depict the flow field distribution around the train, the pressure distribution on the surface of the train at each time, and accordingly, the magnitude of the pressure fluctuation. The numerical method for solving this equation is described in detail in the next chapter.

3. Numerical Method

3.1. Numerical Method for Calculating Aerodynamic Loads

3.1.1. Discretization of Control Equation

In Figure 1, over time interval \( \Delta t \), the general governing equation of fluid (17) is integrated in the control volume, and the order of integration is exchanged as follows:

\[
\int_{V} \left( \int_{t}^{t+\Delta t} \frac{\partial (\rho \varphi)}{\partial t} dt \right) dV + \int_{S} \left( \int_{t}^{t+\Delta t} \left( \rho \varphi U - \Gamma_{\varphi} \text{grad} \varphi \right) dS \right) dt = \int_{V} \int_{t}^{t+\Delta t} S_{\varphi} dV dt
\]

where the first term on the left-hand side is the increment of \( \varphi \) in the control volume in \( \Delta t \); the second term is the decrease of \( \varphi \) value caused by convection and diffusion; the right-hand side is the increase of \( \varphi \) caused by source term. Further, the volume of \( V \) is the control unit centered on \( P \) point, and the surface area of \( S \) is the control volume.

![Figure 1. Flow field control unit.](image)

3.1.2. The Linear Equations

(1) Processing of source items

The generalized source term \( S_{\varphi} \) in equation (17) contains the sum of all other terms that cannot be included in the governing equation, such as the unsteady term, the convection term, and the diffusion term. At present, one of the most used methods for source term processing is local linearization, which assumes that the source term can be expressed as a linear function of the unknown quantity \( \varphi \) within a small range of changes in the unknown quantity. In the control volume \( P \), the source term can be expressed as follows:

\[
\int_{V} \int_{t}^{t+\Delta t} S_{\varphi} dV dt = S \Delta V = \Delta t (s_{u} + s_{p} \varphi_{p})
\]

where \( s_{u} \) is the constant part and \( s_{p} \) is the slope of the curve of \( S \Delta V \) varying with \( \varphi \) at point \( P \).
(2) The linear equations

By integrating other terms of Equation (18) with the help of Gauss theorem, making time difference and space difference, respectively, the discrete equations of the flow field control equation can be obtained:

\[
a_P \phi^p_n = \sum_m A_m \phi^m_n + s_u + B_0^P \phi^0_P
\]

where

\[
B_0^P = \frac{(pV)^0}{\Delta t}; A_P = \sum_m A_m - s_P + B_0^P.
\]

3.2. Numerical Method for Calculating the Pressure Wave during Train Crossing

The crossing of maglev trains is a typical unsteady problem. In order to ensure that the velocity, pressure and density in the flow field are not decoupled in the same mesh, it is also necessary to select the pressure implicit split-operator (PISO) with multistep correction operation, according to the Rhie–Chow momentum interpolation [20]. Multistep correction can be carried out at the time layer, and the convergence solution of the current time layer can be obtained by the last step of correction. The implementation steps of the PISO algorithm are as follows:

(1) Prediction stage

According to the initial assumption, the pressure field \(p^{(0)}\) can be calculated from the \(k\)-layer, and the momentum equation is thus solved as:

\[
A_P u^{(1)}_{i,P} = \sum_m A_m u^{(1)}_{i,m} + B_0^P u^{0}_{i,P} + s_u + D_P (p^{(1)}_{N+} - p^{(1)}_{N-})
\]

where \(u_{i,P}\) are the velocity components of node \(P\); \(p_{N+}\) and \(p_{N-}\) are the pressures of adjacent nodes to node \(P\); and \(D_P\) is the geometric coefficient. In this step, both \(u^{(1)}_{i,P}\) and \(p^{(0)}\) satisfy the present momentum equation, but \(u^{(1)}_{i,P}\) does not necessarily satisfy the requirement of mass conservation.

(2) First correction stage

In this step, the updated pressure value \(p^{(0)}(p^{(0)} + a_P p^{(0)})\) and the corresponding velocity \(u^{(2)}_{i,P}\) are determined so that the latter can satisfy the continuity equation. Meanwhile, \(u^{(2)}_{i,P}\) is required to satisfy the momentum equation explicitly, and then the following results can be obtained:

\[
A_P u^{(2)}_{i,P} = \sum_m A_m u^{(1)}_{i,m} + B_0^P u^{0}_{i,P} + s_u + D_P (p^{(1)}_{N+} - p^{(1)}_{N-})
\]

where the pressure correction equation is:

\[
A_P p^{(1)}_{i,P} = \sum_m A_m p^{(1)}_{m} + b^{(1)}
\]

(3) Additional correction stage

Based on \(p^{(1)}\) and \(u^{(2)}_{i,P}\) that were obtained in the first step, the follow-up improvements of \(p^{(q)}\) and \(u^{(q+1)}_{i,P}\) will continue until they satisfy both the momentum equation and the continuity equation:

\[
B_p^{(q+1)} - B_0^P + \sum_j (\rho^{(q+1)} u^{(q+1)}_{j,S}) = 0
\]
The corresponding pressure correction equation is:

\[ A_p u_{i,j}^{(q+1)} = \sum_m A_{m,i} p_{i,j,m}^{(q)} + B_{p,i,j}^{(q)} s_u + D_{p}(p_{N+}^{(q)} - p_{N-}^{(q)}) \]

where, \( q = 1, 2, \ldots, n \) is the number of corrections.

After \( n \) times of correction, if both the velocity field and pressure field satisfy the linearized momentum equation and mass conservation equation, the procedure will go back to the prediction step and initiate the calculation of the next time layer. Until all time layers are completed, the numerical solution of the flow field can be obtained.

4. Modeling and Calculation of Pressure Wave during Train Crossing

In this section, detailed modeling and calculation of air flow field during train crossing are given.

4.1. Train Modeling and Computing Zoning

The maglev train is shown in Figure 2. The train is 3.7 m wide, 4.16 m high, and 79 m long (three section). The train runs on the bridge that is 10 m high. The distance between the two tracks is 5.1 m, and the levitation height of trains is set to 10 mm. Because there are two opposite trains in the computational domain, and the shape, length, and speed of the two vehicles are not necessarily the same, the whole space flow field is thus divided into three regions, namely, I, II, and III, as illustrated in Figure 3 (not in scale). The boundary between the regions coincides, and there is no overlap among those regions.

![Figure 2. The Maglev train.](image_url)

![Figure 3. Flow field calculation area and division: (a) top view, (b) side view.](image_url)

It should be noted that in order to ensure the accuracy of calculation, the ratio of length to width of the mesh should not be too large, as the levitation height of the maglev train is only 10 mm, which is quite different from the size of the whole train. If the whole train is calculated with mesh detail covering the levitation height, the scale of the meshes is bound to be very large. Therefore, in order to improve the accuracy of calculation, this paper only calculates the pressure wave at the head of the train.
train. That is, the train can be assumed to be of “infinite length” with shape change only at the head, which can greatly reduce the computational mesh and get reasonable calculation results under limited computational resources. This simplification is based on facts that the pressure wave in other crossing states is not much different from that in the front of the train, according to the test results on the actual track. The only exception is the case of dynamic train crossing at different speeds; the pressure wave formed on the tail of the longer train by the faster train is slightly larger (ca. 15%) due to the influence of boundary layer.

4.2. Moved Mesh Technique and Mesh Information Exchange

Due to the relative motion between the two trains, the boundary of calculation area changes constantly. This situation needs to be handled by moved mesh technology, by which the problem of mesh movement and information exchange has to be solved.

4.2.1. Moved Mesh

In the computational domain, as the train moves forward continuously, the mesh connected with the train moves forward at a constant speed with time. Therefore, the spatial position and speed of each mesh point must be calculated in each time step. At the initial time step (i.e., time \( t = 0 \)), the initial mesh is the mesh system initially established. At each subsequent physical time \( t \), the positions of trains and mesh points in zones I and II relative to the static zone III need to be recalculated according to the speed of train. Therefore, after \( n \) times of calculations, the position of trains and mesh points in Zones I and II are calculated as follows:

\[
x_n = x_0 + n\Delta t \vec{V}_f
\]

where \( x_0 \) is the initial position of the mesh in Zone I and Zone II; \( n \) is the number of computations; and \( \Delta t \) is the time step.

4.2.2. Mesh Information Exchange

Because the whole flow field contains two kinds of mesh systems, moving and stationary, it is necessary to solve the problem of information exchange between moving and stationary meshes. The exchange of flow field information between moving and stationary meshes is achieved through interpolation of interfaces. Figure 4 depicts a mesh near the interface of Zone I and Zone III in the computational domain. The area interfaces A–B, B–C, C–D and E–F, F–G, G–H overlay with each other to form two common areas a–e, e–b, b–f, f–c, c–g, g–d and d–h. At this time, the flow field information of unit 2 is transferred from unit 1 to unit 4 and unit 5 through e–b and b–f planes, while that of unit 2 is transferred to unit 5 and unit 6 through f–c and c–g planes, respectively.

![Figure 4. Information transfer between mesh interfaces.](image-url)

In Figure 4, there are two cases in the information exchange process: 1) the size of the interface is completely coincident; as shown in Figure 5a, if the units 1, 3, 4, and 6 in Figure 3 are located at the boundary of the computational domain, the nodes A and E coincide, D and H coincide, and there are
no faces A–E and D–H; 2) the size of the interface is not completely coincident; as shown in Figure 5b, there are faces A–E and D–H. Therefore, the boundary conditions of face A–E should be taken into consideration carefully in the latter case.

![Diagram](image_url)

**Figure 5.** Mesh interface: (a) complete coincidence of two interfaces; (b) partial coincidence of two interfaces.

When the interface between the two regions is not completely coincident, those meshes without interface with other regions are “redundant” because they no longer need to exchange information with other regions. The flow field information they can get is completely obtained from the meshes in their region. It shows that the flow field information generated by another train motion no longer needs these meshes to transfer, so this part of the meshes can be moved out of the computational domain. This method can thus simplify the setting of boundary conditions and reduce the burden of calculation.

4.2.3. Mesh Addition and Mesh Removal

The process of mesh addition and removal can be found in Figure 6. Because the flow field area uses hexahedral-structured meshes, the addition and removal of meshes are realized through the operation of the whole mesh. For illustration, let A, B, C, D be the computational domain.

At time step \( t \), the light gray mesh layer has not been added and the blue mesh layer has not been removed, as shown in Figure 6a. When the calculation proceeds to \( t + \Delta t \), the train moves forward with a distance \( d_s = V_1 \cdot \Delta t \). At this time, the blue mesh layer remains in the computational domain, but the distance of \( V_1 \cdot \Delta t \) has shrunk (reduced distance equivalent to the distance removed from \( d_s \)). Meanwhile, the light gray mesh layer is added to the computational domain, but its width direction is only the distance of \( V_2 \cdot \Delta t \) (equivalent to the distance added only to \( d_s \)), as shown in Figure 6b. As time goes forward, the blue mesh is gradually reduced, and the width of light gray mesh is increased, until \( t + n\Delta t \) (\( n = \Delta x / (V_1 \cdot \Delta t) \)) reaches the iteration time needed to move the distance of a single layer mesh (\( \Delta x \) is the mesh step size), as shown in Figure 6c. The light gray mesh layer enters completely, and the blue mesh layer is completely removed out from the computational domain. At time step \( t + (n + 1)\Delta t \), the process of adding and removing the next mesh is re-entered.

It should be noted that the meshes added in the calculation process must be pregenerated and compressed on the A–D boundary in reverse order. In other words, the last compressed mesh is added first, and the first compressed mesh is added last; the removed mesh in the calculation is compressed on the B–C surface. Through the process of adding and removing the mesh, the boundary of the region can be completely coincided, and the computational region can be guaranteed to remain unchanged throughout the calculation process.
Figure 6. Addition and removal of meshes: (a) t moment; (b) t + Δt moment; (c) t + nΔt moment.

4.3. Computation and Analysis of Pressure Wave during Train Crossing

4.3.1. Amplitude of Pressure Wave of Train Crossing

Under the condition of line spacing 5.1 m, the calculation results of the pressure wave of a TR-SH (Shanghai Maglev train) vehicle running at speed 500 km/h on the open line are shown in Table 2. Although the law of pressure variation is the same at each point on the side of the train during the crossing, the magnitudes of pressure wave are different. In order to meet different calculation needs, Table 2 gives the magnitude of pressure wave at five different locations on the side of the train crossing. As shown in Figure 7, measurement points P1–P5 are defined as follows: (1) P1 is at the center of the train door; (2) P2 is at the center of the train window; (3) P3, P4 are in the same cross-section of P2, while P3 is 0.85 m lower than P2, P4 is 0.7 m lower than P3; (4) P5 is in the middle of the front vehicle, and at the same height as P3. Besides, both P3 and P5 are in the maximum width of the train.

Table 2. Computation results of pressure wave of test vehicle meeting on open line at speed 500 km/h.

| Point | P1  | P2  | P3  | P4  | P5  |
|-------|-----|-----|-----|-----|-----|
| Δp (Pa)| 4905| 3790| 4222| 3952| 4013|
Simulation results showed that the pressure waveforms at each measuring point are of similar shape, thus only the pressure change process at point P3 in the intersection process is investigated, as shown in Figure 8. As can be seen from Figure 8, during the whole process of passing through the head of the train, all points on the train surface on the intersection side undergo a positive and negative alternating pressure change, which sweeps across the whole train surface in the longitudinal direction. Because of the short duration and large amplitude of the change of train pressure, on one hand, it is possible to damage the train window glass by pressure impact; on the other hand, the fatigue damage of train structure is also highly possible during a long-term operation, which should be considered in the structural design.

![Figure 7](image-url) **Figure 7.** The point of pressure wave of test vehicle during crossing.

![Figure 8](image-url) **Figure 8.** Calculation results of pressure change process of P3.

### 4.3.2. Flow Field Distribution around Trains during Crossing

The air velocity and pressure between two trains change dramatically due to the crossing. The flow fields around the train at point P3 in 0.036 s during the crossing process are given in Figures 9–14. It is noticed that the flow fields between the two trains overlap with each other. In the direction perpendicular to the train surface, because the direction of the train wind is opposite, the speed after the overlap decreases gradually before the crossing intersection, while the pressure increases gradually, until the positive peak value of the two trains’ wind and pressure meets. This is when the speed drops to the lowest and the pressure rises to the highest. Thereafter, the peak values of wind of the two trains stagger with each other, the speed increases gradually, and the pressure decreases until the peak values of negative pressure on the side of the two trains meet, decreasing the pressure between the two trains to the lowest level.
ith each other, the speed increases gradually, and the pressure decreases. When the peak values of negative pressure on the side of the two trains meet, the air velocity and pressure between two trains change dramatically due to the crossing. The flow fields between the two trains overlap with each other. In the direction, the peak pressure points around the train have staggered, so the impact of train crossing as shown in Figure 8.

Figure 9. Velocity and pressure distribution at $t = 0.1296$ s: (a) velocity distribution; (b) pressure distribution.

Figure 10. Velocity and pressure distribution at $t = 0.1368$ s: (a) velocity distribution; (b) pressure distribution.

Figure 11. Velocity and pressure distribution at $t = 0.1440$ s: (a) velocity distribution; (b) pressure distribution.
Figure 12. Velocity and pressure distribution at $t = 0.1512$ s: (a) velocity distribution; (b) pressure distribution.

Figure 13. Velocity and pressure distribution at $t = 0.1584$ s: (a) velocity distribution; (b) pressure distribution.

Figure 14. Velocity and pressure distribution at $t = 0.1656$ s: (a) velocity distribution; (b) pressure distribution.
It can also be seen from figures that the positive and negative pressures around the head of the two cars reach their maximum before the maximum cross section of the train passes, and the peak pressure points of the two cars also meet at the head of the train. When the maximum cross section of the two cars meets, the peak pressure points around the train have staggered, so the impact to the head of the train is greater than that of the side. Comparing the pressure distribution in the process of train crossing as shown in Figures 9–14, it can be concluded that during the whole process of train crossing, the flow field characteristics outside the two crossing trains do not change much, and the pressure distribution law is basically unchanged.

The pressure and velocity distribution around the car body at certain cross sections during the crossing are depicted in Figures 14 and 15. The right side of the figures is the observing train. The figures show the velocity distribution and pressure distribution around the train at \( t = 0.16776 \) s and \( t = 0.18072 \) s. The pressure amplitude at point P3 reaches \( p_{\text{max}} \) and \( p_{\text{min}} \) at the two time steps, respectively, that is, this point sustains a complete cycle of pressure wave. It can be seen from Figure 14 that the point on the side of the observation train has already been affected by \( p_{\text{max}} \), even before the head of the train arrives at the cross section. At this time, because the train-induced wind on the side of the vertical observation train is very small, the wind field generated by the train directly acts on the observation train surface, and as the train continues to move forward, the wind in the vertical direction of the train surface is perceived at point P3. The pressure increases gradually until the train wind at point P3 reaches its maximum, that is, when the peak pressure of the lateral flow field of the train arrives, the pressure impact at point P3 reaches its maximum \( p_{\text{max}} \).

As the train continues to move forward, the wind generated by the train at point P3 becomes smaller, and the pressure effect at point P3 becomes smaller as well. Until the arrival of the vortex separation zone on the lateral side of the train, that is, when the negative peak pressure point on the side of the train arrives, the pressure impact on P3 reaches the minimum value of \( p_{\text{min}} \). Thus, a positive and negative fluctuation is completed through the train at point P3. It can also be seen from the pressure distribution in Figure 15 that the most impacted area is at the widest spot of the train. When the maximum width moves along the train surface to the top and bottom, the amplitude of the pressure wave on the side of the train decreases gradually. On the crossing section of the observed train as shown in Figures 15 and 16, P3 is the most impacted point due to the pressure generated by the passing train.

![Figure 15. Velocity and Pressure Distribution at \( t = 0.16776 \) s: (a) velocity distribution; (b) pressure distribution.](image-url)
4.3.3. Pressure Distribution on Train Surface during Crossing

One of the most critical effects of the pressure wave is that it may cause damage to the window glass. Therefore, it is important to understand the pressure distribution on the body surface during the train crossing to mitigate the impact or even harm of the pressure wave. Figures 17 and 18 present the pressure distribution on the top and side of the train when \( t = 0.1656 \) s and \( t = 0.20016 \) s, respectively. It can be seen that when passing through the head of the train, a high-pressure area is formed at the corresponding position on the side of the train, followed by a low-pressure area. The high-pressure area and the low-pressure area move forward at the same speed as the train passing through. Thus, the pressure fluctuation caused by the train crossing can be measured at every point on the lateral side of the train.

Figure 17. Pressure variation on train surface during crossing at \( t = 0.1656 \) s: (a) top view; (b) left view.
5. Conclusions

In this paper, the aerodynamic characteristics of a high-speed maglev train running at speed 500 km/h and the pressure wave during train crossing on the open-air line are numerically modeled and analyzed. The aerodynamic load is then provided for calculation of the vehicle’s structural dynamics. The modeling procedure can be summarized as follows:

1. By investigating the turbulence model and the flow field control equation corresponding to the air flow in the maglev train, the calculation model of the pressure wave in the maglev train is given in this paper.

2. The governing equations are discretized by the numerical method, with aerodynamic loads, the source terms, and boundary conditions modeled in detail. On this basis, the numerical solution of the flow field of vehicle crossing is obtained by PISO algorithm.

3. The corresponding model and its partition are established in the simulation software. Considering the relative motion between the two trains makes the boundary of the calculation area change constantly, it is then necessary to use the moved mesh technology to characterize the changing boundary of the computational area due to the relative motion.

Afterwards, based on the numerical model of aerodynamic loads, the amplitude of the pressure wave, the flow distribution around the vehicle, and the pressure distribution on the vehicle surface are calculated, respectively. According to the calculation results, the transient pressure changes at each point on the intersection side of the train surface, where P3 is the most impacted point by the pressure. Ultimately, the calculation of the pressure wave during train crossing in this paper reveals the complex dynamic interaction between two trains and can be used as input for the operating safety analysis of the railway. In practical applications, the air pressure fluctuation is unavoidable, therefore it is of high practical necessity to study the strength and vibration problems to which the pressure variation may bring in.

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