Simulating the flow around a train passing through a tornado

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Abstract. A flow simulation was developed to understand the flow surrounding a train that was passing through a tornado and the resulting aerodynamic forces acting on the vehicle. Unsteady Reynolds averaged Navier–Stokes equations were solved to reproduce a previously-conducted laboratory experiment, in which a model train runs through a stationary tornado-like swirling flow. The simulation reproduced the unsteady aerodynamic forces acting on the train reported in the experiment. Furthermore, the computation successfully revealed how the flow field changes as a train passes through a tornado-like swirling flow.

Keywords: Tornado, Train, Flow simulation, Aerodynamic force

1. Introduction

A tornado is a violent natural disaster that can cause damage and casualties. Several trains have been derailed by tornadoes in Japan, such as the Touzai line in 1978 [1]. In 2005, a train on the JR Uetsu line was overturned by a gust of wind that was presumably generated by a tornado or downburst [2]. A train on the JR Nippo line was overturned by a tornado in 2006 [3]. The frequency of tornadoes in Japan may increase significantly in the future due to the effects of global warming [4], increasing the possibility of a train encountering a tornado; hence, countermeasures against tornadoes are becoming more important for railway safety.

Improving railway safety against tornadoes requires predicting their occurrence and assessing the risk of a train overturning. Research has begun involving the use of Doppler radar to observe and predict gusts, including tornadoes along railway lines; however, it is still dif-
difficult to reliably predict the occurrence of tornadoes [5]. To evaluate the risk of a train overturning, it is essential to precisely determine the aerodynamic forces acting on the vehicle. Much research has been conducted on the stability of trains under strong winds and the characteristics of the aerodynamic forces acting on the trains have been elucidated [6]. However, the literature has only considered winds from one direction, with limited studies investigating winds that constantly change direction with respect to a moving train, e.g., tornadoes.

Suzuki et al. developed a laboratory experiment with a moving model rig and a tornado generator to measure the aerodynamic forces acting on a train traveling through a stationary tornado-like swirling flow [7]. They validated the flow field produced by their tornado generator using full-scale data. Their results demonstrated that the aerodynamic forces changed relative to the position of the train. However, their experiment did not reveal the flow field that generates these aerodynamic forces. Baker et al. proposed a methodology for estimating the risk of a tornado overturning a train [8]. Using a model of tornado wind fields, they demonstrated how to calculate the aerodynamic forces on a moving train and the resulting risk of the train overturning. However, their method is provisional and has not been verified.

In laboratory experiments, the size and strength of tornadoes that can be reproduced are limited. Moreover, it is difficult to reveal the entire unsteady flow field around a train. Numerical simulations can be expected to overcome some of these limitations and provide an overall picture of the unsteady flow field. Computational studies have been conducted to reproduce the flow of the laboratory tornado generators, and investigate the characteristics of tornadic flow fields and their effect on civil engineering structures [9,10,11]. Recently, Xu et al. simulated a flow field around a train passing through a tornado-like vortex to obtain the aerodynamic loads [12]. They then performed a modal analysis on a train dynamic system to determine the dynamic response of the vehicle. However, their flow simulation was not validated by experimental results.

This study develops a numerical reproduction of a laboratory experiment through the solution of unsteady Reynolds averaged Navier-Stokes equations. A tornado-like swirling flow was simulated with reference to the laboratory tornado generator used in Suzuki et al.’s experiment, with the running train modeled by a moving mesh. The computational results were compared with the experimental data to validate the simulation and the unsteady flow field around the moving train was then examined.

2. Method

2.1. Governing equations and turbulence model

Although large eddy simulation has been widely used for practical applications, the flow in this study was calculated using the unsteady Reynolds averaged Navier–Stokes equations, with a turbulence model; a large eddy simulation reproducing a tornado-like swirling flow.
and moving train would be too computationally costly. The continuity and momentum equations are given by:

\[
\frac{\partial u_i}{\partial x_i} = 0, \quad (1)
\]

\[
\frac{\partial u_i}{\partial t} + U_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial}{\partial x_j} (\tau_{ij} - \rho \bar{u}_i \bar{u}_j), \quad (2)
\]

where \( x_i \) is Cartesian coordinates (\( i = 1, 2, 3 \)), \( t \) is time, \( U_i \) is the mean velocity vector, \( \rho \) is air density, \( P \) is mean pressure, and \( u_i \) is the velocity vector; the overbar indicates a time-averaged quantity. \( \tau_{ij} \) is the mean viscous stress tensor:

\[
\tau_{ij} = 2 \mu S_{ij}, \quad (3)
\]

here, \( \mu \) is viscosity and \( S_{ij} \) is the mean strain rate tensor, given by:

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \quad (4)
\]

The last term in equation (2) is known as the Reynolds stress tensor, expressed by Boussinesq’s hypothesis:

\[
-\rho \bar{u}_i \bar{u}_j = 2 \nu_t S_{ij} - \frac{2}{3} \rho k \delta_{ij}, \quad (5)
\]

where \( \nu_t \) is the kinematic turbulent viscosity, \( k \) is the turbulent kinetic energy, and \( \delta_{ij} \) is the Kronecker delta. The \( \zeta - f \) model [13] was employed for the turbulent viscosity:

\[
\nu_t = C_\mu \zeta k \tau, \quad (6)
\]

where \( C_\mu \) is a coefficient, \( \zeta \) is the velocity scale ratio obtained from the following:

\[
\frac{d \zeta}{dt} = f - \frac{\zeta}{k} P_k + \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_\xi} \right) \frac{\partial \zeta}{\partial x_j} \right]. \quad (7)
\]

Here, \( \nu \) is the kinematic viscosity, \( \sigma_\xi \) is a coefficient, and the time scale, \( \tau \), and production of \( k \), \( P_k \), are described as:

\[
\tau = \max \left[ \min \left( \frac{k}{\varepsilon' \sqrt{\nu \sigma_k}}, C_\tau \frac{\nu}{\varepsilon} \right)^{1/2}, \right], \quad (8)
\]

\[
P_k = -\bar{u}_i \bar{u}_j \frac{\partial u_i}{\partial x_j}, \quad (9)
\]

where \( C_\tau \) is a coefficient. The turbulent kinetic energy \( k \) and dissipation \( \varepsilon \) are expressed by the following:

\[
\frac{dk}{dt} = P_k - \varepsilon + \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right], \quad (10)
\]

\[
\frac{d\varepsilon}{dt} = \frac{(C_{\varepsilon 1} P_k - C_{\varepsilon 2} \varepsilon)}{\tau} + \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right], \quad (11)
\]

where \( \sigma_k, \ \sigma_\varepsilon, C_{\varepsilon 1} \) and \( C_{\varepsilon 2} \) are coefficients. The elliptic relaxation function \( f \) is formulated as follows:
\[ L^2 \nabla^2 f - f = \frac{1}{\tau} \left( c_1 + C_2 \frac{P_k}{\varepsilon} \right) \left( \zeta - \frac{2}{3} \right), \]  
(12)

where \( c_1 \) and \( C_2 \) are coefficients. The length scale \( L \) was obtained from:

\[ L = C_L \text{max} \left( \min \left( \frac{k^{3/2}}{\varepsilon}, \frac{k^{1/2}}{\sqrt{6}C_p \| \boldsymbol{S} \|} \right), C_\eta \left( \frac{\nu^3}{\varepsilon} \right)^{1/4} \right), \]  
(13)

where \( C_L \) and \( C_\eta \) are coefficients. The coefficient values for these equations, which are based on an empirical study [13], are shown in Table 1. The \( \zeta - f \) model is very robust and more accurate than the simpler two equation eddy viscosity models. Krajnović et al. used this turbulence model to simulate flows around two trains passing by each other and around a train exiting a tunnel with a gust wind, and succeeded in obtaining the flow field with similar accuracy as a detached eddy simulation [14].

The momentum equations were discretized using a second-order upwind scheme. The equations (7), (10), and (11) were discretized using a first-order upwind scheme. The SIMPLE algorithm [15] was employed for velocity–pressure coupling and the simulation conducted using the commercial finite volume solver AVL FIRE. The time step was set to 0.001 seconds.

| \( C_\mu \)  | \( C_{c_1} \)  | \( C_{c_2} \)  | \( c_1 \)  | \( C_2 \)  | \( \sigma_k \)  | \( \sigma_\varepsilon \)  | \( \sigma_\zeta \)  | \( C_\tau \)  | \( C_L \)  | \( C_\eta \) |
|-------------|-------------|-------------|--------|-------|--------|--------|--------|-------|-------|-------|
| 0.22        | 1.4(1+0.012/\( \zeta \)) | 1.9         | 0.4    | 0.65  | 1.0    | 1.3    | 1.2    | 6.0   | 0.36  | 85    |

### 2.2. Computational mesh and boundary conditions.

Figure 1 shows the computational mesh. The simulation was performed by combining two computational domains: in the first, a stationary tornado-like swirling flow occurs and in the second, the train runs (displayed in brown). The number of cells was 5.4 million. A homogeneous Neumann boundary condition was employed at the sides and top boundaries in the second region. A no-slip wall boundary condition was applied to the train surface and the ground.

To simulate a tornado-like swirling flow, the geometry and boundary conditions of the area where the swirling flow occurs were selected based on the experimental settings of Suzuki et al. [7]. Their tornado generator included a fan, inner and outer ducts, and guide vanes (Fig. 2). The fan at the center generated an updraft that passed through the equally spaced guide vanes. The guide vanes were attached at an angle of 50°, generating the flow’s rotational component. The flow then descended through the outer duct. This cycle produced a tornado-like swirling flow on the stage, with a maximum tangential velocity magnitude of 8 m/s and a core radius of 100 mm.
In the present computation, the tornado-like swirling flow was modeled only in the area between the stage and the tornado generator in order to save computational memory and time (Fig. 3). Its dimensions are the same as those in the experiment. There are inlet and outlet boundaries at the top of the computational domain, corresponding to the outer and inner ducts of the experimental apparatus, respectively. The tangential velocity, $V_t$, and normal velocity, $V_n$, were set at the inlet boundary (displayed in purple in Fig. 3). Since no experimental data on the inlet velocity was reported, $V_t$ was determined using the Rankine vortex model. The Rankine vortex model is the simplest two-dimensional tornado model and has been widely used in tornado research [16]. In the Rankine model, the tangential velocity distribution in the inner region is proportional to the distance from the center, whereas the tangential velocity distribution in the outer region is inversely proportional to the distance from the center:
\[ V_t(x) = \begin{cases} \frac{V_{\text{max}} |x|}{R} & |x| < R, \\ \frac{V_{\text{max}}}{|x|} & |x| > R, \end{cases} \] (14)

where \( x \) is the distance from the vortex center, \( V_{\text{max}} \) is the maximum tangential velocity magnitude, and \( R \) is the core radius. Here, the values of the maximum tangential velocity magnitude and the core radius of the swirling flow generated at the stage observed in the experiment, i.e., \( V_{\text{max}} = 8 \) m/s and \( R = 100 \) mm, were used. The normal velocity, \( V_n \), was tentatively determined using a guide-vane angle of 50 °: \( V_n = V_t \cot 50 \) °. A homogeneous Neumann boundary condition was employed at the outlet (displayed in cyan in Fig. 3) and side boundaries. A no-slip wall boundary condition was applied at the top wall (displayed in yellow) and stage (displayed in gray) boundaries.

Figure 3: Laboratory tornado generator and corresponding computational domain

Figure 4: Mesh around train (unit: mm)

Figure 4 shows the mesh around the train. The model train had a single rectangular body that was 1/40 of the size of a full-scale car, with dimensions of 492 mm \( \times \) 74 mm \( \times \) 70 mm. These values were consistent with the experimental conditions. Although boxes for mounting wheels (displayed in red) were reproduced, the wheels themselves were omitted from the computational model. Rails on the stage were also omitted. The surface mesh size was 0.3 to 5 mm and the height of the cells on the train surface was 0.015 mm. The model train com-
prised 25 thousand cells. The model train ran through the swirling flow at a speed of 4 m/s, the same as the experiment. A moving mesh with a mesh-deformation formula [15] was used to represent the space around the train. This mesh was divided into two parts: deforming and non-deforming cells (Fig. 5). The non-deforming cells contained the train. The deforming cells are located in front of and behind the non-deforming cells. Initially, the length of the front deforming cells was 3,000 mm, and rear one was 600 mm. The length of the non-deformed cells was 4,400 mm and the train was located in the middle of it. Thus, initially, the center of the train was located 1,200 mm away from the center of the swirling flow domain. As the train moves, the front deforming cells are compressed and the rear deforming cells are stretched. This moving mesh slides through the surrounding stationary mesh as the train moves. The moving mesh and the stationary mesh are connected through a common surface at the boundary between them, so called arbitrary interface. Flow field information, such as velocity and pressure, is exchanged through this interface.

![Figure 5: Moving mesh to model a running train](image)

### 3. Results and discussion

#### 3.1. Velocity distribution of tornado-like swirling flow

Before simulating the model train passing through the tornado, the simulated tornado-like swirling flow field was examined. The results demonstrate that the maximum tangential velocity magnitude, $V_{\text{max}}$, was 6 m/s, 25% less than the experimental value of 8 m/s. As there was no experimental data available at the inlet boundary, this is predominantly due to the inlet velocity, estimated from the Rankine vortex model using the maximum tangential velocity magnitude, and the core radius of the swirling flow generated on the stage. It is expected that the inlet velocity will be measured experimentally. However, when the velocity is normalized by the maximum tangential velocity magnitude, $V_{\text{max}}$, the velocity distributions of the computational and experimental results are almost the same (Fig. 6). The Reynolds number, based on the maximum tangential velocity magnitude and train width, was $2.8 \times 10^4$. This is slightly lower than the experimental Reynolds number of $3.8 \times 10^4$. However, the shape of the vehicle is rectangular and the Reynolds number dependence of the flow field does not seem to be significant within this range. The difference of the maximum tangential velocity magnitude between the experiment and simulation also results in differences in the wind direction relative to the train, so called yaw angle. The yaw angle at the point where the maxi-
mum tangential velocity occurs is 63 degrees in the experiment and 56 degrees in the simulation, and the difference is 11 %. Suzuki et al. conducted a wind tunnel test with a running single-car train, which has a rectangular shape similar to our model, to measure the side force [17]. Their result showed that the side force did not change significantly at the above yaw angle range. Therefore, the difference in the yaw angle does not seem to have much of an effect on aerodynamic forces.

![Figure 6: Tangential velocity distribution at half the height of the train](image)

3.2. Aerodynamic forces acting on the train

Calculation of the side forces, lift forces, and rolling moments are required to assess the risk of train overturning [18]. Their coefficients, $C_S$, $C_L$, and $C_M$ are defined as follows [14]:

$$C_S = \frac{F_S}{\frac{1}{2} \rho V_{\text{max}}^2 A}, \quad (15)$$

$$C_L = \frac{F_L}{\frac{1}{2} \rho V_{\text{max}}^2 A}, \quad (16)$$

$$C_M = \frac{M_R}{\frac{1}{2} \rho V_{\text{max}}^2 Ah}, \quad (17)$$

where $F_S$ is the side force, $F_L$ is the lift force, $M_R$ is the rolling moment, $A$ is the side area of the train (0.03444 m$^2$), and $h$ is the body height (0.07 m). In calculating the aerodynamic forces, the forces acting on the box under the body, which corresponds to the real train bogie, were excluded. Figure 7 defines the directions of the aerodynamic forces and moment acting on the train.

Figure 8 shows the time history of the simulated side force coefficient, plotted alongside the experimental results. The horizontal axis represents the position of the train’s center, $x_c$. The train runs from negative to positive $x_c$. The vortex center of the swirling flow is located at $x_c = 0$. As the train passes through the swirling flow field, the side force changes from
positive to negative, before $x_c = 0$. Although the simulated peak values are slightly smaller than the experimental ones, the present simulation effectively reproduces the experimental result.

![Diagram](image)

**Figure 7**: Definition of side and lift forces and rolling moment acting on the train and rotational direction of the swirling flow

![Graph](image)

**Figure 8**: Time history of the side force acting on the train

The calculated lift force deviated from the experimental results (Fig. 9). Up until $x_c = -300$ mm, the calculated lift force increases similarly to the experimental result. However, the calculated result subsequently gradually decreases, while the experimental result continues to increase until the vortex center and subsequently decreases. This discrepancy between the present and experimental results may be due to omitting the wheels and rails from the simulation. In the experiment, the height of the rails was about 20% of the distance from the bottom of the train to the ground, and the diameter of the wheels was close to that distance in length. Therefore, when the train reaches the vortex where the crosswind are stronger, the wheels and rails can have a significant effect on the flow under the train. Figure 10 shows the pressure distribution on the roof and the bottom of the train at the center section ($y = 0$) when the train reaches the vortex center ($x_c = 0$). The vertical axis indicates the pressure coefficient, $C_p$, normalized by the maximum tangential velocity magnitude, $V_{max}$. Note that pressure on the bottom of the vehicle are not shown at $x = -201$ to $-131$ mm and $x = 131$ to 201 mm because there are the boxes for mounting the wheels. Pressure on the roof of the train does not agree between the experiment and the simulation near the head of the train, but thereafter they both are in close agreement. On the while, after the front box ($x < 131$ mm), the experimental results are
higher than the calculated pressure at the bottom. This could be due to the wheels and rails blocking the airflow and reducing the flow speed. In the simulation, the absence of the wheels and rails may have resulted in a faster flow, reducing the pressure under the train and decreasing the lift force.

![Figure 9: Time history of the lift force acting on the train](image)

![Figure 10: Pressure distribution on the roof and the bottom of the train at the center section (y = 0) when the train reaches the vortex center (x_c = 0)](image)

Figure 11 shows the time history of the rolling moment coefficient. No experimental data has been reported for the rolling moment. As the train passes through the swirling flow field, the rolling moment changes from positive to negative at x_c ≈ −220 mm. Since there are no experimental results for the swirling flow, the simulated rolling moment coefficient is compared to the results of a wind tunnel test with a unidirectional wind [19]. The comparison is made using the results of the experiment under bridge and embankment conditions for the leading car of the 485 series train, which has a less rounded roof and is relatively close in shape to our model. The ratio of the rolling moment coefficient to the side force coefficient, C_M/C_S, is compared, since the reference velocity used to calculate the aerodynamic coefficients is different between the experiment and the calculation, i.e., the reference velocity for
the experiment is the wind speed for the train, while the reference velocity for this study is the maximum tangential velocity magnitude. While the range of $C_M/C_S$ calculated using the experimental results in the reference [19] is 0.08 to 0.14 depending on the bridge and embankment structures and wind direction, the computational one is 0.09 to 0.16 for $x = -400 \sim -300$ and $x = 300 \sim 400$, where $C_M$ and $C_S$ are larger. Although a simple comparison is not possible due to the difference of the ground structures between the experiment and the simulation, the range of $C_M/C_S$ values for the two are almost the same.

Figure 11: Time history of the rolling moment acting on the train

3.3. Flow field around the train

Next, the flow field was visualized using an iso-surface of the second invariant of the velocity gradient tensor, $Q$, and the pressure distribution to demonstrate the changing flow field as the model train passes through the swirling flow.

Figure 12 illustrates the flow field before the train reaches the vortex center. The center of the train is located at $x_c = -640$ mm. The iso-surface of the second invariant of the velocity gradient tensor ($Q = 1300$) is colored, with the flow velocity normalized by $V_{max}$. The pressure distribution is on the horizontal plane at half the height of the train. The flow around the train has already been affected by the tornado-like swirling flow at this point. The pressure on the right side of the train in the running direction increases and the pressure on the opposite side decreases. (Hereinafter, the left and right sides of the train in the running direction are simply referred to as the “left side” and “right side”.) Vortices caused by flow separation from the right side edge also appear. However, the vortex core of the swirling flow is not significantly influenced by the train.

Figure 13 illustrates the flow field when the head of the train reaches the vortex center. The center of the train is located at $x_c = -250$ mm. Vortices caused by flow separation around the train are more distinct; the pressure drops on the left side of the train, causing the bottom of the vortex core to move toward the left side of the train, bending the axis of the
vortex core. The low pressure on the left side of the train results in a large positive side force, as shown in Fig. 8.

![Flow field before the train reaches the vortex center](image1)

(a) Iso-surface of the second invariant of the velocity gradient

(b) Pressure distribution on the horizontal plane at half the height of the train

**Figure 12:** Flow field before the train reaches the vortex center

![Flow field when the head of the train reaches the vortex center](image2)

(a) Iso-surface of the second invariant of the velocity gradient

(b) Pressure distribution on the horizontal plane at half the height of the train

**Figure 13:** Flow field when the head of the train reaches the vortex center

![Flow field when the center of the train passes through the vortex center](image3)

(a) Iso-surface of the second invariant of the velocity gradient

(b) Pressure distribution on the horizontal plane at half the height of the train

**Figure 14:** Flow field when the center of the train passes through the vortex center

When the center of the train passes through the vortex center \( (x_c = 0) \), the vortex core collapses and the flow field becomes complex (Fig. 14); at this moment, the flow comes from the left side on the first half of the train and the right side on the second half of the train. The vortices around the train generated by these flows interfere with the vortex of the swirling...
flow in complicated ways. The front part of the train has a low-pressure region on the right side and a high-pressure region on the left side, whereas the rear part of the train has a high-pressure region on the right side and a low-pressure region on the left side; these high and low pressures almost balance each other, producing a negligible resultant lateral force, as shown in Fig. 8.

Figure 15 illustrates the flow field after the train has passed through the vortex center \( (x_c = 560 \text{ mm}) \). The vortices generated from the train as it passes through the vortex core remain behind the train and interfere with the swirling flow. Although the iso-surface of \( Q \) remains complicated, the vortex core of the tornado-like swirling flow begins to reform. The swirling flow creates low pressure on the right side of the train and generates high pressure on the left side of the train.

![Iso-surface of the second invariant of the velocity gradient](a)

![Pressure distribution on the horizontal plane at half the height of the train](b)

Figure 15: Flow field after the train has passed through the vortex center

4. Concluding remarks

A computational simulation was developed for the flow around a train passing through a stationary tornado-like swirling flow, using unsteady Reynolds averaged Navier–Stokes equations with the \( \zeta - f \) model. The computational results were compared with experimental data. The time histories of the aerodynamic forces showed relatively good agreement with the experimental results. The calculation was able to realistically reproduce a very complex unsteady flow around the train. While it is too early to discuss the risk of the train overturning induced by real tornadoes, the present study demonstrates that simulation can be a useful tool for understanding the flow field around the train passing through a tornado-like swirling flow. To improve the simulation, further work is required to precisely reproduce the swirling flow and consider the effects of the wheels and rails. If computational resources allow, large eddy simulation will be a better option for obtaining a more accurate flow field.

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