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Aerodynamic forces on a railway vehicle in a tornado: moving model tests and estimation

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SUMMARY
To investigate the aerodynamic forces acting upon railway vehicles encountering tornadoes, a moving model test was conducted using a tornado simulator linked to a moving model rig. This enabled quantitative evaluation of the unsteady aerodynamic forces exerted. Furthermore, based on the yaw angle characteristics obtained from steady-state wind tunnel tests, a method was developed to predict aerodynamic forces during vehicle motion. The predicted results showed good agreement with experimental data, demonstrating the validity of the proposed method.

Keywords: Tornado, Train, Aerodynamic force

1. INTRODUCTION

Tornadoes are characterized by their extremely small spatial scale and brief duration, making them exceptionally difficult to predict. Despite being transient phenomena, they cause devastating human and material damage when they occur. In Japan, the maximum intensity of tornadoes is limited to approximately JEF3 (Japanese Enhanced Fujita Scale), smaller in scale than the giant tornadoes observed in the United States. Nevertheless, multiple incidents of railway vehicle derailments and overturns have been recorded domestically.

Understanding the aerodynamic forces acting on vehicles during a tornado passage is essential for developing effective countermeasures. Traditionally, extensive research has focused on wind tunnel experiments examining aerodynamic forces under steady crosswinds from a single direction. However, when a moving vehicle encounters a vortex flow such as a tornado, both wind speed and direction fluctuate transiently. Due to the inherent difficulty of experimentally reproducing such unsteady phenomena, sufficient understanding has yet to be established.

The authors have previously conducted aerodynamic force measurements on vehicles travelling through vortex flows by integrating a tornado vortex generator into a moving model test apparatus (Inuzuka et al., 2022). Meanwhile, Baker et al. proposed a set of similarity parameters (geometric, dynamic, kinematic) and their corresponding ranges to ensure consistency between real tornadoes and simulation apparatus (Baker and Sterling, 2019). Verification of these parameters on the authors' conventional apparatus revealed that only some geometric requirements were met. Consequently, a new, larger-scale tornado simulator capable of addressing a broader set of requirements was constructed (Suzuki and Okura, 2025). Whilst dynamic and kinematic similarity remain unachieved, all geometric parameters are now successfully met. This paper reports experimental results using this new apparatus and proposes a method for estimating moving model results based on aerodynamic characteristics derived from conventional wind tunnel testing.

2. EXPERIMENTAL METHOD

The experimental apparatus consists of a tornado vortex generator (TVG) and a moving model rig (MMR), as shown in Fig. 1. The TVG is designed as an Iowa State University-type simulator (Haan et al., 2008), comprising an internal duct, an external duct, a motor, a fan, guide vanes, and a stage. An updraft is generated by a fan installed within the internal duct, after which the airflow is directed through the guide vane at the top of the apparatus. The guide vanes are set at an angle relative to the radial direction, imparting a tangential velocity component to the flow. This induces a spiralling downward flow within the external duct, generating a tornado-like vortex on the stage. Although the guide vane angle is adjustable, it was fixed at 70 degrees for this study. Under these conditions, a two-cell vortex with a maximum tangential velocity of 11.6 m/s and a core radius of 140 mm is formed.

The MMR comprises a linear track, a launcher, and a braking system. The track is positioned to ensure the model vehicle passes through the center of the tornado vortex generator. The model is propelled by a launcher utilizing rubber elasticity, imparting an initial velocity within the range of 3.3 to 8.3 m/s. After traversing the vortex, the vehicle is safely decelerated by a braking unit employing sponges to apply lateral pressure.

The experiment employed a 1/30 scale single-vehicle railway model (Fig. 2). This model features 96 pressure ports distributed across its entire top, bottom, and side surfaces. The vehicle is equipped with an on-board measurement system comprising pressure sensors, a data logger, and a battery. Differential pressure was measured between symmetrically positioned ports on the top/bottom and left/right sides. To ensure statistical reliability, ten experiments were conducted under each condition, with results ensemble-averaged. Based on these pressure measurements, lee rail rolling moment was calculated.

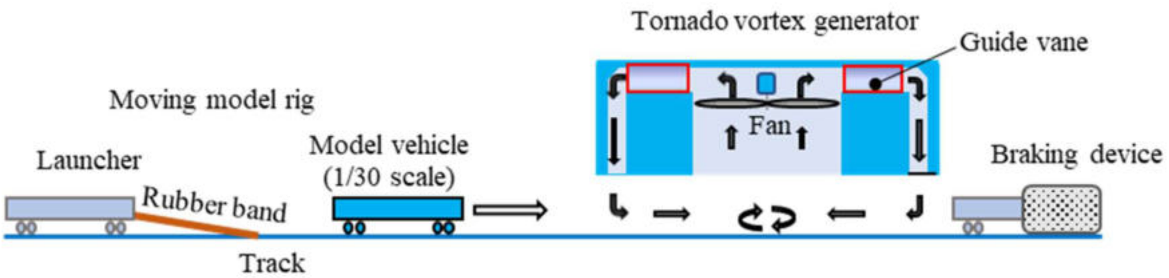

Figure 1. Schematic of the experimental setup comprising the TVG and MMR

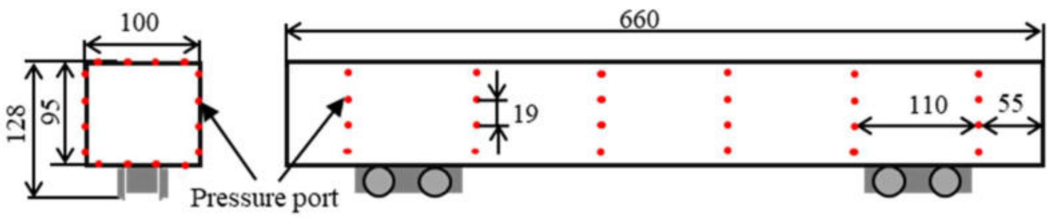

Figure 2. Details of the 1/30 scale model vehicle and pressure port layout

3. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 illustrates an example of the variation in the lee rail rolling moment coefficient C_{RL} at a vehicle speed of 3.3 m/s travelling through the vortex. The horizontal axis represents the distance from the vortex center to the vehicle center, normalized by the core radius R, with the vehicle moving from the negative to the positive side.

The moment coefficient reaches a local maximum around $x/R \approx -2.2$ before decreasing, then shows a minimum around $x/R \approx 1.5$ before exhibiting a recovery trend. Notably, the amplitude of the minimum peak is 1.3 times that of the maximum peak. This amplitude difference between the two peaks suggests that the combination of the vehicle's translational velocity and the vortex's radial velocity amplifies the risk of overturning on the exit side compared to the entry side.

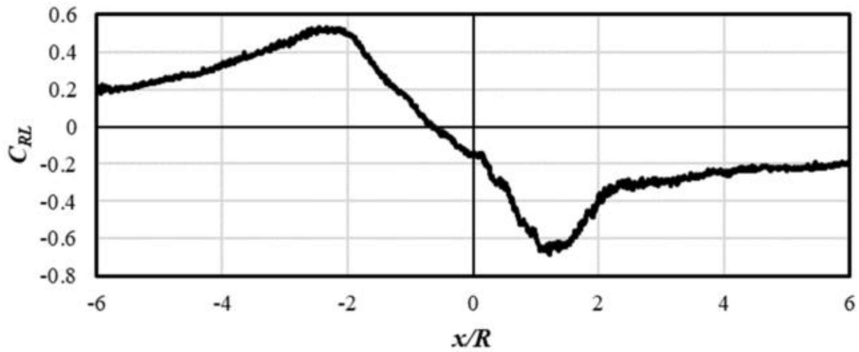

Figure 3. Variation of the lee rail rolling moment coefficient during vortex passage

4. AERODYNAMIC FORCE ESTIMATION METHOD

To estimate the aerodynamic forces acting on a vehicle travelling through a vortex, a quasi-steady analysis method based on steady-state aerodynamic characteristics obtained from wind tunnel tests is proposed. The estimation procedure consists of the following two stages:

1) Calculation of local flow conditions

First, the velocity distribution along the vehicle's path is determined from the tangential and radial velocity components of the flow field generated by the vortex generator. By calculating the resultant vector of the local flow velocity and the vehicle's translational velocity, the local wind speed and wind direction angle (yaw angle) are determined for each discretized longitudinal section of the vehicle body.

2) Estimation of total aerodynamic force

Next, aerodynamic forces acting on each longitudinal section are calculated based on aerodynamic characteristics (coefficients) as functions of wind direction angle, obtained from conventional wind tunnel tests. Subsequently, the total aerodynamic force acting on the entire vehicle is estimated by integrating these local forces over the full vehicle length.

5. ESTIMATION RESULTS AND DISCUSSION

Figure 4 compares the lee rail rolling moment coefficient C_{RL} estimated using the proposed quasi-steady method with results obtained from the moving model experiment. The estimated values show good agreement with the experimental data for the initial peak located near $x/R \approx -2.0$. However, the magnitude of the second peak occurring after the vehicle passes through the vortex center is somehow overestimated by the proposed method. This discrepancy is thought to stem from changes in the vortex structure caused by the presence and passage of the train itself. While quasi-steady estimation assumes the vortex field remains undisturbed, in actual experiments, the moving train may distort the vortices, potentially reducing the aerodynamic loads compared to idealized estimates.

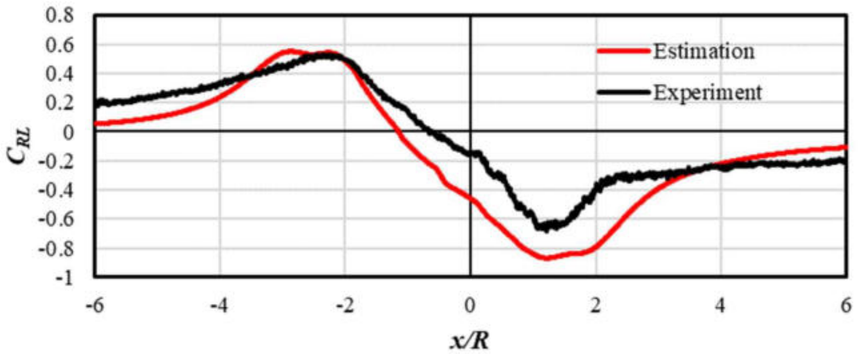

Figure 4. Comparison of C_{RL} between experimental data and quasi-steady estimation

6. CONCLUDING REMARKS

This study investigated the aerodynamic forces acting on railway vehicles travelling through a tornado-like vortex using an improved simulation apparatus. Moving model experiments revealed that the maximum aerodynamic load occurring after the vehicle passed through the vortex center was more pronounced than the initial peak observed at the vortex entry point. The proposed quasi-steady estimation method accurately predicted this initial peak but tended to overestimate the load after the vehicle passed through the vortex center. This discrepancy between estimated and experimental values suggests that the vortex structure is altered by the presence and motion of the vehicle.

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