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The calculation of train stability in tornado winds

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ABSTRACT

This paper presents a novel methodology for calculating the risk of a train overturning accident due to tornadoes. It applies a recently developed model of tornado wind fields to the complex case of a moving vehicle passing at different distances from the centre of a moving tornado. The wind speed and direction relative to the vehicle can thus be calculated. Through the use of quasi-steady force coefficients and an allowance for dynamic effects, this allows aerodynamic forces and moment time histories on the vehicle to be calculated. A parametric investigation of the effects of tornado size, strength and translational speed, and vehicle speed is then presented. A stochastic analysis methodology is then set out that allows the probability of a train overturning accident to be determined for specified statistical distributions of tornado parameters and vehicle operational parameters. It is shown that the reduction of train speed at times when tornadoes are expected would lead to a very significant reduction in accident risk. Finally the requirements for further work to refine the methodology are set out – specifically the need for statistical distributions of tornado parameters and for force and moment coefficients obtained from proper physical or numerical simulations of tornado characteristics.

1. Introduction

In recent years the wind engineering community has given increasing attention to the effects of tornadoes, and there have been a number of campaigns to attempt to measure tornado parameters in the field, e.g. [Bluestein et al., 2003: Lee and Samaras, 2004; Pietrycha et al., 2004]; a number of tornado vortex generators have been built and tested, [Haan et al., 2008; Mishra et al., 2008; Refan et al., 2014; Refan and Hangan, 2016]; and various CFD techniques have been applied to simulate tornado properties, [Ishihara et al., 2011]. In a recent paper, the authors have developed a novel analytical model of tornado wind fields and applied this to a study of the flight of wind borne debris in tornadoes (Baker and Sterling, 2017). This analytical model is based on a solution of the high Reynolds number Navier Stokes equations and gives simple analytical expressions for the three velocity components, pressure and buoyancy flux for a range of tornado types. In a further paper [Baker and Sterling 2018] they developed this work further and produced an outline of a methodology to calculate the tornado loads on stationary structures. In the current paper, the methodology is applied to the case of a train passing through a tornado. There is some evidence that recent wind induced accidents in Japan have been caused by tornado winds [Matsui et al., 2009, Suzuki et al., 2016a,b]. Takeuchi and his co-workers [Takeuchi et al., 2008; Takeuchi and Maeda 2010] have looked at the problem, with particular regard to the dynamic overshoots of wind induced forces that might be expected to occur in the rapidly varying wind speeds observed by trains as they pass through tornadoes, and Suzuki et al. (2016a,b) have reported some preliminary model tests to measure tornado induced forces on train models as they pass through a tornado vortex generator. Japan Railways East have developed a sophisticated tornado early warning system, that uses data from a series of onshore meteorological stations and an array of Doppler Radar stations to detect tornadoes as they form over the sea, and to predict their strength and their path. If it looks as if the path will cross a railway line, appropriate operational control measures are put in place.

Section 2 sets out the wind model that will be used, based on the work of Baker and Sterling (2017) (2018), as applied to a vehicle moving through a tornado. Section 3 describes the calculation of train rolling moments for trains passing through tornadoes; investigates the effect of dynamic overshoots; and carries out a parametric investigation to understand the effect of the controlling parameters on the rolling moment time histories. Section 4 then sets out a framework for a risk analysis procedure and carries out some calculations to illustrate the methodology. Finally some concluding remarks are made in section 5.

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2. Tornado wind field

2.1. Wind field model

The tornado wind model developed by the authors in Baker and Sterling (2017) begins with the following form for radial inflow velocity U.

$$\overline{U} = \frac{-4\overline{r}\overline{z}}{(1+\overline{r}^2)(1+\overline{z}^2)} \tag{1}$$

where $\overline{U} = U/U_r$, $\overline{r} = r/r_r$ and $\overline{z} = z/z_r$ and r is the distance from the vortex centre and z is the distance above the ground, U_r is the reference radial velocity and r_r and z_r are reference values of radius and height. The radial velocity is assumed to have a maximum value (U_r) at the reference values of radius and height, which seems physically realistic and empirically models the boundary layer beneath the tornado. The reference height effectively defines the near ground tornado boundary layer where the velocity is slowed down by ground friction, and Baker and Sterling (2017) shows this is of the order of 5–10 m. This formulation is the simplest of those outlined in that paper and represents a simple single cell vortex with a radial inflow and an upflow around the tornado centre. The use of the continuity and circumferential momentum equation then gives the following expression for circumferential velocity V

$$\overline{V} = \frac{2.88S\overline{r}[\ln(1+\overline{z}^2)]}{(1+\overline{r}^2)} \tag{2}$$

where $\overline{V} = V/U_r$ and S is a swirl ratio ($=V_{max}/U_r$). This definition of the swirl ratio is different from that usually adopted for tornado vortex generators, and is based on specific tornado properties rather than the vortex generator geometric parameters. It should be noted that the absolute values of the swirl ratio as defined in this way are around three times larger than those obtained from the conventional definition. Equivalent expressions for the vertical velocity and pressure can also be derived, but they will not be used in the analysis that follows where it is assumed that the only forces on vehicles are the inertial forces due to the horizontal wind speed, and that any pressure changes as the vehicle passes through the tornado acts equally all round the vehicle. The reason for ignoring the vertical velocity component is that the force coefficients that will be used to characterise the train aerodynamic forces have been obtained from standard wind tunnel tests with no vertical velocity component. In this sense the methodology applied here is a simplified version of that adopted in Baker and Sterling (2018) where the loading on simple stationary building structures was calculated, caused by horizontal inertial forces and the differential pressure loading between the inside and outside of the structure. We further make the assumption that in what follows $\overline{z} = 1$, i.e. the velocity of concern is at the top of the internal tornado boundary layer. This leads to simple expressions for the dimensionless radial and circumferential velocities that will be used in what follows.

$$\overline{U} = \frac{-2\overline{r}}{(1+\overline{r}^2)} \tag{3}$$

$$\overline{V} = \frac{2S\overline{r}}{(1+\overline{r}^2)} \tag{4}$$

Note that this formulation is for the one-cell vortex model outlined in Baker and Sterling (2017). They also present a two-cell version of this model, which inevitably is somewhat more complex algebraically. Nonetheless many tornadoes with higher swirl ratios are known to be of the two-cell type and this more complex version of the wind model could be utilised if required. For the sake of simplicity however, this paper uses only the one-cell model.

2.2. Wind field relative to a moving vehicle

We now consider the wind field relative to a moving train. Here the situation is more complex than the stationary building case considered in Baker and Sterling (2018), where both tornado and vehicle are moving. The situation being considered is sketched in Fig. 1. Here we assume that a tornado is travelling at a speed Q_t along the x-axis (dimensionless speed $\overline{Q}_t(=Q_t/U_r)$), and will reach the origin at a dimensionless time $\overline{t}(=tU_r/r_r)$ of zero (where t is the actual time). The vehicle is moving at a speed Q_v (dimensionless equivalent $\overline{Q}_v = Q_v/U_r$) at an angle of ε to the x-axis, and passes through the point (0, $\overline{Y}$) at a dimensionless time ($\overline{t}$) of zero. The situation thus modelled is of a tornado passing across the path of travel of a train with a defined closest position of the train and the tornado centre as shown in Fig. 1. The distance of the vehicle to the centre of the tornado is given by

$$\overline{r} = \left(\left(\overline{Y} + \overline{s}\sin(\varepsilon)\right)^2 + \left(\overline{s}\cos(\varepsilon) - \overline{X}\right)^2\right)^{0.5} \tag{5}$$

and the angle between the x-axis and the line connecting the vortex centre to the train is given by

$$\theta = \text{atan}\left(\frac{\overline{Y} + \overline{s}\sin(\varepsilon)}{\overline{s}\cos(\varepsilon) - \overline{X}}\right) \tag{6}$$

The dimensionless distances $\overline{X}$ and $\overline{s}$ are given by

$$\overline{X} = \overline{Q}_t\overline{t} \tag{7}$$

$$\overline{s} = \overline{Q}_v\overline{t} \tag{8}$$

Referring to Fig. 1, the wind velocity component relative to the train in the direction of tornado movement (i.e. the abscissa) is given by $(\overline{Q}_v\cos(\varepsilon) - \overline{Q}_t + |\overline{U}|\cos(\theta) + |\overline{V}|\sin(\theta))$. The first term in this expression is the wind speed relative to the train caused by train movement; the second term is caused by tornado translation, the third term is the component of the radial vortex velocity; and the fourth term is the component of the circumferential vortex velocity. Similarly the component in the direction of the ordinate is $(\overline{Q}_v\sin(\varepsilon) + |\overline{U}|\sin(\theta) - |\overline{V}|\cos(\theta))$. Here of course there is no component due to tornado translation. In setting up these equations for numerical solutions, care needs to be taken over the sign of the tornado vortex velocities – the radial velocity is always directed inwards towards the tornado centre (and thus is always negative) and the circumferential velocity is always anti-clockwise.

The velocity relative to the vehicle $\mathscr{V}$, and the yaw angle ψ (the angle of the wind relative to the vehicle direction of travel) can then be calculated from

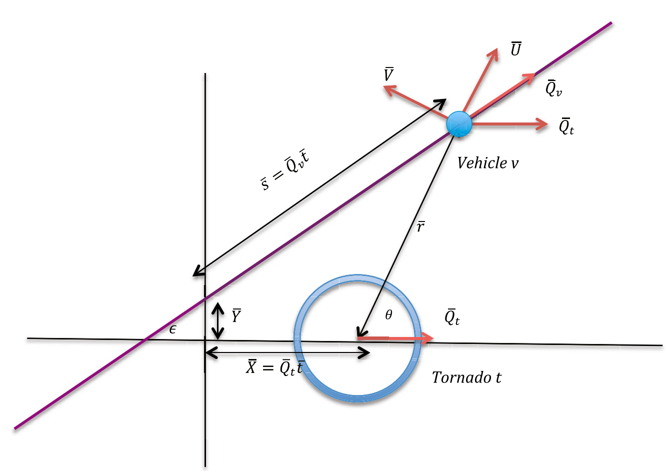

Fig. 1. Vehicle moving through a tornado.