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Modelling wind fields and debris flight in tornadoes

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ABSTRACT

This paper describes the derivation of a simple yet realistic engineering model of tornado wind and pressure fields. This novel model is shown to be capable of providing a method for predicting wind speed and pressure time histories and debris impact energies that can ultimately be used in the development of a rational risk-based design methodology for tornado wind loads on buildings. A stationary one-cell tornado vortex is first considered, and the circumferential and vertical velocities and pressure profiles derived from a simple assumption for radial velocity (that is bounded in the radial and vertical directions) and the use of the Euler equations. The generalisation of this model to a two-cell tornado form is then set out. This model is then used to investigate the trajectories of wind borne debris in tornado wind fields, and for the first time, this analysis reveals the important dimensionless parameters of the problem and the parameter boundary between falling and flying debris. An asymptotic long time solution for debris paths is also derived.

1. Introduction

Tornadoes are complex meteorological phenomena often associated with severe convective atmospheric conditions. In simple terms they consist of a swirling circumferential flow, a radial inflow or outflow, and a vertical flow component. Wind speeds for the most severe tornadoes can reach 100 m/s. It is a well-observed fact that, in some parts of the world, severe tornadoes can cause significant structural damage and loss of life. That being said, most of the efforts of the engineering community over the last few decades have concentrated on predicting and designing for the wind loads from large scale synoptic storms, and until recently little attention has been given to the wind loads due to tornadoes and other small scale convective storm types, and only the crudest of design procedures have been established for such storms, usually based on simple maximum wind speeds. Until recently there was a tendency to assume that the effects of wind (regardless of its origin) would be largely the same – an assumption which has been demonstrated to be incorrect (Jesson et al., 2015). In recent years however the situation has changed, and there is ongoing work to determine the structure of tornadoes from field tests (eg Bluestein et al., 2003); in the development of model scale tornado vortex generators which can be used to give surface pressure data on structures during tornado events (eg. Haan et al., 2008, Mishra et al., 2008a,b, Case et al., 2013, Hangan and Kim (2008), Hashemi-Tari et al. (2010), Refan and Hangan (2016)); and also some investigators have used unsteady CFD methods to predict tornado wind fields (eg Ishihara et al., 2011). These investigations have significantly enhanced the understanding of tornado wind load effects through giving insight into the nature of tornado wind flows. Also in recent years much work has been carried out on the calibration of physical models against full scale data by both laboratory specialists and full scale experts (e.g. Refan et al., 2014).

Essentially there are three types of loading caused by the passage of a tornado over a structure – loads directly related to the flow over the structure resulting in time varying surface pressure fields; loads due to the difference in the rapidly changing low pressure in the tornado core, and the higher, less rapidly changing pressures within buildings; and impact loads due to impact of the flying debris that is often found in tornadoes. Tornado loading is usually taken into account only for highly sensitive structures such as nuclear power plants. The methodology used in the US nuclear industry is given in USNRC (2007). This is based on maximum wind speeds of a specified risk, pressure drops calculated from a simple Rankine vortex model (see below) and debris impact velocities for a restricted range of debris types from numerical trajectory models. However, a conceptual method of how all these essentially time varying effects could be incorporated into design for a range of risk levels is yet to be developed, although there is some ongoing work by Tamura et al. (2015) that is attempting to build a tornado database for use in design in Japan. It is nonetheless clear that a pre-requisite of such a method would

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be a consistent and simple description of the tornado flow field that could be used in design to predict velocity and pressure time histories and to enable debris trajectories to be calculated. In this paper we set out the development of such a simple analytical model of tornado wind and pressure fields that has the potential to meet these needs and apply these models to the calculation of debris trajectories.

Section 2 of this paper describes the available full-scale data for tornado wind and pressure fields and recent work in debris trajectory modelling. Section 3 firstly develops an analytical model for a stationary one-cell tornado, based on a solution of the high Reynolds number Navier-Stokes equations (Euler equations) for wind and pressure distributions, and validates it against full scale data as far as possible. A more complex two-cell formulation with a central downdraft is also set out. Section 4 then considers debris flights in tornadoes, identifying the major dimensionless parameters that are of importance, and calculating debris trajectories over a wide parameter range. The parameter boundary between flying and falling debris is defined. An asymptotic analysis of debris trajectories is also presented. Finally some concluding remarks are set out in section 5.

2. Earlier investigations

2.1. Full scale data

In the modelling work we describe below, we base the development of the model on available, if rather sparse, full scale data. We have not attempted to relate the model to computational of physical model simulations of tornadoes as these are themselves models of a complex reality. Such data has been measured for a number of decades, mainly using radar techniques (eg Wurman et al., 1996; Wurman and Gill, 2000; Bluestein et al., 2003; Lee and Wurman, 2005; Sarkar et al., 2005). These are able to give some details of the tornado structure in terms of geometric scale and wind speeds and directions, but are unable to give a great deal of detail of tornado structure near the ground, which is of course of most interest to wind engineers. Sometimes, usually fortuitously, surface pressure measurements were taken (Lee and Samaras, 2004; Karstens et al., 2010). From this data the following broad conclusions could be drawn.

- Whilst the classic single cell tornado (radial inflow and central updraft) was often observed with circumferential circulation, multi-cell tornadoes also exist, some with downdrafts in the central core that may or may not extend to ground level. Multi-cell tornadoes have been observed more often than single cell ones.
- Tornadoes are very transitory, with properties varying through the life of the tornado.
- Maximum tangential wind speeds of 90–110 m/s have been recorded, but for most tornadoes the wind speeds are significantly lower.
- The core radius (the distance from the centre to the maximum tangential velocity) is of the order of 50–200 m.
- The translational velocities are of the order of 5–15 m/s.

More recently Refan et al. (2014) have collated a large dataset of tornado wind speeds measured by the Ground Based Velocity Track Display technique (Lee at al 1999). These were for relatively low wind speed tornadoes, with maximum wind speeds between 36 and 62 m/s, but nonetheless do give detailed circumferential velocity distributions over a range of heights. The data, which is for both single-cell and two-cell tornadoes, will be used to verify the new model later in the paper.

At this point it is worth pointing out that there are two aspects of tornado flows about which there is very little information, and which will be seen to be important in what follows. The first is that of the near ground boundary layer, where the velocity will increase from zero to some “free stream” value. This must exist physically, but to the author's knowledge no information on its form is available. The second is the turbulent statistics of the tornado. One would expect small scale turbulent eddies to exists within the overall flow structure, but again there seems to be little information available on this from full-measurements, although there are a number of (unverified) model-scale datasets.

2.2. Debris flight

The damage caused by flying debris in tornadoes is clear from a study of the damage investigations that have taken place in recent years – see for example Brooks and Doswell (2001), and this subject has been studied since the 1970s. Lee (1974), Redmann et al. (1976) and Twisdale et al. (1979) all developed wind field models and trajectory models that described debris flight in tornadoes. The wind field models however were essentially empirical relationships that sought to capture some of the main features of tornadoes, and were not set in a consistent analytical framework. Similarly the debris flight models were also somewhat ad hoc and lacked a general framework and thus their use in design was limited. Nonetheless these models were used to predict impact velocities from missiles in tornadoes that proved to be the basis for codification and testing over the following decades (McDonald, 1990). In the early years of this century, a number of authors considered the issue of debris flight afresh, and consistent analytical frameworks were developed – see for example the work of one of the authors in Baker (2007), although this is only one of a number of similar investigations. Of perhaps most significance was the formal definition of three types of debris – compact with all three dimensions similar in magnitude, sheet – flat plates defined by two dimensions; and rod – with one dimension much greater than the others. Also the importance of the dimensionless parameter known as the Tachikawa number (Holmes et al., 2006), which is based on the early work of Tachikawa (1988) in Japan, has been recognised. This is essentially the ratio of the inertial forces in the flow to the weight of the debris. More recently the focus of engineering tornado studies has turned to physical and numerical simulation (Mishra et al., 2008a, b; Sarkar et al., 2005). With regard to the latter, two recent investigations have also looked at the flight of debris in tornadoes – Maruyama (2011) and Noda et al. (2015) using Large Eddy Simulation, and whilst these results are interesting and give a very great deal of the flow fields and trajectories, the resources required mean that the simulations are somewhat idealised and uncalibrated (often attempting to match the geometry of physical models) and present the results for only a small number of cases.

3. The tornado model

3.1. Existing tornado wind models

In this section we briefly consider the analytical formulations of tornadoes that have been previously proposed by earlier workers. The simplest of these is the Rankine vortex, which effectively consists of a forced vortex core and a free vortex outer region. The circumferential velocity field is given by

$$r < r_m \quad V = \frac{V_m r}{r_m} \quad r > r_m \quad V = \frac{V_m r_m}{r} \tag{1}$$

where $V = V_m$ is the maximum velocity at a radius $r = r_m$. Note that no radial or vertical velocities are specified and thus for the purposes set out in section 1 (the calculation of loads and debris trajectories), it is not of any use, although a number of authors have shown it is a good fit to some full scale data (Wood and Brown, 2011). Also note that there is a sharp discontinuity at $r = r_m$. This model is however used in the loading methodology of USNRC (2007). A rather more complex formulation of tornado flows is offered by the Burgers-Rott vortex model (Burgers, 1948; Rott, 1958), which is a solution of the full Navier-Stokes equations. This begins from the assumption that the radial velocity is an inflow with a magnitude proportional to the radial distance. Applying the continuity and circumferential momentum equations then leads to the following