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ERIES-TNG: Insights into tornado vortex wandering

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SUMMARY

Tornado vortex wandering is a term coined to describe the seemingly random movement of tornado-like vortices. In this paper, we postulate that such motion can be described by a coupled precession (related to the rotation of an air mass) and turbulent fluctuations. We examine measurement data from several tornado-like experiments of stationary vortices and propose an improved method of identifying the vortex centre based entirely on the ground pressure field. This approach facilitates tracking of the tornado-like structures and highlights repeated circular patterns or vortex wandering, particularly with respect to stationary tornadoes. Furthermore, we draw an analogy between vortex wandering and gyroscope precession and propose an analytical model which represents the vortex wandering precession. Due to the relative simplicity of formulation and satisfactory agreement with experimental results, this model could be implemented in CFD simulations of tornadoes with vortex wandering.

Keywords: *tornadoes, non-synoptic winds, experimental data, vortex wandering, precession*

1. INTRODUCTION

This paper focuses on the often overlooked issue of ‘tornado vortex wandering’, an oscillating movement of the vortex core, with a variable amplitude resulting from its vorticity and the background turbulence (Iungo et al., 2009). This complicates analysis of experimental data as it distorts the time-averaged vortex velocity field. Despite occurring in all physical simulations of tornadoes, only limited attempts have been made to properly examine and quantify this issue. Snow and Lund, (1997) estimated that errors of up to 50% of the maximal tangential velocity and 46% of the core radius resulted from the wandering of an experimentally simulated Rankine-combined vortex. Gillmeier et al., (2017) employed proper orthogonal decomposition to decouple the influence of vortex wandering from the main flow field and estimate its relative effect on tornado-like vortices with varying swirl ratios. Ashton et al., (2019) compared two different methods of correcting the measured velocity fields for wandering effects, finding that re-centring the velocity data in relation to the instantaneous vortex centre location is more accurate than a convolution of a bi-variate normal probability density function of vortex centre locations.

The methodology and results presented in this paper are based on measurements from a physical simulation of a stationary tornado-like vortices at the WindEEE Dome undertaken as part of the ERIES-TNG experimental campaign. For the sake of brevity, the reader is referred to the publicly available data in Sterling et al., (2025) for the scope of the tests and experimental setup details. More detailed information about the facility can be found in Hangan, (2014).

2. IDENTIFYING THE VORTEX CENTRE

Locating the vortex centre is crucial in analysing tornado flow fields. It is often done by finding the instantaneous pressure minimum and assuming it coincides with the corresponding pressure tap. However, this approach can be unreliable, as it depends on grid resolution and may misidentify the centre at one of the smaller-scale subvortices instead of the parent vortex.

To address these challenges, we have analysed the entire ground pressure field and identified the presence of rather regular, circular patterns created by different isobars. It is not unreasonable to assume the centre of the tornado-like vortex at the same location as the centre of these patterns (not always identical to the location of the absolute pressure minimum). A procedure was developed (Figure 1) to identify the instantaneous vortex centre based on these principles, which can be applied to both stationary and translating vortices and consists of the following steps: (a) interpolating the instantaneous ground pressures at each time step over a Delaunay mesh, (b) extracting a specific isobar from the ground pressure map and fitting a circle to it at each time step, (c) locating the centre of the circle at each time step, identified as the instantaneous vortex centre.

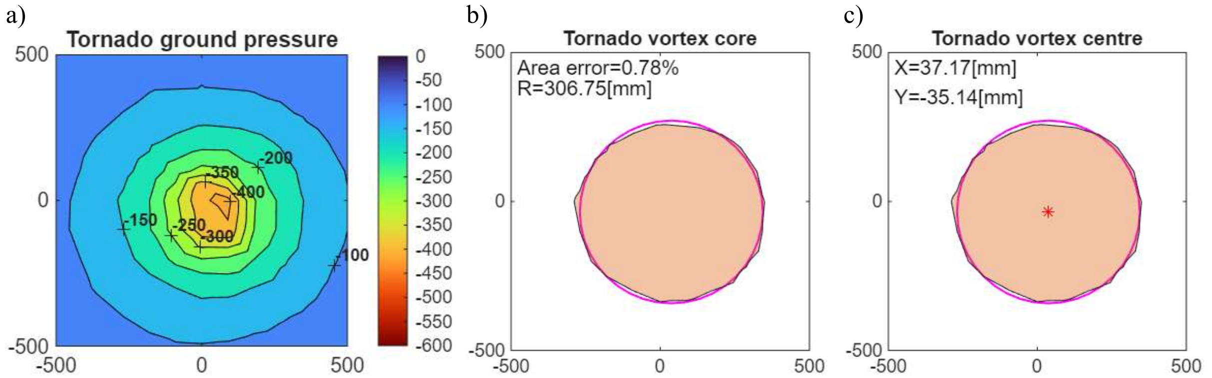

Figure 1: An illustration of the proposed approach of locating the vortex centre.

3. WANDERING OF STATIONARY VORTICES

The wandering motion of a stationary vortex has been analysed in three different setups: without the building (a), with the building at nominal vortex centre (b) and with the building offset 0.6 m from the vortex (c). A ‘helical’ pattern can be clearly distinguished in the data (Figure 2) suggesting that the motion is not random but follows a circular pattern, albeit with strong disturbances.

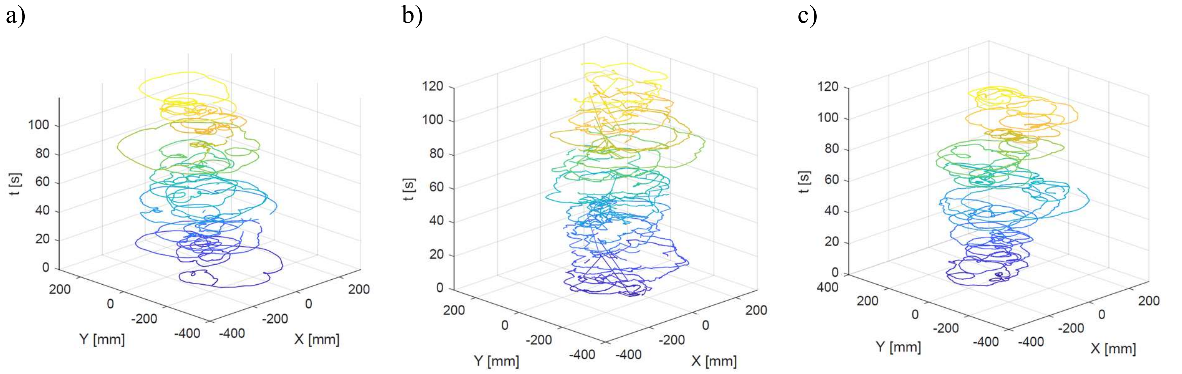

Figure 2: Vortex wandering patterns (instantaneous locations of the vortex centre) over time.

Interestingly, the disturbances in the helical patterns (Figure 2) are less prevalent in case 2, where the vortex overlaps the building. Similar observations regarding the radial pressure distribution for each case suggest that the building may be filtering out some of the smaller-scale fluctuations of the flow and indicate that vortex wandering may not be an entirely random and chaotic process, but rather an intrinsic physical characteristic of tornado-like vortices.

4. ANALYTICAL MODEL FORMULATION

In the following, we will consider the vortex core to act as a rotating, cylindrical mass of air and that the tangential velocity component dominates and is significantly larger than the vertical and radial components, neglecting the potential contributions that these components may make to wandering. We assume that most of the vortex mass is concentrated in the core region. Figure 3 illustrates an idealised schematic of a vortex preceding around an origin ($O(\bar{x}_c, \bar{y}_c)$).

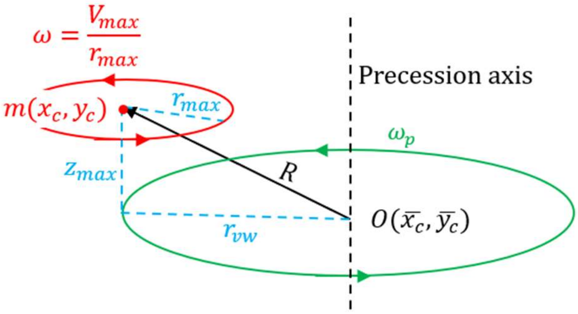

Figure 3: Simplified model of vortex wandering based on spinning top motion.

In Figure 3, the red dot marks the centre of mass of air (m) corresponding to the tornado core located at the coordinates of the vortex centre (x_c, y_c). This mass is assumed to be located at a height z_{max} above the ground and at a horizontal distance r_{max} from the origin. **R** is a vector connecting these two points, ω is the angular velocity of the tornado at the radius of maximum velocity r_{max} and V_{max} is the maximal mean value of the tangential velocity at r_{max}. r_{vw} is the radius of the vortex wandering and ω_p is the precession (wandering) angular velocity. Starting from the equation for the angular velocity of precession for a spinning top and moment of inertia for a spinning, cylindrical mass of air, we can derive the following equations for the precession angular velocity ω_p and period of vortex wandering T_p, presented here in the final form:

$$\omega_p = \frac{2g\sqrt{\lambda + \frac{\delta^2}{\lambda}}}{V_{max}}; \; T_p = \frac{2\pi}{\omega_p} = \frac{\pi V_{max}}{g\sqrt{\lambda + \frac{\delta^2}{\lambda}}} \tag{1}$$

where $\lambda = r_{vw}/r_{max}$ and $\delta = z_{max}/r_{max}$.

The values calculated through the model were compared with data. Although it is slightly more difficult to assess the precession alone (without the overlapping smaller-scale fluctuations) from the measurements, the results obtained through both methods show a satisfactory comparison, which can be seen in Table 1, which shows dimensionless values normalised by vortex wandering period obtained through measurements for each analysed case.

Table 1. Comparison of vortex wandering period values obtained through the proposed analytical model and from the experimental results

Dimensionless vortex wandering period $\overline{T_v}$ [–]	Case 1	Case 2	Case 3
Measurements	1.0 ± 0.232	1.0 ± 0.126	1.0 ± 0.233
Analytical model	0.968 ± 0.035	1.108 ± 0.041	0.820 ± 0.028

5. CONCLUSIONS

This research sheds new light on the issue of tornado vortex wandering, both from experimental and analytical perspectives. The novel approach to locating the vortex can be applied in experimental data processing, often limited by measurement inadequacies related to the complexities of tornadic wind fields. We can draw the following main insights from this research:

1. A novel approach is proposed to locate the centre of a vortex, which can be used when surface pressure measurements are sparse and/or when an obstacle is present. This method is suitable for translating and non-translating tornadoes.
2. The wandering pattern of a stationary tornado-like vortex shows severe fluctuations even without any terrain roughness or obstacles.
3. The presence of an obstacle (e.g., a building, which in the analysed case was of a similar size to the vortex core) can filter the smaller-scale fluctuations of the wandering motion.
4. Precise identification of the vortex centre can significantly improve the accuracy of modelling the tornadic wind field through established analytical models, even with limited measuring capabilities, an inherent issue with tornadic measurements.
5. The proposed analytical model of vortex wandering closely reproduces the measured quantities and captures the detailed variations in angular velocity across cases with distinctly different setups.

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