August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

A novel measurement method of dynamic deformation and wandering of a tornado-like vortex

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SUMMARY:
In order to investigate the fluid dynamics of tornadoes by using tornado-like vortex (TLV) generators, it is essential to deal with the smoothing of velocity distribution due to vortex wandering. A novel tornado core shape analysis method was proposed based on vortex re-centering and core detection. The method enabled the measurement of the dynamics of TLV based on instantaneous measurement data. From the series of experiments, we have discovered that the inconsideration of vortex wandering has a significant impact on the characteristic geometrical parameters of TLVs. The existence of core interface deformation was revealed from the usage of instantaneous data.

Keywords: Tornado-like vortex, Ward-type chamber, Particle image velocimetry

1. INTRODUCTION

Tornadoes show a dynamic behavior, associated with turbulence and instability (Rotunno, 2013). Attempts have been made to generate them in a laboratory scale (Church, 1979; Refan and Hangan, 2016). The Ward-type (Ward, 1972) is a commonly used Tornado-like Vortex (TLV) generator to date. This design concept has the advantage of having explicit boundary conditions, by restricting the height of the confluence region, where the boundary layer develops.

One major issue when analyzing the data from TLV generators is the smoothing of the velocity distribution associated with vortex wandering (Zhang and Sarkar, 2012; Ashton et al., 2019). This refers to the effect that when the core center of the vortex shifts as the TLV wanders, it smooths the velocity profile of vortices when time-averaged. Several algorithms were introduced (Jiang et al., 2002; Wong and Yip, 2009) which are applicable to the vortex re-centering.

Although some studies apply such re-centering methods on TLV generator measurements, they typically time average the re-centered data, which may induce smoothing if the vortices are significantly deformed. In this study, we first introduce a TLV generator, capable of measuring in both high spatial and temporal resolution, while conducting high Reynolds number (Re) experiments. We then applied the re-centering method of Bannigan et al. (2022), which is applicable to a highly deformed vortex, and developed a novel method to obtain the core shape of the TLVs. The deformation of TLVs was discussed based on instantaneous measurement data.

2. METHODS

2.1. Experimental Setup

The experiments were conducted in a Ward-Type TLV simulator at the Central Research Institute of Electric Power Industry, named TOrnado VORtex SIMulator with High Reynolds number (TOVORSIM-HR). The schematic diagram of the apparatus is shown in Fig. 1. The geometric parameters were decided with reference to the VorTECH facility at Texas Tech University (Tang et al., 2018) and scaled down to a 1/10 size. The body was made of transparent acrylic material. The facility was equipped with an 18.5 kW electronic blower, roughly capable of producing 12 kPa of differential pressure, giving the capability of achieving high radial Reynold number experiments that match the full-size VorTECH facility. The vane wings were mounted at an angle of 10 degrees to the normal direction of the inlet.

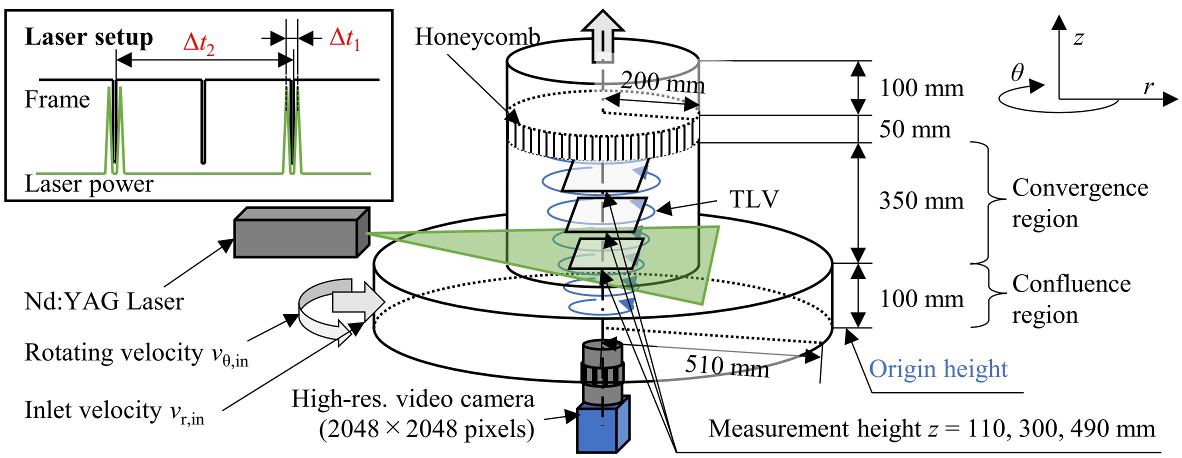


Figure 1. Schematic diagram of TOVORSIM-HR facility.

The measurement of TLV was conducted with a high-res. video camera and a double-pulse laser unit. The video camera was mounted upwards at the bottom of the test section. The experimental conditions are shown in Table 1. A particle image velocimetry (PIV) measurement was conducted by tracking glycerine droplets mixed into the inlet air. The reason for z = 110 mm being the minimum measurement height was to avoid the light scattering from vane wing panels. The consistency of vortices at the confluence and convergence region was confirmed, prior to the experiment. The image resolution was 0.038–0.065 mm/pixel, depending on measurement height.

Table 1. Experimental condition

Inlet flow rate	$Re_r = (Q/\nu h)$, $h = 0.1$ m	Measurement height	Δt_1	Δt_2
0.111 m^3/s	7.39×10^4	110, 300, 490 mm	120 ms	0.143 s
0.240 m^3/s	1.59×10^5	110, 300, 490 mm	80 ms	0.143 s
0.377 m^3/s	2.49×10^5	110, 300, 490 mm	50 ms	0.143 s
0.640 m^3/s	4.23×10^5	110, 300, 490 mm	20 ms	0.143 s

2.2. Post-Processing

A series of data processing was conducted to measure the geometric parameters of the vortex. The data processing flow is shown in Fig. 2. The vortex detection algorithm (Fig. 2 a–c) was based on the method of Bannigan et al. (2022). The PIV results were first converted into vorticity.

Then, the normal lines against the velocity vector at high vorticity points were calculated. The junctions of these lines were averaged and defined as the core center (x_c, y_c):

$$(x_c, y_c) = \sum_{k=1}^{N} (x_{t,k}, y_{t,k}) / N \tag{1}$$

Then, a straight line was drawn for every $\Delta\theta$ from the center coordinate. In the present measurement, $\Delta\theta = \pi/6$ rad was enough to obtain stable results. The velocity was interpolated along the straight line, and the argument with the maximum horizontal velocity ($v_{\theta,max}$) along the line (r_0) was defined as the core interface point of the TLV (Fig. 2d). Also, the tangential velocity (v_θ) distribution along this straight line was nondimensionalized by $v_{\theta,max}$, and r_0. By doing so, the values were spatially averaged for all directions. The core interface points were also used to obtain the characteristic geometrical parameters by fitting its shape with a tilted ellipse, using the least-squares method (Fig. 2e). The ellipse parameters such as major/minor axis length (a, b), and tilt angle from the cartesian coordinate (θ_e) were extracted from fitting data.

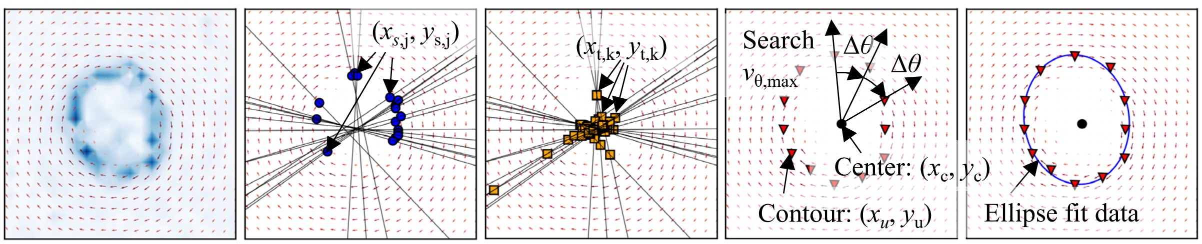
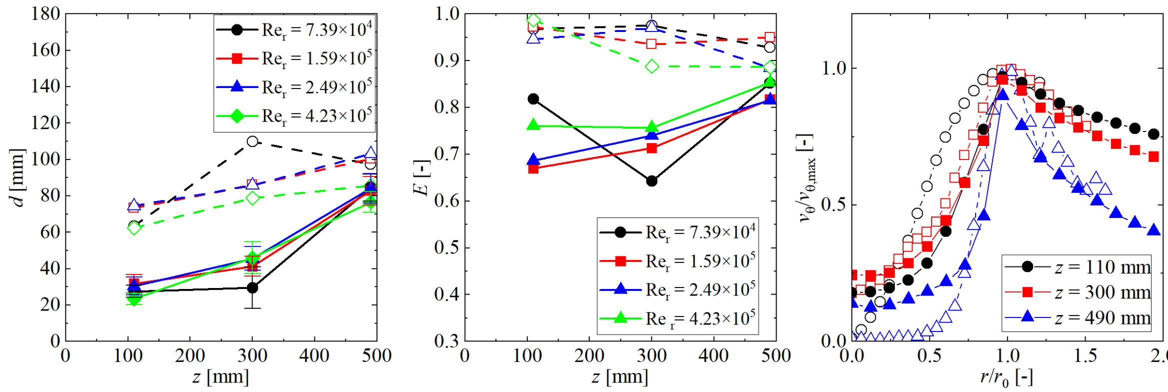


Figure 2. The flow of data processing.

3. RESULTS AND DISCUSSIONS

The characteristics of TLVs with and without core re-centering were investigated. The data processing in Fig. 2 was applied to each of the time series data. As for the data without re-centering, the velocity distribution was simply time-averaged before going through the same process. The comparisons of the results for various TLV parameters are shown in Fig. 3. The diameter in Fig. 3a was defined as the areal equivalent diameter of the ellipse fitting results ($d = 2(ab)^{0.5}$). The data with re-centering showed more apparent measurement height dependencies for all Re_r. The experimental results indicated that the TLV diameter may be increasing drastically near the outlet region. The aspect ratio of the core interface (Fig 3b) was defined as the ratio of the minor and major axis ($E = b/a$). The results show that if the TLVs were averaged without considering its wandering, the shape could be approximated as a perfect circle, whereas, when the instantaneous TLV shape is extracted, its shape will be significantly deformed. The deformation became smaller as Re increased, except for Re = 7.39×10^4, z= 110 mm. We assume this was because the wandering for this condition was large, and the contour came out of frame, frequently. Finally, the radial $v_\theta/v_{\theta,max}$ distribution is shown in Fig. 3c, with a specific case of Re = 2.49×10^5. The velocity distribution inside the core region (r/r_0<1) without re-centering showed significant height dependencies, while for the data with re-centering, such a difference was not apparent, except for z = 490 mm. This seems to be the effect of the honeycomb rectifier plate placed just above at z = 500 mm. Note that the velocity with re-centering around the center

(r/r_0<0.3) was exceptionally unreliable due to large standard deviations. As for velocity distribution outside the core region (r/r_0>1), the re-centering did not show a significant impact. The results for other Re also showed similar results.



(a) Diameter (b) Aspect ratio (c) $v_\theta/v_{\theta,max}$ at $Re_r = 2.49 \times 10^5$

Figure 3. Comparison of results with and without core re-centering. Solid lines and plots show conditions with re-centering, and hollow plots and dashed lines show conditions without re-centering.

4. CONCLUSIONS

In this study, a novel method that can obtain the interfacial shape of the TLVs based on instantaneous TLV shape information was developed. From the series of experiments and data analyses, it was concluded that the re-centering of TLVs does have a significant impact on their diameter, core interface deformation, and velocity distribution. In particular, the existence of interface deformation was revealed from instantaneous data.

ACKNOWLEDGEMENTS

Mr. Takayoshi Mizuno and Mr. Jun Takahashi from Ceres Inc. have conducted the visualization.

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