

Advancing Tornado-Like Vortices (TLVs) Modeling in Straight-Line Simulators

M. A. Hasan^a, M. F. Khaled^b, F. T. Lombardo^c

^aTexas Tech University, Lubbock, TX, USA, has24395@ttu.edu

^bTexas Tech University, Lubbock, TX, USA, faiaz.khaled@ttu.edu

^cUniversity of Illinois at Urbana-Champaign, Urbana, IL, USA, lombaf@illinois.edu

SUMMARY

To advance the study of transient wind events, a numerical modelling approach is adopted in this study, which is capable of generating tornado-like vortices with realistic features. The computational domain is generated to mimic the University of Florida boundary layer wind tunnel (UF BLWT). The BLWT is modified by adding a transverse wall, an all-through low barrier, and a set of rotating louvers, which will play a key role in generating translating TLVs in the BLWT. To simulate the dynamic mesh associated with the rotating louvers, the arbitrary mesh interface (AMI) technique is employed in this study, which enables the rotation to the louvers while maintaining numerical stability in the simulation. A large eddy simulation (LES) turbulence model in conjunction with the wall-adapting local eddy-viscosity (WALE) sub-grid scale model is chosen for this study. The features of the generated TLVs conform well with the experimental and field observations.

Keywords: Tornado-like Vortex (TLV), Large Eddy Simulation (LES), Dynamic Mesh, Transient Wind Events.

1. INTRODUCTION

Transient wind events (e.g., tornadoes, thunderstorms, and hurricanes) cause significant property damage and loss of life across the world. Between 2018 and 2024, tornadoes were associated with roughly 56 fatalities and 602 injuries per year and caused about \$1.47 billion in total annual damages in the United States (NWS/NOAA). A recent tornado database archived more than 100,000 tornadoes worldwide, and at least 35,000 recorded casualties, including 21,548 fatalities in the USA, 8,325 fatalities in Bangladesh, and 5,297 fatalities in the rest of the world (Maas et al., 2024). These transient wind events affect structures differently from large synoptic wind systems and can leave behind catastrophic destruction. Vortices of various temporal and spatial scales are observed in these transient wind events. As generating the whole wind field of a windstorm is not practical due to the limitations concerning experimental and computational resources, this abstract focuses on a technique to generate tornado-like vortices with realistic features in straight-line simulators using Large Eddy Simulation (LES).

Aerodynamic features generated by the interaction between buildings and wind systems strongly influence windstorm damage. As the full-scale data of the tornado-induced loading is unavailable and the near-ground wind measurements are very limited, modeling tornado-like vortices (TLVs) can be of significant help. Researchers in the wind engineering community mostly rely on tornado vortex generators (TVGs) to simulate TLVs interacting with bluff bodies physically. Even though the TVGs have played a pivotal role in informing the community about TLVs and induced loading, some limitations of TVGs are identified by (Baker & Sterling, 2019). To address these limitations, the co-authors of this abstract proposed a novel approach (Khaled et al., 2025) that produces TLVs maintaining realistic geometric and kinematic similarities in a Boundary Layer Wind Tunnel (BLWT) setting.

This paper computationally investigates the capability of rotating louvers to generate TLVs with realistic features using LES. The computational domain was modelled based on the University of Florida boundary layer wind tunnel (UF BLWT). The domain was modified with a flow management apparatus, including a transverse wall, an all-through barrier, and a set of vertical louvers along the crosswind direction (Figure 1 (a)). Computational Fluid Dynamics (CFD) simulations, including a dynamic mesh, have been a long-standing challenge in the wind engineering community, as the interpolation of the flow field (e.g., pressure, velocity) across the dynamic and static mesh interfaces is a complex process. The objective of this paper is to propose a technique that can handle the complexities associated with dynamic mesh and produce vortices with realistic features.

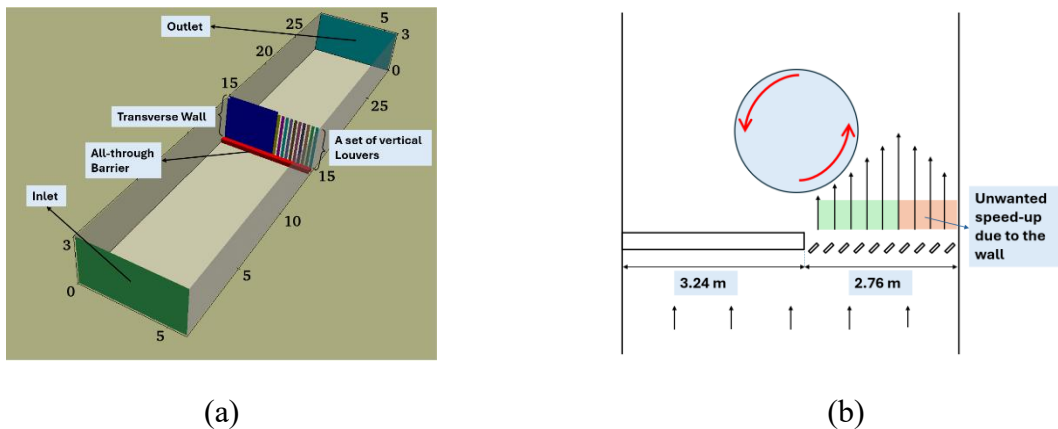


Figure 1: Entire CFD domain with the flow management apparatus, and (b) vortex generation concept by introducing horizontal shear instability.

2. METHODOLOGY

The vortex generation method relies on the principle of introducing horizontal shear instability through a set of rotating louvers that can be opened and closed at a specific angular speed and acceleration (Figure 1 (b)). At the beginning of the simulation, the flow field is restricted upwind of the flow management apparatus, as the louvers are in a closed position, resulting in a pressure buildup in that region. Then, the louvers are quickly rotated to a specific angular position and at a certain angular speed and acceleration. As a result, horizontal shear instability is introduced in the flow field and translating TLVs are generated in the downwind region (Figure 2 (a)). In this study, an LES turbulence model is chosen in conjunction with the wall-adapting local eddy-viscosity model (WALE) as the sub-grid scale (SGS) model. For the rotating louvers, the Arbitrary Mesh Interface (AMI) approach is employed, which handles interpolation across non-conformal mesh interfaces (i.e., the interface between a static and a dynamic mesh). This approach allows six degrees of freedom (6DoF) motion of the dynamic meshes while maintaining numerical stability. The pimpleDyMFoam solver of OpenFOAM 5.0, which is a modified version of the pimpleFoam solver, was developed to handle transient simulations of incompressible Newtonian fluid flows in dynamic meshes. An adaptive temporal discretization scheme is employed in this simulation, where the time step is adjusted at each iteration to limit the maximum Courant number to 1.0.

3. RESULTS

A detailed grid convergence study is conducted to determine the optimal mesh required for this flow problem, and all subsequent results are based on that converged mesh case. The characteristics of the generated TLVs are compared with the field observations and analytical models at a specific downwind location. The comparisons are done based on three widely recognized criteria of TLVs: (a) radial profile of pressure, (b) radial profile of tangential velocity, and (c) vertical profile of resultant velocity at the radius of maximum wind (RMW). The ratios of the tangential speed to radial speed and translation speed to tangential speed are measured as the indicators of swirl ratio and vortex translation, respectively. One of the major difficulties in realistic TLV simulation is maintaining the swirl ratio and vortex translation within a range that aligns with field observations. The proposed method successfully generates TLVs with realistic swirl ratios and vortex translations, indicating the kinematic similarity with field observations. In this paper, only the results from the single pulse are presented, as the single-pulse result is used to identify the optimal pulse duration. The radial profile of pressure conforms well to the field observations obtained from the Manchester and Webb tornado and previously published pressure profile using the wall-based LES mechanism (Figure 2 (b)). Additionally, the radial profile of tangential velocity aligns better with the Burgers Rott Model compared to wall-based LES results (Figure 2 (c)). Furthermore, the vertical profile of resultant velocity at the RMW shows good conformance with radar observations of tornado events (Figure 2 (d)).

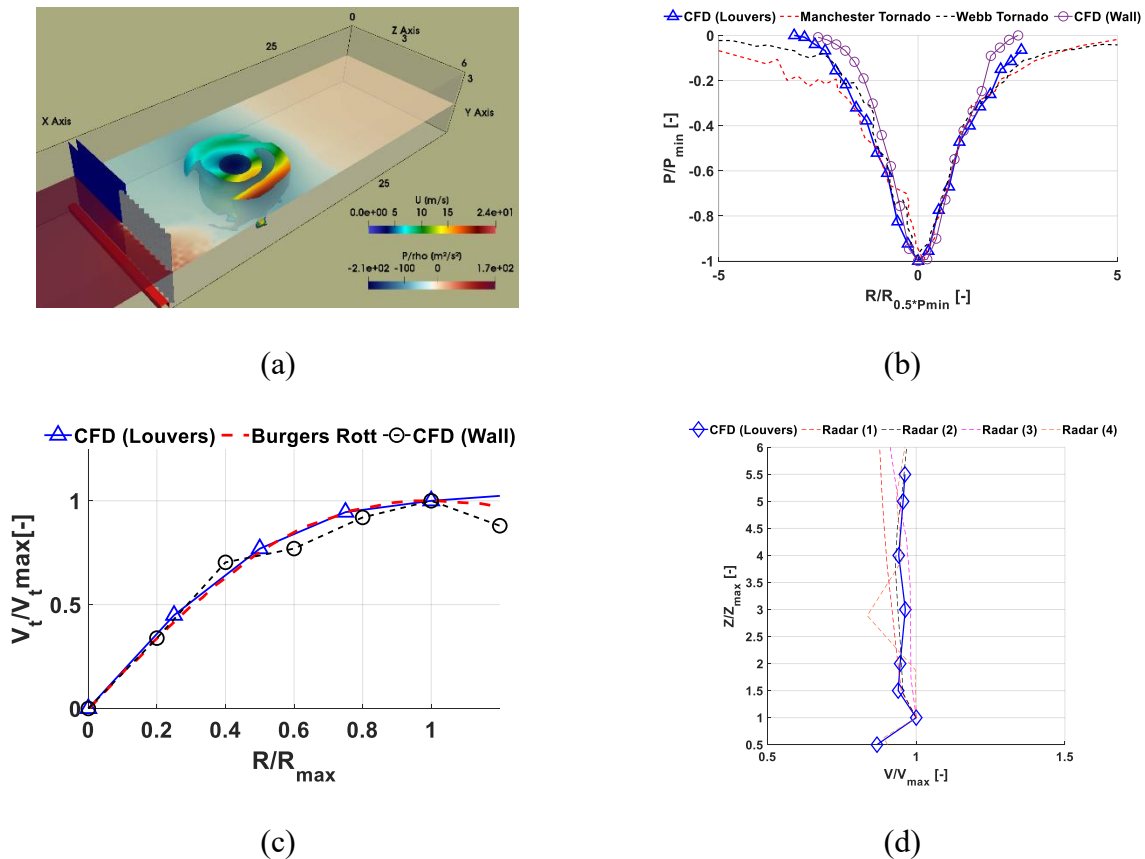


Figure 2: (a) Generated vortex using the louver mechanism, (b) comparing radial profile of pressure with standard targets, (c) comparing radial profile of tangential velocity with an analytical model, and (d) comparing vertical profile of velocity at the RMW with radar measurements.

An attempt to control the vortex features is made by changing the louver opening angle. This study creates a foundation for future studies about controlling the transient features of the vortices. A total of four louver opening angles (40-55 degrees, with a 5-degree increment) is considered. The angles are measured with respect to the crosswind direction (Figure 3 (a)). A consistent trend is found among the transient features of the vortices. As the louver opening angle increases, the magnitude of the core pressure decreases (Figure 3 (b)), along with the maximum tangential velocity and the translation speed of the TLV. However, the swirl ratio increases as the angle of opening increases.

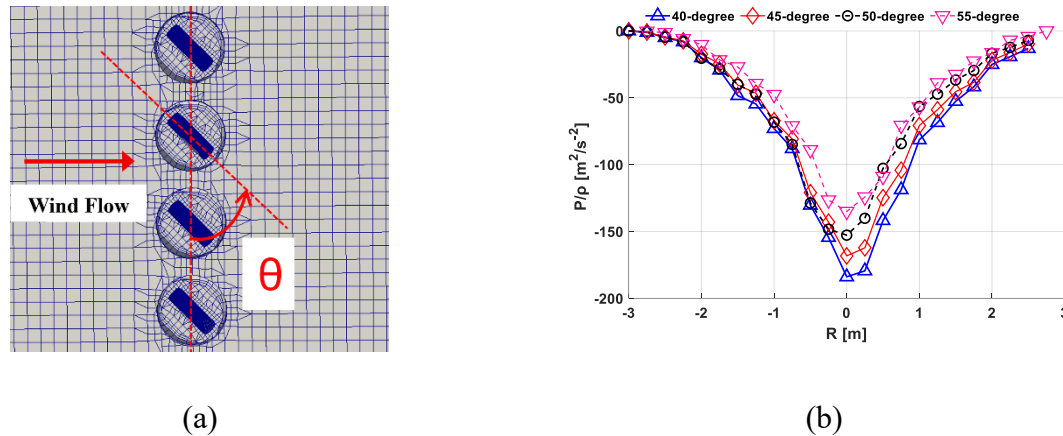


Figure 3: Top view of the mesh refinement around the louvers: (a) 45-degree position, and (b) comparing the radial profile of pressure for four angular openings.

4. CONCLUSION AND FUTURE WORK

The results obtained from the single pulse demonstrate that the dynamic mesh technique based on AMI can generate TLVs with realistic features as well as offer the ability to control vortex characteristics. This approach will advance the study of tornado-like vortices (TLVs) and their interactions with the built environment using computational and physical simulations. For future work, in-depth research will be conducted to control the vortex features. The loading due to the vortices on an isolated structure and a small neighbourhood will also be investigated.

References

- Baker, C., & Sterling, M. (2019). Are Tornado Vortex Generators fit for purpose? *Journal of Wind Engineering and Industrial Aerodynamics*, 190, 287–292. <https://doi.org/10.1016/j.jweia.2019.05.011>
- Khaled, F., Lombardo, F. T., & Gurley, K. (2025). Modeling of vortices in straight-line wind simulators. *Journal of Wind Engineering and Industrial Aerodynamics*, 257. <https://doi.org/10.1016/j.jweia.2024.105992>
- Maas, M., Supinie, T., Berrington, A., Emmerson, S., Aidala, A., & Gavan, M. (2024). The Tornado Archive: Compiling and Visualizing a Worldwide, Digitized Tornado Database. *Bulletin of the American Meteorological Society*, 105(7), E1137–E1152. <https://doi.org/10.1175/BAMS-D-23-0123.1>