Comparison between stationary downburst-like impinging jets and analytical models

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SUMMARY:
A "downburst" is defined as a diverging wind system that occurs when a strong downdraft induces an outflow of damaging winds on or near the ground. Severe wind damage in many parts of the world is often due to thunderstorm outflows and their knowledge is therefore relevant for structural safety and design wind speed evaluation. Nevertheless, there is not yet a shared model for thunderstorm outflows and their actions on structures. This study concentrates on the comparison of five impinging jet models of downburst outflows present in the literature and Large Eddy Simulations (LES) calibrated from experimental tests of a vertically stationary downburst at the WindEEE Dome facility. The comparison of LES and experimental data shows that downburst-like winds (DLW) simulated by impinging jets are characterized by the development of a primary vortex ring which strongly influences the temporal variation of the characteristic nose-shaped vertical profile. The study reveals that none of these five analytical models can adequately simulate the radial velocity vertical profile obtained by LES simulations and experimental tests and suggests that the use of these analytical models for structural safety evaluations may underestimate the downburst wind loads on structures.

Keywords: CFD Simulations, WindEEE Dome Experiments, Downbursts Analytical Models.

1. INTRODUCTION

The study of intense thunderstorm downbursts and their actions and effects on structures has been a dominant research topic in wind engineering over the last forty years. Thunderstorms are non-stationary phenomena at the mesoscale, which occur in convective conditions with velocity vertical profiles substantially different from those that are typical of the atmospheric boundary layer (ABL). Design wind velocities with mean return periods greater than 10–20 years are often associated with such phenomena (Solari, 2014). However, this matter is still affected by large uncertainties and a shared model of downburst outflows and their actions on structures like the one formulated by Davenport (1961) for synoptic cyclones is not available yet. Downburst-associated loads on structures depend on a variety of parameters such as the diameter of the downdraft, the relative position between the center of the downburst (i.e., downdraft touchdown) and the structure, the translation velocity of the parent storm cell and so on. These aspects make the assessment of downburst wind loads very complex and require the formulation of simplified analytical or empirical models of this phenomenon able to capture their main features.

This study focuses on the comparison of five analytical models provided in the literature and Large Eddy Simulation (LES) calibrated on experimental tests by Canepa et al., (2022) of stationary DLWs in the WindEEE Dome facility. The chosen analytical models are the Oseguera and Bowles (1988) model, the Vicroy (1992) model, the Wood et al. (2001) model, the Li et al. (2012) model and the Abd Elaal et al. (2013) model. The study shows that none of these models can satisfactorily simulate a stationary DLW based on impinging jets during its strongest phase, which occurs underneath the passage of the Primary Vortex (PV).

2. RESULTS

Downburst winds produce particular nose-shaped vertical profiles of radial velocity, continuously changing in time and space, that causes highest velocities near the ground surface. Figure 1 (a) shows the comparison between a LES simulation of the radial velocity vertical profile with the experimental results previously obtained at the WindEEE Dome facility by Canepa et al. (2022) for a stationary DLW. Since the maximum registered radial velocity in the experiments was observed at $R/D = 1.0$, this location was selected as the representative one (where R is the radial distance from the downburst centerline and D is the diameter of the downburst downdraft). Both LES and experimental data shown in Fig. 1(a) depict a slowly-varying mean wind velocity with averaging window of 0.1 s. Hereby, the simulated LES vertical profile of radial velocity is compared against a selected single experimental repetition (grey line), and with the ensemble average of twenty repetitions (black line). The experimental variability of the repetitions is considered using a two-sided error bar which is centered around the ensemble average value. The two edges of the error bar represent the minimum and maximum velocity value over all twenty repetitions. Note that z = 0.5 m represents the maximum measurement height in the experiments. As the simulated data are similar to the experimental data, in Fig. 1(b) the LES results are used for comparison with the five analytical models introduced in Section 1. In Fig. 1(b), the radial velocity is normalized with respect to its maximum value recorded in the LES simulation (u_{max} at $R/D = 1$), whereas the vertical coordinate is normalized by the height at which the maximum radial velocity is observed in the LES simulation (z_{max}, at $R/D = 1$). As Fig. 1(b) clearly shows, none of these analytical profiles can represent the radial velocity vertical profile obtained through LES and, WindEEE Dome experiments with a sufficient level of accuracy.

Fig. 2(a) shows the residuals between the LES simulation and the fitted analytical models. Residuals display a systematic pattern common to all analytical models: apart from the maximum nearby the surface, they strongly underestimate the radial velocities up to z/z_{max}~30. Figure 2 (b) shows the frequency of occurrence of the residuals. For a good fit it is expected that the histogram of residuals can be approximated by a normal distribution with zero mean, while in this case a bimodal pattern with a mean different from zero is observed, which is again a clear sign of a systematic error. Lastly, Table 1 contains the goodness-of-fit statistics between the five analytical models and the LES simulation. The table shows the mean of the residuals, the sum of squares due to error (SSE), the root mean square error (RMSE) and the R-Square (R^2). A value close to zero of the SSE and RMSE indicates that the model has a smaller random error component while a value closer to 1 of R^2 statistics indicates that the model successfully explains the variation in the simulated data. In all cases, these statistics indicate a poor fit between the models and the LES data.

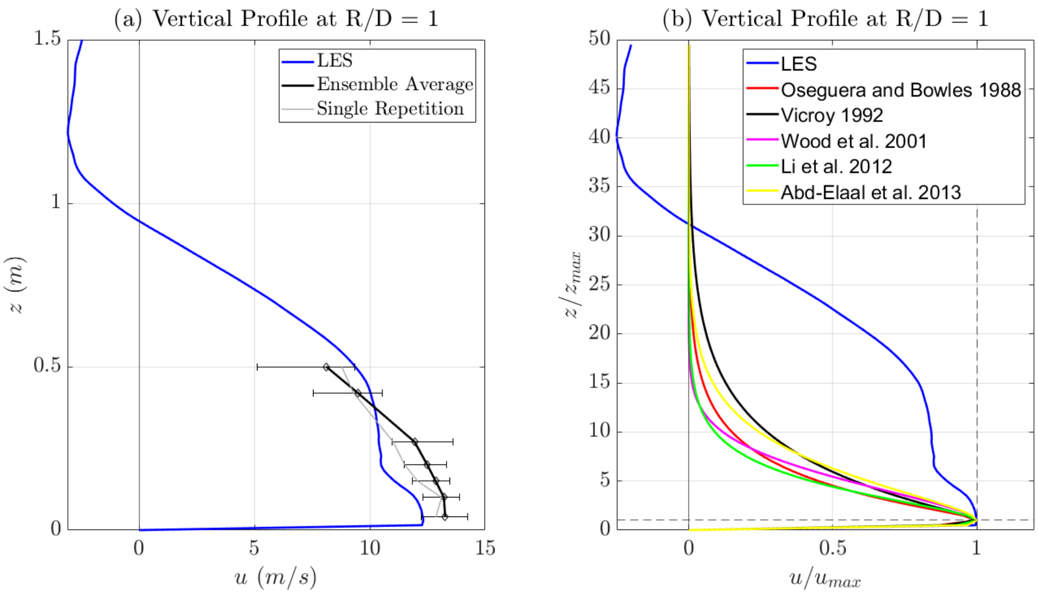

Figure 1. (a) Comparison between LES simulations and WindEEE Dome experiments of the radial velocity vertical profiles. (b) Comparison between LES simulations and analytical models of the radial velocity vertical profile.

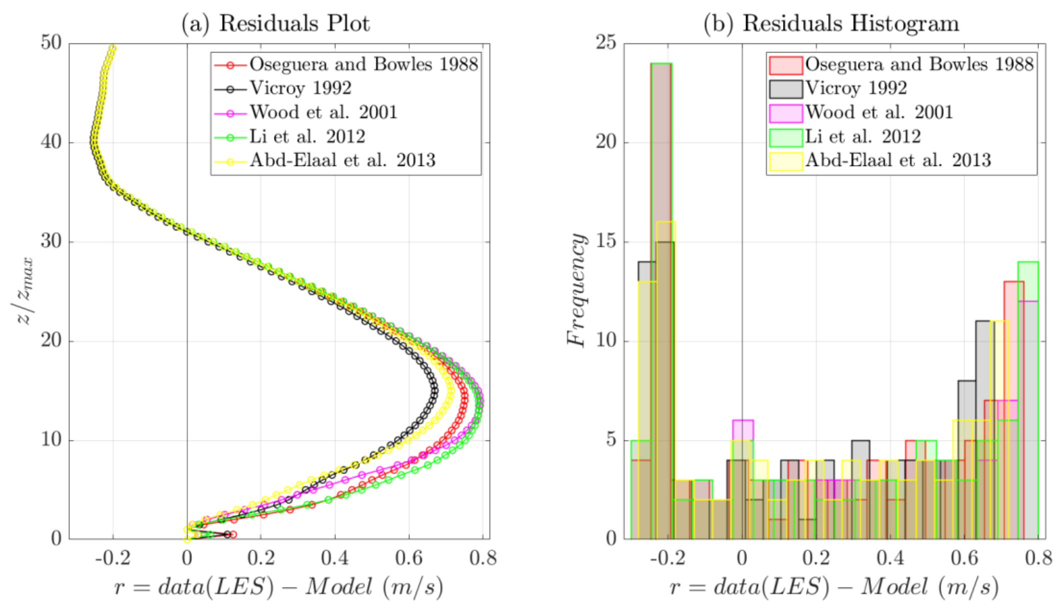

Figure 2. (a) Residuals between CFD simulations and analytical models for the vertical radial velocity profiles. (b) Frequency of occurrence of the residuals.

Table 1. Goodness-of-fit statistics between the LES simulation and the analytical models.

Analytical Models	Mean	SSE	RMSE	R^2
Oseguera and Bowles (1988)	0.2194	18.9344	0.4351	0.4555
Vicroy (1992)	0.1779	14.7351	0.3839	0.4244
Wood et al. (2001)	0.2164	19.4339	0.4408	0.5112
Li et al. (2012)	0.2313	20.6774	0.4547	0.4890
Abd Elaal et al. (2013)	0.1862	15.8876	0.3986	0.4790

3. CONCLUSIONS

This paper shows a comparison of five analytical downburst models and LES simulations calibrated on experimental tests of a stationary DLW carried out in the WindEEE Dome. None of these analytical models can satisfactorily simulate the LES vertical profile of the radial wind velocity. The reason for this difference may relate to the fact that analytical models provide the radial velocity profile of a fully developed impinging jet flow that has reached a steady-state regime. Therefore, analytical models tend to describe the flow scenario after the passage of the PV. However, experimental tests and the LES simulation clearly show that the maximum velocities occur when the PV is at the radial position $R/D = 1$, approximately. As a result, in order to have reliable analytical models which do not underestimate the wind profiles produced by stationary DLWs, it is necessary to simulate the complete transient vortex dynamics. Therefore, vortex ring analytical models (e.g., Shultz, 1990) might instead be more suitable to simulate the radial velocity vertical profiles development.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

A. Xhelaj: Data curation, formal analysis, model comparisons with CFD and Experimental data, writing original draft. J. Žužul: CFD simulations, data curation, review and editing. F. Canepa: WindEEE tests, data curation, review and editing. M. Burlando: Overall supervision, writing – review and editing. Djordje Romanic: Supervision of WindEEE tests, writing – review and editing. Alessio Ricci: Supervision of CFD simulations, writing – review and editing. Horia Hangan: Supervision of WindEEE tests, writing – review and editing.

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