ASSESSMENT OF A HIGHLY PARAMETERIZED STEADY-STATE MICROSCALE WIND SIMULATOR FOR URBAN AIR MOBILITY APPLICATIONS

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Abstract

Urban Air Mobility (UAM) envisions carrying passengers and goods over dense urban cities by operating electric Vertical Take-off and Landing aircraft (eVTOL) closer to ground and built structures, where microscale turbulent wind conditions are prevalent. So, it is of utmost importance to assess and mitigate the effects of microscale wind-relevant challenges on UAM aircraft. However, the scarcity of low-altitude – i.e. less than 2km Above Ground Level – weather observation and UAM operational data has impeded the progress within this sector. Therefore, to resolve the gap of wind data deficiency, this paper assesses the adoption of a steady-state wind simulator, QES-Winds, which is employed within the Atmospheric Science sector for UAM applications. At first, a series of simple wind tunnel test scenarios and high-fidelity CFD simulation test cases are identified and replicated in QES-Winds. Then, the resultant data are qualitatively analysed and compared with the adopted original wind tunnel and CFD simulations data to understand the advantages and limitations of QES-winds for applicability within the UAM sector.

Keywords: Microscale wind modelling; Urban weather; Urban Air Mobility; eVTOLs; QES-Winds

1 Introduction

Urban environment boasts structures of numerous shapes and sizes that increase the terrain roughness and wind flow distortion. These conditions generate turbulent wind fields and microscale flow patterns which have been studied by Atmospheric Scientists and Wind Engineers for decades in the context of predicting pedestrian comfort, forecasting localised weather, determining loads on turbine blades, etc., with the help of prognostic or diagnostic wind field simulation models. However, most of these models trade-off on the computation time for high resolution and accuracy in the prediction of wind flow characteristics within the urban canopy. Adopting such models for UAM applications would be imperceptive, as a typical UAM flight initially would only last for a few minutes due to the current battery limitations of eVTOLs. Likewise, wind fields in the urban environment also make flight testing UAM vehicles within the urban airspace for certification laborious and time consuming, due to the need of elaborate risk mitigation approaches to avoid being unsafe. Therefore, to overcome the weather-pertinent hurdles for quicker and safer development of UAM, it is essential to generate wind data and develop modelling techniques that satisfy the UAM requisite for an accurate and a faster prediction or forecasting of urban wind fields.

Thus far, majority of the publications within the UAM domain that investigate wind flow modelling have been noticed to explore the adoption of hybrid wind prediction or forecasting models that utilize CFD (Computational Fluid Dynamics) techniques in combination with historical mesoscale observational data or statistical models based on Machine Learning or Artificial Intelligence or semi-empirical models like WRF (Weather Research and Forecasting model) [1]. Such coupled simulation techniques are claimed to increase the accuracy of the forecast for a reduced computational cost. However, the computation time still falls way out of the range of a typical UAM flight operational time. So in truth, these models cannot be used for routine UAM operations and are developed primarily for the generation of wind databases or atlas for the urban environment. While such databases would provide the ability to strategically avoid and alleviate the wind-induced complexities and effects on the development of UAM for multiple location-specific scenarios, it is still crucial to develop wind models that execute faster for quicker population of the database [2]. Therefore, this paper aims to assess the usability of a fast computing wind model, QES-Winds [3], for UAM applications.

Quick Environmental Simulation (QES)–Winds is a steady-state microscale wind simulator that is part of the open-source QES pollutant dispersion modelling system [4]. It works on the principle of mass conservation and is developed for neutral atmospheric stability. It is generally used by atmospheric scientists for the quick prediction of pollutant dispersion within the urban canopy. Unlike the CFD solvers, QES does not include momentum or energy conservation, thus solving without shear effects [4]. The solver employs empirical parameterizations that are based on the Length, L, Width, W and Height, H of the objects in the simulation domain to represent the different flow regions such as the recirculation zone within the street canopy, separation zone above the roofs, wake region, leeward and windward side cavity, etc. Furthermore, it allows for the integration of user defined initial velocity profile and provides an option to import ESRI-based shapefiles or terrain elevation files. Overall, QES-Winds produces a 3D quasi-time-averaged velocity field for a short computation time when compared to the traditional CFD based models.

As shown in Figure 1, the overall idea of the paper is to replicate wind tunnel and/ or high-fidelity CFD simulation test scenarios in QES-Winds to assess the software and underlying wind modelling technique for UAM applications through results comparison.

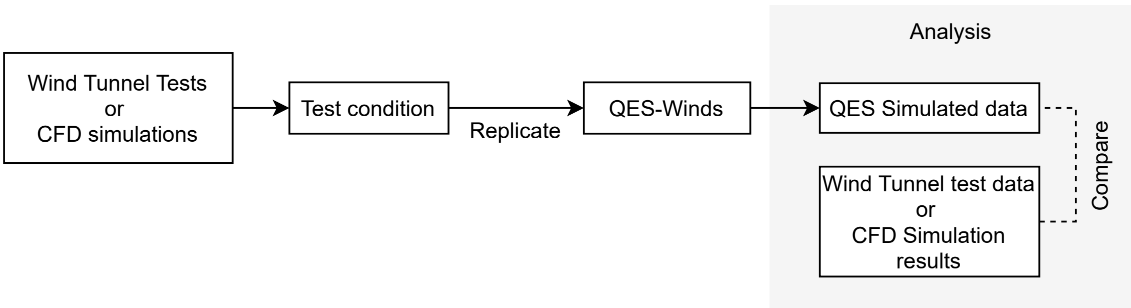

Figure 1 – Flow chart representing an overview of the methodology.

Firstly, the test conditions to be replicated for this study are chosen from 4 papers by keeping in mind the UAM operational area (i.e., dense urban areas, rooftop of a building, etc.,) during the take-off/landing phase as described in the existing UAM ConOps [5, 6] and Vertiport design guidelines [7, 8]. These test cases are detailed in Section 2 and the simulation test results are established in Section 3 along with the comparative analysis. Lastly, in Section 4, a summary of the findings and shortcomings of the QES-Winds for UAM applications are provided along with suggestions for future work.

2 Simulation Setup

A total of 5 simple test scenarios (TS1, TS2, TS3, TS4, TS5) and the corresponding test conditions are drawn from [9, 10, 11, 12]. TS1, TS2, TS3, TS4 and TS5 represent flow over an isolated cubical building, a step-up canyon, a step-down canyon, a ship-shaped object with and without mast, respectively.

The QES-winds input parameters for TS1 are derived from [9], where Meroney et Al use a cube with $L_1 = W_1 = H_1$ dimensions in a wind tunnel under neutral atmospheric boundary layer conditions to study the dispersion and concentration levels of a gas near a cubical model. Likewise, TS2 and TS3 input parameters are adopted from the wind tunnel test studies conducted by Pardyjak et Al in [10, 11]. For TS2, a smaller building of height, H_{2u}, is placed upwind to a taller building of height, H_{2d}, while for TS3, a taller building of height, H_{3u}, is placed upwind of a smaller building of height, H_{3d}. The ratio of height of the building downwind to the height of building upwind, H_d/H_u, used in TS2 and TS3 are 3 and 0.69, respectively. Whereas, the length,L_2, L_3, and width, W_2, W_3 of the buildings in

Table 1 – QES-Winds input test parameters for the 5 test cases.

ID	$U_r(m/s), \beta(deg)$	Wind profile	Roughness,Z_0	Domain size(X,Y,Z)	Mesh size(m)
TS1	4.5, 270°	Power Law	0.075	1400x600x300	0.01
TS2	5, 270°	Power Law	0.15	1000x90x250	0.1
TS3	7.2, 270°	Power Law	0.15	1000x90x250	0.1
TS4 & TS5	4.792, 270°	Power Law	0.1	1200x600x200	0.01

TS2 and TS3 are assumed to be equal to the street-canyon width, W_c, at 3m. Contrary to the first 3 test cases, TS4 and TS5 input parameters are obtained from [12], where Neda et Al experimentally inspect the topology of flow field over a ship-like object using an Atmospheric Boundary Layer Wind tunnel. Although the wind tunnel tests conducted in [12] are originally intended to characterise the topology of wind flow field over a simple frigate ship, the ship-like object can be considered as an obstacle with complex geometry in the urban landscape. Thus, TS4 and TS5 were selected as special test cases to determine the abilities of QES-Winds to parameterize the different flow regions for a complex geometry. The only difference between TS4 and TS5 is that the geometry of TS4 looks like a ship equipped with mast, whereas the geometry of TS5 is devoid of mast and appears similar to a stacked-building.
A detailed overview of the key QES input parameters derived from the above referenced papers for the recreation of the flow fields are tabulated in 1, and representations of QES domain for the 5 test cases are shown in Figure 2

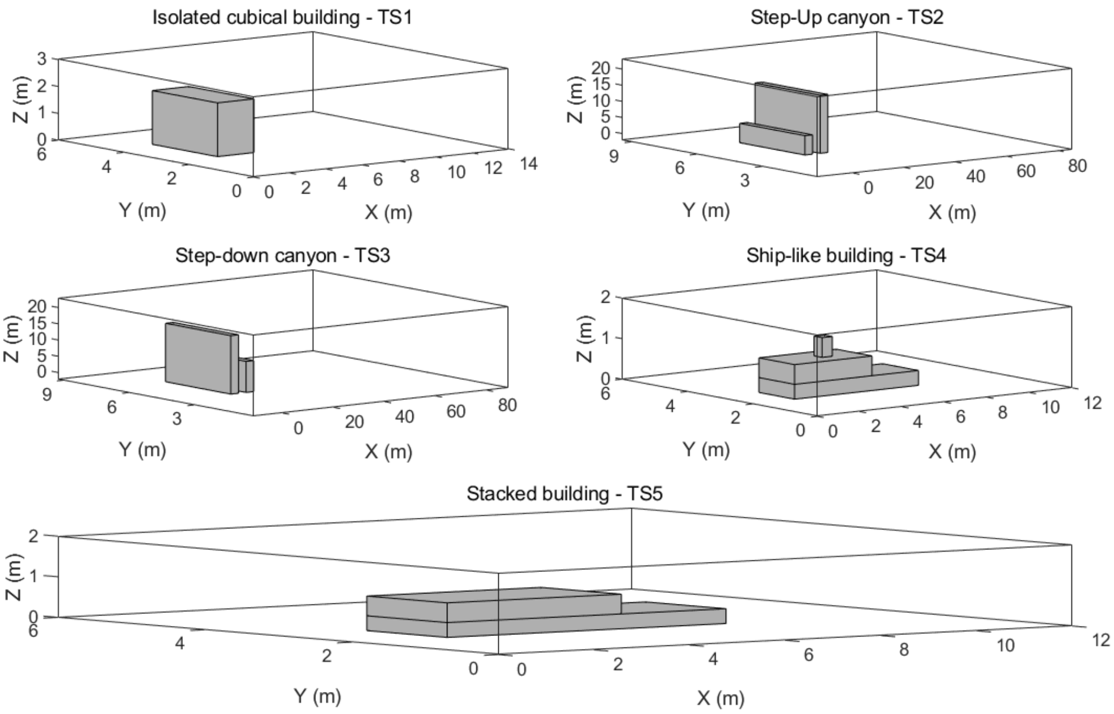

Figure 2 – QES domains for TS1, TS2, TS3, TS4 and TS5.

All the tests are performed under a uniform stair-step mesh configuration with the side wall, leeside vortex, far wake, upwind cavity and rooftop circulation parameterizations set to the default QES setting (refer to figure 3). Similarly, the input wind profile for all the tests are set to follow the power law profile:

$$\frac{U}{U_r} = \left(\frac{Z}{Z_r}\right)^{Z_0}$$

where U_r is the wind velocity at the reference height Z_r (2m for TS1, 6m for TS2, 18m for TS3, and 1.5m for TS4 and TS5) and Z_0 is the surface roughness.

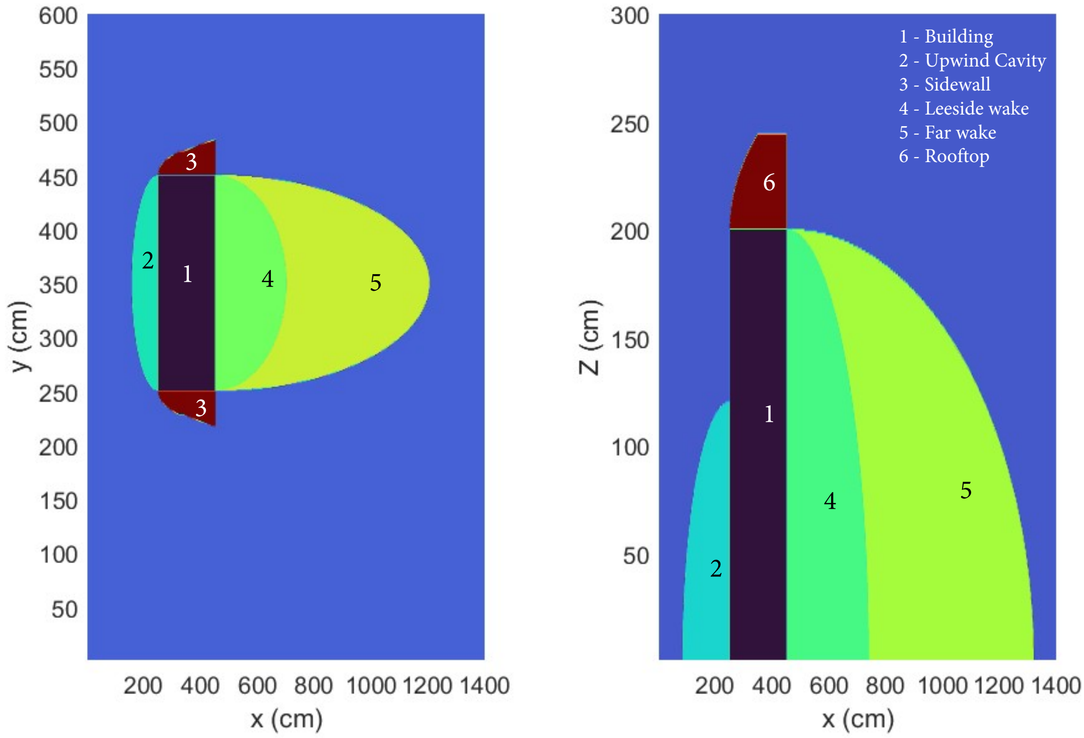

Figure 3 – TS1 flow region parameterizations shown in XY and XZ plane.

The test object geometries for TS1, TS2 and TS3 are defined in an XML file format, while for TS4 and TS5 an ESRI based .shp shapefile is utilized to define the ship-like geometry. Although, QES allows for 3 different ways (DEM (Digital elevation models) rasters, ESRI Shapefiles, and XML files) to define the object geometries within the simulation domain, a careful choice of the file format has to be made depending on the test case. For example, DEMs can only be used to represent topographical elevations (such as mountains, hills, etc.) and not buildings, whereas, XML and Shapefiles can be employed to describe building attributes within the simulation domain.

In addition to the general simulation setup, during the execution, each test cases were executed twice. This repetition was carried out primarily to obtain metrics on the computation time taken by the CPU and GPU based QES solver for the comparison analysis.

3 Simulation Test Results and Comparative Analysis

This section furnishes the 3D flow fields simulated by QES-Winds for TS1, TS2, TS3, TS4 and TS5 along with a comparative study. The QES results for each test cases are compared with the data obtained from [13, 14, 15] and the referred papers in section 2. Alike this assessment paper, the authors in [13] obtain test conditions from [9] to evaluate LES and RANS based wind solvers. In a similar fashion, the test cases in [14, 15] are referred back to [10, 11]. Thus, it was concluded that it would be apt to use also the results from [13, 14] and [15] for the TS1, TS2 and TS3 comparative analysis, respectively. Additionally, for better comprehension and to ensure parity of this comparative analysis with the referred papers, the flow fields presented in this section focuses only on the following regions: 1. Rooftops and wake behind the buildings for TS1; 2. Street canyons for TS2 and TS3; and, 3. Wake region on the deck of the ship-like object for TS4 and TS5. Thus, the 3D data are processed only at the mid-planes of the above listed regions as shown in Figure 4 for all the test cases.

The key performance metrics opted for the comparative analysis are the computational time and accuracy of the data produced by QES-Winds for each test cases. The accuracy is qualitatively evaluated by comparing the flow fields reproduced by QES-winds at different regions to the flow and velocity field figures published in the referred papers. Whereas, the computational time is obtained from the CPU and GPU clock time for executing each test cases in QES-winds. These metrics are chosen keeping in mind the dissonant UAM requisite for a fast and accurate wind data.

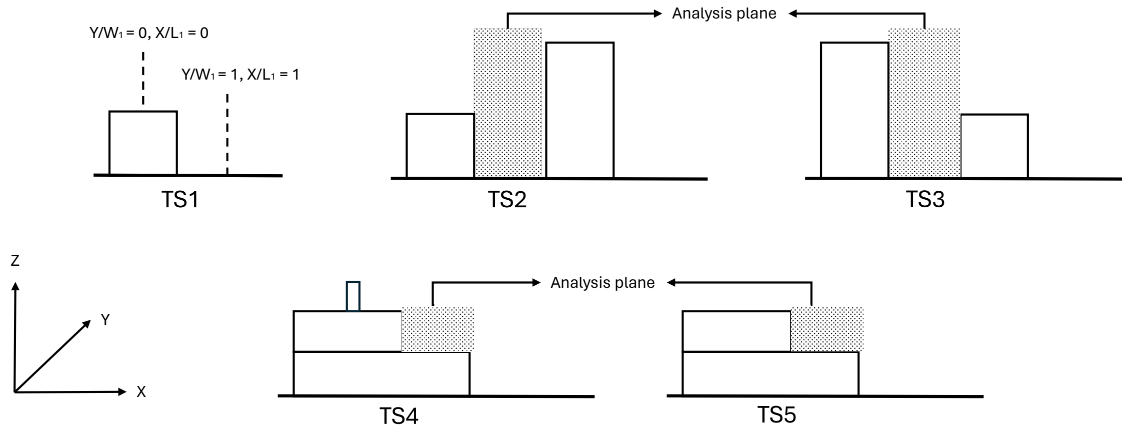

Figure 4 – Planes where data are processed for the test cases.

3.1 TS1 - Flow over an isolated cubical object or building

The flow field generated by QES for TS1 is shown in Figure 5. It can be noted that a stagnation point is predicted at $Z/H_1 = 0.625$ where the flow reverses to create a vortex in the upwind region of the model. Likewise vortex regions can be seen on the leading edge and close to the trailing edge of the building rooftop. A recirculation zone is formed behind the building and stretches upto 2.5m downwind of the cubical object. Although, the wind field generated by QES appear similar to the descriptions made in many literature about the topology of flow over an isolated cube, the length of reattachment zones, vortex regions and flow velocities predicted by QES are slightly overestimated when compared to CFD based numerical simulations and wind tunnel tests.

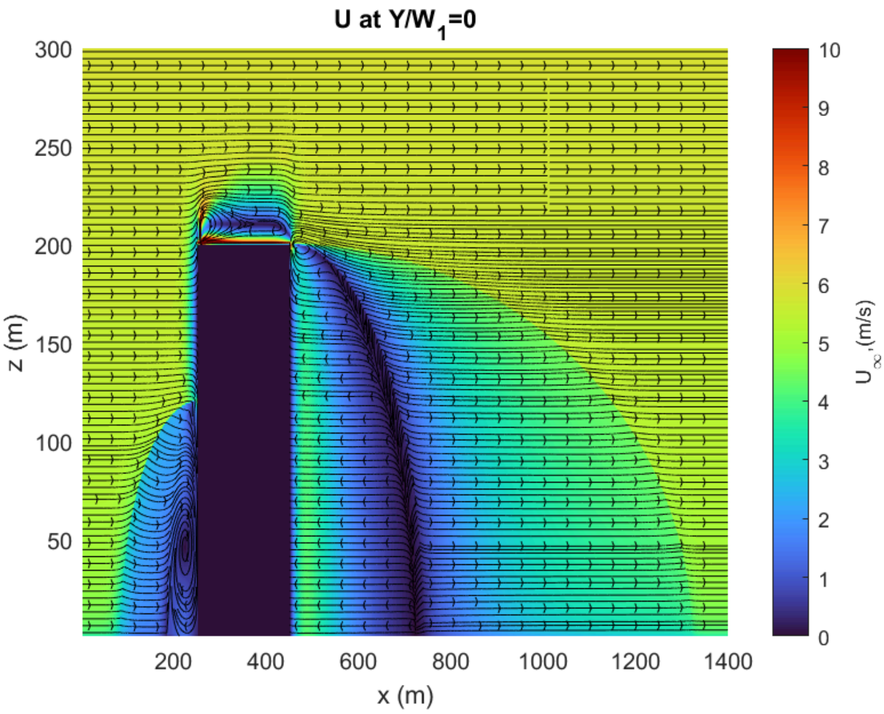

Figure 5 – Change in U magnitude and streamlines of flow over an isolated cubical building simulated by QES-Winds (TS1) in XZ plane.

For example, in Figure 6, it can be noticed that the vertical distribution of the streamwise velocity predicted by QES at the rooftop and wake region behind the building is higher when compared to the values generated by LES, RANS and wind tunnel experiment. Table 2 compares the reattachment lengths predicted by QES with that of the Wind Tunnel test data, LES and RANS simulations at

Table 2 – Reattachment length comparison for TS1 (* values adopted from [13].

	Rooftop	Wake Region
Wind Tunnel*	0.64L_1	1.33L_1
LES*	0.79L_1	1.54L_1
RANS*	0.87L_1	2.46L_1
QES-Winds	0.95L_1	2.375L_1

rooftop and wake region. The values in the table further signify that the vortex region at the rooftop is amplified by QES, while the length of wake zone estimated by QES is marginally better when compared to RANS.

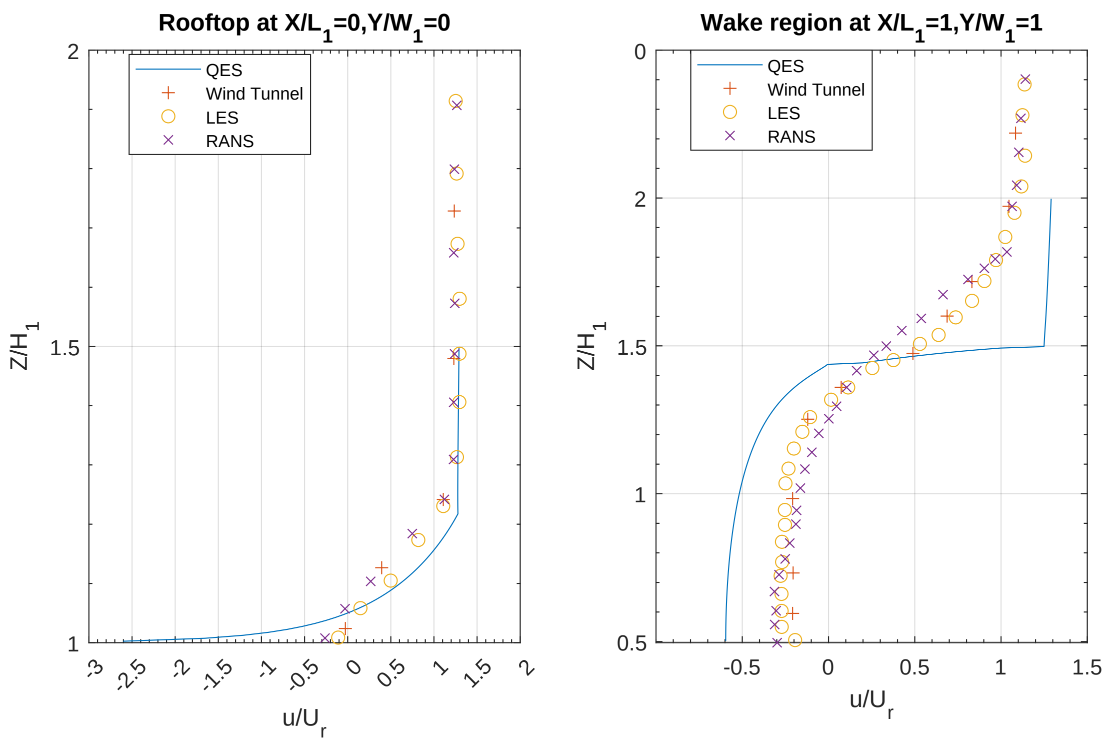

Figure 6 – Streamwise velocity profile at the rooftop and wake region of the TS1 object.(*Datapoints for Wind Tunnel, LES, and RANS are obtained from [13].)

3.2 TS2 and TS3 - Flow fields in a step-up and step-down street canyon configuration

The streamlines of velocity magnitude for TS2 predicted by QES is shown in Figure 7. In [10], the wind tunnel test data obtained by the authors for the same test conditions show the existence of strong negative vertical motions in the canyon region, however, QES under predicts these vertical motions in the canyon region. Furthermore, the stagnation point from the QES data is approximately located at $Z/H_{2d} = 0.6$. This is much lower compared to the stagnation point attained through wind tunnel tests and CFD based numerical simulations in [10, 14]. Similarly, the position of the vortex core in the canyon region is observed to be comparatively much higher for the QES generated data.

Alike TS2, the updraft within the canopy region predicted by QES for the step-down canyon configuration (TS3) is significantly under estimated when compared to the Wind-tunnel test data in [11]. The leeside vortex core of the taller building is positioned at approximately $Z/H_{3u} = 1.2$ in the data simulated by QES, while the core is situated closer to the trailing edge of the upwind building rooftop in the PIV data [15]. It can also be observed that QES pushes the vortex further up in the leeward side of the tallest building for both TS2 and TS3, this is suspected to be due to an issue with how the wake and rooftop regions are parameterized for the tallest object in the step-up and step-down type

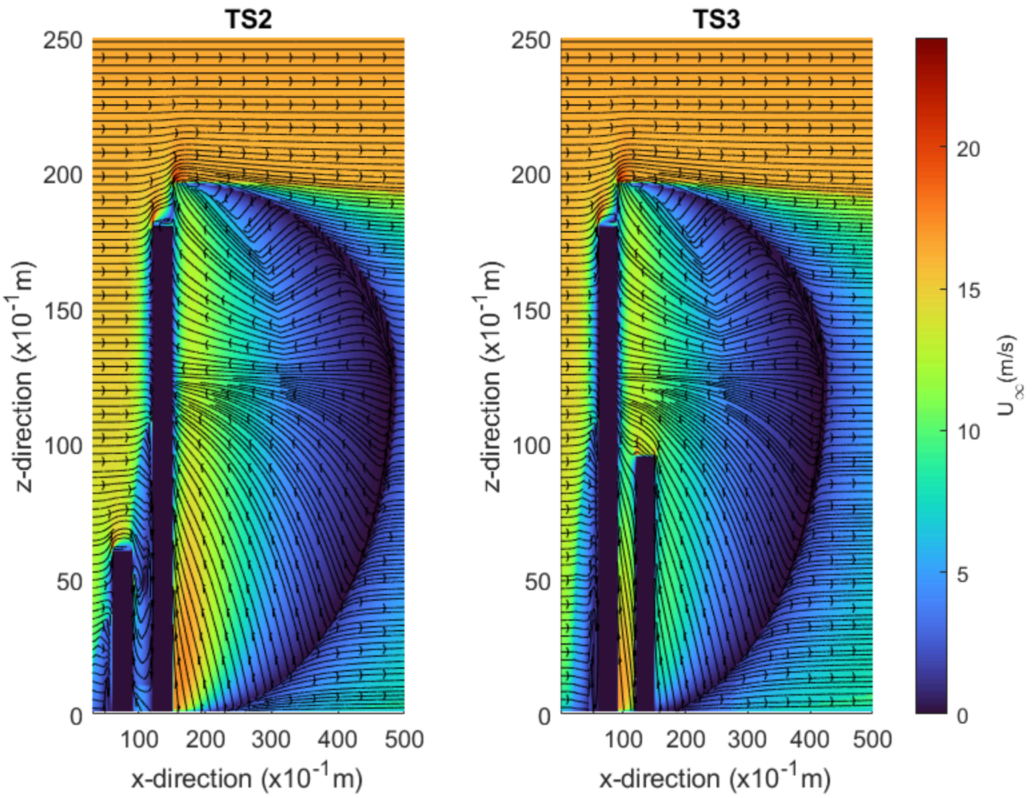

Figure 7 – Streamlines of flow and velocity field for TS2 and TS3 in XZ plane at $Y/W_2 = 0$ and $Y/W_3 = 0$, respectively.

configuration. Overall, it can be said that flow field estimated by QES for TS2 and TS3 configurations vary significantly while also underestimating the updraft within the canyon regions.

3.3 TS4 and TS5 - Flow over a ship-like object with and without mast

As previously mentioned, TS4 and TS5 where chiefly executed to test the ability of QES to generate flow fields for complex geometry. The aim of these two test cases were to obtain a flow field similar to the one produced in wind tunnel tests conducted by Neda et al in [12]. However, it is evident from Figure 8 that the flow field generated by QES is very convoluted. Especially, for TS4, the presence of the third structure (mast) introduces more contortion to the flow when compared to the streamlines generated by QES for TS5. It can be observed that the vortex formation for TS5 is maybe slightly comprehensible to TS4, but the velocity field produced by QES for both TS4 and TS5 is erroneous. Similarly, a secondary vortex can be seen on the deck-top with the QES generated data. These adverse faulty predictions have been identified to be due to the following reasons:

1. Firstly, QES-Winds software can only read simple geometries that have a uniform L and W for different H. For example, an object like a cube is effortlessly parsed by the software when compared to an object that have varying L, W with H. This limitation in the current release of the software (v2.2.0) is a hindrance when wanting to simulate wind flow fields over complex geometries like the ones used in TS4 and TS5, as the user will have to define 3 different geometries each with H values commencing from the ground. However, this workaround will overlay the 3 geometries on top of each other, creating further complications that ripple through the overall backend process of the software.

2. Second important reason is the way the different flow regions are parameterized in QES-winds. As QES is a diagnostic 3D steady state wind field simulator that only works on the principle of conservation of mass, the wake region, upwind cavity and the rooftop zones, etc., are estimated using the L, W, and H of the objects in the domain. For example, the leeside wake region is

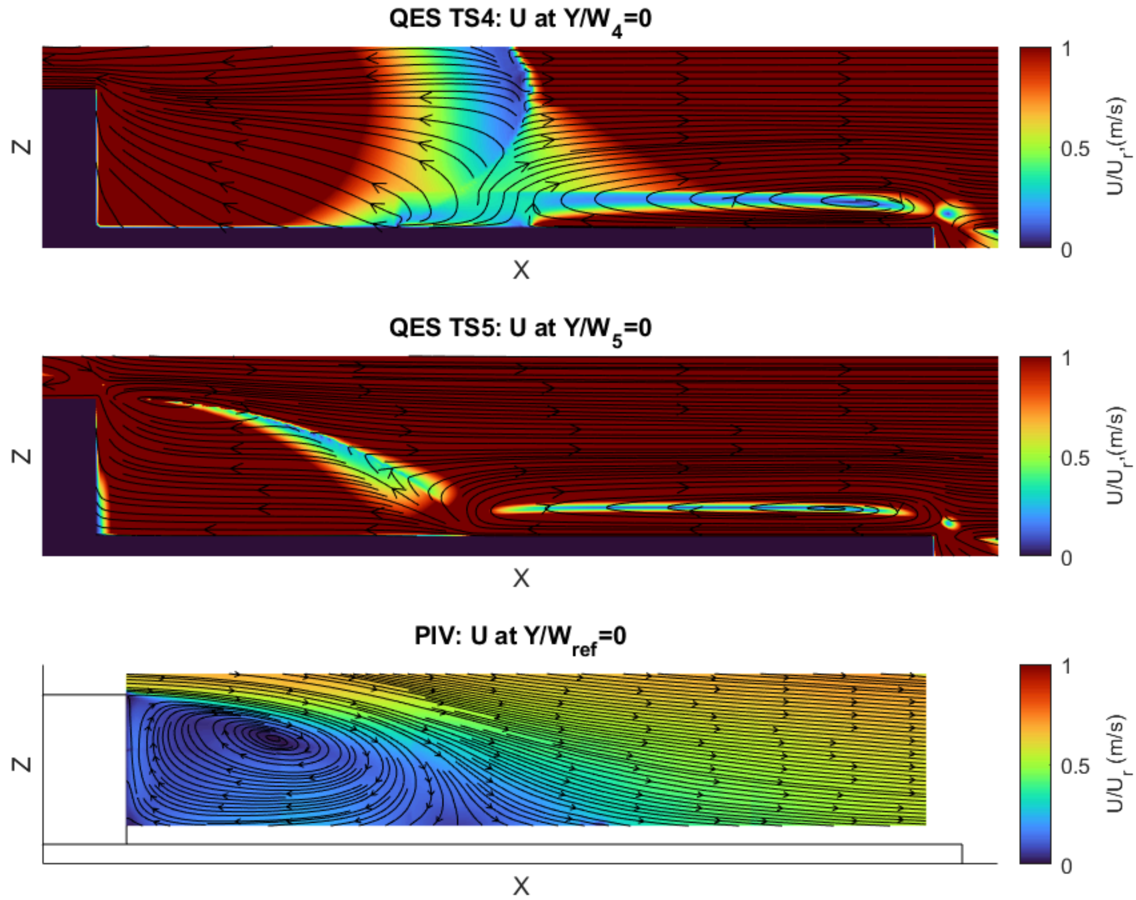

Figure 8 – Velocity magnitude of flow over a ship-like object with mast and without mast in XZ plane.

defined as an ellipsoid with Length, L_R, that stretches a certain distance downstream behind the object using the L, W, and H of the object [4] as:

$$\frac{L_R}{H} = \frac{1.8\frac{W}{H}}{\left(\frac{L}{H}\right)^{0}.3\left(1+0.24\frac{W}{H}\right)}$$

Such assumptions and calculation would work fine with configurations that use simple geometries within the simulation domain, but strain with geometries that have varying L and W with respect to H.

3. Lastly, as a repercussion of the previous two points (QES-Winds inability to process complex input geometries and the overlay of parameterizations (see figure 9), especially in the wake region), the velocity field is exaggerated unrealistically in the leeside of the test object. As the velocity field in the wake region is estimated by:

$$\frac{u(x,y,z)}{U_r} = \left(1 - \left(\frac{d}{x}\right)^{1.5}\right)$$

'd' is the ellipsoid shaped cavity length along the streamwise direction that depends on L_R, L, W, and H of the object [4].

The computation time taken by QES to solve for the wind fields is extremely fast and cheap when compared to computational cost and CPU clock time listed in ([13, 14, 15]) for the CFD based numerical simulations such as RANS and LES. However, it has to be mentioned that both RANS and LES of TS2 and TS3, use a 3.2m=1m scale for a domain size of 576x198x162 while QES uses 1cm=1m scale for a domain of 1000x90x250. This further implies that QES winds has a lower computation time to the CFD based RANS and LES solvers.

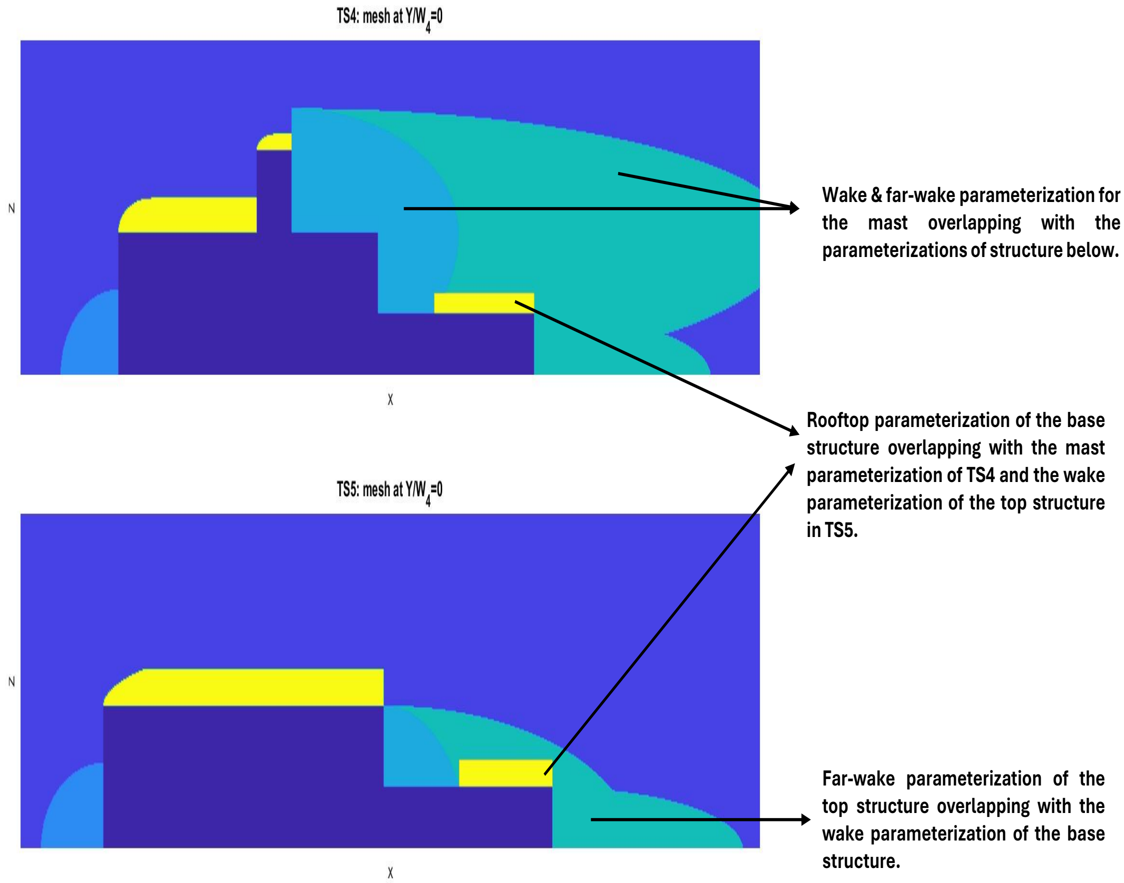

Figure 9 – Overlapping parameterizations in TS4 and TS5.

Table 3 – Computation time comparison.

	QES (CPU)	QES (NVIDIA GeForce RTX 9030)	RANS	LES
T1	41min	61s	unknown	25xRANS
T2	49s	3s	5hrs	2.5days
T3	49s	3s	5hrs	2.5days
T4	56min	37s	-	-
T5	18min	27s	-	-

4 Conclusion

In summary, this paper assesses a fast computing steady-state 3D diagnostic wind solver, QES-Winds, that simulates microscale wind conditions, for UAM applications. A series of 5 test scenarios were identified through an initial literature review. Then, these test cases were replicated using QES and the resultant microscale wind data from QES were qualitatively compared with Wind tunnel and CFD based simulation data from the referred papers.

From the qualitative comparison analysis, it has been deciphered that the performance of QES varies significantly with respect to the test scenarios and geometries of the object within the simulation domain. That is, QES is observed to overestimate velocity fields for test case considering flow over a simple cubical object, whereas it is seen to undervalue the updraft within the street canopy and incomprehensibly distort velocity fields for test objects with geometries whose L and W vary with H. Such inconsistent behaviour of QES stipulates the need for further testing by taking varied test scenarios into consideration for a thorough understanding of the QES-winds potential for simulating different flow regimes and scenes of urban environment. Along similar lines, although the accuracy of QES is expectedly less compared to the high fidelity CFD solvers and wind tunnel test data, it is not bad for a highly parameterized wind simulator that only employs the principles of conservation of mass. In fact, this slight tradeoff has enhanced the computational efficiency significantly when compared to the traditional CFD based wind simulators. Thus, considering one of the key requisite for safe UAM operations –i.e. a faster and accurate low-altitude microscale wind simulator and forecaster that takes into account the complex structures within the urban canopy– it can be said that QES still has the possibility to be an efficient wind solver. But, to firmly ascertain that QES-Winds can be used for UAM applications, it is still essential to quantitatively evaluate the accuracy of data generated by QES-winds. Moreover, this would also pave way for determining whether the current algorithm could be further tuned for lesser errors. However, due to lack of data samples for validation, a quantitative evaluation of the wind velocity fields predicted by QES could not be performed within this study.

Another difficulty that was confronted in this study is the inability of the current QES software version to parse input geometries that have varying L,W and H, due to how the input data are processed in the backend. This underlying software issue is also suspected to be the reason for extreme contortions in the parameterizations of the flow regions for test cases involving complex geometry. This suggests the need to improve the QES algorithm to allow for simulation of flow fields over complex urban structures as a typical urban environment would not just comprise of cubical buildings.

Therefore, future works with QES should include the following tasks: 1. Redevelopment of the software to allow for parsing shapes whose L,W vary with H; 2. Revision of parameterization techniques to enable simulations of flow over complex geometries; 3. Extensive testing of the QES solver for different test scenarios; 4. Validation of QES-results and quantitative evaluation of the performance of QES-winds. Moreover, it is also necessary to state that QES-winds will not be applicable for use as a standalone software for UAM applications. Thus, integration of low altitude turbulence simulators or models and mesoscale wind data from WRF (Weather Research and Forecasting) models or other forecasters must also be explored.

In conclusion, while this study provides insights on the capabilities and limitations of QES-Winds for simulating steady-state microscale low-altitude wind conditions rapidly, there is still substantial amount of work to be done. Thus, the findings and the recommendations from this study can be used as a starting point to further investigate the use of highly-parameterized wind models like QES-Winds for UAM aircraft operations, testing and certification.

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7 Copyright Statement

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