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Advanced Air Mobility and Building Design: Understanding the Impact of Shape on Wind Conditions

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ABSTRACT

Drones are planned to fly in close proximity to buildings as a part of the Advanced Air Mobility (AAM) concept, but there are gaps in our understanding of the flow structures around buildings and their associated temporal and spatial velocity distributions relevant to drones and their planned flight trajectories. The detached shear layer above buildings and the vortices emanating from the corners of buildings at oblique angles to the wind are expected to be particularly problematic for flight. This paper outlines preliminary results and plans to study the flow field around different building geometries thus highlighting the need for careful consideration of building geometry in the planning and design of AAM landing and takeoff areas to ensure safe and efficient operations.

1. The increasing demand for AAM and knowledge of wind conditions near buildings

Advanced Air Mobility (AAM) involves the use of flying vehicles, such as drones and electric vertical takeoff and landing (eVTOL) aircraft, for transporting goods or personnel, which are envisioned to operate from rooftops and vertiports. AAM, therefore, has the potential to revolutionize transportation by providing faster, more efficient, and more environmentally friendly means of travel. However, for AAM to become a viable mode of transportation, it is important to ensure safety during landing and takeoff operations. One of the key factors for AAM safety is the flow field surrounding vertiports; AAM craft will routinely fly through these complex flow fields surrounding buildings which can be hazardous during high wind magnitudes or gusting conditions.

Whilst the effects of the interaction of the atmospheric boundary layer have been studied for over fifty years, the focus has been on the effects of high winds on building surface pressures, forces and moments rather than on the local wind field per se (Blocken 2014). Exceptions to this are studies on ground-level winds under strong winds and studies on the dispersion and movement of pollutants under light winds, for example (Robins and Castro 1977; Leuzzi and Monti 1998). With the advent of AAM, there is a need to understand the wind fields under a range of wind speeds and directions for typical flight paths over and around buildings. The detached shear layer is problematic since the rapid change in wind speed and direction at the shear layer is significant, so a UAV passing through it will experience large and abrupt disturbance. A numerical analysis was undertaken proving the detrimental effect of flying through shear layers (Mohamed et al. 2022). The recirculation region is also highly turbulent with strong downwash which will be challenging when trying to land or take off vertically. The corner vortices are also expected to cause control issues as vortices generate large pitch and roll inputs. Characterising these aerodynamic phenomena for different building geometries will help guide vertiport design and inform safe AAM operations.

2. The Flow field Around Buildings

Vertiport buildings, as part of the built environment, can have a significant impact on wind flow patterns, and thus, it is important to consider the effects of building geometry on local wind conditions. The presence of nearby buildings can also change wind flow patterns in the vicinity of AAM landing and take-off areas, however a thorough understanding of the flow field around an isolated building is first needed before considering the surrounding buildings. The goal of the research is to evaluate the impact of different geometric parameters on the building's aerodynamics and local wind conditions, which will inform the design of future buildings to optimize wind conditions for advanced air mobility operations. Wind magnitude and direction are expected to affect the shear layer and the corner vortices; corner vortices only appear when the flow is not perpendicular to the building's leading edge (Holmes and Bekele 2021), and the CFD study by Kono, Kogaki, and Kiwata (2016) on the influence of a building's horizontal aspect ratio and wind direction on conditions for roof-mounted wind turbines showed a large variation in the size and shape of the detached shear region with wind angle.

2.1 Preliminary Wind Tunnel *Experiments*

Experiments have been carried out at RMIT's industrial wind tunnel with a model of a nominally cuboid building previously studied by Mohamed et al. (2015). The building model was pressure tapped at strategic locations on its surface to measure the pressure distribution across the building model. These measurements provided detailed insights into the aerodynamic behaviour of the building model and how its shape affects the surrounding wind conditions. The building's geometry and the pressure-tap locations are shown in Figure 1 below along with a sample measurement from the one of the pressure taps.

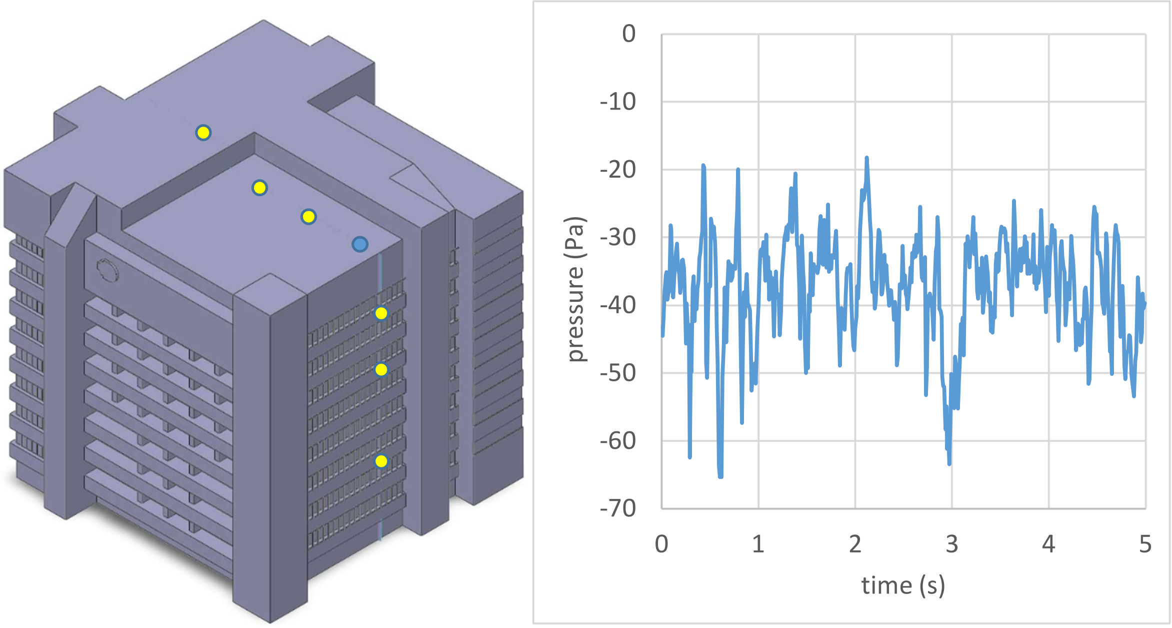

Figure 1. Model geometry with pressure-tap locations and surface static pressure sampled at the location shown by the blue dot.

The flow field around cuboids, that are aligned with the flow, is relatively independent of Reynolds' number above 20,000–30,000 which is well below the typical Reynolds numbers for buildings and the scale models used to study them. Cuboids at 45 degrees to the flow appear to be sensitive to Reynolds number at higher Reynolds' numbers though, including in the range relevant to scale experiments of buildings and the buildings themselves. The plot from the paper by Lim, Castro, and Hoxey (2007) shown in Figure 2 below illustrates this quite nicely: it shows the surface-pressure coefficient measured at a point on a cube plotted against Reynolds' number and shows a clear Reynolds sensitivity up to Re=320,000 and suggests sensitivity to at least Re=2.4x10^6. The point where the surface pressure was measured is near the leading edge on the upper face. This area is particularly sensitive to Reynold's number, presumably because it is beneath the vortex rolling up off the leading edge. This indicates the vortices forming around buildings, and hence the flow field in general for buildings not aligned with the wind, are probably also sensitive to the difference in Reynolds' number between full-scale and the scale experiments representing them.

The Reynolds' number for the experiments is about 500,000 based on height of the baseline unmodified 1/100th-scale cube and the mean flow speed at that height – 1/20th that of the full-scale building. The orange and red lines in Figure 2 show the Reynolds' numbers for the scale model and the full-scale building respectively. There are not enough data points between the scale-model and full-scale Reynolds' numbers to confirm there are Reynolds number effects in this range, but the linear trend of the other data points strongly suggests Reynolds' number effects are present and will need to be considered when interpreting results from the scale experiments.

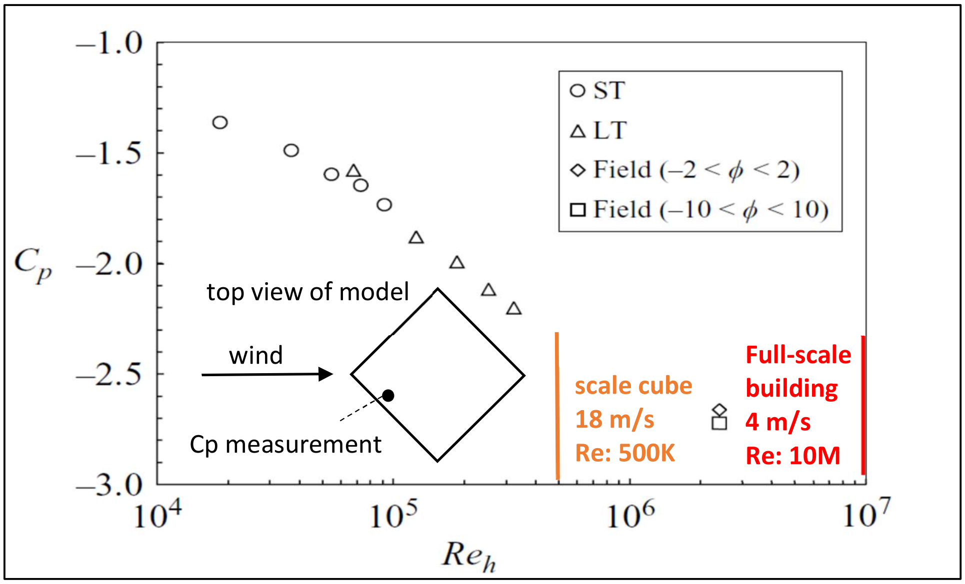

Figure 2. Mean surface static pressure at a point 0.356h along the leading edge and 0.069h from it as a function of Reynold's number and measurement location on the roof of the model (inset). ST and LT refer to datasets taken in 'small' and 'large' wind tunnels respectively. Adapted from Lim, Castro, and Hoxey (2007)

2.1.1 Modelling the Suburban Boundary Layer

To capture the correct flow physics, the Atmospheric Boundary Layer (ABL) needs to be modelled. This is done with an arrangement of barriers to achieve a scale suburban ABL profile. The resulting time-averaged velocity profile is shown in Figure 3 on the left. The blue line is the velocity profile for a 'suburban' ABL based on the power law provided by Walshe (1972). On the right is the turbulence intensity profile which has been calculated from the Cobra-probe data, which was sampled at 2.5kHz.

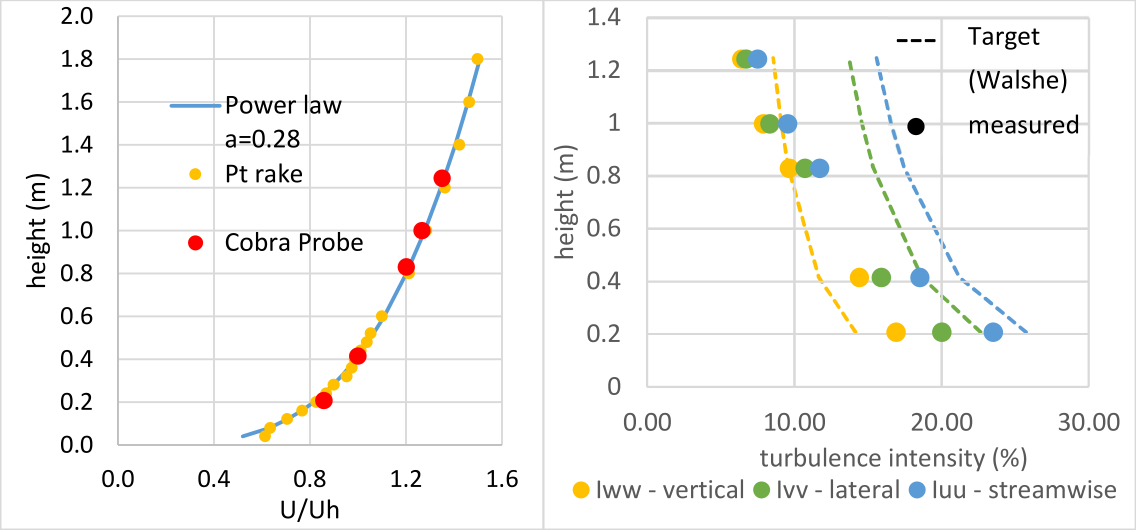

Figure 3. (left) measured time-averaged velocity profile. (right) measured turbulence intensity profile.

2.1.2 Preliminary Particle-Image Velocimetry (PIV) Results

Flow mapping around the leading edge of a scale cube has been done using particle image velocimetry (PIV). 0.3mm helium bubbles were used as the tracked particles and illumination was provided by an LED light sheet. Video for the PIV analysis was recorded at 1000 frames per second via a high-speed camera. Figure 4 below shows contours of the mean and instantaneous velocity and vorticity from the PIV analysis, with computed streamlines overlaid on top of the contours. The cube's location is shown by the grey coloured region, the black area was excluded from the analysis due to shadowing.

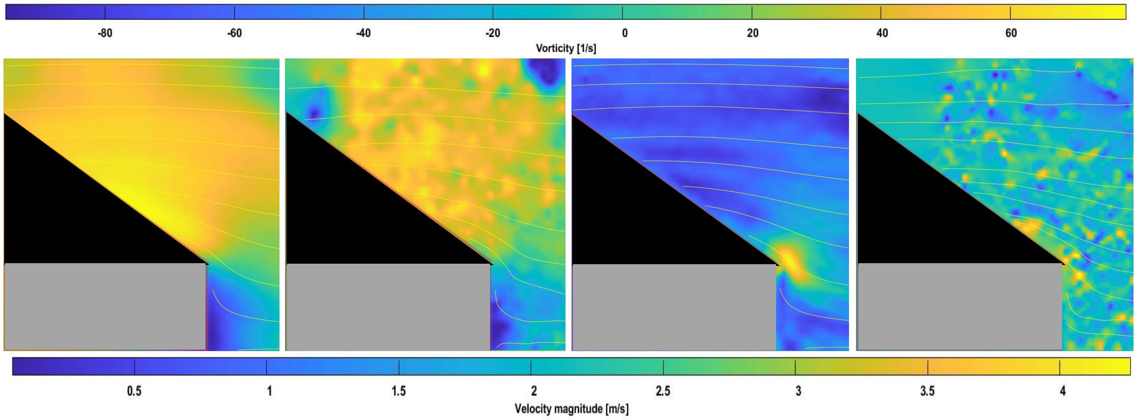

Figure 4. PIV velocity contour coloured by (a) mean velocity magnitude, (b) instantaneous velocity magnitude, (c) mean vorticity, (d) instantaneous vorticity. (a) & (c) are time-averaged over a 5-second period.

3. Future Work

Wind tunnel experiments can be combined with other analysis to provide more insight. We intend to undertake a combination of numerical CFD simulations and full-scale measurements, in a suburban ABL. This will include wind measurements from fixed and moving drones around an existing, nominally 40m cuboid building which has been the subject of prior studies (White et al. 2012; Mohamed et al. 2015; Lim et al. 2016). The full-scale data sets are being compared to 100th-scale wind-tunnel replication and CFD simulations. After examining the veracity of the wind-tunnel and CFD studies via the full-scale data we plan to extend the studies to include a range of building geometries relevant to future vertiports. The varied parameters will focus on aspect ratio and wind direction.

3.1 Full-scale measurements

The full-scale measurements will be taken around the 40m nominally cuboid building mentioned in section 3. It is isolated from structures of a similar height, so should be exposed to a relatively 'clean' suburban atmospheric boundary layer profile, see (Watkins et al. 2015) for further details on the building and it's surrounds. The Reynolds' number based on the building height and the average wind speed at that height is about 10 million. Wind velocity around the building will be measured with Cobra probes (multi-hole pressure probes) for locations near to the building, and wind-sensing drones for harder-to-reach areas.

Our previous research involved the use of airborne wind sensing through the integration of multi-hole pressure probes with multirotor drones for in situ atmospheric measurements (Prudden et al.). Preliminary experiments demonstrate that small scale turbulent structures can be resolved in flight. Further research is currently being undertaken to develop a swarm of hexa-rotor drones, see Figure 5, to enable simultaneous measurements at different spatial positions that would represent virtual wingspans of AAM vehicles. This would allow for better understanding of likely disturbances to the expected flight path due to turbulence or violent gust events within the urban environment. This system could also be used to validate scale models and CFD simulations, as well as survey flow fields around existing structures for the retrofitting of vertiports.

Figure 5. A hexa-rotor drone with multi-hole anemometer system

3.2 Numerical simulation

Numerical simulations of the geometries will be combined with the experimental results to avoid some of the limitations associated with each method and improve the accuracy and 'completeness' of the data. A simulation of wind around the 40m nominally-cuboid building was used as part of a previous study on the updraughts and turbulence levels upwind of the building for soaring UAV's (Mohamed et al. 2015). The simulation was an unsteady scale-resolving simulation using the Improved Delayed Detached Eddy Simulation (IDDES) turbulence model, and successfully modelled the mean velocity and time-varying velocities on the scales relevant to small UAV's, and hence AAM craft by default. Similar CFD simulations will be done on the geometries used in the wind-tunnel testing in this study. Numerical modelling will also be used to extend the range of geometries tested, due to the relative ease of running multiple simulations. It will likely be used to study the geometries at additional wind angles and to study additional geometries although how the study is extended will be guided by analysis of the initial results.

4. Concluding Remarks

This paper highlights the need for further research on the flow patterns and velocity distributions around buildings in relation to drone flight as a part of the Advanced Air Mobility (AAM) concept. The potential challenges posed by the turbulent air above buildings and vortices from building corners at angled winds are emphasized. The importance of considering building design in the planning and design of AAM landing and takeoff areas for safe and efficient drone operations is also highlighted. Further studies on the flow patterns around different building shapes are needed to ensure safe drone operations in proximity to buildings. This paper presents initial findings and plans to research the flow patterns around different building shapes, highlighting the importance of considering building design when planning AAM landing and takeoff areas for safe and efficient drone operations.

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