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Scale-resolving simulation to predict the updraught regions over buildings for MAV orographic lift soaring

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ABSTRACT

Birds have been observed to soar over ridges, mountains and cliffs to extend their flight duration with minimal energy expenditure. There is an opportunity to replicate this behavior to enhance the flight duration of Micro Aerial Vehicles (MAVs) which operate in urban environments by exploiting the vertical flow component (orographic lift) of flow over buildings. This paper therefore studies the flow field in a representative urban environments to enhance the operational capability of MAV platforms by increasing range and endurance. The feasibility and benefits of employing Computational Fluid Dynamics (CFD) are investigated, to simulate the turbulent wind flow conditions around a building configuration. A three-dimensional, scale-resolving simulation, utilizing a derivative of the Detached Eddy Simulation approach was considered. The atmospheric boundary layer velocity and turbulent intensity profiles were calibrated at the inlet boundary of the computational domain, to replicate nominal operating conditions. Recent validation of the Improved Delayed Detached Eddy Simulation (IDDES) approach has shown excellent agreement for a number of relevant flows. This provided the motivation for the study of a full-scale multi-building configuration, and suggests that the use of high-fidelity turbulence modeling is able to predict updraught regions of buildings in an urban environment.

1. MAV orographic lift soaring

Harvesting energy from the over-speed regions of buildings is a novel research area. There are a number of techniques available for extracting energy from these over-speed regions and updraughts (e.g. wind-turbines), but this paper focuses more on the benefits to Micro Air Vehicles (MAVs) (Mohamed et al., 2012; White et al., 2012). Whilst the development of MAVs has benefited from miniaturization of batteries and on-board electronics, range and endurance are still limited. There is significant research in developing aerial platforms that can track and exploit thermals as an energy source to gain height (Allen, 2005; Allen and Lin, 2007; Edwards, 2008; Wharington and Palmer, 2009). However, exploitation of updraughts over buildings (orographic lift) remains relatively unexplored. Orographic lift, as an energy source, suits urban MAV operations due to the abundance in urban environments, known stationary location, and relatively higher intensity compared with thermals (Bohrer et al., 2012). Fig. 1 summarizes the preference of orographic lift over thermals.

Due to the novel nature of the application and associated challenges, little experimental work exists (Wharington and Palmer, 2009). The feasibility of exploiting orographic lift for MAVs is mostly limited to flight path simulations which do not consider the complex flow field (Cutler et al., 2010; Langelaan, 2007). The work presented in this paper therefore attempts to investigate the use of Computational Fluid Dynamics (CFD) to

1. Accurately predict updraught intensity in complex environments to complement flight path simulations;
2. Aid the understanding of the complex flow behavior in urban environments for MAV operation.

1.1. Utility of CFD

In reality wind direction and magnitude can vary significantly, thus requiring a number of representative conditions to be examined. GPS coordinates of the updraught regions can then be extracted from the relevant numerical models and uploaded to the MAV navigation system to use when calculating an optimal trajectory for minimal energy consumption. This approach requires numerous simulations for exploring disparate operating conditions. However, to accurately predict the detached flow regions emanating from buildings the use of high-fidelity turbulence modelling is required, capable of resolving eddies of a wide range of sizes in the turbulence spectrum. Furthermore, the resolution of turbulence scales of the order of the MAV

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Nomenclature

C_s, C_w, C_{DES}	constants
d_w	wall distance
G	filter over the volume
$h_{\max}$	maximum edge length of the cell
h_w	wall-normal grid spacing
k	turbulence kinetic energy
k^+	equivalent sand grain roughness
L_T	turbulent length-scale
L_∞	characteristic length
N	number of boundary layer cells
Re	Reynolds number
S	strain rate
t_T^*	total time of simulation
U_∞	reference velocity
$U(y)$	ABL velocity profile
u^*	friction velocity
V	volume
x, y, z	coordinate system
x^+, y^+, z^+	non-dimensional cell size
y_∞	reference height
y_0	equivalent aerodynamic roughness height
Δt^*	time step
δ	boundary layer thickness
Γ	circulation
κ	turbulence kinetic energy
η	spatial distribution
ρ	air density
τ_{ij}	stress tensor due to molecular viscosity
τ_{ij}^{SGS}	sub-grid (modelled) stress tensor
μ_T	Eddy viscosity
ω	specific dissipation
Ω	flow domain
φ	filtered scalar
θ	wind crossflow angle

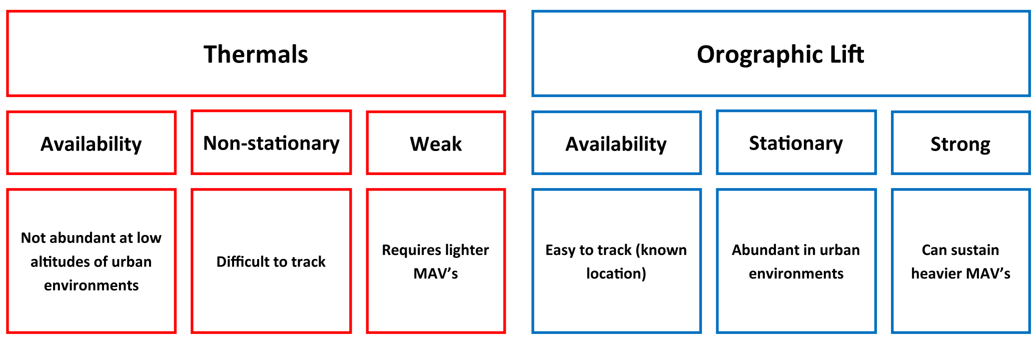

Fig. 1. Advantages of orographic lift over thermals in urban environments for MAV exploitation of updraughts.

wing span is necessary to investigate potential flight conditions. Traditionally this has seen the use of Large Eddy Simulation (LES) methods (Hanna et al., 2006; van Hooff et al., 2011; Yoshie et al., 2011; Park et al., 2012; Blocken et al., 2012; Gousseau et al., 2013). However the intractable mesh requirements near the wall (see, for example, the excellent paper by Menter, 2012) makes this approach impractical for the proposed study scope, especially at full-scale Reynolds numbers. The requirements for resolving detached regions are much more forgiving (Pope, 2000; Menter, 2012) which has led to the pursuit of more feasible scale-resolving numerical methods.

Paramount to predicting the updraught over buildings (whether by experimental or computational means), is the replication of accurate wind profiles. The Atmospheric Boundary Layer (ABL) has been documented by a number of researchers. In Australia, meteorological agencies have compilations of mean wind speeds throughout the year for Bundoora where the representative building configurations reside. The average wind speed for this region at a height of 10 m is approximately 11 km h^{-1} (Watkins et al., 2010). Numerical models of the turbulent ABL have been implemented for studying and analyzing building envelopes, natural ventilation, wind loading, dispersion of air pollutants and other flow predictions (Tutar and Oguz, 2004; Blocken et al., 2007; Salim et al., 2011), as well as studies focused on updraughts over rooftops (Mertens, 2003; Walker, 2011). There have been studies in the literature on velocity profiles, which are known to vary with elevation and ground roughness (Walshe, 1972; Blocken et al., 2007). To replicate the effects of a resolved turbulence field for scale-resolution poses more of a challenge. This paper follows the procedure of Mathey et al. (2006) by imposing random fluctuations on the velocity in the streamwise direction.

As the air travels over buildings, there will be a local increase in wind speed due to the adverse pressure gradients. Velocity magnitudes will therefore need to be mapped in the region where updraughts are expected. With a suitable CFD modelling procedure, the updraught field may be characterized, thus providing an indication of the potential energy available for harvesting, which is the focus of the current study.

1.2. Scope and structure

The remainder of this paper details the numerical simulation results of a representative urban environment, using a derivative of the popular Detached Eddy Simulation (DES) technique for turbulence scale resolution known as Improved Delayed Detached Eddy Simulation (IDDES). The following sections are structured as follows. Section 2 details the strategy proposed to simulate the flow over an urban environment; Section 3 details the validation procedure undertaken to enhance confidence in simulation results computed; and Section 4 details the results produced for the flow over a representative urban environment.

2. Solution methodology

This paper presents the use of the finite-volume code ANSYS Fluent 15 to model the flow-field over a representative building configuration. The representative geometry selected for the study are Building 201 and surrounding buildings of the RMIT University Bundoora campus. The unique position and surrounding terrain of the building matched the topography of a suburban terrain (see Fig. 2). This section presents the CFD methodology and procedure adopted for the following study, including turbulence modelling and boundary conditions.