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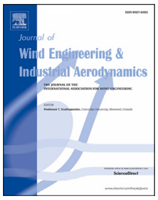

Measuring wind with Small Unmanned Aircraft Systems

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ABSTRACT

Small Unmanned Aircraft Systems (SUAS) are an emerging technology that is suitable for multitude of applications requiring small sensor payloads including airborne wind measurement. This work discusses the considerations and limitations of different SUAS configurations, in particular Multi-rotor UAS (MUAS), and their capabilities when operating within the Atmospheric Boundary Layer (ABL). Several methods for measuring fluctuating flows from SUAS are discussed, and preliminary results from a quadrotor-mounted Multi-Hole Pressure Probe (MHPP) "flying anemometer" platform are presented. Flights at a range of altitudes demonstrated that in-situ measurements of both mean wind velocity and turbulence intensity from hovering airborne platform are feasible. This indicates that MUAS can be used as flexible wind sensing platforms with good high spatial resolution. Suggestions for how future SUAS technological and operation developments may further improve wind engineering applications are also discussed.

1. Introduction and objectives

Unmanned Aircraft Systems (UAS), also known as Remotely Piloted Aircraft Systems (RPAS) are a broad range aircraft that are particularly useful for conducting "dull, dirty and demanding" missions (English et al., 2014). UAS range in weight from grams to thousands of kilograms - Small UAS (SUAS) are a category weighing less than 25 kg and have been gaining popularity for carrying sensors in applications such as research, search and rescue, law enforcement and media (AUVSI, 2015). These systems typically require low acquisition and operating costs, present lower risk when compared to manned aircraft and their relatively small size permits operations away from runways and in confined spaces. SUAS exist in fixed-wing and rotorcraft configurations, with Multi-rotor UAS (MUAS) becoming increasingly dominant due to their ability to hover, mechanical simplicity, ease of use, and greater manoeuvrability than fixed-wing systems (particularly in the lateral and vertical directions as well as in yaw).

The Atmospheric Boundary Layer (ABL) is a region typically below 1 km where the winds are heavily influenced by the Earth's surface roughness (Watkins et al., 2010). Measurements of these flows can be used for tracking pollutants, forest fires and heat/vapour dispersion (Chao and Chen, 2010). Measurements in the upper portion of the ABL (and altitudes above the ABL) are typically conducted by tracking weather balloons using Doppler radar, satellites or by ground-based Sound Detection and Ranging (SODAR), which offer low spatial resolution (Walterscheid, 2009). At low altitudes below 100 m, wind measurements at point locations are typically conducted using anemometers mounted to tall masts. While masts can provide long-duration continuous measurements, they are difficult and costly to emplace and only offer a limited number of lateral sensing positions once erected. This can be a major limitation for applications requiring measurements at several locations with high spatial resolution, such as around buildings and at wind turbine sites (Giebel et al., 2012). LIDARs can provide remote ground-based wind measurements at altitudes on the order of 1–2 km (Kumer et al., 2014), but they are expensive, suffer from limited resolution, and produce spatially-averaged results over a relatively large sensing area (Lim et al., 2016). Fig. 1 demonstrates that the ABL contains a broad spectrum of fluctuation frequencies. Although documentation of the low frequency fluctuations requires the use of fixed-mounted sensors, the micro-meteorological range with fluctuations of less than 1-h duration fall within the flight endurance capabilities of SUAS. This aspect, combined with the ability to traverse the entire altitude range of the ABL and carry sensor payloads, make SUAS suitable platforms for measuring atmospheric turbulence. SUAS also require significantly less infrastructure and training to operate than manned aircraft and can undertake predetermined waypoint missions, making them cheaper to operate (Martin et al., 2011).

Fixed-wing platforms have been a major focus for SUAS-based wind measurement applications due to their relatively high endurance and ability to traverse large distances. This makes them particularly suited to

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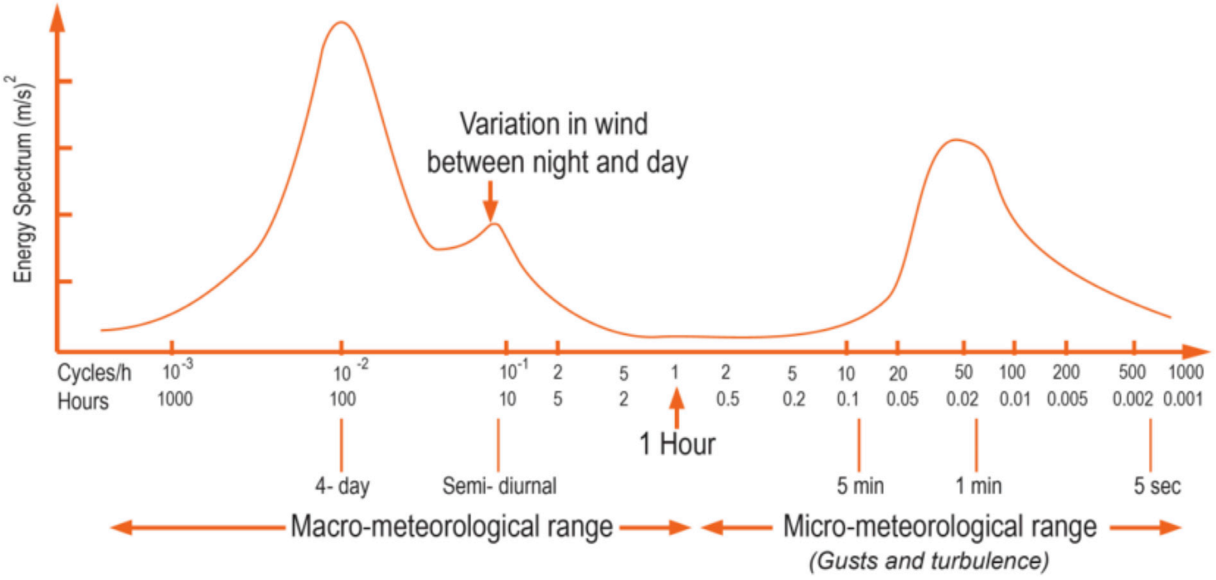

Fig. 1. Power spectral density plot of velocity fluctuations within the atmosphere at 100 m AGL (adapted from (Van der Hoven, 1957)).

reaching the upper regions of the ABL and conducting mean wind profiles measurements. Existing applications for fixed-wing UAS-based measurements include wind turbine wake structures and wind farm locations (Giebel et al., 2012), vertical atmospheric wind profiles (Finn et al., 2017), and air quality (Villa et al., 2016). Aircraft such as the Meteorological Mini Unmanned Vehicle (M^{2}AV), Small Unmanned Meteorological Observer (SUMO) and Multipurpose Airborne Sensor Carrier (MASC) have been used to successfully measure high frequency turbulence fluctuations on several research projects at altitudes up to 1500 m and flight durations of up to 1 h (Martin et al., 2011), (Giebel et al., 2012), (van den Kroonenberg et al., 2008), (Reuder et al., 2009), (Wildmann et al., 2017). While the forward-flight nature of fixed wing platforms can be useful for capturing data over a broad range of locations, it can be a hindrance if continuous measurements at specific point locations are required (i.e. replicating a mast). Fixed-wing aircraft can "wind hover" if the wind speed is sufficiently fast to overcome stall speed, however this is situation-dependent and cannot be relied upon.

SUAS are also being increasingly considered as platforms for in-situ gust and turbulence measurements in low altitude urban environments for applications such as orographic soaring (White et al., 2012), pedestrian comfort (Tsang et al., 2012), and the design and construction of tall buildings and facades (Stathopoulos, 1984), (Hoxey and Richards, 1993), (Fu et al., 2008). These urban applications present additional operational challenges such as accurate position hold, manoeuvrability, and stability in high turbulence intensities, where existing fixed-wing based wind sensing platforms may be unsuitable. Rotorcraft SUAS, in particular Multi-rotor UAS (MUAS), present potential platforms to perform as successful "flying anemometers" for turbulence measurements in urban environments.

The objectives of this work are to review the design considerations and challenges of utilising rotorcraft SUAS as flying wind platforms, review existing ground, fixed-wing and rotorcraft-based wind measurement methods to analyse their suitability, and to present the development of a new MUAS-based "flying anemometer".

2. Considerations and challenges for rotorcraft SUAS configurations

The ability for rotorcraft UAS to hover, take off and land vertically as well as manoeuvre in all directions creates opportunities to reliably undertake wind measurements at specific points in space, especially close to structures. However, their effectiveness depends on several factors including endurance, payload capacity, stability in high wind speeds or turbulent environments as well as effects of the flow induced by rotors on the wind measurements and the ability to avoid or calibrate for these effects.

2.1. Endurance considerations

All types of rotorcraft must rely solely on their rotors to produce sufficient thrust to overcome weight for hover or climb. Rotary wing aircraft typically have about half the endurance of fixed wings of the same weight with a moderate lift/drag ratio (L/D) of four (Green and Oh, 2005). Endurance is heavily influenced by disk loading, which is defined as the weight per area swept by the rotor. The power required for generating thrust is proportional to thrust times velocity. For a given thrust, increasing the rotor diameter will result in a larger mass flow rate and lower induced velocity increment. This allows for a reduced power requirement and therefore improved endurance (Thielicke, 2014). Therefore, disk loading can be improved by either increasing the rotor swept area or reducing the total mass – the latter becomes a major consideration for sensor payloads.

The power consumption required to maintain hover places limitations on available energy sources, with nearly all small rotorcraft utilising batteries. In these aircraft, the battery forms a large percentage of the total mass that remains constant throughout during operation, and must be carefully selected to optimise for endurance and payload capacity requirements (Avanzini et al., 2016). Whilst this technology has been steadily evolving in recent years, even the batteries with highest specific energies or energy densities (Lithium Polymer (LiPo) and Lithium Ion (LiIon) have far less than those of fossil fuels (Mulgaonkar et al., 2014). Therefore, despite their inherent inefficiency, internal combustion engines (ICE) burning fossil fuels can generally provide SUAS rotorcraft with significantly longer endurance. Battery-powered systems Hybrid systems utilising methods such as fuel cells have the feasibility to improve the endurance of electric systems, however currently there are few commercially viable systems for rotorcraft.

2.2. Helicopters

Unmanned helicopters were the mainstay of unmanned rotorcraft for many years – being built upon tried and proven concepts from manned