J3.1 EXPLORING THE RANGE OF WEATHER IMPACTS ON UAS OPERATIONS

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1. INTRODUCTION

The history of unmanned aircraft systems (UAS) predates that of manned aircraft, as kites, hot air balloons, and unmanned experimental gliders all existed before the Wright Brothers' monumental flight. The lack of control of these early unmanned aerial vehicles, however, resulted in limited application. Effective flight control for UAS came in the form of three key inventions around the early 1900s: control surfaces (e.g. rudder), the radio, and the autopilot. These inventions shaped the definition of modern UAS as an autonomous or remotely piloted aircraft that utilizes an autopilot or transmitter (Marshall 2016).

The first application of modern UAS can be traced back to the development of the aerial torpedo in 1916, a weapon intended for use against naval warships in World War I (Marshall et al. 2016). As one might expect, the majority of UAS research efforts throughout the remainder of the 20th century were focused primarily on military application. At the turn of the century, however, unmanned aircraft under 55 lb, or small UAS (sUAS), became increasingly popular for hobbyists, academia, industry, and the commercial sector.

In response to this widespread interest in sUAS, the Federal Aviation Administration (FAA) established a registration process for all aircraft weighing in the range 0.25 kg to 25 kg in December 2015. Just two months later, the number of sUAS registered with the FAA surpassed that of manned aircraft, reaching 235,000 (Janson 2016).

The rapid expansion of sUAS has called into question the safety of operating them in the presence of manned aircraft and over populated areas. To address this, a new regulation was published by the FAA in 14 CFR Part 107 (2016), with requirements that include unaided visual line of sight (VLOS) operation at all times. However, many of the requirements in Part 107, including VLOS operations, can be waived and few directly address the increased risk of flying in poor weather conditions, which can result in reduced visibility, loss of communication, or loss of control; all of which can lead to loss of aircraft. Additionally, in VLOS operations, visual observers and operators are exposed to weather conditions on the ground, which may affect their health and impair their ability to see and control the aircraft.

With the increasing demand for sUAS, there is a need to better understand the effects that different forms of weather have on these systems (that includes operators, observers, and aircraft) in order to successfully plan and execute a mission. This paper gives a broad overview of the weather impacts on sUAS under current VLOS restrictions and discusses how they change when flying beyond visual line of sight (BVLOS).

2. WEATHER HAZARDS FOR SUAS OPERATIONS

Classification of weather hazards of concern for sUAS operations range from moderate, to adverse, to severe (Table 1). Here, we classify moderate hazards as those that result from phenomena that reduce visibility but otherwise do not harm the aircraft, such as fog, haze, glare, and cloud cover.

Adverse hazards then add those weather conditions that have the potential to cause loss of control, loss of communication, diminished aerodynamic performance, and may negatively affect the operator, such as wind, turbulence, rain, solar storms, temperature extremes, humidity, snow and ice.

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Severity	Hazards	Weather Types
Moderate	• Reduced Visibility	• Fog • Haze • Glare • Cloud cover
Adverse	• Loss of communication • Loss of control • Loss of command • Diminished aerodynamic performance • Reduced operator effectiveness	• Wind and turbulence • Rain • Solar storms • Temperature and Humidity • Snow and Ice
Severe	• Severe damage to or loss of aircraft • Unacceptable risk to operator and personnel	• Lightning • Hail • Tornadoes • Hurricanes

TABLE 1: Classification of weather hazards for sUAS in terms of severity.

Lastly, we define severe hazards as those which would result in severe damage to or loss of aircraft, and put the operator or other personnel in a dangerous situation. These hazards include thunderstorms, lightning, hail, tornadoes, hurricanes, and the like. Since it is generally understood that one should avoid flying in severe weather, the remainder of this paper will focus on the impacts that moderate and adverse weather conditions have on sUAS operations.

3. VISUAL LINE OF SIGHT OPERATIONS

Current aircraft regulations do not address many of the weather hazards for sUAS. The restrictions listed in Part 107 that pertain to weather include remaining 500 ft (152 m) below and 2000 ft (610 m) away from clouds, maintaining visibility for 3 mi (4.83 km), and operating under unaided visual line of sight at all times (FAA 2016a).

This effectively eliminates weather that includes clouds or otherwise reduces visibility, but it does not address the safety hazards presented by weather that can exist under clear skies. The primary types of weather phenomena that fit into this category are glare, wind and turbulence, temperature extremes, humidity, and solar storms. Because pilots are legally free to fly in these conditions, it is of highest priority to understand what the impact of these weather conditions is on sUAS and their operation.

3.1. *Glare*

Glare is a weather phenomenon that occurs in clear skies, and yet affects visibility in a couple of ways. The first is by hindering direct observation of the aircraft. In addition to the difficulty of spotting a small aircraft on a bright day, looking too close to the sun can result in watery eyes and spotted vision. In preparation for a mission on a sunny day, visual observers should take care to pack sunglasses.

Secondly, sUAS operations often require a user interface displayed on a monitor, tablet, or other screen that enables the operator to send commands (e.g., waypoints), change control derivatives, or track the aircraft, while receiving telemetry or payload updates. The reflection of the sun on these screens can overpower LCD brightness such that it can be difficult to see or send the correct information to navigate or control the aircraft. To mitigate this problem, the operator should shield the display from glare, either by operating from a shaded location or using a display hood.

3.2. *Wind and Turbulence*

Wind and turbulence play the largest role in aviation weather accidents. A study conducted by the FAA (2010) on data from 2003-2007 on weather related aviation accidents showed that wind accounted for 53.6% of manned aircraft accidents, higher than any other factor by 35%. This number was even greater for smaller non-commercial aircraft. Regarding UAS accidents, a preliminary FAA report (Joslin 2015) showed 297 cited UAS accidents between October 2009 and April 2015. Of these, roughly 3% were related to weather and turbulence, although the report does not elaborate on how many pertain to wind specifically. These numbers of are limited value for sUAS, however, because 60% of the data in this report comes from large military UAS, such as the Predator and Guardian, and give no sense of the numbers of unreported accidents for sUAS.

Despite limited data for sUAS accidents, it stands to reason that wind affects these lighter weight aircraft in a similar manner, yet more radically than large UAS or manned aircraft. The major ways in which wind affects sUAS include changing the flight trajectory, limiting control and reducing endurance (e.g., battery life).

3.2.1. *Flight Trajectory*

Strong winds have the capacity to affect the ground speed and flight path of an unmanned aircraft. Similar to larger manned aircraft, headwinds and tailwinds, respectively, increase or decrease the ground speed of sUAS. Unlike typical manned aircraft, however, wind speeds can easily surpass the maximum speeds of sUAS. Fig. 1 shows a histogram of the maximum flight speeds listed for 92 different sUAS compared to the

Beaufort wind scale. This histogram shows that over half of the sUAS surveyed have maximum speeds that are below the wind speeds one would find in a storm. In general, multi-rotor aircraft have slower maximum speeds than those of fixed-wing aircraft, which make them more likely to struggle even in lower wind speeds.

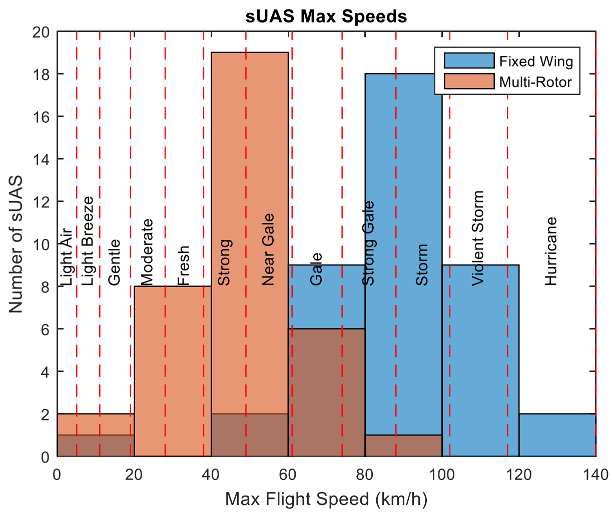

FIG. 1. sUAS maximum speeds compared to Beaufort wind scale. The darker brown indicates overlap between fixed wing and multi-rotor aircraft.

Flying in a headwind with a greater velocity than that of the aircraft results in stationary or backwards flight. Furthermore, flying in a crosswind can cause the sUAS to drift with the crosswind rather than at the intended heading. Strong winds may result in the sUAS to be blown over a populated, dangerous, or unrecoverable area. It could also lead to the sUAS being blown into an area or to an altitude where one can no longer see the aircraft. Moreover, winds are often associated with gusts that can easily be a factor of two greater than the sustained wind speed.

3.2.2. *Aircraft Control*

Wind gusts, wind shear, and turbulence all have the potential to reduce aircraft control. Aircraft control refers to the ability to maneuver the aircraft by use of pitch, yaw, and roll. Pitch changes an aircraft's angle of attack, yaw changes the aircraft's heading, and roll rotates the aircraft around the axis of the fuselage (Fig. 2). These change the aircraft's altitude, the direction the nose is pointed, and turn the aircraft, respectively.

FIG. 2. The effect of wind gusts on the pitch, yaw, and roll of an aircraft. Smaller arrows indicate smaller magnitude wind gusts.

Wind gusts are sudden increases in wind speed that typically last no longer than 20 seconds (NOAA 2013). Horizontal gusts affect the yaw of a fixed wing aircraft by blowing against the rudder. For roll stability, most low-wing aircraft are designed with dihedral, where the wings are angled upward from the horizontal plane as shown in Fig. 3. A horizontal gust can roll the aircraft by blowing underneath one of the wings, and because banking (rolling) an aircraft changes its direction of flight, horizontal gusts are particularly dangerous while flying near obstructions.

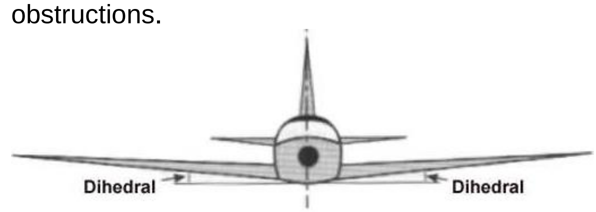

FIG. 3. Dihedral angle on an aircraft wing. (Jackson 2001)

Vertical gusts can roll a fixed-wing sUAS if there is a gradient in the gust's magnitude from one wing to the other. For a fixed-wing or multi-rotor aircraft, a gradient between the front and the back of the aircraft can cause a pitching or diving motion (Fig. 2). If the sudden pitch caused by a gust exceeds the critical angle of attack for the sUAS, the wing will stall, meaning there is no longer enough lift produced by the wing to keep the aircraft flying. If the vertical gust is strong enough, this may even tip the sUAS upside down.

Wind shear and turbulence affect sUAS in a similar manner to gusts. Wind shear refers to changes in wind speed or direction that often occur due to strong temperature inversions or density gradients (FAA 2008), while turbulence refers to changes in density or air flow velocity that result in chaotic mixing motions in the air (Kundu et al. 2012). Because wind shear and turbulence are associated with sudden changes in airflow, their effect on aircraft control is unpredictable and difficult to compensate for. This is further exacerbated by the Part 107 requirement for sUAS to fly below 400 ft (120 m). At low altitudes, wind shear and turbulence are worsened by obstructions such as buildings, trees, or mountains.

Additionally, from the ground to a height of approximately 50 m, strong vertical wind shear and small scale turbulence are caused by varied atmospheric and land surface processes, convection, and surface roughness in the natural planetary boundary layer (Sharman 2016).

3.2.3. *Aircraft Endurance*

Wind reduces the endurance (flight time) of an aircraft if it causes higher than expected current draw from the batteries. In order to fly at a constant ground speed in a headwind or crosswind, or to compensate for sudden changes in aircraft motion due to turbulence, the thrust produced by the motor must increase. Fig. 4 shows the change in battery endurance that occurs when increasing the thrust of a typical sUAS propulsion motor.

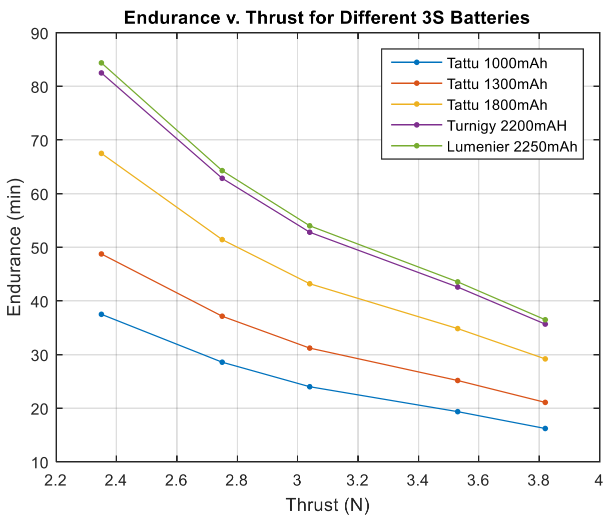

FIG. 4. Endurance (flight time) decreases by half its value as thrust of motor increases from 50% to maximum.

The motor used in this example is a Tiger Motor MT2212 750 KV motor that has a 9x3 propeller attached and is supplied by 6 different 11.1 V lithium polymer batteries of varying capacities. The smallest thrust value shown on the graph is 50% of the maximum thrust this motor-propeller combination can produce. This is in the range of the typical percentages used for flying at cruise speeds on a windless day (Ardupilot 2016). If flying in a headwind or crosswind, one can assume that the thrust required will be greater than that for zero-wind cruise in order to maintain a certain ground speed. From the graph, one can see that as the thrust increases to its maximum, the endurance drops by over half of what it is at typical cruise levels.

The endurance values calculated here assume a constant current draw and a linear relation to the battery capacity,

$$t = \frac{Q}{I},$$

where *t* is the endurance, *Q* is the battery capacity and *I* is the current draw. For example, a battery capacity of 2 Ah drained at 4 A should be able to produce half an hour of flight time. In reality, there would be less than half an hour due to the Peukert effect, which states that as the current draw increases, the battery capacity becomes less effective. The endurance calculation adjusted for the Peukert effect is,

$$t = \frac{Rt}{I^n}\left(\frac{Q}{Rt}\right)^n,$$

where *Rt* is the battery hour rating (i.e. discharge time over which the capacity was determined) and *n* is a constant discharge parameter dependent on the temperature and type of battery (Traub 2011). For a typical lithium polymer battery operating at room temperature, *n* = 1.3. The additional loss of flight time with this discharge parameter is illustrated in Fig. 5 using *Rt* = 1 houfr, and *Q* = 2 Ah.

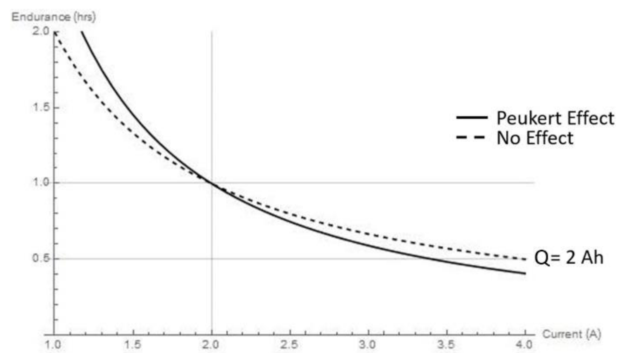

FIG. 5. The Peukert effect on a 2 Ah battery's endurance for different current discharge levels compared to the endurance levels with no effect.

Although most sUAS have a low battery indicator, the rapid decrease in battery life due to windy conditions results in a much shorter flight than anticipated and may put the operator in a position where sighting or controlling the aircraft for a safe landing might be impossible before the battery capacity is exceeded.

3.3. *Temperature*

Typical operating temperatures for unmanned aircraft lie between 253 K to 323 K; however, minimum operating temperatures can range from

223 K to 273 K and maximum operating temperatures can range from 308 K to 343 K. Extreme temperatures have negative implications for the physical components of an aircraft as well its aerodynamic performance.

3.3.1. *Batteries and Electronics*

The batteries most commonly used in sUAS are nickel-cadium (NiCad), nickel-metal-hydride (NiMH), and lithium polymer (LiPo). Because NiCad and NiMh batteries lose a significant portion of their charge daily and are heavier than LiPo batteries, LiPo batteries are the more common battery type used in sUAS (Warner, 2015).

The standard operating temperatures for LiPo batteries are 253 K to 318 K. Although high temperatures rarely present a hazard during flight, continued charge or discharge at these temperatures will reduce the life cycle of the battery. On the opposite end of the spectrum, as a typical battery's temperature decreases from about room temperature, the internal resistance increases and the chemical reaction that produces a current across the two battery leads slows considerably (Warner 2015). In other words, as temperature decreases, a LiPo's battery capacity drops, as exemplified in Fig. 6.

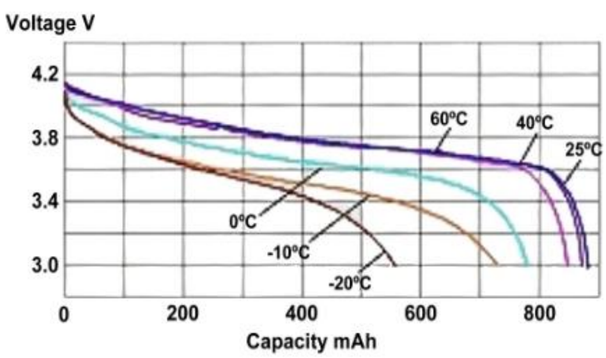

FIG. 6. An 850 mAh battery drained from 4.2 to 3 V in varying temperatures. (IBT Power, 2016)

In this graph, an 850 mAh LiPo battery was discharged from 4.2 V to 3 V at various temperatures. At -20°C (253 K), the battery lost 30% of its listed capacity. Flying in temperatures lower than this may cause the battery to alter its behavior or stop functioning altogether. This altered behavior is the main concern for the other electronics onboard the aircraft as well.

3.3.2. *Materials*

The types of materials generally used for an sUAS airframe include wood, plastic, carbon fiber, foam and metal (Benson 2015). If one uses a plastic in construction, low temperatures can cause the plastic to become brittle and crack under force of impact or when screwing down parts. For example, polypropylene becomes brittle at 253 K (Zeus Industrial Products 2005). This material also has a tendency to deform in high temperatures. As a result, tougher plastics are more frequently used in construction, such as Polycarbonate or ABS for the airframe and Nylon for propellers (Benson 2015).

3.3.3. *Air Density*

In addition to affecting the aircraft, the local air temperature directly affects the air density at a given altitude. The ideal gas law shows that at a constant pressure, air density decreases with increasing temperature. This in turn affects the speed and angle of attack (angle of the wing relative to the incoming air) of the aircraft required to generate the required lift for flight. Because they are linearly related, lift changes by the same percentage as the change in air density. Between the typical operating temperatures for sUAS, 253 K and 323 K, there is a 21% variation in air density. If one flies at the high end of the spectrum, lift will decrease from that of room temperature by 10%. To compensate for the decrease in lift, one must increase the velocity of the aircraft which, in turn, increases RPM and decreases flight time. Contrarily, flying at the low end of the spectrum results in a 15% increase in lift and the motor becomes more efficient. However, the aforementioned effects of flying in cold temperatures detract from this benefit.

3.4. *Humidity*

Humidity presents a problem if the moisture in the air condenses on the electronics used in an sUAS. Water can cause electronics to short, which results in erroneous behavior, loss of functionality, or high amounts of heat output that could lead to a fire.

The basic electronics onboard a sUAS, besides those that are mission specific (e.g., camera), are to provide communication, command, and control. Some examples of these electronics include autopilots, flight controllers, receivers, servos, electronic speed controllers, and motors. The loss of functionality of any of these during flight is detrimental to mission success and likely to result in a crash.

A short that results in an electrical fire is particularly dangerous when operating with LiPo batteries. These batteries release hydrogen as part of their discharge. If a LiPo battery is damaged, the buildup in hydrogen combined with the sparks from a short can result in an explosion (Drone Registration 2016). For this reason, LiPo batteries are contained in plastic housing and sealed with Kapton tape or other insulating materials to prevent damage to the battery (Seidle, 2014). This being the case, small amounts of water on the battery itself will most likely cause no harm. The danger comes from the potential for other electronics to catch fire near the battery.

Maximum relative humidity specifications on sUAS range typically from 50% to 100%. Humidity is a greater problem in the morning, when there are relatively lower temperatures and higher humidity levels. According to the National Oceanic and Atmospheric Association (NOAA 2016), the average relative humidity levels between the hours of 4 am and 6 am are greater than 50% for all 50 states in the US. Furthermore, relative humidity varies significantly with geographic location. In areas with high average humidity, it is particularly important to check humidity levels before flight and verify that electronics are watertight.

3.5. *Solar Storms*

Solar storms, such as flares and coronal mass ejections (CMEs), disrupt GPS transmissions. Most sUAS use GPS to determine the position and speed of the aircraft, provide altitude and location information for Earth observations, and in some autonomous systems, steer the aircraft (Terris GPS 2016).

GPS radio signals travel from a satellite through the ionosphere to the receiver on the GPS module of a sUAS. GPS systems use a model to compensate for the ionosphere's effect on the accuracy of position, but when solar flares occur, these models no longer approximate the average ionosphere correctly (NOAA 2017). Solar flares interfere with the ionosphere by sending electromagnetic radiation and increasing the number of electrons present. In some cases, solar flares have such an impact on the ionosphere that the position is off by many meters or, in worst-case scenarios, the GPS receiver cannot locate the satellite signal at all. CMEs are an even greater hazard for GPS systems. CMEs eject particles from the sun that reach the Earth in three to five days. These particles can collide with GPS satellites and disrupt the electronics on board (Fox 2013).

Much like atmospheric weather, solar storms are forecasted and monitored by NASA and NOAA. These forecasts are available online and reported to electric companies, airline pilots, and spacecraft operators. As such, sUAS operators can account for solar storms during mission planning if they intend to rely heavily on GPS navigation systems.

4. BEYOND VISUAL LINE OF SIGHT OPERATIONS

The weather impacts on sUAS that have been described to this point all occur in clear conditions. Because any certified pilot can currently fly legally in clear conditions, understanding these weather impacts takes precedence over the impacts that occur in cloudy skies or in situations where one cannot see the aircraft. Although visual line of sight operations are required by Part 107, one can legally fly beyond visual line of sight if the operator obtains a waiver from the FAA. These waivers are granted upon safe demonstration of beyond visual line of sight (BVLOS) flight. As of December 2016, three such waivers have already been granted and this number is expected to increase in the future (FAA 2017). For this reason, the weather impacts of BVLOS flying have to be considered, and this section will briefly highlight some of the weather challenges that may arise.

4.1. *Fog, Clouds, and Haze*

BVLOS operations require some form of first person view (FPV), often in the form of an onboard camera. Dense fog, clouds, or haze reduce the distance a camera can see. Consequently, flying in these situations is dangerous as sUAS may fly into buildings, manned aircraft, power lines, vehicles, and any other number of hazardous objects.

Fog is produced when the temperature of the air near the ground cools to the air's dew point, that is, when saturation is reached (100% humidity) and clouds form (Identified Technologies 2016). Flying through clouds can result in condensation on the camera lens. Haze is where dust, smoke, or other particulates obscure the sky and most commonly associated with air pollution (Tang 2008). Therefore, one is more likely to encounter haze in urban areas.

Some sUAS use other sense-and-avoid technologies in conjunction with the on board camera to detect motion and other objects in the area. Some of these include light detection and ranging (LIDAR), traffic collision avoidance system (TCAS), and automatic dependent surveillance broadcast (ADS-B). During the creation of Part 107, these technologies were suggested for BVLOS operations. However, they do not solve many of the issues presented by fog, clouds and haze. LIDAR, for example, cannot penetrate fog and clouds, and is limited in dense haze. ADS-B and TCAS can sense other manned aircraft, but cannot sense terrain or buildings. That being stated, an operator should take the necessary precautions when entering areas of dense fog, haze, or low-altitude clouds and not rely solely on FPV or other vision-based sense-and-avoid technologies.

4.2. *Precipitation*

Precipitation affects sUAS in a variety of ways. Just as with fog and high levels of humidity, precipitation can reduce visibility and damage electronics. Though limited data exists, if we assume that precipitation affects fixed-wing sUAS in a similar manner to manned aircraft, then it may limit aircraft control and reduce aerodynamic efficiency.

4.2.1. *Aircraft Control*

As a sUAS flies forward, raindrops strike the leading edge of the wings with backward and downward momentum. This momentum imparts a torque that causes the aircraft to pitch downward (Fig. 7). Additionally, aircraft control is affected by the accumulation of raindrops on the surface of a sUAS. This creates an uneven water film that roughens the wings and increases mass (Cao et al. 2014). The uneven film may cause a change in the pressure distribution over the wing of the aircraft, which would in turn relocate the center of pressure. The center of pressure of the aircraft is the longitudinal location along the airframe at which the overall aerodynamic lift force can be presumed to act. The lifting forces at this point produce a torque about the center of gravity. Thus, changing this value has adverse implications for control input, such as affecting trim (the balance of the aircraft in flight) (NASA 2016).

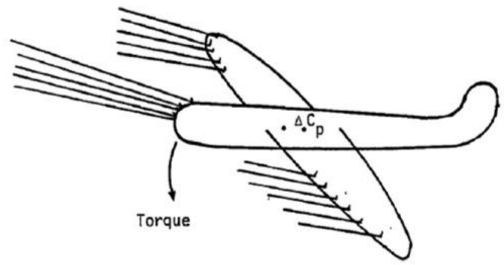

FIG. 7. Rainfall causing a torque on the leading surfaces of an aircraft. (Luers 1983)

4.2.2. *Aerodynamics*

As rain intensity increases, aerodynamic performance decreases. The seriousness of this degradation depends upon the type of airfoil used in the design of the aircraft. Hansman et al. (1987) conducted a study that tested three different airfoils for aerodynamic performance in heavy rainfall: a NACA 0012, a NACA 64-210, and a Wortmann FX67-K170 (Fig. 8).

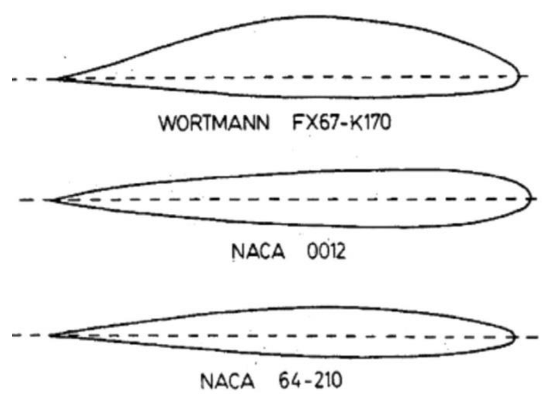

FIG. 8. NACA 0012, NACA 64-210, and Wortmann FX67-K170 airfoils. (Hansman1987)

In each case, the coefficient of lift was reduced at angles of attack below 14°. The rain had the greatest impact on the Wortmann FX67-K170, which lost 25% of its lift capability, and the least impact on the NACA 64-210, which lost about 5%. Contrarily, at high angles of attack, the rain increased the coefficient of lift of the two NACA airfoils. Moreover, for the NACA 0012, the critical angle of attack, which determines the stall point for an aircraft, increased by 4° in the wet condition.

Aerodynamic performance in rain also changes with Reynolds number. The Reynolds number (Re) is a dimensionless number that gives the ratio of inertial forces to viscous forces. Low Re are generally associated with laminar flow and high with turbulent flow. For sUAS, a low Re is on the order of 10^4, whereas a high Re is on the order of 10^6. Most sUAS operate at Re between 50,000 and 300,000 (Ananda 2012). Marchman et al. (1987) conducted studies of the effects of rain on aerodynamic performance at Re numbers ranging from 100,000 to 300,000. The study showed that at all the tested Re, the rain reduced the coefficient of lift. At the highest Re, the drag increased significantly and worsened with high aspect ratio wings.

4.3. *Icing*

Low-altitude icing occurs when super-cooled liquid water droplets in the atmosphere freeze upon contact with a foreign particle, such as those contained in man-made structures. This generally happens between 253 K and 273 K (Sorenson 2016).

An aircraft can encounter icing conditions during flight in two ways: precipitation and in-cloud icing. Precipitation combined with freezing temperatures results in either wet snow, dry snow, or freezing rain, the latter of which is the most hazardous to aircraft due to its inclination to freeze immediately upon impact.

In-cloud icing in general is a greater threat to manned aircraft and larger unmanned aircraft than to sUAS due to the high altitude of most clouds and the tendency of these clouds to contain large super-cooled water droplets. Unlike freezing rain, these larger water droplets do not freeze immediately, but rather run back along the wing and produce a sheet of clear ice that is difficult to remove and can change the shape of the airfoil and thus flight performance (FAA 2016b).

Smaller water droplets do freeze immediately and form rime ice, a rough and opaque form of ice (FAA 1975). Because smaller water droplets are present in fog and stratus clouds, which form anywhere from ground level to 1980 m, rime ice is a hazard for low-altitude UAS (Politovich 2015). Rime ice typically forms on the leading edge of an aircraft wing, which can negatively affect aerodynamic performance. For sUAS, this is further exacerbated by the lack of on board de-icing equipment. In relation to aircraft icing hazards, droplet size is less important than the amount of liquid water content in the atmosphere (LWC) and the temperature (Pavlow, 2016).

Research on the risks of ice formation on sUAS is ongoing. For fixed-wing aircraft in general, ice develops along the leading edge of the wings, the front surfaces, and the tail of the aircraft (Politovich 2015). Rotorcraft generally develop ice along the rotor blades. In a similar manner to the effects of precipitation, icing reduces lift and increases drag. Fig. 9 shows the lift and drag coefficients for common airfoils both with and without ice. For rotorcraft, the centrifugal force of the rotating blades can theoretically act as a natural de-icing solution. However, if the ice is not shed symmetrically, the uneven accretion causes vibration and imbalance in the rotors, which can be very dangerous (Brouwers 2010).

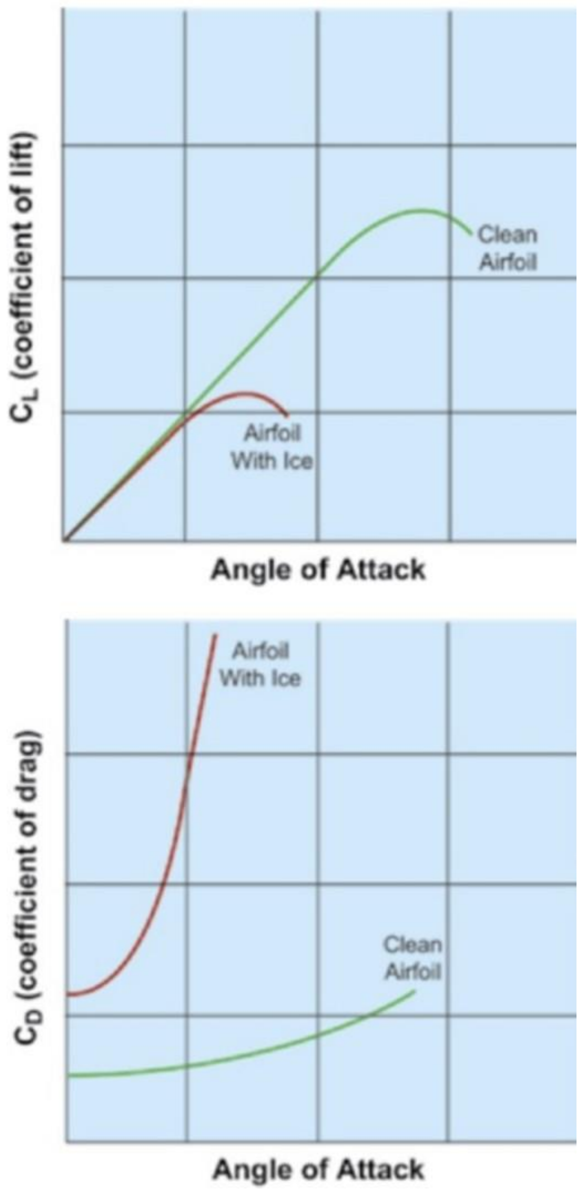

FIG. 9. The lift and drag coefficients on a clean airfoil and on an airfoil with ice. (FAA 2012)

5. SUMMARY

Understanding the safety of sUAS operations has become a high priority due to the exponential growth in the numbers of sUAS being used in academia, industry, and especially the commercial sector throughout the last two decades.

Although the FAA has established Part 107 to address many of the safety hazards associated with sUAS, such as requiring visual line of sight operations, these regulations do not eradicate the weather impacts that exist in clear conditions, such as glare, wind and turbulence, temperature extremes, humidity, and solar storms. Furthermore, waivers for beyond visual line of sight operations are expected to become more numerous in the future. This introduces additional potential weather impacts caused by haze, fog, clouds, precipitation, and icing, among more serious types of weather.

Further research needs to be conducted to fully appreciate weather impacts on UAS operations, as well as to understand the differences in impacts between fixed-wing UAS and multi-rotor UAS. This paper provided a survey of some of the moderate and adverse weather effects that may be encountered during flight. Moving forward, research and development is needed to provide operators with relevant guidance for mission planning and execution that will account for negative weather impacts and thus ensure mission success.

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