THE INFLUENCE OF METEOROLOGICAL CONDITIONS ON UASs' FLIGHT PERFORMANCE

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Abstract: *Military aviation is currently undergoing constant changes. The technological progress in the mentioned field aims to invest in autonomous aircraft to reduce both the costs and human risks. The multitude of missions that these unmanned aircraft systems can perform is affected by the unfortunate weather conditions. This paper addresses icing as a meteorological phenomenon that is hazardous to UAS's flight. To illustrate the risk arising from icing accretion, a comparative method between three types of wing icing accretion on an airfoil similar to MQ-9 Reaper is used.*

Keywords: *flight safety, aerodynamic analysis, XFLR5, icing, UAS, weather conditions*

Symbols and acronyms:

UAS	*Unmanned Aircraft System*	*Cl*	*Lift Coefficient*
MALE	*Medium-Altitude Long-Endurance*	*Cm*	*Moment Coefficient*
UCAV	*Unmanned Combat Aerial Vehicles*	*AoA*	*Angle of Attack*
Cd	*Drag Coefficient*		

1. INTRODUCTION

The development of aviation over the years, has highlighted impressive technological developments. This factor has facilitated aviation activities to extend in a safe environment. Each aviation accident has served as a wake-up call for specialists, prompting them to implement rigorous measures to prevent such tragedies from recurring.

The increasing use of UASs in armed forces missions, owing to their cost advantages, has shifted attention from conventional aircraft to these autonomous vehicles designed for various missions. The progress of UASs has required regulations and operational standards. Among the most critical research conducted to optimize the safety of UAS flights is in the field of Meteorology. Due to their smaller size compared to conventional aircraft, UASs react differently when encountering various weather phenomena, as in Table 1. Therefore, this paper intends to focus on a significant meteorological factor that has consistently posed a threat to aviation: icing.

In the military field, many UAS flights have been canceled due to bad weather conditions, which has affected the mission's accomplishment. Consequently, it is necessary to understand the process of ice accretion and to expand the counter methods in order to ensure a safe operating environment for UAS.

Table 1. Classification of weather hazards for UAS [5]

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

2. ICE ACCRETION HAZARDS

Icing presents a general danger to aviation. Although many studies in the literature address the impact of in-flight icing, they have focused exclusively on manned aircraft. Due to their small size, UAS are more susceptible to icing problems. UASs limited to a flight altitude of less than 10 km must contend with an environment predominantly filled with supercooled water droplets, whereas conventional aircraft operate at higher altitudes above 10 km where the extreme low temperatures diminish the droplets. However, UASs that may reach the upper layers of the atmosphere, encounter icing environments during take-off and landing. Furthermore, UAS with slower flight speeds are exposed to the icy circumstances for longer periods. UAS are also limited in terms of installing ice-removal equipment due to weight and power restrictions.

Ice accretion is a process whereby supercooled water droplets from the atmosphere, run into a surface and freeze. Ice encountered on the structure of a UASs is divided into three general forms: rime, glaze, and mixed ice (Fig.1). [6]

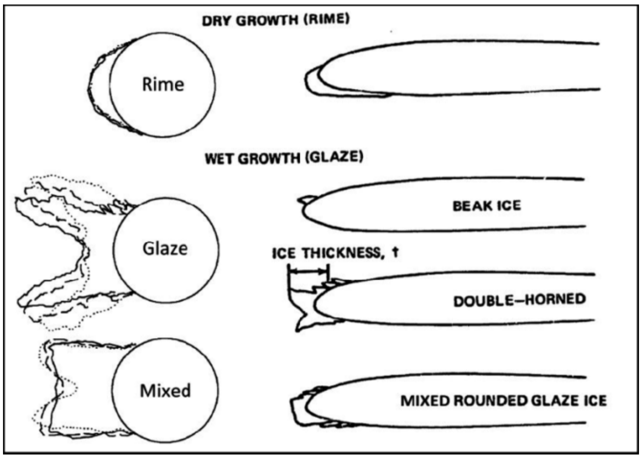


FIG 1. Three types of accreted ice on cylinder and airfoil [3]

3. METHODOLOGY AND AERODYNAMIC ANALYSIS INSTRUMENTS

3.1 MQ-9 Reaper MALE UCAV

The MQ-9 Reaper (fig.2) is an modern remotely piloted aircraft developed by the USAF together with NATO members to perform intelligence, surveillance, and reconnaissance (ISR) missions, and strike operations. It is classified by NATO as a

MALE UAV, meaning that the UAS can be operated at high altitudes and benefits from increased flight endurance, making it suitable for prolonged missions. The sophisticated sensors added to its considerable dimensions, recommend it for both combat and non-combat purposes. The values of the parameters concerning MQ-9 Reaper, presented in the analyses are true to reality (Fig.3).

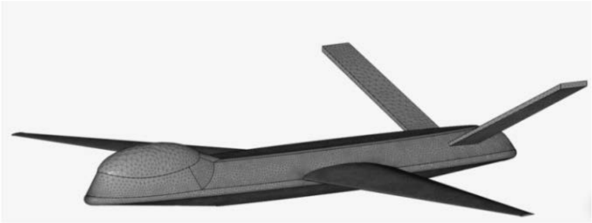
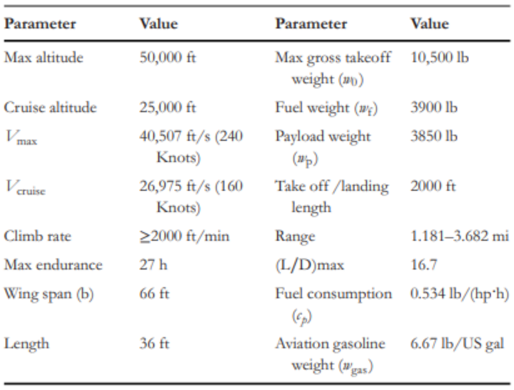


FIG. 2 MQ-9 Reaper [4]



Parameter	Value	Parameter	Value
Max altitude	50,000 ft	Max gross takeoff weight (w_0)	10,500 lb
Cruise altitude	25,000 ft	Fuel weight (w_f)	3900 lb
V_{max}	40,507 ft/s (240 Knots)	Payload weight (w_p)	3850 lb
V_{cruise}	26,975 ft/s (160 Knots)	Take off /landing length	2000 ft
Climb rate	≥2000 ft/min	Range	1.181–3.682 mi
Max endurance	27 h	(L/D)max	16.7
Wing span (b)	66 ft	Fuel consumption (c_p)	0.534 lb/(hp·h)
Length	36 ft	Aviation gasoline weight (w_{gas})	6.67 lb/US gal

FIG.3 MQ-9 Reaper technical characteristics[8]

3.2 XFLR5

XFLR5 is a well-known software tool used in the field of aerodynamics for the purpose of designing and analyzing the airfoils and aircraft's wings. This software offers both 2D and 3D analysis, displaying a useful perspective of aerodynamic performance under varying conditions. For 2D analysis, XFLR5 utilizes the panel method and boundary layer models to simulate airflow around airfoils, capturing pressure distribution and performance metrics such as lift and drag coefficients. For 3D simulations, the program apply the Vortex Lattice Method and the lifting line theory to study the behavior of wings or full aerodynamic configurations in a virtual environment. These methodologies enable researchers and engineers to optimize design and enhance the aerodynamic efficiency of new aircraft models.[1]

4. AERODYNAMIC ANALYSES OF RIME AND GLAZE ACCRETION

4.1 2D airfoil analysis

The first step in conducting a 2D analysis was to select the wing airfoil. I chose the GW 27 Drela profile, developed by Professor Mark Drela at MIT, which was implemented in the MQ-1B Predator model—the predecessor of the MQ-9 Reaper [7]. I then used the 'Edit foil coordinates' option to model rime and glaze icing. I analyzed the three profiles consecutively: clean wing, rime icing, and glaze icing (Fig.4), to highlight the negative effects of icing on aerodynamic performance and ultimately on flight safety.

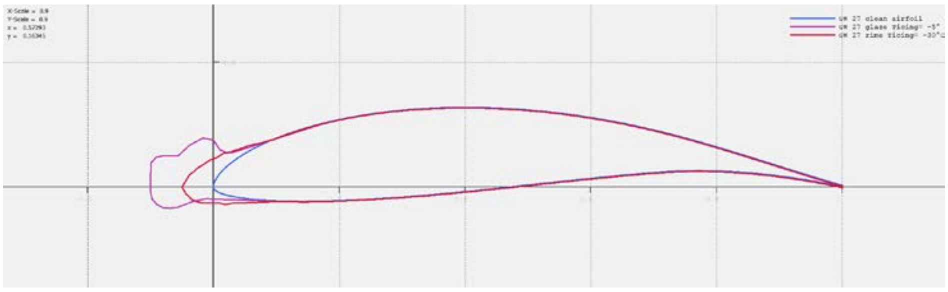
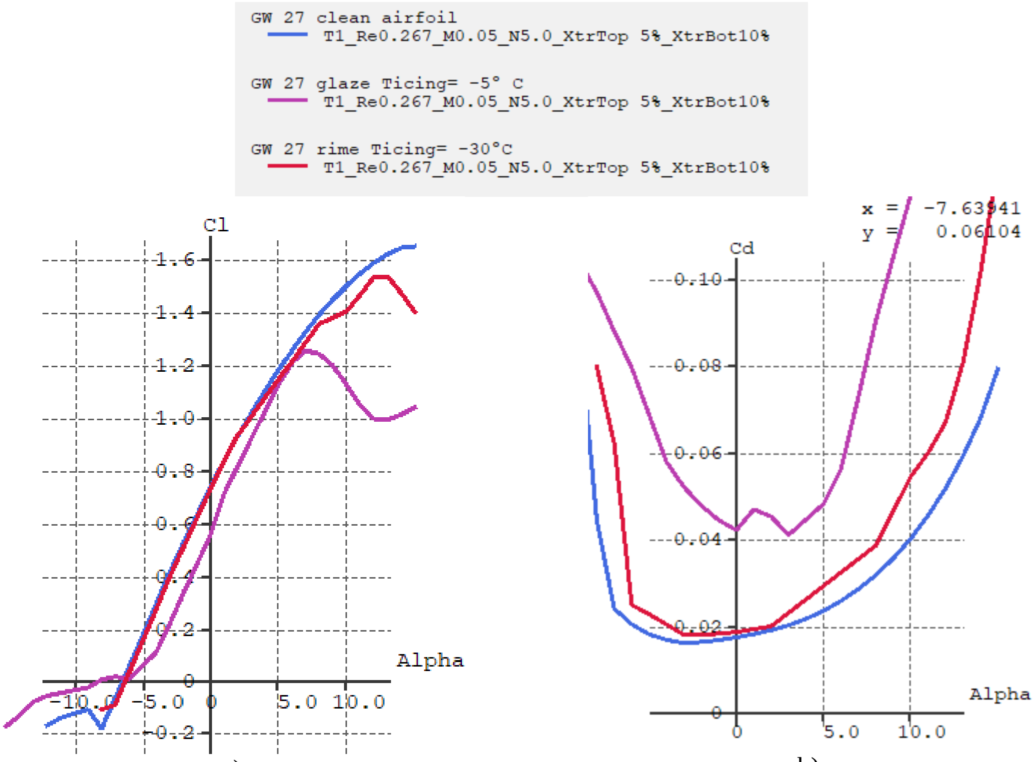


FIG.4 Overlaid clean, rime and glaze airfoils [2]

When conducting two-dimensional analysis through Direct Foil Analysis, the profiles that are to be analyzed are first imported and processed. Subsequently, specific analysis parameters are established under the "Define Analysis" section. These parameters are tailored according to factors such as Reynolds number, Mach number, and angle of attack, as detailed in Table 2. Once set, these parameters will be consistently maintained across all three analysis scenarios.

Table 2. Analysis conditions

Parameter	Value	Parameter	Value
Analysis Type	Type 1	Airfoil	GW 27 clean airfoil/ glaze/ rime
Re	266803	AoA	-10º -15º
Mach	0.05		

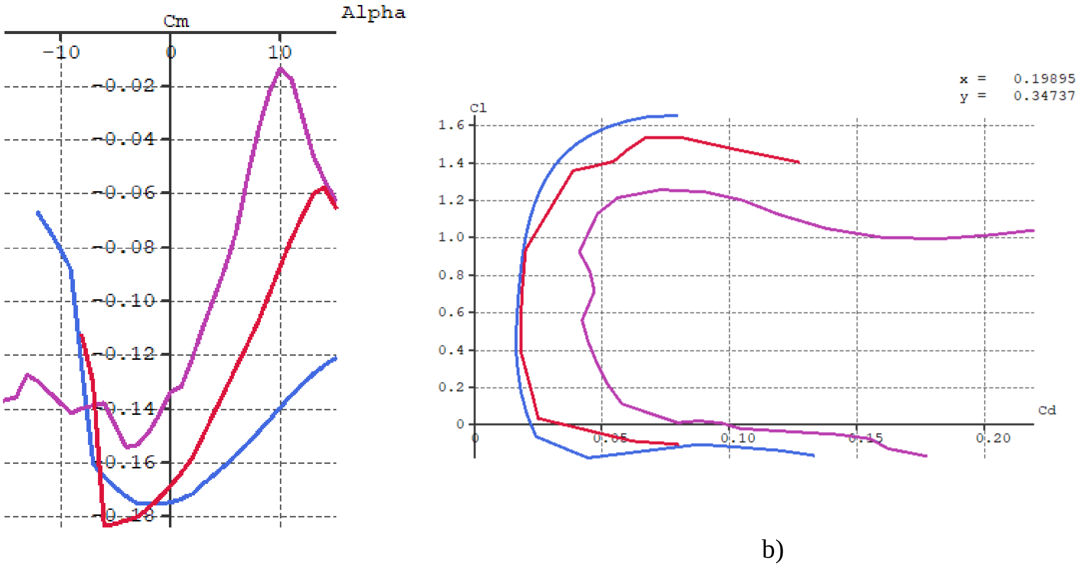


a) b)

FIG. 5 The polars a) Cl-AoA, b) Cd-AoA

In the Fig. 5 a) the clean airfoil shows a gradual increase of lift with angle, until reaching its peak and then designating a probable decrease. On the other hand, both curves indicating icing contamination on the wing, reach the maximum value of lift coefficient earlier. As an observation, the effect of ice accretion determines reduces possibilities for any given angle of attack due to the preliminary drop of lift, indicating the instauration of stall effect.

As in the Fig. 5 b) all studied airfoils stipulate increasing drag with an increase of the angle of attack. Still, the lowest drag across all angles indicates the clean airfoil, which is argued to maintain an efficient aerodynamic performance. Glaze icing exhibits the highest values of drag, underlining the negative impact of horn ice accretion.



a)

b)

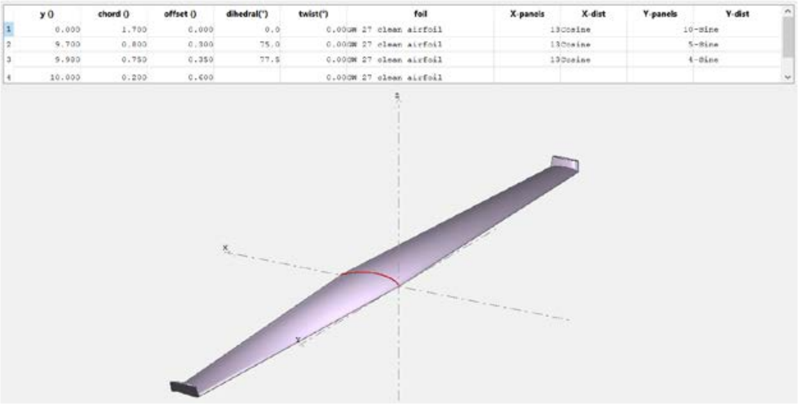
FIG. 6 The polars a) Cm-AoA, b) Cl-Cd

The moment coefficient polar presented in Fig. 6 a) illustrates a stable evolution and relatively symmetrical around the center, interpreted as a balanced distribution of aerodynamic forces on the wing. The stat of the glaze icing curve represents a chaotic variation, culminating with the drastic decrease around value of 10. In the negative part of the graph, the red line representing rime icing reassembles to the clean illustration, but meets its peak earlier.

Figure 6 b) represents the graph visualization of lift coefficient in relation with drag. The optimal aerodynamic efficiency is indicated by the clean airfoil, due to the typical correlation between lift and drag, with the former increasing simultaneously with the decrease of the latter. The wing affected by glaze icing shows significantly lower Cl values for any given Cd. As a result, there are noticeable chances in the aerodynamic efficiency.

4.2 3D airfoil analysis

For the 3D analysis, the very first step was to define a new plane (for each of the three icing conditions), and to exploit the option > Define Wing to set the numerical values of its configuration, as in fig. 7. Due to the restrained access regarding technical aspects of MQ-9 Reaper, I relied on an online measure instrument named Photo Measure to determine the approximated values of each element.



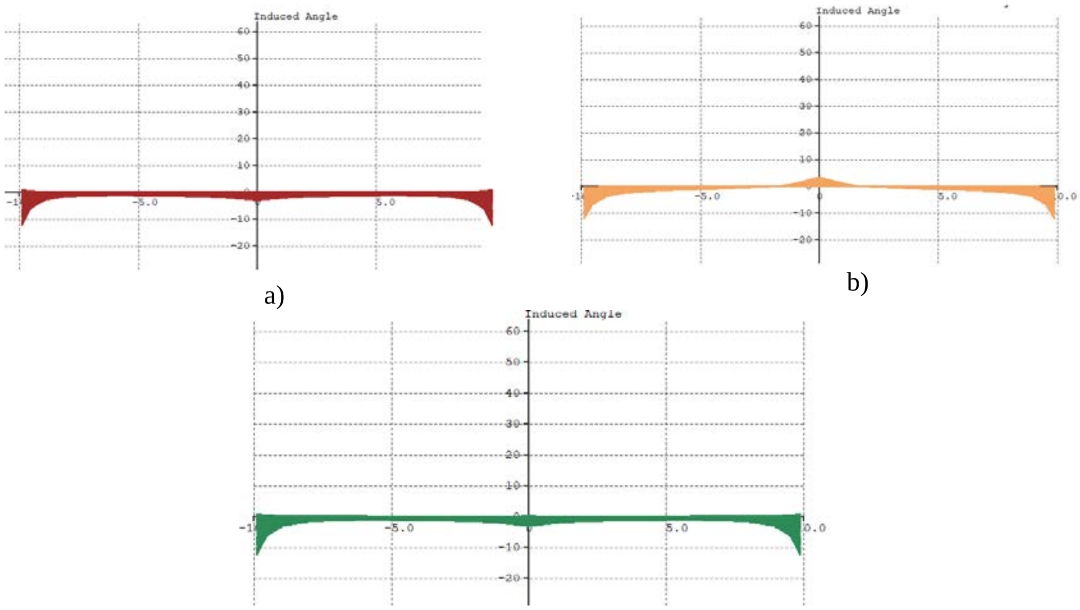
	y ()	chord ()	offset ()	dihedral(°)	twist(°)	foil	X-panels	X-dist	Y-panels	Y-dist
1	0.000	1.700	0.000	0.0	0.00	GM 27 clean airfoil	13	Cosine	10	-Sine
2	9.700	0.800	0.300	75.0	0.00	GM 27 clean airfoil	13	Cosine	5	-Sine
3	9.900	0.750	0.350	77.5	0.00	GM 27 clean airfoil	13	Cosine	4	-Sine
4	10.000	0.200	0.600		0.00	GM 27 clean airfoil				

FIG 7. Wing geometry

Table 3. Declared conditions for 3D analysis

Parameter	**Value**	**Parameter**	**Value**
Polar Type	Type 1 (fix speed)	Temperature	15º, -5º, -30º
v∞	82 m/s	Altitude	3000 m
Tip Re	1,014,359	Density	0,982236 kg/m³
Root Re	8,622,055	v	1.617e-05 m^2/s
Analysis Method	LLT (wing only)	ρ	0,982 kg/m³

The induce angle representation (Fig. 8) for the clean wing (red) reveal a stable and uniform distribution that implies no aerodynamic disturbance and ideal lift generation.



a)

b)

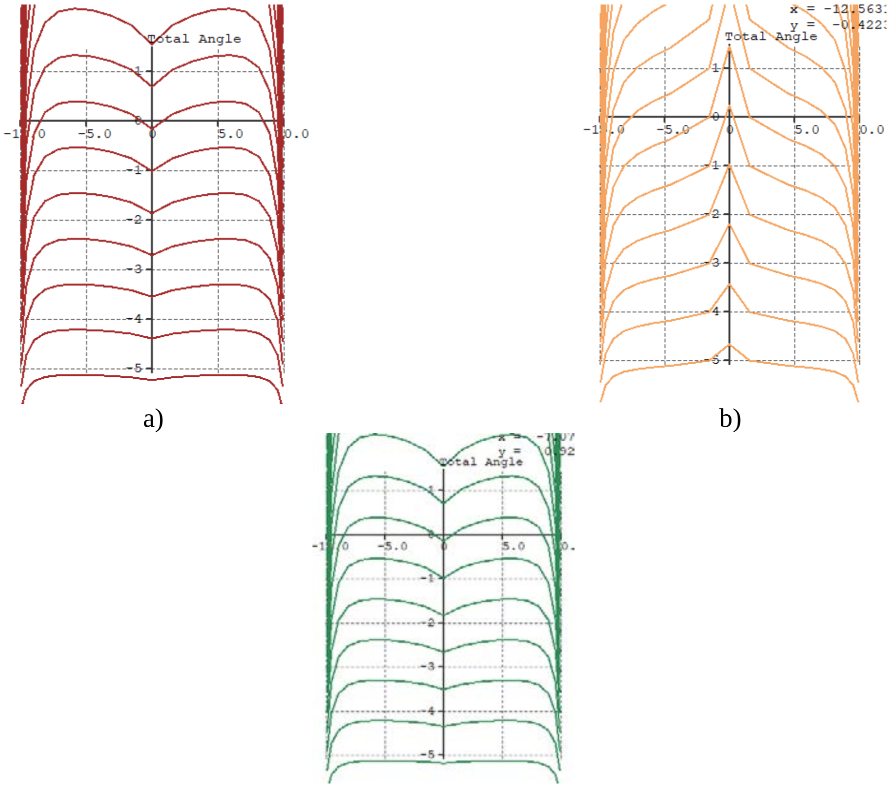
c)

FIG 8. Graphic representation of the induced angle

The orange curve, representing the wing affected by glaze ice, presents a remarkable variation near the center, which denotes negative perturbation because of the change of wing’s structure. The outcome of rime ice accretion (green) is less severe that the glaze icing, but still not close to the clean wing results.

The total angle for the clean wing maintains a symmetrical profile, favorable to predictable and efficient flight dynamics. On the other hand, the wing with glaze icing presents significant deviations, potentially leading to increased stall risks and reduced aerodynamic efficiency. The rime ice condition presents a moderately disturbed profile, pointing to a lesser, yet noticeable impact on wing performance.

In terms of local lift, the clean wing displays an ideal lift distribution with peaks at the center, diminishing predictably towards the tips. This pattern is disrupted in the glaze ice scenario, where lift generation is significantly compromised, particularly at the wing tips. The rime ice scenario, while better than glaze ice, also shows a reduction in lift. Regarding drag, the clean wing condition shows minimized airfoil drag, ideal for efficient flight. Both ice conditions increase drag, with glaze ice leading to a substantial increase, detrimental to fuel efficiency and flight duration.

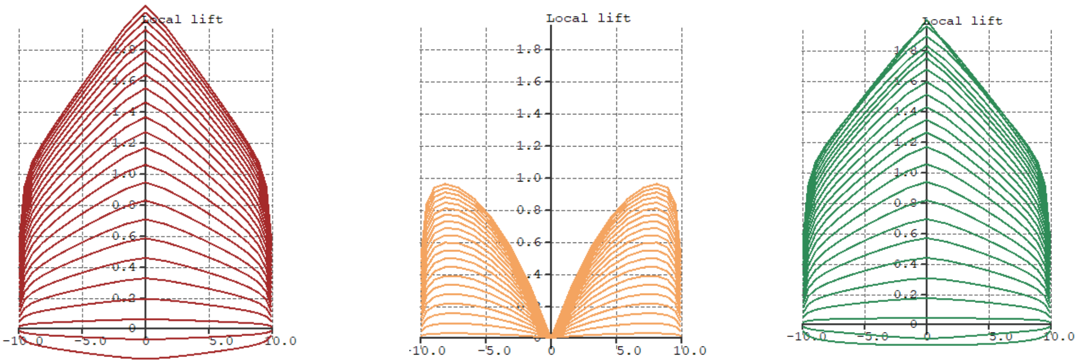


a)

b)

c)

FIG. 9 Graphic representation of the total angle



a)

b)

c)

FIG. 10 Graphic representation of the local lift

CONCLUSIONS

To conclude, the paper presented above studies the impact of ice accretion on the performance of UASs' flight, using XFLR5 bi-dimensional and tri-dimensional analysis features. The results obtained revealed a change in the aerodynamic parameters related to flight stability and efficiency. Both glaze and rime icing shows a lower value of lift coefficient for any given drag coefficient, compared with the clean wing. Therefore, the ice accretion implies increased weight, leading to instability risks, than can eventually cause serious damage to the unmanned aircraft.

Some future research directions exhibits the export of wings' profile as a STL file to the Ultimaker Cura program, in order to be printed and to analysis their behavior in the environment of an aerodynamic tunnel. The application will be performed under the presence of induced smoke, so that the fluid flow can be spotted and indicated in the analysis.

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