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Engineering Notes

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Sensitivity of Aircraft Performance to Icing Parameter Variations

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I. Introduction

AIRCRAFT icing is widely recognized as a significant hazard to aircraft operations. For this reason, aircraft and ice protection systems must be certified for flight into icing conditions. The aircraft certification and icing research communities rely on icing wind tunnels as an efficient way to produce ice accretions in a controlled environment. The aerodynamic performance of aircraft with these ice accretions contributes to the certification of aircraft. It is therefore critical to ensure that the ice accretions are simulated within a known aerodynamic uncertainty.

The aerodynamic performance of an airfoil containing an ice accretion is highly dependent on the geometry of the ice accretion, which is in turn dependent on icing conditions such as temperature, liquid water content (LWC), and median volume diameter (MVD). Icing wind tunnels have the capability to vary LWC and MVD, however, the accuracy in LWC and MVD required to create an aerodynamically representative ice accretion is not known. This research addressed the problem of "how good is good enough" by determining the relationship and sensitivity of iced-airfoil performance to these icing cloud parameters. In addition, these data were placed in perspective by relating measurable or significant aircraft performance changes to the underlying changes in airfoil aerodynamic performance.

Recent NASA studies [1,2] in the Icing Research Tunnel (IRT) measured the effect of icing parameter variations on ice-accretion geometry. These studies showed that small variations in LWC and MVD corresponded to distinct changes in ice-accretion geometry. In addition, the effect of ice-accretion geometry on aerodynamic performance has been recently investigated [3–6]. Papadakis et al. [3,4] used spoilers to simulate horn ice and showed that $C_{l\max}$ degradation was related to the horn height (k/c). Kim and Bragg [5], and Broeren et al. [6] showed that k/c and surface location (s/c) had the biggest impact on airfoil performance degradation.

This study used ice tracings from the NASA studies [1,2] as a basis to examine the sensitivity of aerodynamic performance to icing parameter variations. Eleven ice-accretion tracings were selected from the 39 measured by Miller et al. [2] to reasonably span the range of LWC and MVD tested. The selected ice tracings were modeled as two-dimensional smooth simulated ice shapes for wind-tunnel testing.

The experiments for this research were performed in the Illinois subsonic, low-turbulence, open-return wind tunnel. The airfoil model was an aluminum NACA 0012 airfoil with an 18 in. chord, 33.6 in. span, and a removable leading edge to facilitate installation of the ice simulations. Testing was performed at a Reynolds number of 1.8 million, and a Mach number of 0.18. The results of the aerodynamic testing were related to the corresponding icing parameters in the form of two sensitivities: airfoil performance to icing parameter variations, and derived aircraft performance to icing parameter variations. More details can be found in Campbell et al. [7,8].

II. Sensitivity of Iced-Airfoil Performance to Changes in Icing Parameters

The ice-accretion geometry results of Miller et al. [2] formed the basis of the experiment to determine the sensitivity of aerodynamic performance to icing parameter variations. The following parameters were held constant in Miller et al. [2]: $t = 15$ min, $V = 200$ kt, $\alpha = 2.5$ deg, $T_{\text{tot}} = 23°\text{F}$, and $T_s = 13.5°\text{F}$. The nominal freezing fraction was 0.39, but it varied slightly at off-nominal conditions. The baseline ice accretion corresponded to LWC $= 0.827$ g/m^3 and MVD $= 28.7$ μm, which was run 49 of Miller et al. [2]. The change in LWC and MVD from the baseline condition was calculated for each ice accretion, and then compared with the corresponding change in airfoil performance, as determined from the aerodynamic wind-tunnel test. Figure 1 shows the variation in $C_{l\max}$ with respect to the run 49 baseline condition as a function of ΔLWC and ΔMVD.

A different perspective on these data was obtained by analyzing the ΔLWC and ΔMVD corresponding to a measurable or significant change in $C_{l\max}$. A measurable change in $C_{l\max}$ was considered to correspond to the aerodynamic wind-tunnel testing uncertainty. The uncertainty in measured $C_{l\max}$ for the airfoil which contained the baseline ice accretion was approximately 0.001 [7]. Figure 1 was interpolated to show that the uncertainty in $C_{l\max}$ corresponded to a ΔLWC of ± 0.004 g/m^3 at constant MVD, or a ΔMVD of ± 0.2 μm at constant LWC. This analysis effectively shows that the ΔLWC and ΔMVD required to discern changes in airfoil performance on the order of the aerodynamic wind-tunnel uncertainty are currently unobtainable in an icing wind tunnel [9].

A significant change in $C_{l\max}$ was defined for the purpose of this research as the $\Delta C_{l\max}$ corresponding to the difference between two- and three-dimensional simulations of the same ice accretion. Gurbacki [10] found that a NACA 0012 with a three-dimensional simulated ice shape had a $C_{l\max}$ that was 0.03 greater than a two-dimensional smooth simulation of the same ice accretion. The difference in $C_{l\max}$ between two- and three-dimensional simulated ice shapes then represents, at least for Gurbacki's [10] test, the accuracy with which an ice accretion can be simulated for aerodynamic testing. Using the same interpolation scheme as before, the ΔLWC and ΔMVD corresponding to a $\Delta C_{l\max}$ of 0.03 were ± 0.11 g/m^3 and ± 4.6 μm, respectively. This accuracy in ΔLWC

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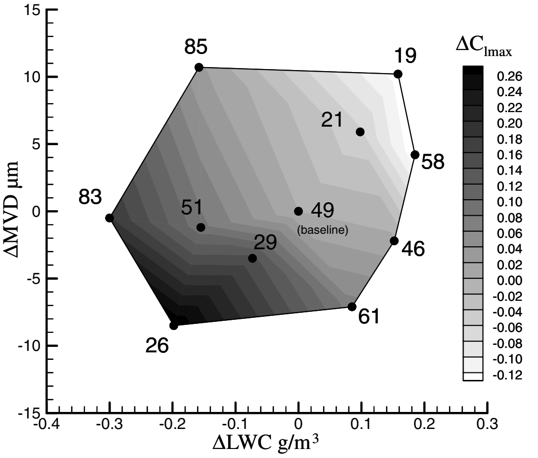

Fig. 1 Effect of icing cloud parameter variations on $C_{l\max}$ from the case 49 baseline; NACA 0012, $Re = 1.8 \times 10^6$, $M = 0.18$. Numbers correspond to IRT run number [2].

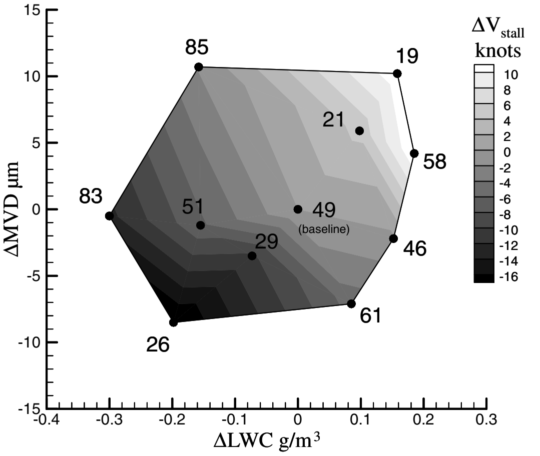

Fig. 2 Effect of icing cloud parameter variations on V_{stall} from the case 49 baseline. Numbers correspond to IRT run number [2].

and ΔMVD is controllable in an icing wind tunnel [9]. Table 1 presents the ΔLWC and ΔMVD corresponding to measurable and significant values of $\Delta C_{l\max}$.

III. Sensitivity of Aircraft Performance to Changes in Icing Parameters

A generic model of a turboprop transport aircraft was developed to relate a change in stall speed to $\Delta C_{l\max}$, and then to ΔLWC and ΔMVD. The model aircraft was assumed to be a transport category turboprop, at 10,000 ft with a weight of 25,000 lbs. The sensitivity of stall speed to LWC and MVD variations is presented in Fig. 2 and was found by combining the aerodynamic wind-tunnel results and the aircraft model.

According to Federal Aviation Administration (FAA) Advisory Circular AC-25-7A [11], stall speed is required to be known within 0.5 kt for the certification of transport airplanes. Additionally, if ice accretions are shown to increase stall speed by 3 kt or greater, the reference airspeeds for that aircraft are required to be recalculated. Therefore, a $\Delta V_{\rm stall}$ of 0.5 kt was considered a measurable change in $V_{\rm stall}$ and 3 kt was considered a significant change in $V_{\rm stall}$. For $\Delta V_{\rm stall} = \pm 0.5$ kt, Fig. 2 was interpolated to give $\Delta\text{LWC} = \pm 0.025\ \text{g/m}^3$ at constant MVD, and $\Delta\text{MVD} = \pm 1.1\ \mu\text{m}$ at constant LWC. By the same procedure, if $\Delta V_{\rm stall} = \pm 3$ kt, then $\Delta\text{LWC} = \pm 0.12\ \text{g/m}^3$ and $\Delta\text{MVD} = \pm 5.5\ \mu\text{m}$. Table 2 presents the accuracy of LWC and MVD required to simulate measurable and significant values of $\Delta V_{\rm stall}$.

IV. Conclusions

A comparison of the required accuracy in LWC and MVD for $\Delta V_{\rm stall} = \pm 3$ kt and $\Delta C_{l\max} = \pm 0.03$ showed that the results were similar and obtainable in an icing wind tunnel. Therefore, one answer to the question of "how good is good enough" might be LWC accuracy within 0.12 g/m³ and MVD accuracy within 5.5 μm. However, it should be noted that this sensitivity is only valid for this airfoil about the baseline condition of $\text{LWC} = 0.827\ \text{g/m}^3$ and $\text{MVD} = 28.7\ \mu\text{m}$. Additional research is required to extend this sensitivity to other baseline conditions.

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Table 1 Required accuracy of ΔLWC and ΔMVD based on iced-airfoil performance at the baseline condition ($\text{LWC} = 0.827\ \text{g/m}^3$, $\text{MVD} = 28.7\ \mu\text{m}$, run 49)

Change in airfoil performance	Qualitative significance	ΔLWC	ΔMVD	ΔLWC, % from baseline	ΔMVD, % from baseline
$\Delta C_{l\max} = \pm 0.001$	aerodynamic wind-tunnel uncertainty [7]	±0.004 g/m³	±0.2 μm	0.5%	0.7%
$\Delta C_{l\max} = \pm 0.03$	change in $C_{l\max}$ between a two- and three-dimensional ice accretion [10]	±0.11 g/m³	±4.6 μm	13.3%	16.0%

Table 2 Required accuracy of ΔLWC and ΔMVD based on iced-aircraft performance at the baseline condition ($\text{LWC} = 0.827\ \text{g/m}^3$, $\text{MVD} = 28.7\ \mu\text{m}$, run 49)

Change in aircraft performance	Qualitative significance	ΔLWC	ΔMVD	ΔLWC, % from baseline	ΔMVD, % from baseline
$\Delta V_{\rm stall} = \pm 0.5$ kt	stall speed must be known within 0.5 kt [11]	±0.025 g/m³	±1.1 μm	3.0%	3.8%
$\Delta V_{\rm stall} = \pm 3$ kt	if $\Delta V_{\rm stall} > 3$ kt due to ice, reference airspeeds need to be recalculated [11]	±0.12 g/m³	±5.5 μm	14.5%	19.2%

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