Effect of Ice on Airfoil Stall at High Reynolds Numbers

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Introduction

IN wing design it is very important to determine the maximum lift coefficient as accurately as possible, since this lift coefficient corresponds to the stall speed that is the minimum speed at which controllable flight can be maintained. Any further increase in angle of incidence will increase flow separation on the wing upper surface, resulting in a loss of lift and a large increase in drag.

Despite the significant advances in computational fluid dynamics, our ability to predict the maximum lift coefficient and poststall behavior of single airfoils, wings, multielement airfoils, or wings is still not satisfactory. The chief culprit is the lack of an accurate turbulence model to represent flows with extensive separation. Inaccuracies of numerical solutions of the conservation equations at these flow conditions, as well as difficulties in modeling of flow near the trailing edge of an airfoil or wing, add to this dilemma.

Recently Cebeci et al.[1] described an interactive boundary-layer method, together with the e^n approach to the calculation of transition, for predicting stall and poststall behavior of airfoils at low and high Reynolds numbers. The turbulence model was based on the Cebeci–Smith algebraic eddy-viscosity formulation with improvements for strong pressure gradient effects and transitional flows at low Reynolds numbers. Comparison of calculated results for incompressible flows indicated good agreement with experiment for a wide range of Reynolds numbers. Preliminary calculations for low-Mach-number flows with this interactive method that applies compressibility corrections to the panel method also indicated good agreement with data and showed that at a Mach number of 0.30, the compressibility effect on $(C_\ell)_{\max}$ was not negligible.

The ability of the calculation method of Ref. 1 to predict the effect of ice on airfoil stall at high Reynolds numbers is examined here, and the results are presented in the following section. The interactive boundary-layer method previously developed for iced airfoils[2] and coupled to the LEWICE code for predicting ice shapes[3,4] is replaced with the calculation method of Ref. 1. Appropriate changes are made to this method, including roughness effects due to ice, and the results are presented in the following section.

Results and Discussion

The ability of the calculation method to predict the effect of ice on the stall and poststall behavior of an airfoil with leading-edge rime ice was investigated by first computing the ice shape on a NACA 0012 airfoil for given atmospheric conditions and for a given ice accretion time. The roughness effects in the turbulence model were accounted for by using the modifications to the Cebeci–Smith model discussed in Ref. 5. The mixing length expression in the inner eddy viscosity formula was expressed as

$$\ell = 0.40(y + \Delta y)\{1 - \exp[-(y + \Delta y)/A]\} \qquad (1)$$

where Δy is a function of an equivalent sand grain roughness k_s, which, in terms of dimensionless quantities k_s^+ and Δy^+, is given by

$$\frac{\Delta y u_\tau}{\nu} = \Delta y^+ = \begin{cases} 0.9\left[\sqrt{k_s^+} - k_s^+ \exp\left(-k_s^+/6\right)\right] & 5 \le k_s^+ \le 70 \\ 0.7(k_s^+)^{0.58} & 70 \le k_s^+ \le 2000 \end{cases} \qquad (2)$$

with k_s^+ defined by $k_s u_\tau/\nu$. The equivalent sand-grain roughness k_s for ice was determined from the expressions used in the LEWICE code.[3]

The interactive boundary-layer calculations with these modifications to the turbulence model were then performed for the computed ice shape at a specified chord Reynolds number at various angles of attack that included stall and poststall conditions. Before these results are presented, however, it is useful to review the accuracy of the calculation method for the same airfoil without ice at chord Reynolds numbers of 3×10^6 and 2×10^5.

Figure 1 shows the variation of the lift coefficient with angle of attack at two Reynolds numbers. The results in Fig. 1 indicate that the Reynolds number has a significant effect, not only on the value of maximum lift coefficient, but also on the stall angle. With this change in Reynolds number, the $(C_\ell)_{\max}$ is reduced from a value of 1.5 to a value slightly over 1. The corresponding reductions in angle of attack are from 16 to around 11 deg.

Having demonstrated the ability of the calculation method to predict stall and poststall behavior of the NACA 0012 airfoil at $R_c = 3 \times 10^6$ and the significant effect of Reynolds number on $(C_\ell)_{\max}$, we now present results for the same airfoil at a chord Reynolds number of 1.5×10^6. Figure 2 shows the ice shapes accumulated on the airfoil leading edge after 15, 30, and 60 s for atmospheric conditions corresponding to a static temperature $T_s = 260.44$ K, ambient pressure $p_\infty = 907548$ Pa, liquid-water content LWC $= 0.50$ g/m^2, freestream velocity $V_\infty = 129$ m/s, and droplet size of 20 μm. These results, obtained with LEWICE, show that in practically all cases the extent of the leading-edge ice is about 5% of the chord.

Figure 3 shows the effect of ice shapes on the lift coefficient at various angles of attack including stall and poststall. The dashed lines, which correspond to the lift coefficient of the iced airfoil, show the strong effect of ice on the lift loss. With very small ice accretion, the stall angle decreases from about 15 to between 7 and 8 deg with a corresponding lift loss of almost 50%. It is interesting to note that the stall angle is not very sensitive to the size of the rime ice. Even 1-s ice is sufficient to cause a drastic change in the stall angle.

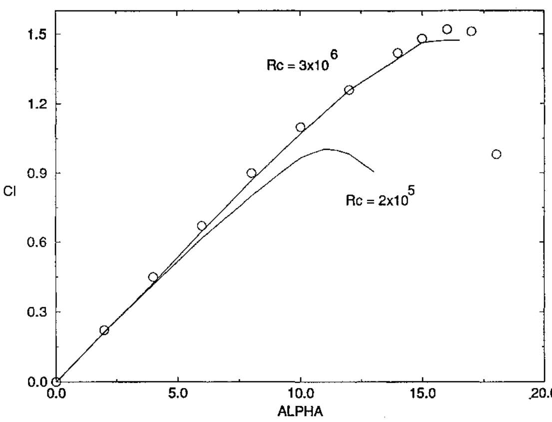

Fig. 1 Variation of lift coefficient of the NACA 0012 airfoil at two Reynolds numbers. The symbols denote experimental data.

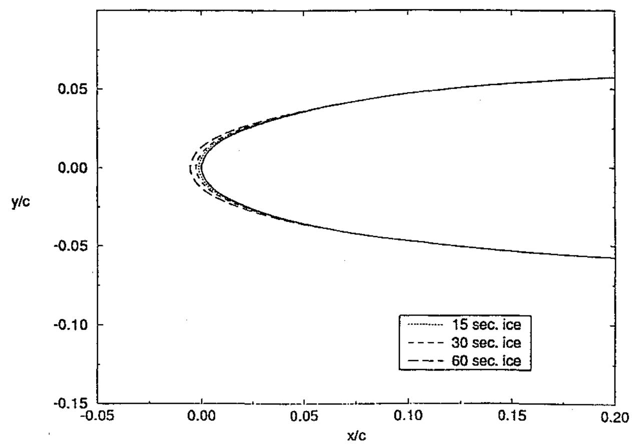

Fig. 2 Ice shapes for 15, 30, and 60 s on the leading edge of the NACA 0012 airfoil.

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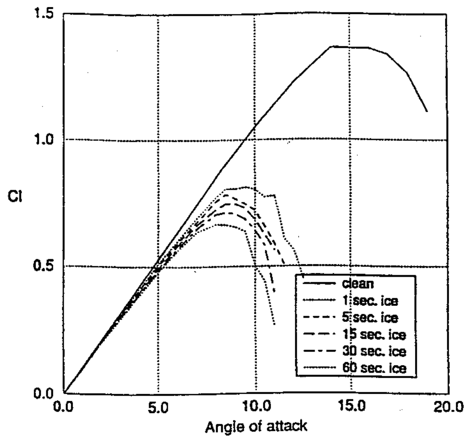

Fig. 3 Ice shapes for 15, 30, and 60 s on the leading edge of the NACA 0012 airfoil.

Recent studies[6] with the calculation method of Ref. 1 also indicate excellent agreement between calculations and measurements on clean airfoils where the Reynolds number is low. It will be interesting to extend this study to an iced airfoil operating at low Reynolds numbers. For example, typical Reynolds numbers for the blades of a rotorcraft near the hub may be around 2×10^5. For the NACA 0012 airfoil, the stall angle without ice accretion is 11 deg at this Reynolds number (Fig. 1). The question would be, will a small leading-edge ice reduce the stall angle as drastically as it does in the higher Reynolds number case, and what will that stall angle be?

References

[1]Cebeci, T., Roknaldin, F., and Carr, L. W., "Prediction of Stall and Post-Stall Behavior of Airfoils at Low and High Reynolds Numbers," AIAA Paper 93-3502, Jan. 1993.

[2]Cebeci, T., "Calculation of Flow Over Iced Airfoil," *AIAA Journal*, Vol. 27, No. 7, 1989, p. 853.

[3]Ruff, G. A., and Berkowitz, B. M., "User's Manual for the NASA Lewis Ice Accretion Code (LEWICE)," NASA CR-185129, May 1990.

[4]Cebeci, T., Chen, H. H., and Alemdaroglu, N., "Fortified LEWICE with Viscous Effects," *Journal of Aircraft*, Vol. 28, No. 9, 1991, pp. 564–571.

[5]Cebeci, T., and Chang, K. C., "Calculation of Incompressible Rough-Wall Boundary-Layer Flows," *AIAA Journal*, Vol. 16, No. 7, 1978, p. 730.

[6]Chen, H. H., and Cebeci, T., "The Role of Separation Bubbles on the Aerodynamic Characteristics of Airfoils, Including Stall, at Low Reynolds Numbers," *International Journal for Numerical Methods in Fluids* (submitted for publication).

Investigations of Angle Bias Errors in Laser Velocimetry Measurements

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Nomenclature

I = streamwise turbulence intensity, $(u')_{\text{rms}}/\bar{U}$
N = number of fringes required to validate a measurement
N_T = total number of physical fringes in LV probe volume
T = threshold level
$\bar{U}$ = mean streamwise velocity
u' = fluctuating component of streamwise velocity
V_f = fringe velocity, down mixed Bragg frequency $*$ fringe spacing
V_p = particle velocity
γ = particle trajectory angle, 0 deg being perpendicular to the fringe planes, opposing the Bragg cell frequency shift direction
σ = standard deviation

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Introduction

In 1987, a panel of recognized experts in the field of laser velocimetry was assembled and tasked with addressing problems of statistical bias errors in laser velocimetry (LV).[1] One source of statistical bias addressed by the panel was fringe bias or, more appropriately, angle bias. Angle bias had been studied theoretically, and limited experimental data supporting the theory had been published. Although the panel members had confidence that the theoretical predictions were accurate, additional detailed experiments were recommended to confirm the quantitative accuracy of the theory.[1] Following this recommendation, angle bias experiments have been conducted at West Virginia University and will be discussed in this paper.

Background

Angle bias results from the decrease in probability of measuring the velocity of a seed particle as the trajectory angle of the particle becomes increasingly more parallel to the fringe planes in the LV measurement volume (i.e., as $\gamma \rightarrow \pm 90$ deg). If angle bias is present within a system, the flow turbulence statistics will not be measured accurately since LV system response as a function of particle trajectory angle is nonisotropic. The importance of understanding and minimizing the potential of angle bias prior to taking measurements is that 1) it is a systematic error source whose effects can be minimized by user intervention and 2) to date, there are no postprocessing techniques to correct for it. Consider a single component LV system measuring a steady, turbulent flow. For any particle passing through the probe volume, the exact particle trajectory angle is unknown, making an angle bias correction method impossible to apply. The same argument applies for two or three component systems operating in a noncoincident measurement mode. For a three-component LV system acquiring coincident measurements, the particle trajectory angle can be determined providing a linear trajectory through the probe volume is assumed. However, to apply an angle bias correction scheme, the LV system response must be accurately known for all flow angles encountered by each component. This behavior is, of course, instrument and flow specific, and difficult to assess.

Prior to the present study, efforts to describe the angular response characteristic for a single component, counter-type processor system were undertaken by Whiffen et al.[2] with the hopes that their findings may be applied to a three-component system. Whiffen et al. derived a simple expression for the probability of particle detection (PPD) as a function of the particle trajectory angle γ:

$$\text{PPD}(\gamma) = \sqrt{1 - \left(\frac{N/N_T}{\cos(\gamma) + V_f/V_p}\right)^2} \tag{1}$$

The derivation of Eq. (1) is based on geometrical considerations of a two-dimensional probe volume model. Whiffen et al. justify the simplification of two dimensionality by stating that the useful portion of the probe volume is nearly cylindrical permitting PPD calculations to be performed assuming a constant probe volume cross-sectional area. However, since the actual probe volume is three dimensional, the validity of this assumption is not without question. Additionally, Eq. (1) predicts the PPD for particles traveling at a given trajectory angle γ. For turbulent flows, particles will pass through the probe volume over a range of trajectory angles, changing the average probability of particle detection. It was desired to obtain computational and experimental data including the effects of turbulence and probe volume three dimensionality to determine the quantitative accuracy of the theory expressed by Eq. (1).