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Problems with Leading-Edge Flow Control Experiments

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I. Introduction

THE leading-edge high-lift system on a typical transport aircraft wing typically contributes 2–3% to the overall wing weight. There is therefore considerable incentive to explore leading-edge flow control solutions that could approach the performance of mechanical leading-edge devices but at considerably reduced weight. Indeed, the application of flow control devices at the leading edge has been reported from various sources claiming enhancement in low-speed performance in terms of increased C_L and reduced C_D [1–5]. However, the technical issue of whether flow control works at the leading edge should be replaced by the technological issue of whether flow control works realistically and successfully at flight Reynolds number conditions.

The aim of this Note is to act as a guide for future leading-edge flow control activities conducted in wind tunnels operating at low to medium Reynolds numbers ($Re < 10 \times 10^6$) and is specifically applied to civil transport aircraft. The objectives are as follows:

1) Provide a review of relevant literature.

2) Identify airfoil geometric parameters relevant to designing leading-edge flow control experiments.

3) Discuss the effect of Reynolds number on the validity of leading-edge flow control experiments.

4) Describe a wind-tunnel experiment that highlights many of the problems associated with subscale testing of leading-edge flow control.

A. Thickness Parameter to Identify Airfoil Stalling Characteristics

It is unwise to extrapolate separation control results for airfoils that exhibit the trailing-edge type of stall to those in which stall occurs at the leading edge, because the stall characteristics are different. Reference [6] describes the low-speed stalling characteristics of aerodynamically smooth airfoils as reported by McCullough and Gault [7], which are 1) thin-airfoil stall, 2) leading-edge stall and 3) trailing-edge stall. It is evident that if flow control is applied to the leading edge of airfoils that inherently exhibit the trailing-edge type of stall, then only modest gains would be obtained [2,3]. It is much more beneficial to apply flow control at the leading edge if the airfoil exhibits leading-edge stall and, correspondingly, for trailing-edge stall-biased airfoils. Reference [6] graphically illustrates the relevance of the airfoil upper ordinate at the $x/c = 1.25\%$ station, with the Reynolds number as a means to identify the stalling characteristics. This thickness parameter also provides a guide to the maximum leading-edge nose radius that can be drawn so that airfoils exhibiting a specific and predefined type of stall can be designed.

B. Laminar Separation Bubble

It is well known that a laminar separation bubble appears at the leading edge during wind-tunnel testing over a range of Reynolds numbers. Early experimental studies by Gault [8] have depicted that there are no detailed data of laminar bubbles at Reynolds numbers greater than 10×10^6. Experiments performed below this threshold Reynolds number have clearly illustrated regions of laminar separation bubbles at the leading edge [1,7–10]. It is known that increasing the turbulence levels to replicate higher Reynolds number conditions shortens the chordwise extent of the bubble [8]. Over the years, *turbulators* of various kinds have been used to fix the transition [11]. Hurley and Ward [12] claimed to be able to simulate high Reynolds number conditions at a test chord Reynolds number of approximately 4×10^6 by using discrete air jets located between 0.42 and 0.52% c. They concluded that the results were representative of high Reynolds number cases, because they were not unnecessarily increasing the boundary-layer thickness above that of a normal laminar layer at separation. Although benefits were obtained, these were regarded as transition control and not separation control. However, some experiments looking into leading-edge flow control have tended to neglect the presence of the laminar separation bubble and persisted in the application of flow control devices at the leading edge [9,13,14]. It has to be remembered that what is actually being carried out is transition control in which lift and drag improvements would be obtained by the manipulation of the laminar bubble. Separation control results obtained in wind tunnels by the manipulation of the laminar bubble are questionable as to their real meaning at flight Reynolds number conditions in which the laminar bubbles do not exist at the leading edge, as the flow is inherently turbulent. However, these results can be used in applications such as micro unmanned aerial vehicles (UAVs) or turbine blades that operate at Reynolds number regimes that are characterized by the presence of the laminar bubbles at the leading edge.

Stall at the leading edge at flight Reynolds numbers is associated with the severe adverse pressure gradient occurring due to the thin and sharp nose profile. To be geometrically consistent, similar models in wind tunnels come with the undesirable by-product of a laminar bubble, because of the same severity of pressure gradient. To obtain a representative flight-condition flow at the leading edge, it is usual to artificially trip the leading edge by using roughness elements to generate a turbulent flow. Early review papers of this topic include the work of Tani et al. [15] and Von Doenhoff and Braslow [16]. However, although it was assumed that a fully developed turbulent boundary layer would be obtained immediately after the admissible roughness elements, Kerho and Bragg [17] reported that the transition was never observed to be a switch and can take up to 30% c to reach a fully turbulent state at a chord Reynolds number of 1.2×10^6.

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C. Wind-Tunnel Activities

Wind-tunnel studies have been conducted by the authors on a constant-chord swept wing. A description of the model can be found in [18]. Tests with the original leading edge confirmed the analytical conclusion obtained from [6]: the wing exhibits a trailing-edge biased type of stall. Thus, a new leading-edge profile, LE 1, was designed so that stall was obtained at the leading edge. Figure 1 identifies the relevant thicknesses at $x/c = 1.25\%$, which eventually defines the airfoil stalling behaviors. The leading-edge stall region at a Reynolds number of 1.2×10^6 falls between $1.60 < (z_{1.25}/c) \times 100 < 1.90$, as illustrated in [6]. This thickness range is clearly identified in Fig. 1 at $x/c = 1.25\%$ for the tested airfoil's chord of 0.548 m. Consequently, an airfoil that has a leading-edge curvature passing above this limit would exhibit trailing-edge stall, as illustrated by the upper ordinate of a NACA 0015 at $x/c = 1.25\%$. A representation of thin-airfoil stall is illustrated by a NACA 0009 airfoil. A typical airfoil that exhibits leading-edge stall, NACA 0012, is also illustrated.

The leading-edge radius ($r/c = 2.18\%$) of the original airfoil was crossing $x/c = 1.25\%$ above the leading-edge stall region, as illustrated in Fig. 1, and thus was concluded to be exhibiting a trailing-edge biased type of stall. Experimental evidence supports this hypothesis, as illustrated in Fig. 2, indicated by the gradual drop of lift coefficient at increasing angle of attack.

Figure 1 illustrates that a leading-edge stall-biased wing is characterized by a thinner nose profile than the original wing. Details of how to draw the radius of the nose circle and the thickness distribution are available from [6,19]. In brief, the thickness distribution is added to the mean line, whereas the center for the leading-edge radius is found by drawing a line through the end of the chord at the leading edge with a slope equal to the slope of the mean line at that point and laying off a distance from the leading edge along this line equal to the leading-edge radius.

Leading-edge stall was obtained on the model labeled "new LE 1" in Fig. 2, as illustrated by the sudden drop in lift coefficient. The design parameters of the new leading edge were $r/c = 1.58\%$ and $z/c = 1.67\%$ at $x/c = 1.25\%$, eventually merging with the original wing profile at $x/c = 7.60\%$. The leading-edge radius of the new model has been reduced from the original wing, and the thickness parameter $z/c = 1.67\%$ corresponds to the lower leading-edge stall limit, as defined in Fig. 1.

Oil-flow visualization was then performed at the leading edge to detect the separation line. It was found that the paint tripped the flow and stall failed to occur at $\alpha = 14$ deg (at which the clean wing normally stalled). When the paint was wiped off the surface, α_{stall} was back to 14 deg. The stable laminar bubble could be clearly observed, extending up to 3% c. It was concluded that the laminar flow was very sensitive and it was required to fix the transition such that a representative turbulent flow was available at the leading edge before application of flow control to delay separation. A similar observation was made by Ingelman-Sundberg and Eriksson [10], who clearly illustrated improvements in $C_{L\max}$ with trip devices used to manipulate the laminar bubble. Although the flow control effect was experienced using trip devices at the leading edge, from knowledge now acquired, it is clear that the transition control via the manipulation of the laminar bubble was being performed.

Attempts to fix the transition and suppress the laminar bubble on LE 1 started by positioning a 1.2-mm-thick and 3-mm-wide roughness strip (grit number 40) just before the laminar bubble ($\sim 1\% c$). A similar tripping mechanism was previously employed in the original wing to suppress the bubble completely. It was found that complete suppression of the bubble did not occur, although its chordwise extent was greatly reduced. Tufts (0.2 mm in diameter) were then used at the leading edge to detect separation, but they were producing transition control by manipulating the laminar bubble through the generation of small-scale random turbulence. The improvement in low-speed performance can be clearly seen in Fig. 2. Apart from an increase in α_{stall} by 3 deg and $C_{L\max}$ by 8%, the stalling behavior changed to the trailing edge, indicating virtual modification of the leading-edge parameters.

The experiment concluded that a turbulent leading-edge stall cannot be readily achieved at wind-tunnel Reynolds numbers of 1.2×10^6. Although it is still possible to design separation-free transition by delicate contouring of the airfoil near the minimum pressure point to lessen the severity of the adverse pressure gradient [9], it is likely that the end profile would modify the leading-edge parameters to such an extent that the airfoil would exhibit a trailing-

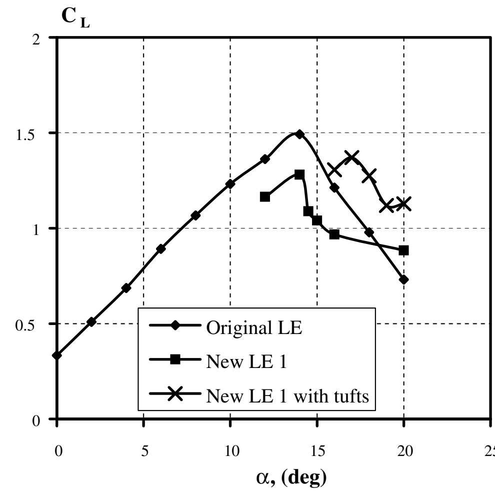

Fig. 2 Experimental lift distributions to identify stall behavior.

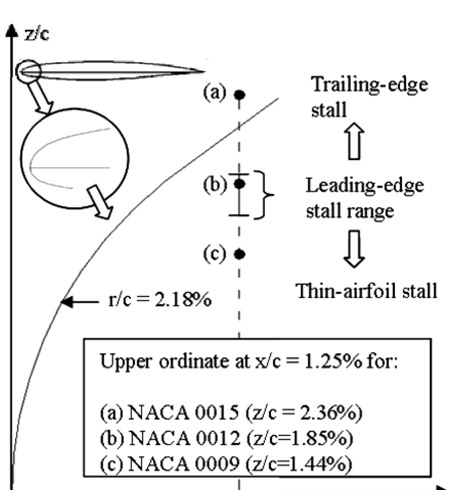

Fig. 1 Upper surface ordinates at $x/c = 1.25\%$ defining airfoil stall types.

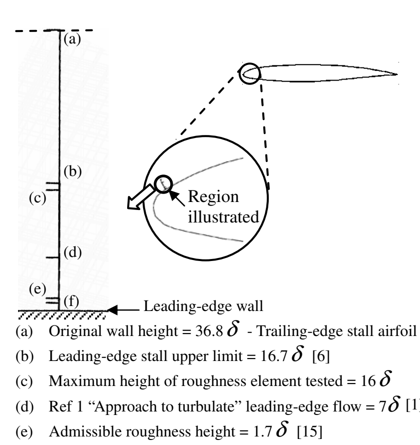

Fig. 3 Illustration of relative thicknesses on LE 1 model perpendicular to airfoil wall at $x/c = 1\%$.

edge biased type of stall. Figure 3 illustrates the relative thicknesses described previously.

It can be seen that the maximum height of the roughness elements tested is very close to the limit at which trailing-edge stall starts to occur, as defined by [6]. Thus, further increasing the height of roughness elements is not justified, because the leading-edge profile will then be modified to such an extent that the resulting geometry will produce an airfoil biased toward trailing-edge stall. Additionally, it was not evident from the oil-flow visualization that an increase of 0.7 mm in the roughness elements' heights would suppress the stable laminar bubble.

Thus, it appears that the low Reynolds number condition in the wind tunnel is not an appropriate environment to simulate flight Reynolds number conditions for the leading-edge studies. The undesirable by-product formed in terms of laminar separation bubble is very stable, strong, and impractical to eliminate, certainly for the test Reynolds number of 1.2×10^6. Although the elimination of the bubble is more easily done at higher Reynolds numbers, it was reported that its presence was detected even at a Reynolds number of 5.6×10^6 [7]. Environmental tripping was considered as an alternative to produce the turbulent flow at the leading edge, but then the wind-tunnel turbulence level would be nonrepresentative of the flight Reynolds number condition. Also, any disturbance placed in front of the model would produce a shedding frequency based on the Strouhal number and the flow control devices implemented at the leading edge would be controlling a single frequency, which is nonrepresentative of flight conditions.

D. Reynolds Number Effect

Liebeck [20] reported that there is a critical Reynolds number of 2×10^5 that is considered minimum for meaningful aerodynamic data. This has been reinstated by Greenblatt and Wygnanski [1]. Results obtained from tests performed below this threshold Reynolds number are questionable as to their validity when applied to flight Reynolds number regimes [2,4]. Although these results can possibly have a meaning for low Reynolds number applications, as in the case of transition control on micro UAVs, they cannot be applied for separation control on civil aircraft.

II. Conclusions

Careful thought must be given to the airfoil being used for leading-edge flow control activities. It has to be realized that results obtained while doing these types of experiments can be easily misinterpreted as separation control, which makes scaling of the results to flight conditions irrelevant. The conditions surrounding leading-edge flow control experiments in wind tunnels operating at Reynolds number of less than 10×10^6 are not appropriate for separation control, because the flow is dominated by the presence of the laminar separation bubble at the airfoil's nose, and it is difficult to generate turbulent flow at the leading edge without unnecessarily increasing the height of the boundary layer above that of a normal laminar layer at separation. These types of experiments demand high Reynolds number flow conditions that can be more easily obtained in cryogenic wind tunnels, if not in the aircraft at flight conditions, but come with an associated penalty of increased operating cost. Leading-edge flow control experiments performed below the threshold Reynolds number of 10×10^6 should be documented as transition control and not separation control, unless alternative ways are found to *turbulate* the flow while ensuring that the turbulence level is representative of flight conditions.

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