Table 1 Summary for two split-'S' maneuvers

Parameter	No. 1	No. 2	Units
Entrance altitude	8880	6850	ft
Entrance velocity	320	340	KTAS
$\bar{\rho}$	0.0628	0.0663	lb/ft^3
W	15,100	14,800	lb
Average C_L	0.80	0.81	——
Average α	13.0	13.3	deg
Average n	4.5	4.6	——
Δh measured	4890	4340	ft
Δh estimated by Eq. (14)	5010	4580	ft
Δh estimated by Eq. (15)	>4930	>4510	ft
Δh estimated by Eq. (16)	4860	4430	ft

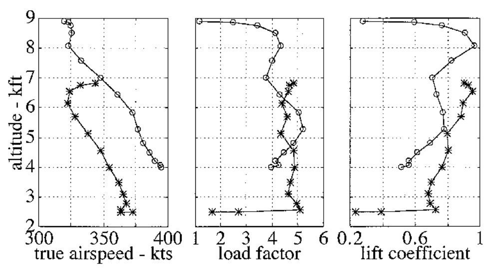

Fig. 3 Altitude histories of the true airspeed, load factor, and lift coefficient in two full-throttle split-'S' maneuvers.

should be, roughly, 250–150 ft less than in run 1 (idle, same airspeed). These estimates accord the numerical simulation, altitude loss in run 3 is about 300 ft less than in run 2, whereas the loss in run 4 is about 200 ft less than in run 1.

Flight Tests

Altitude histories of two sample full-throttle maneuvers are shown in Fig. 3; pertinent data are summarized in Table 1. Aircraft acceleration, velocity, and position have been taken from its navigation system. The lift coefficient was estimated from the acceleration, angle of attack, and either model thrust or model drag; the thrust- and drag-based estimates have agreed to within 1%. Midmaneuver density $\bar{\rho}$ has been computed using the actual temperature and pressure on the test day (that was approximately ISA+3). Average lift coefficient, angle of attack, load factor, and aircraft weight have been computed on the part of the maneuver where the flight-path angle γ was between $7/6\pi$ and $11/6\pi$ (the mid-two-thirds of the maneuver). Based on these averaged values, Eq. (14) overestimates the actual altitude losses of the two runs by 120 and 240 ft. As compared with the altitude loss of about 4500 ft, the accuracy of this approximation is about 5%. Thrust correction turns out to be roughly 150 ft by Eq. (17), whereas Eq. (16) underestimates the altitude loss in the first run by 30 ft and overestimates the loss in the other by 90 ft.

Summary

As compared with both flight tests and numerical simulations, Eq. (15) seems to predict the loss of altitude in a split-'S' with reasonable accuracy. This loss depends, basically, on the wing loading, air density, and the lift coefficient; it is insensitive to variations in the entrance velocity (as long as the lift coefficient remains unlimited by the structural limit), and the throttle setting. Still, an altitude loss in an open-throttle split-'S' will typically be less than in a comparable maneuver executed with throttle on idle.

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Base Drag Reduction Caused by Riblets on a GAW(2) Airfoil

Channa Raju* and P. R. Viswanath†
National Aerospace Laboratories,
Bangalore 560 017, India

Nomenclature

C_{DB} = base drag coefficient, $[-C_{pb}(t/c)]$
C_{DT} = total drag coefficient
C_p = pressure coefficient, $(p - p_\infty)/q_\infty$
C_{pb} = base pressure coefficient, $(p_b - p_\infty)/q_\infty$
c = airfoil chord
h = riblet height
h^+ = hu_*/ν
p = local static pressure
p_∞ = freestream static pressure
q_∞ = freestream dynamic pressure
t = trailing-edge thickness
u_* = friction velocity
x = distance along the chord
y = distance normal to tunnel axis
α = angle of attack
ΔC_D = $(C_{D\text{riblet}} - C_{D\text{noriblet}})$
ν = kinematic viscosity

Introduction

AMONG various methods explored for turbulent drag reduction on aerodynamic surfaces, riblets have been the most promising.[1] As much as 4–8% of viscous drag reduction has been reported for simple two-dimensional configurations. Plastic sheets with symmetric v-grooves (manufactured by the 3M Co.) have been employed widely in research. Assessment of viscous drag reduction on two-dimensional airfoils, both at low and transonic speeds, has been reported as well.[2–6] Excellent reviews on the subject covering aspects of drag reduction and flow structure are contained in Refs. 1 and 7.

There have been very few attempts exploring the use of riblets in separated flows, either from the point of view of drag reduction or separation control.[8,9] Recently, Krishnan et al.[8] showed that riblets actually increase the base drag (about 8%) on a long axisymmetric body with a blunt base at low speeds; the base diameter was about four times the boundary-layer thickness ahead of the base corner. They used 3M riblet sheets and systematically studied the effect of h^+ on base pressure. They also speculated that, while riblets caused an increase in the base drag for a large-scale separated flow (like on the axisymmetric blunt base[8]), the effect could be favorable on an airfoil with a blunt trailing edge, which is a case of a small-scale separated flow.

The present investigation was undertaken specifically to assess the effect of 3M riblets on the base pressure of an airfoil with a blunt trailing edge. Experiments were made at low speeds on a 13.6% thick GAW(2) airfoil model, which has a trailing-edge thickness ratio of 0.5%. The results show very clearly that the base drag reduction of an engineering value can be achieved for the optimized riblet geometry.

Experiments

Facility and Model

The experiments were conducted in a 300 × 1500 mm boundary-layer tunnel. The GAW(2) airfoil model, with a c of

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*Scientist, Experimental Aerodynamics Division.
†Head, Experimental Aerodynamics Division. Associate Fellow AIAA.

600 mm and a span of 300 mm, having a trailing-edge thickness of 3 mm, was mounted vertically in the test section. The model was instrumented with 38 static pressure taps of o.d. 1.2 mm on the upper and lower surfaces. The base pressure was measured and averaged using three ports distributed along the vicinity of the midspan of the model.

Measurements

The tests were performed at a freestream velocity of 30 m/s, providing a chord Reynolds number of 1×10^6. The boundary layer on the top and bottom surfaces of the model was tripped at 10% chord from the leading edge using a sandpaper strip (24 grade, 30 mm wide).

Riblet films with a height of 0.076 and 0.152 mm were used in this work; they were applied between 0.12 and 0.96c on both the top and bottom surfaces. Streamwise variations of h^+ calculated using an integral turbulent boundary-layer code[10] for the measured pressure distributions on the airfoil upper surface at $\alpha = 0$ and 6 deg are displayed in Fig. 1. The riblet films with $h = 0.076$ and 0.152 mm appear optimum at $\alpha = 0$ and 6 deg, respectively, considering viscous drag reduction.

The freestream dynamic pressure, model surface, and the base pressures were measured using three micromanometers supplied by Furness Controls, UK. The total drag was determined from the pitot and static measurements in the wake using the method of Jones.[11] A constant temperature hot-wire anemometer was used to assess the existence of vortex shedding behind the base. Measurements of model static pressures and pitot profiles in the wake were made over an angle-of-attack range of −2 to 6 deg. The reference configuration for determining drag reduction was the smooth airfoil model without the riblet and with the same transition trip.

Accuracy of the Measured Data

The uncertainties in the measured data estimated using the methodology of Kline and McClintock[12] and taking into account repeatability are

$$\Delta C_p = \pm 0.0035 C_p, \qquad \Delta C_{DT} = \pm 0.015 C_{DT}$$

Two Dimensionality

The two dimensionality of the flow was assessed by employing the two-dimensional momentum integral in the wake. Pitot profiles for the smooth model (without riblets) at three streamwise locations in the wake ($x/c = 2.0$, 2.5, and 3.0) were measured for determining the total drag. Excellent constancy of drag coefficient (within the estimated uncertainty) was observed to suggest good mean flow two dimensionality in the experiments.[13]

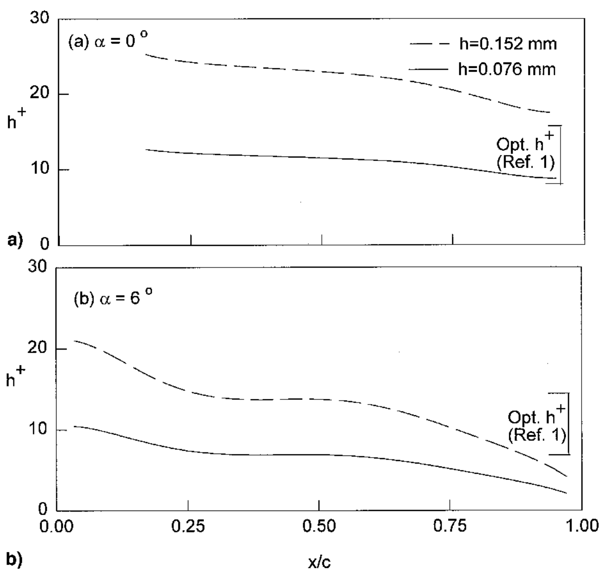

Fig. 1 Variations of h^+ on upper surface of GAW(2) airfoil.

Results and Discussions

Surface Pressure Distributions

The measured surface pressure distributions on the airfoil, both with and without the riblets, revealed[13] that the effects of riblets on C_p distributions were very small (as in many earlier studies[1,3,6]), which suggests that the pressure drag is virtually unaltered because of riblets.

Base Pressure and Base Drag

The base pressure coefficient for the basic airfoil (without riblets) is positive at all α, indicating a base thrust (Fig. 2). It is interesting to note that the base pressure progressively increases with riblet height in the α range considered. These results are in contrast with those measured on an axisymmetric blunt base at low speeds.[8] As may be expected, the base drag coefficient is obviously negative because of base thrust, and its magnitude increases further with riblet height. The ratio of

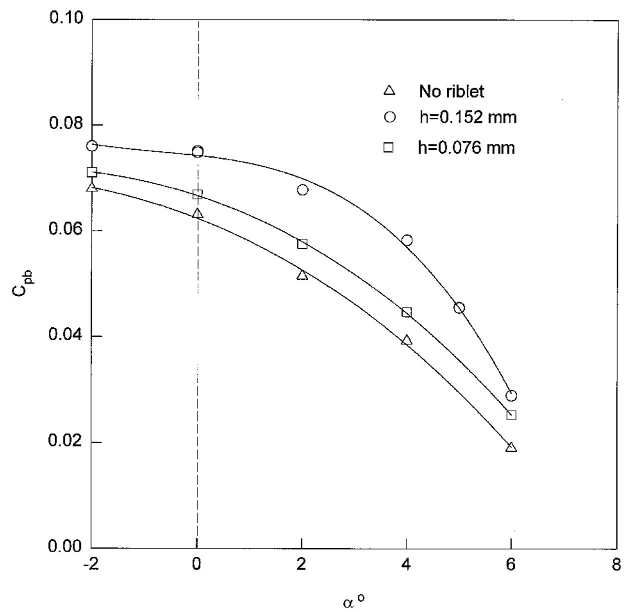

Fig. 2 Variation of base pressure coefficient with incidence.

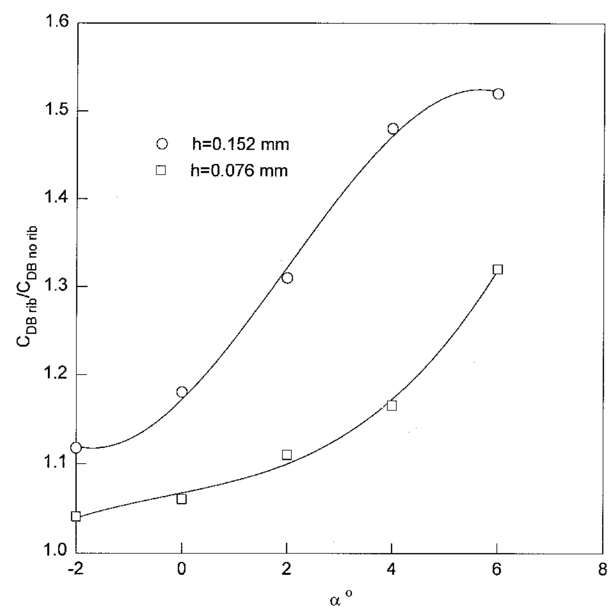

Fig. 3 Variation of normalized base drag with incidence.

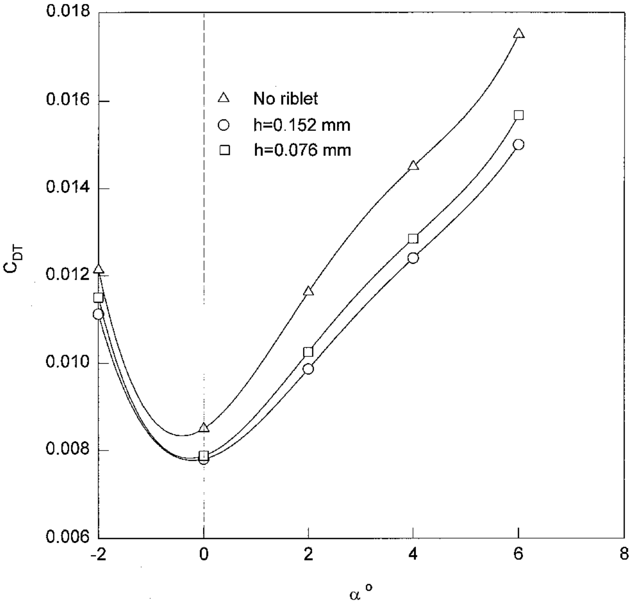

Fig. 4 Variation of total drag coefficient with incidence.

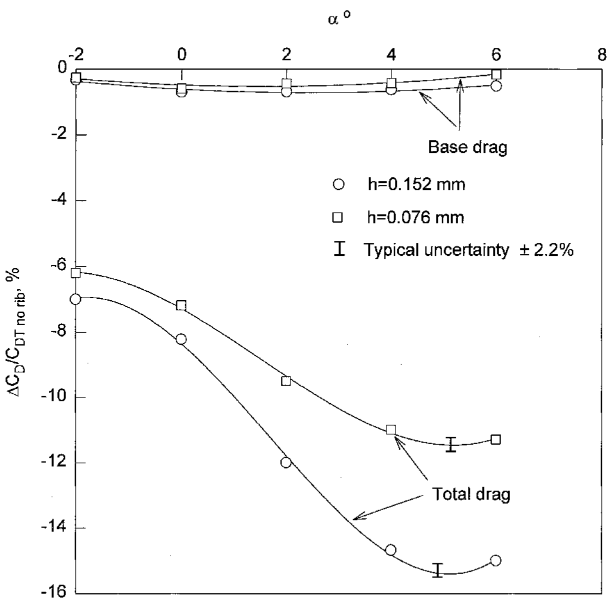

Fig. 5 Total drag and base drag reductions with incidence.

base drag coefficient with riblets relative to no riblets is shown plotted in Fig. 3. The increase in base thrust is as high as 50% at $\alpha = 6$ deg for the riblet height of 0.152 mm. The effectiveness of riblet films with $h > 0.152$ mm could not be assessed because they are not manufactured currently by 3M Co.

Total Drag

Results of measured total drag coefficient (C_{DT}), both with and without riblets, are plotted against airfoil angle of attack in Fig. 4. The riblet film with a height of 0.152 mm has the lowest drag consistent with the optimum h^+ variation (discussed in Fig. 1). Figure 5 displays the results of percentage total drag reduction as well as base drag reduction (relative to the smooth baseline configuration); the normalizing factor for both total and base drag reduction is the total drag coefficient of the smooth airfoil at each α. The increasing trend of total drag reduction with α is a feature already observed by Sundaram et al.[3] and Subaschandar et al.,[5,6] and has been attributed to the increased effectiveness of riblets in adverse pressure gradients. The maximum base drag reduction (equivalently an increase in base thrust), of about 0.7% of the total drag observed for $h = 0.152$ mm, is nearly constant with α.

Possible Flow Mechanisms

Having observed the increase in base pressure because of riblets, it is appropriate to speculate on possible flow mechanisms that may be responsible for the same. Measurements using a hot-wire probe in the near-wake showed no evidence of vortex shedding for the baseline as well as the ribbed airfoil configurations, suggesting that the increased base pressure is obviously caused by mean flow changes because of riblets. It is well known, e.g., Refs. 1, 3, and 7, that riblets lead to lower boundary-layer displacement thickness (δ^*) and, therefore, the effective base height (including δ^* effect) is smaller compared with the smooth airfoil, and an increase in base pressure can be expected.[14] In the context of base flow dynamics, it is generally known[14–17] that the base pressure depends on the development of the free shear layer, which in turn depends on the initial boundary-layer conditions just ahead of the base. Earlier studies[1,7] revealed that the near-wall flow is strongly affected by riblets, which includes a reduction in turbulent intensities (as much as 10–20%)[1,3,18] and Reynolds shear stress, e.g., about 15% in the experiments of Walsh[18] and Suzuki and Kasagi.[19] It would therefore seem likely that the combination of lower (mean) velocity gradient and reduced levels of turbulent intensities and shear stress in the wall region of the approaching boundary layer (ahead of the base plane) will favorably affect the shear-layer development because the mixing zone is relatively short (comparable to the trailing-edge thickness). It is suggested that the increase in base pressure is primarily influenced by the initial conditions of the boundary layer just ahead of the base because of riblets leading to (relatively) lower velocity along the dividing streamline of the shear layer and, hence, a higher base pressure[14] in the presence of riblets.

Conclusions

It has been demonstrated for the first time that riblets can also provide a base drag reduction of engineering value on a blunt trailing airfoil at low speeds; the results further show that the base drag reduction is maintained up to an airfoil incidence of 6 deg. Although the base drag reduction is large (as much as 50% of the smooth airfoil base drag), its contribution as a fraction of the total drag in only about 0.7% because the base drag component itself is small on the airfoil. It is suggested that the increase in base pressure is a direct consequence of certain favorable changes in the boundary layer as a result of riblets ahead of separation; these include a lower effective base height of the airfoil (including boundary-layer displacement thickness) and reduced mixing in the free shear layer leading to lower velocity along the dividing streamline. It would be very informative and valuable to assess base drag reduction because of riblets on supercritical airfoils with a blunt trailing edge at transonic speeds, as well as to investigate, in detail, flow mechanisms responsible for the base pressure increase with these riblets.

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