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Viscous Drag Reduction Using Riblets on NACA 0012 Airfoil to Moderate Incidence

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Results of viscous drag reduction using riblets from 3M on a NACA 0012 airfoil model up to moderate angles of attack are presented. Measurements made consisted of model surface pressure distributions, mean velocity and streamwise turbulence intensity profiles in the boundary layer (just ahead of the trailing edge), and total airfoil drag for two riblet heights of 0.152 and 0.076 mm. Results show significantly higher skin friction drag reduction with incidence compared to flat plate flows; the reduction was as high as 16% at $\alpha = 6$ deg. Results of mean velocity profiles show that a larger contribution to drag reduction results from the suction side of the airfoil, indicating increased effectiveness of riblets in adverse pressure gradients. Examination of turbulence intensity profiles in the wall region indicates an appreciable reduction in the presence of riblets; correspondingly, the spectra show reduced energy levels at low frequencies.

Nomenclature

C_D	= total drag coefficient, drag force/($q_\infty \cdot c$)
$\Delta C_D/C_D$	= $(C_{D\,\text{riblet}} - C_{D\,\text{smooth}})/C_{D\,\text{smooth}}$
C_f	= skin friction coefficient
C_p	= surface pressure coefficient, $(p - p_\infty)/q_\infty$
c	= airfoil chord
H	= shape factor
h	= riblet height
p	= local surface pressure
p_∞	= freestream static pressure
q_∞	= freestream dynamic pressure
Re_c	= freestream Reynolds number based on airfoil chord
U	= friction velocity, $\sqrt{(\tau_w/\rho)}$
U	= mean velocity
U_e	= local boundary-layer edge velocity
U^+	= U/U_*
$\langle u \rangle$	= rms value of streamwise velocity fluctuations
x	= streamwise distance
y	= normal distance
y^+	= yU_*/ν
α	= angle of attack
β	= Clauser pressure gradient parameter, $(\delta^*/\tau_w)(\mathrm{d}p/\mathrm{d}x)$
δ_{te}	= boundary-layer thickness at trailing edge
δ^*	= displacement thickness
θ	= momentum thickness
ν	= kinematic viscosity
ρ	= density
τ_w	= wall shear stress

I. Introduction

STUDY of turbulent drag reduction using riblets has been an area of significant research during the last decade.[1–14] Drag reduction of as much as 4–8% has been measured in a variety of simple two-dimensional flows at low speeds.[1–5] Riblets with symmetric v grooves (height equal to spacing) with adhesive-backed film manufactured by the 3M Company have been widely used in most earlier work that has revealed enormous consistency in the degree of drag reduction observed as well as many aspects of flow structure. In zero pressure gradient flows, the effects of riblets appear to be confined to the wall region ($y^+ \lesssim 100$); the alteration of the wall shear is apparently due to the thickening of the sublayer, relatively quiescent flow in the grooves affecting the energy production near the wall, and inhibition of the spanwise motion in the presence of riblets. Some reduction in turbulence intensity and Reynolds shear stress in the wall region have also been observed in the presence of riblets.[1,4,6,7] Several review papers on riblets have been published, the most recent being that of Coustols and Savill.[2]

Realistic applications involve pressure gradients; three dimensionality, in addition to other factors, and drag reduction under these conditions are currently being assessed. Not many detailed studies have been reported on the effectiveness of riblets on airfoils including the effect of incidence. The boundary layer on the airfoil model is subjected to the combined effects of pressure gradient and streamwise curvature, unlike the flow over a flat plate. Coustols[8] reported measurements of surface pressure distributions and total drag on a LC100D airfoil at low speeds with 3M riblets present only on the upper surface; the test Reynolds number based on the chord Re_c was 5.3×10^5. The results,[8] with a riblet height h of 0.152 mm, showed total drag reduction of 2.7% at $\alpha = 0$ deg, which decreased to about 2% at $\alpha = 6$ deg. In another experiment, Coustols[9] reported results of drag reduction using 3M riblets on a ONERA D swept airfoil model (sweep angle = 22.5 deg) at zero incidence and at a Re_c of 3×10^5; measurements[9] indicated a maximum total drag reduction of 6% for a riblet height of 0.152 mm. Caram and Ahmed[10] studied the near and intermediate wake region of a NACA 0012 airfoil covered with 3M riblets at $\alpha = 0$ deg and $Re_c = 1.8 \times 10^5$. Total drag reduction determined from the wake survey indicated a maximum of 13.3% for $h = 0.152$ mm and comparatively lower reduction for other riblets (2.7% and 7.3% for $h = 0.076$ and 0.023 mm, respectively). The effectiveness of 3M riblets on a CAST 7 supercritical airfoil at transonic speeds and at zero incidence was reported by Coustols and Schmitt[11]; these tests indicated a total drag reduction of 3.5% for the riblet height of 0.152 mm, which implied a skin friction drag reduction of about 7–8%. Recent measurements by Viswanath and Mukund[12] on a supercritical airfoil covered with 3M riblets have revealed skin friction drag reduction of 6–12% (in the α range of -0.5–1 deg) at transonic Mach numbers. Based on a comparison of wake pitot pressure profiles (with and without the riblets), they suggested that riblets may be more effective in adverse pressure gradients.

In addition to the measurements on airfoils just discussed, there have been some observations substantiating the drag reduction capability of riblets in pressure gradients. Choi[13] investigated the effect of longitudinal pressure gradients on a flat plate with machined riblets (1.5 mm high, 2.5 mm pitch) for two values of Clauser parameter β of +3.1 and -0.16. These results showed that the near wall turbulence structure is not altered by the pressure gradient, suggesting

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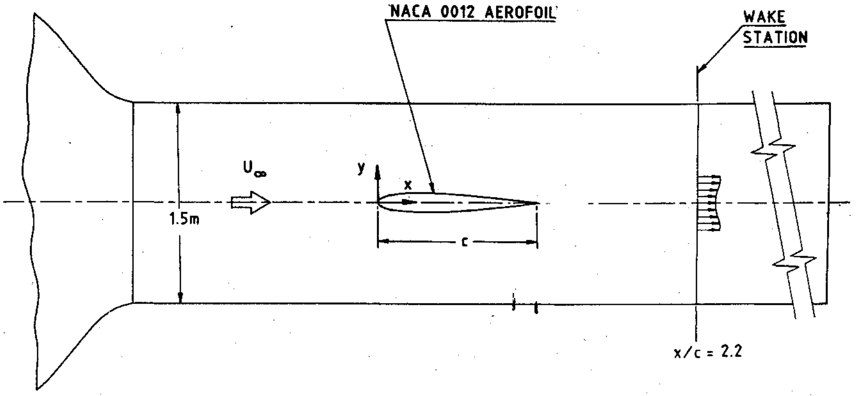

Fig. 1 Sketch of airfoil model and tunnel (not to scale).

that the effectiveness of riblets in reducing skin friction may remain unaltered under pressure gradients. Recent measurements of Nieuwstadt et al.,[14] systematically investigating riblet effects on a flat plate boundary layer in the presence of adverse pressure gradients, showed evidence of slightly increased drag reduction with β.

From the preceding discussion, it is evident that riblets are effective in pressure gradients as well, although the magnitude of drag reduction seem to vary depending on the configuration and the magnitude of pressure gradient. In this paper, we present recent results of viscous drag reduction and some aspects of the flow structure using 3M riblets on a NACA 0012 airfoil at low speeds covering an incidence range of 0 to 6 deg. Total drag was determined from the wake survey method. The results show increased drag reduction with incidence, suggesting increased effectiveness of riblets under adverse pressure gradients.

II. Experiments

A. Facility and Model

The experiments were conducted in the 0.3 × 1.5 m boundary-layer tunnel. A NACA 0012 airfoil model with a chord of 600 mm and spanning the 0.3-m top and bottom walls was mounted vertically in the test section (Fig. 1). The model was equipped with 29 static pressure ports (of diameter 0.8 mm) only on one surface.

B. Measurements

Tests were carried out at a freestream velocity of 30 m/s providing a chord Reynolds number of 1×10^6. The boundary layers developing on the airfoil top and bottom surfaces were tripped at 10% chord from the leading edge using a sand paper strip (24 grade and 30 mm wide). The riblet film (3M) was applied between 0.12c and 0.96c on both surfaces providing a riblet length of 510 mm. The tests were conducted in the incidence range of 0–6 deg in steps of 2 deg.

Total drag was determined accurately from pitot measurements in the wake using the method[15] of Jones. Since the airfoil model had pressure ports only on one side, static pressure distributions for the leeward and windward sides were obtained by making measurements with the model positioned at both positive and negative angles of attack. Static pressure measurements were made using a micromanometer (Furness Controls Ltd., United Kingdom) both with and without the riblet at each α, to assess the influence of riblets on C_p distributions. Boundary-layer mean velocity and streamwise turbulence intensity measurements were carried out at station $x/c = 0.964$ (22 mm upstream of the airfoil trailing edge) at all α to assess the overall effects of riblets. This station was chosen so that it is located immediately downstream of the riblet trailing edge in order to avoid the ambiguity that generally arises in inferring $y = 0$ for the profile measurements. Furthermore, it is known that riblet effects on the flow in the wall region persist over a distance of a few boundary-layer thicknesses downstream of the riblet trailing edge.[1] A 5-μm tungsten hot-wire sensor with 1-mm active wire length was used with a DISA 55M constant temperature anemometer for both the mean velocity and turbulence measurements.

The reference configuration for determining drag reduction was the smooth airfoil with the same transition trip but without the smooth vinyl sheet ($\approx$0.1 mm thick) that is often employed to account for the riblet backing sheet.

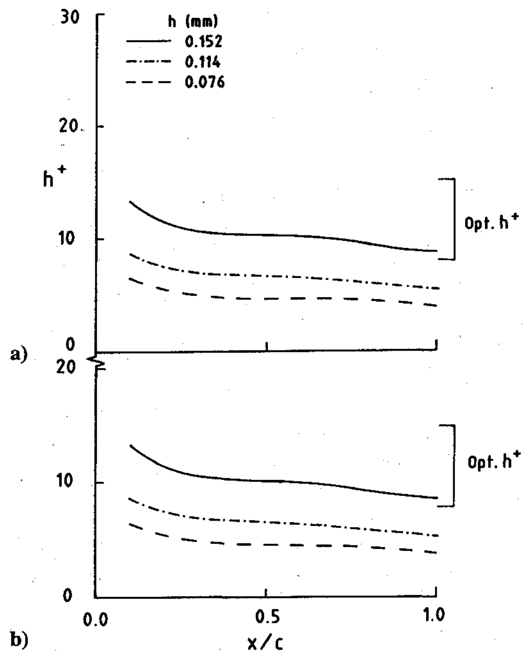

Fig. 2 Variations of h^+ on airfoil upper surface: a) $\alpha = 0$ deg and b) $\alpha = 6$ deg.

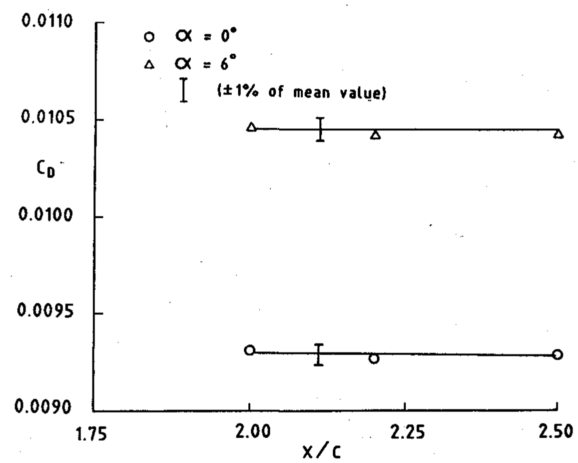

Fig. 3 Variations of total drag coefficient in the wake.

C. Accuracy of the Measured Data

Uncertainties in the measured data, estimated using the methodology of Kline and McClintock,[16] are $\Delta C_p = \pm 0.003 C_p$ (20–1), ΔU m/s (hot wire) $= \pm 0.02U$ (20–1), $\langle \Delta u \rangle = \pm 0.04 \langle u \rangle$ (20–1), and $\Delta C_D = \pm 0.015 C_D$ (20–1).

D. Selection of Riblets

Flat plate experiments using 3M riblets from several experiments have revealed[1] that maximum drag reduction occurs in the h^+ range of about 8–15, with the zero drag reduction crossover point around $h^+ = 20$. Boundary-layer computations[17] employing the lag entrainment method of Green were made using the measured surface pressure distributions on the airfoil to determine the variation of wall skin friction at different angles of attack. The variations of h^+ on the airfoil upper surface for two extreme cases, namely, at $\alpha = 0$ and 6 deg are shown in Fig. 2 for three values of riblet height. The variations of h^+ is well within the optimum range for $h = 0.152$ mm; on the other hand, h^+ variations for the riblet height of 0.114 and 0.076 mm, although not within the optimum range, are still in the drag reduction range.[1] In the present study, detailed measurements have been made for $h = 0.152$ mm, whereas drag measurements alone have been made for $h = 0.076$ mm.

E. Two Dimensionality

Two dimensionality of the flow in the experiments was assessed primarily using the two-dimensional momentum integral technique in the wake. Mean velocity profiles in the wake were measured at three locations ($x/c = 2.0, 2.2$, and 2.5) for a few selected cases of airfoil incidence; the local static pressure was essentially same as the freestream static pressure at these locations. Figure 3 shows that the variations in C_D about its mean value are within $\pm 1\%$ at all three stations. The constancy of C_D with x/c demonstrates excellent two dimensionality of the mean flow in the experiments. In addition, spanwise measurements (at quarter and three-quarter span) of mean velocities in the wake (at $\alpha = 4$ deg and $x/c = 1.8$) showed good agreement with the centerline values, further confirming the two dimensionality of the flow.

III. Results and Discussion

A. Surface Pressure Distributions

The C_p distributions on the airfoil at $\alpha = 0$ and 6 deg are shown in Figs. 4a and 4b, respectively. The effects of riblet on C_p distribution

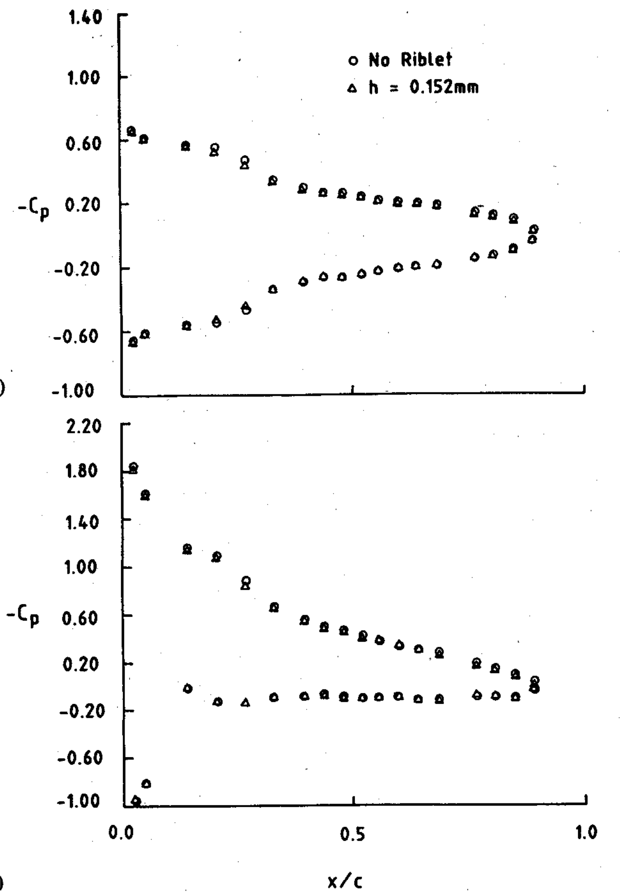

Fig. 4 Airfoil surface pressure distributions: a) $\alpha = 0$ deg and b) $\alpha = 6$ deg.

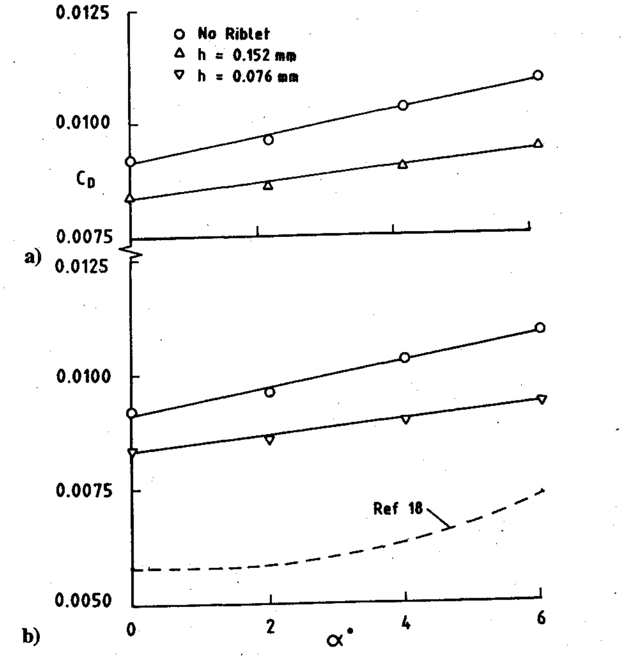

Fig. 5 Total drag reduction due to riblets : a) $h = 0.152$ mm and b) $h = 0.076$ mm.

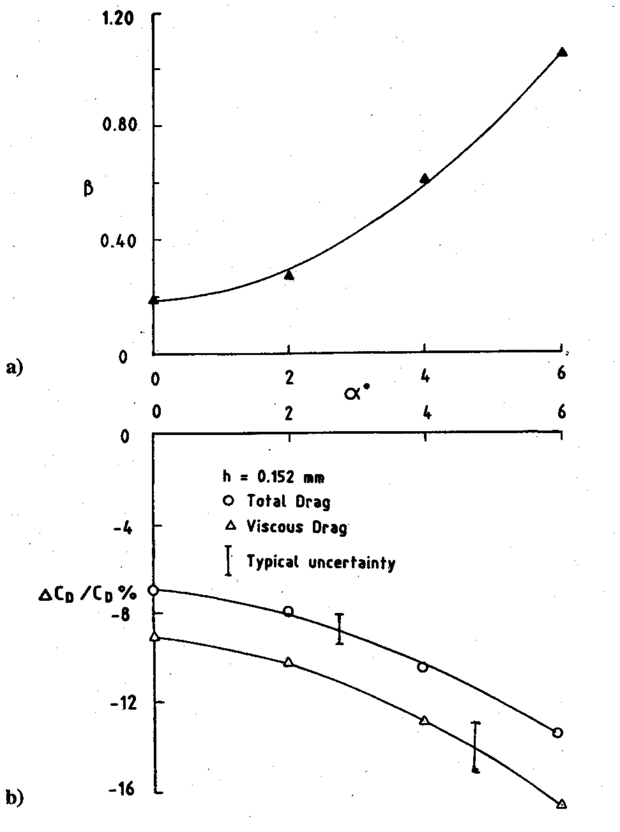

Fig. 6 Variations of percentage drag reduction and Clauser parameter with α for the optimized riblet: a) Clauser parameter and b) total and viscous drag reduction.

are indeed small, similar to the observation made by Coustols[8] on a supercritical airfoil at transonic speeds. Integration of surface pressures, however, showed that the pressure drag in the presence of riblets was typically lower by 1–2% at different α compared to the smooth airfoil.

B. Drag Reduction with Riblets

Results of total drag coefficient C_D with incidence for the smooth airfoil and riblet heights of 0.152 and 0.076 mm are shown in Figs. 5a and 5b, respectively; also included in the figure are standard

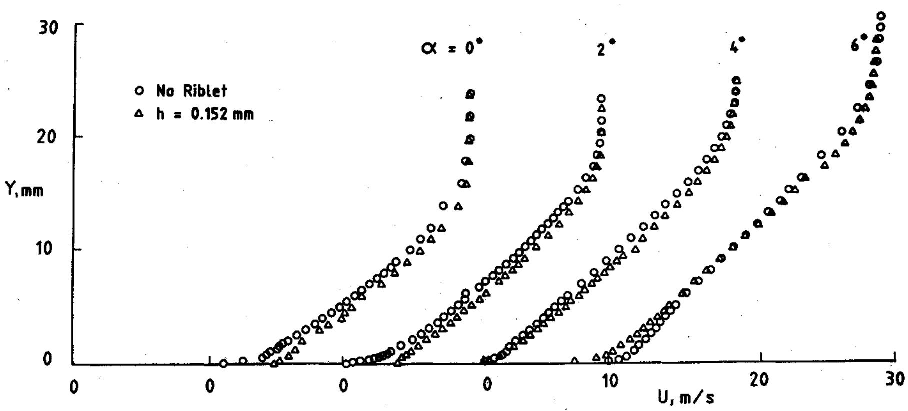

Fig. 7 Mean velocity profiles on the airfoil upper surface at $x/c = 0.964$.

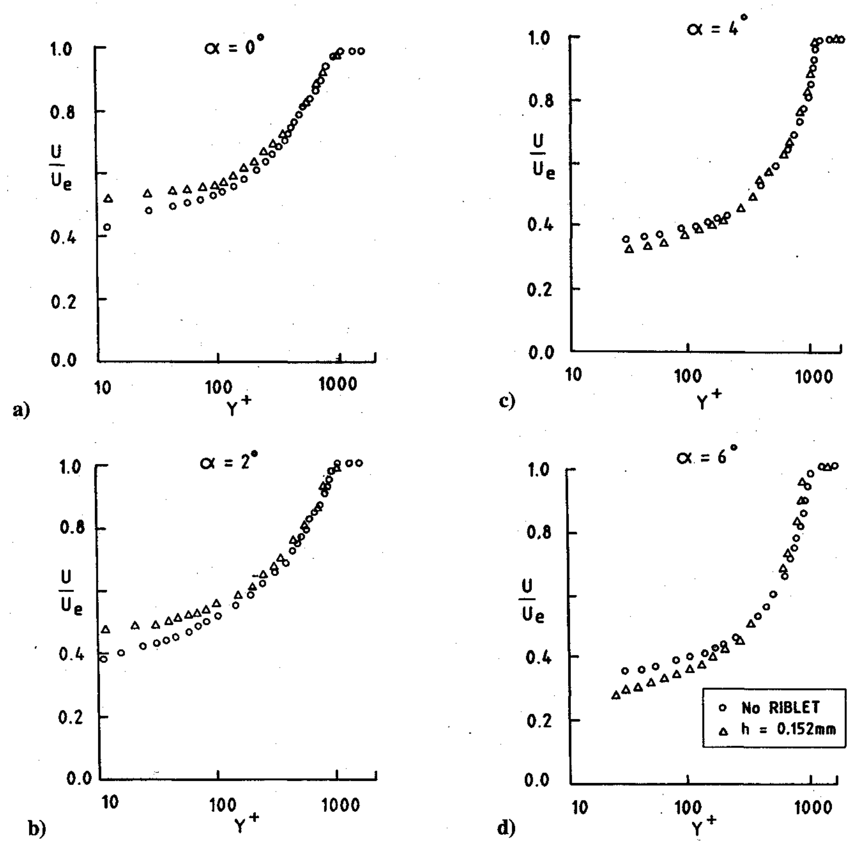

Fig. 8 Mean velocity profiles in wall coordinates at $x/c = 0.964$.

results (dashed line) from Abbot and Von Doenhoff[18] measured at $Re_c = 3 \times 10^6$. It may be seen that in the present experiments the drag values of the smooth airfoil are higher (about 40%), which are largely due to the increase in profile drag as a result of the coarse transition trip used and changes in skin friction coefficient between the two Reynolds numbers.[19] The results show increasing drag reduction with α for $h = 0.152$ mm; interestingly, even the nonoptimized riblet with $h = 0.076$ mm shows drag reduction about as good as the optimized riblet, which was unexpected.

The percentage total drag reduction $\Delta C_D / C_D$ (normalized by the smooth airfoil value at each α) for the optimized riblet and the value of Clauser pressure gradient parameter β estimated at each α are shown in Fig. 6. Here β is estimated from the average adverse pressure gradient (in the region $0.4 \leq x/c \leq 0.95$) on the upper surface of the airfoil with values of δ^* and τ_w taken from the boundary-layer computations[17] for the smooth airfoil. Also included in Fig. 6b are estimates of viscous or skin friction drag reduction obtained form the knowledge of the pressure drag (calculated from the measured C_p distribution) at each α. The total drag reduction increases from about 7% at $\alpha = 0$ deg to 13% at $\alpha = 6$ deg. The results indicate viscous drag reduction as high as 16% at $\alpha = 6$ deg (Fig. 6b), which corresponds to $\beta = 1.06$ (Fig. 6a).

C. Mean Velocity Profiles Ahead of Trailing Edge

The mean velocity profiles measured (at $x/c = 0.964$) on the leeward surface of the airfoil at different α are shown in Fig. 7. To bring out the effects of riblets on the near wall flow, the velocity profiles are shown plotted against y^+ in Fig. 8. At each α, the value of U_* obtained from the boundary-layer code for the smooth airfoil case is used for the riblet case as well in plotting the data. At $\alpha = 0$ and 2 deg, the data on the riblet surface show fuller profiles for $y^+ > 10$ (compared to the smooth airfoil) as in the case of zero or mild pressure gradient flows.[1,3,4] With an increase in adverse pressure gradient (at $\alpha = 4$ and 6 deg), the flow over the riblet surface is more decelerated in the wall region for ($y^+ \leq 200$); however, for $y^+ \gtrsim 200$, the velocities are relatively higher on the riblet surface as at lower values of β (Figs. 8c and 8d). The velocity distributions clearly indicate the significant influence of riblets all across the layer with an increase in adverse pressure gradient. The mean velocity profiles on the windward (or pressure) side showed

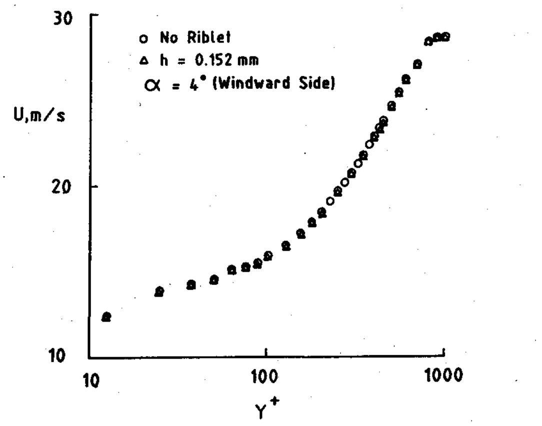

Fig. 9 Mean velocity profiles on the windward side at $x/c = 0.964$.

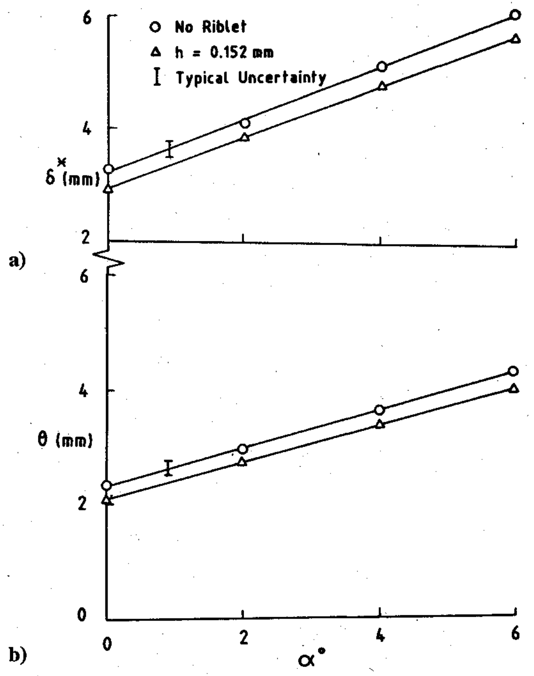

Fig. 10 Variations of boundary-layer displacement and momentum thicknesses with α: a) displacement thicknesses and b) momentum thickness.

only a weak effect due to riblet surface compared to the smooth airfoil; a typical example is shown in Fig. 9 from which one can infer that the reduction in drag at given α arises largely from the changes in the mean velocity profiles on the leeward (or suction) side of the airfoil.

Figures 10a and 10b display variations with α of the (leeward) boundary-layer displacement and momentum thickness measured at $x/c = 0.964$. At any given α, the values of δ^* and θ are lower for the riblet case compared to the smooth airfoil consistent with the mean velocity profiles (Fig. 7.)

D. Turbulence Intensity Profiles

The streamwise turbulence intensity $\langle u \rangle$ profiles in the (leeward) boundary layer measured at $x/c = 0.964$ are shown in Fig. 11. As with mean velocity profiles, riblet effects on $\langle u \rangle$ are seen over a large part of the boundary layer with an increase in adverse pressure gradient. Reduction in turbulence intensities (as much as 10–15%) in the wall region ($y^+ \lesssim 40$) over the riblet surface is evident at all α, although the reduction extends to larger values of y^+ at $\alpha = 0, 2$, and 4 deg. Similar reductions in turbulence intensities due to riblets have been observed in the context of zero pressure gradient flows as well.[3,4]

It may be noted that the hot-wire sensor length used in the present measurements is about 40–50 viscous lengths (corresponding to maximum drag reduction condition), which is higher than that recommended by Ligrani and Bradshaw[20] (about 20–25 viscous lengths) and Johansson and Alfredson[21] (about 32 viscous lengths) for sublayer measurements. It is believed that errors, if any, in the $\langle u \rangle$ measurements may not be significant, since most measurements are made beyond $y^+ = 20$, which is outside the sublayer. Furthermore, the interest here is in showing the differences in $\langle u \rangle$ profiles with and without the riblets, rather than the absolute values.

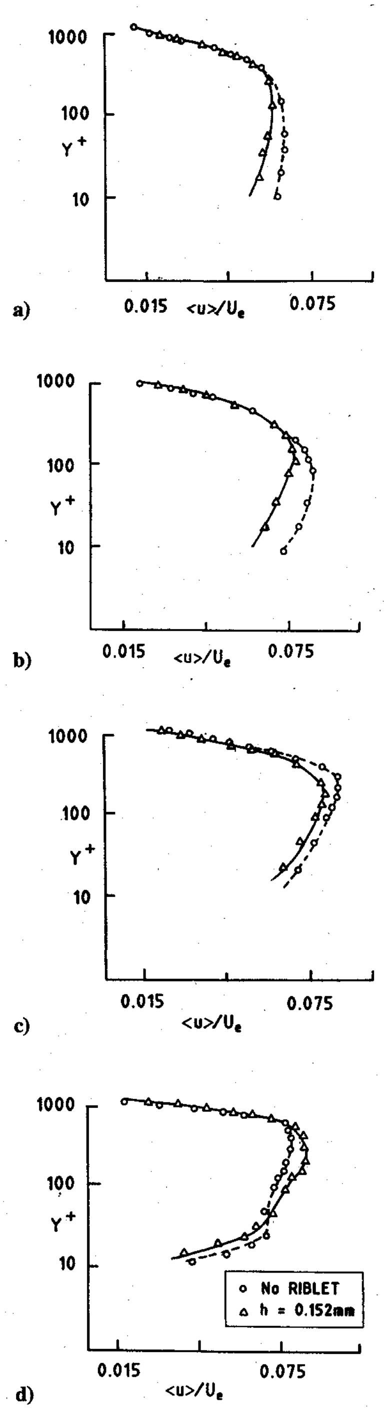

Fig. 11 Streamwise turbulence intensity profiles at $x/c = 0.964$: a) $\alpha = 0$ deg, b) $\alpha = 2$ deg, c) $\alpha = 4$ deg, and d) $\alpha = 6$ deg.

Figure 12 present the corresponding spectra of $\langle u \rangle$ measured near the wall ($y^+ \approx 20$) at different α. The results for the smooth airfoil are also included in the figures for comparison. Reduction in energy levels at low frequencies (below 200 Hz) on the riblet surface is clearly seen at all α, with the degree of reduction increasing with the increase in the level of adverse pressure gradient; such reduction in the energy levels have been observed even in zero pressure gradient flows.[3,4] Small reduction in $\langle u \rangle$ is also observed at higher

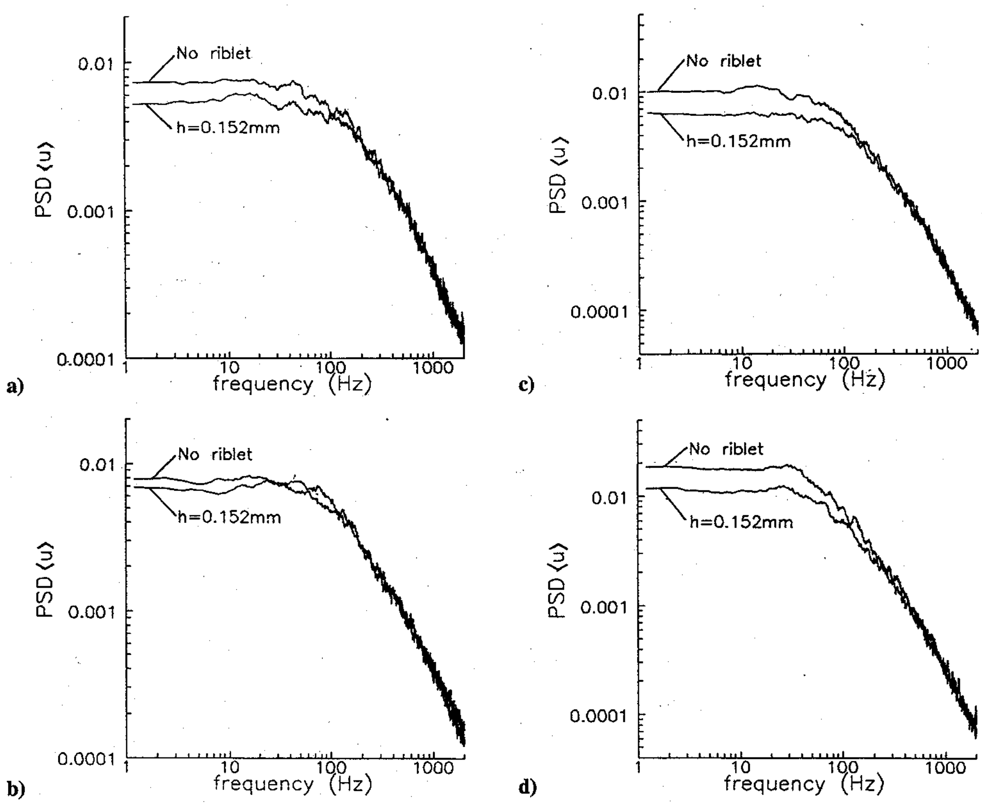

Fig. 12 Power spectral density of streamwise turbulence intensity at $x/c = 0.964$: a) $\alpha = 0$ deg, b) $\alpha = 2$ deg, c) $\alpha = 4$ deg, and d) $\alpha = 6$ deg.

frequencies, with increase in adverse pressure gradients (Figs. 12c and 12d).

E. Possible Flow Mechanisms Leading to Increased Drag Reduction with Incidence

We briefly discuss here the possible role of the different mechanisms that may have contributed to the increased drag reduction with α (Fig. 6). These include effects of convex surface curvature, extended boundary-layer transition due to riblets in favorable pressure gradients (as pointed out by one of the referees), and increased adverse pressure gradient on the upper surface of the airfoil.

On the NACA 0012 airfoil (having a symmetric section), the streamwise surface curvature is identical on the top and bottom surfaces. The boundary-layer growth, on the other hand, being different on the upper and lower surfaces (because of differing pressure gradient on these surfaces) may lead to differing curvature effects. Figure 9 clearly shows that the combined effects of weak pressure gradient and streamwise convex curvature on the airfoil lower surface are small from the point of view of drag reduction.

An assessment of the possibility of stretched transition with α in the presence of riblets has been made by examining the mean velocity profiles (with and without the riblets) at two stations on the airfoil upper surface at $\alpha = 4$ deg, as a typical case (Fig. 13). Interestingly, at both the stations, the mean velocities are higher on the riblet surface for $y^+ > 20$, a feature well known in zero or mild pressure gradient flows.[4,5,22] Also, in zero and mild pressure gradient flows, the velocity profiles on the riblet surface exhibit the universal slope of the log law ($\sim$2.44) but with an increased intercept resulting from the thickening of the sublayer.[4,5,22] An exactly similar feature may be seen in the figure at both the stations; that is, the intercepts are higher with riblets. In addition, the measurements at $x/c = 0.5$ clearly show that the boundary layer in the absence of the riblet is turbulent and fully developed. The values of the shape factor indicated in the figure also suggest that the boundary layers are turbulent. These observations are consistent with typical effects of riblets on a turbulent boundary-layer suggesting that the boundary-layer transition is not stretched with α or increased favorable pressure gradients on the airfoil upper surface.

This leaves the combined effects of adverse pressure gradient and convex curvature (on the airfoil upper surface) as the dominant

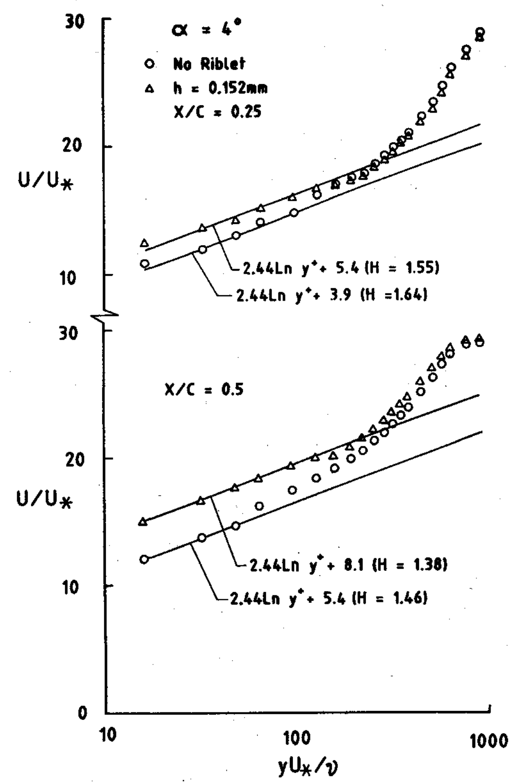

Fig. 13 Mean velocity profiles on the airfoil upper surface at $x/c = 0.25$ and 0.5.

mechanism leading to increased viscous drag reduction. Since, in adverse pressure gradients, the streamlines diverge, the convexity of the streamlines (except possibly very close to the wall) are significantly reduced and, hence, curvature may have only a weak influence on the boundary-layer development. It would, therefore, strongly suggest that the flow alteration near the wall arising from riblets in adverse pressure gradients as the major mechanism contributing to increased viscous drag reduction with α. This conclusion is consistent with the results of Nieuwstadt et al.[14] and the recent study of Debisschop and Nieuwstadt[23] on a flat plate that shows increased viscous drag reduction of about 13% at $\beta = 2.3$.

IV. Conclusions

Experiments have been performed assessing viscous drag reduction using 3M riblets on a NACA 0012 airfoil at low speeds. To the authors' knowledge, this has been the largest scale airfoil experiment involving riblets reported in the literature. The tests, made at a chord Reynolds number of 1×10^6, covered angle of attack up to 6 deg. Accurate measurements of airfoil total drag have been made using the well-known wake survey method.

Results show, for the first time, significantly higher skin friction drag reduction with incidence, compared to flow in zero or mild pressure gradients. The viscous drag reduction measured is as high as 16% at $\alpha = 6$ deg which corresponds to a value of Clauser parameter of 1.06. The tests, currently in progress at NAL, show that both the total and viscous drag reduction decrease rapidly beyond $\alpha = 6$ deg, due to the boundary-layer flow on the airfoil upper surface progressing toward separation. Measurements of mean velocity profiles ahead of the airfoil trailing edge indicate that larger contribution to the drag reduction results from the airfoil upper (or suction) surface. These results clearly imply increased effectiveness of riblets in adverse pressure gradients. Examination of streamwise turbulent intensity profiles shows a noticeable reduction in the wall region in the presence of riblets. Correspondingly, the spectra of $\langle u \rangle$ reveal reduced energy at low frequencies, with the degree of reduction increasing with the magnitude of the adverse pressure gradient.

These observations are in broad agreement with the results on flat plate flows with imposed adverse pressure gradients. Experiments are needed to gain further understanding of the mechanics of riblet action in adverse pressure gradients and to confirm the increased drag reduction potential at much higher Reynolds numbers.

Acknowledgments

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