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Technical Notes

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Turbulent Drag Reduction Using Riblets on a Supercritical Airfoil at Transonic Speeds

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Introduction

NUMEROUS studies in the literature[1–4] have shown that viscous drag reduction of 4–8% at low speeds can be achieved in simple two-dimensional flows at wind-tunnel Reynolds numbers. Because of the encouraging benefits realized at low speeds, an evaluation of riblet effectiveness at subsonic and transonic speeds, both in wind tunnels and flight, has been reported, and results from these investigations have been encouraging.[5–8] Realistic applications involve, among other factors, pressure gradients (e.g., airfoil and wing) and three-dimensionality. Drag reductions under these conditions are being assessed currently. An excellent review on the subject, covering aspects of drag reduction and flow structure, has been written by Walsh.[1]

McLean et al.[5] applied 3M riblets over a part of the wing upper surface of a T-33 airplane in flight and found average skin-friction drag reductions of about 6% in the range of $h^+(=hu_*/\nu$, where $h =$ height of riblet, $u_* =$ friction velocity, and $\nu =$ kinematic viscosity) of 10–15 in the Mach number range 0.45–0.70; these results are significant since the flight tests covered fairly high unit Reynolds numbers in the range of $5–15 \times 10^6$/m. Coustols[2] reported total drag reductions of about 2.7% on an LC100D airfoil at low speeds with riblets present only on the upper surface; the optimum drag reduction was observed in the range of h^+ of 5–10, depending on the angle of attack. Coustols and Schmitt[8] conducted tests using 3M riblets on a CAST 7 airfoil at zero incidence in the Mach number range of 0.65–0.76; the corresponding chord Reynolds number was around 3.3×10^6. Total drag measured using wake survey showed (maximum) drag reductions of 3.5% for $h^+ < 20$; the corresponding skin-friction drag reduction was about 7–8% for the conditions of the test. Limited studies (discussed earlier) suggest that, even under moderate streamwise pressure gradients, riblets retain their effectiveness about as well as those observed in zero pressure gradient flows. This paper presents recent results of drag reduction using 3M riblets on a supercritical airfoil at transonic speeds covering an angle of attack range of −0.5 to 1 deg, which is relevant to cruise conditions.

Experiments

The drag measurements were made on the ADA-S1 supercritical airfoil in the 0.3-m trisonic wind tunnel. The airfoil, having a chord of 150 mm and thickness ratio of 11.6% (Fig. 1a), was provided with 48 static pressure ports of 0.5-mm diam. The boundary layer on the model was tripped at 0.06c from the leading edge using 120 size corborundum particles. Model static pressures were measured using four 70-kPa electronic pressure scanners. Total drag was determined from the measured wake pitot defect (with a rake located at 1.2c downstream of the airfoil trailing edge) using three, 17-kPa electronic pressure scanners. Measurements of pitot defect in the wake were made in the Mach number (M_∞) range of 0.6–0.76 and incidence (α) range of −0.5 to 1 deg. Model static pressures were measured only for a few selected cases in the absence of the riblet. Detailed information of surface pressure distributions over a wider range of M_∞(0.5–0.8) are contained in Ref. 9. All of the tests were conducted at a tunnel stagnation pressure of 190-kPa providing a (nominal) chord Reynolds number of 3×10^6.

The airfoil total drag coefficient (C_D) was calculated using the widely used[10,11] expression ($C_D = 2/(\gamma P_0 M_\infty^2 c) \int \Delta P_0 \, dy$, where P_0 is the tunnel stagnation pressure and ΔP_0 is the pitot defect) which does not require information of the wake static pressure at the measurement location; the only requirement is that the Mach number defect should be small, which is satisfied in the present tests (max $\Delta M/M_\infty < 0.1$). Furthermore, the main focus in the present work is to assess the changes in drag due to the riblet rather than the absolute drag value. Uncertainties in C_D and model static pressure coefficient C_p, estimated using the method of Kline and McClintock,[12] are given as follows:

$$\Delta C_D = \pm 0.021 C_D \quad (20 \text{ to } 1)$$

$$\Delta C_p = \pm 0.012 C_p \quad (20 \text{ to } 1)$$

Riblet size was determined after examining the variations of h^+ along the airfoil upper and lower surfaces for a few typical flow conditions on the airfoil. Boundary-layer calculations[13] were made for the measured static pressure distributions, which provided information on wall skin friction along the airfoil upper and lower surfaces. Examples of C_p distribution and h^+ variations for riblet heights of 0.033 and 0.018 mm for $M_\infty = 0.76$ and $\alpha = 1$ deg are displayed in Figs. 1b and 1c, respectively. The range of h^+ (8–15) for optimum drag reduction in the context of zero pressure gradient flows[1] is also shown in the aforementioned figure. It is evident that the riblet with $h = 0.018$ mm would be an appropriate choice for providing drag reduction, whereas drag increase can be expected from $h = 0.033$ mm (since h^+ variations lie largely in the zone of drag increase). Tests were therefore made with riblet heights of $h = 0.018$ and 0.033 mm with 3M riblet sheets applied between 0.15c and the airfoil trailing edge. The reference configuration for assessing drag reduction was the smooth airfoil (with the trip), but without the smooth vinyl sheet (about 0.1 mm thick), which is often used to account for the riblet backing sheet covering the ribbed length.

Results and Discussion

The variations of the total drag coefficient C_D with M_∞ at four values of α are presented in Fig. 2. At each α, results are shown for the reference airfoil and for the two riblet heights of 0.018 and 0.033 mm. It is interesting to note that the riblet that is optimized ($h = 0.018$ mm) shows a clear drag reduction at all α, whereas an increase in drag is evident for the riblet with $h = 0.033$ mm (except at $M_\infty = 0.76$ and $\alpha = 0.5$ and 1 deg), as may be expected from the h^+ variations (Fig. 1c). These results generally support the methodology used for riblet selection in flows with pressure gradients.

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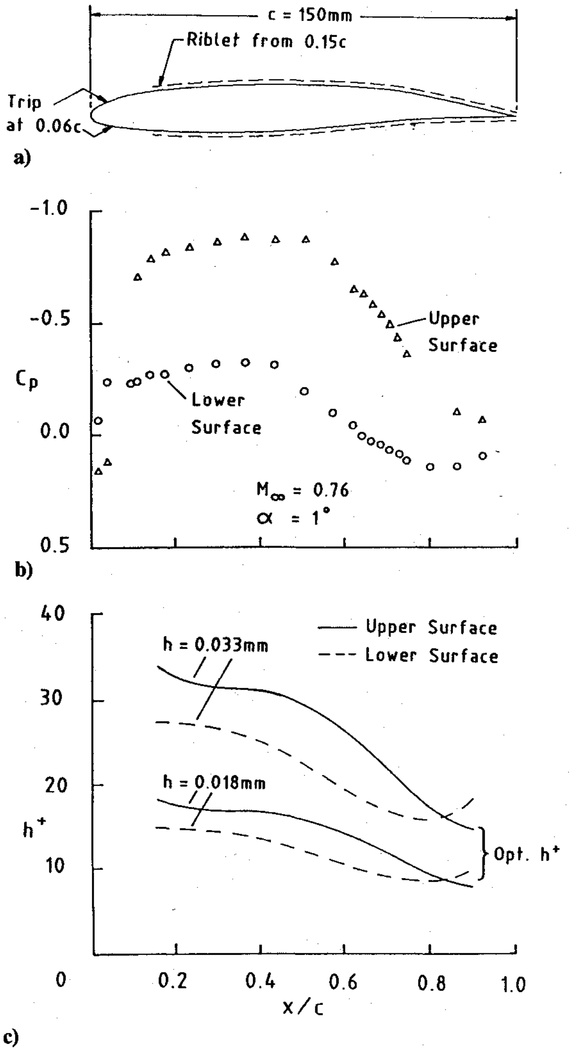

Fig. 1 Aerofoil characteristics: a) geometry, b) static pressure distribution, and c) h^+ variations along the surface.

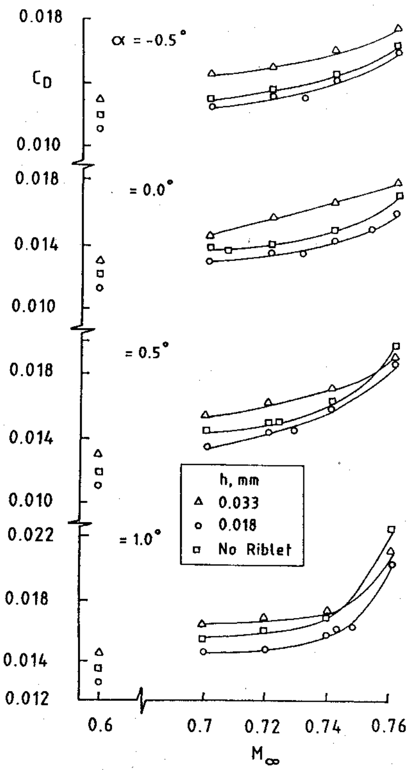

Fig. 2 Total drag characteristics with riblets.

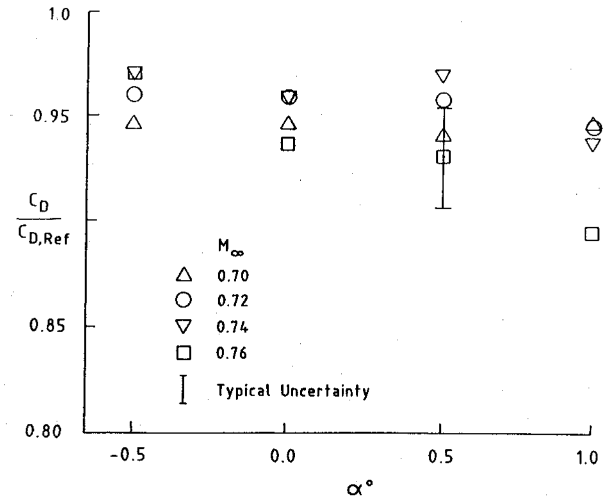

Fig. 3 Percentage total drag reduction with riblets: h = 0.018 mm.

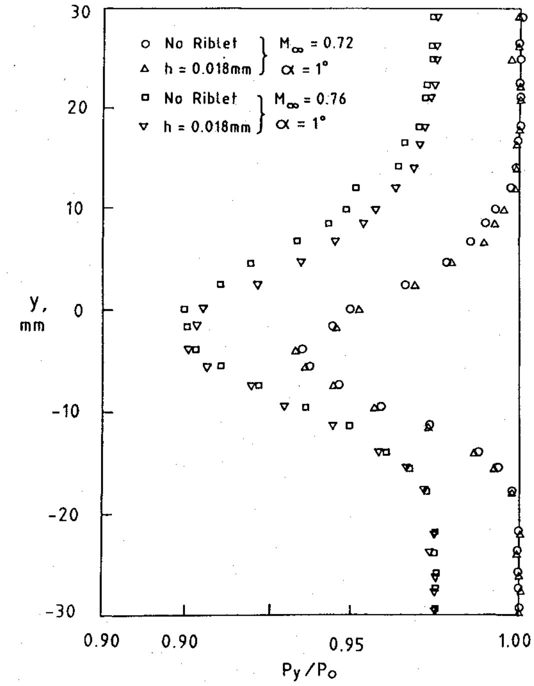

Fig. 4 Wake pitot profiles.

Total drag measured with $h = 0.018$ mm riblet, normalized by the drag value for the reference (smooth) airfoil ($C_{D,\mathrm{Ref}}$), is displayed in Fig. 3; total drag reductions in the range of 3–6% are evident. To make an assessment of the skin-friction drag reduction, we have assumed that the surface pressure distributions are not altered by the riblet. Measurements of Coustols and Schmitt[8] on a supercritical airfoil at transonic speeds at zero incidence and of Sundaram and Viswanath[14] on a NACA 0012 airfoil up to moderate incidence provide justification for the previous assumption. Integration of airfoil C_p distributions (measured without the riblet) yielded pressure drag contributions varying between 40–50% of the total drag in the range of M_∞ and α covered. The measured total drag reduction therefore translates into viscous or turbulent skin-friction drag reductions of about 6–12%, which is appreciably higher compared with the performance of riblets in zero pressure gradient flows.[1] These results are consistent with the observation of Nieuwstadt et al.[15] at low speeds, wherein adverse pressure gradients were imposed on a flat plate turbulent boundary layer.

It is to be noted that the observed drag reduction is conservative for the following reasons. The airfoil total drag measured in the presence of the riblet includes 1) the pressure drag associated with the step (about 0.1 mm thick) formed by the riblet leading edge and 2) the drag due to increased airfoil thickness resulting from the riblet backing sheet (in comparison with the reference configuration). Estimates based on transonic similarity rules[16] show that the drag due to the increased airfoil thickness is in the range of 0.5–1% of the total drag depending on M_∞ and α. The drag due to the step on the top and bottom surfaces, estimated using the correlation given by Gaudet and Winter,[17] is about 1% of the total drag for the conditions of the test. These corrections, if taken into account, would result in skin-friction drag reduction better than the 6–12% indicated.

Figure 4 displays wake pitot profiles, with and without the riblet, for two flow conditions (where P_y is the pitot pressure in the wake). The results show that a larger contribution to the drag reduction results from the airfoil upper surface with increase in adverse pressure gradients.

Conclusions

Experiments have been made to assess viscous drag reduction using 3M riblets on a supercritical airfoil at transonic speeds. The airfoil angle of attack was varied between −0.5 to 1 deg. Results show skin-friction drag reduction in the range of 6–12% for the conditions of the test, which is higher than what has been observed in zero pressure gradient flows. These results suggest increased effectiveness of riblets in adverse pressure gradients.

Acknowledgment

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Sensitivity of Amplification-Factor Transition Criterion for Flow over Roughness Element

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LINEAR stability theory coupled with the empirical e^N method[1,2] is a common approach that is widely used to predict transition location in engineering applications. In this approach, the integrated growth rate (N factor) calculated using linear stability theory is correlated with the onset of laminar turbulent transition. It was found[1–4] that the location at which the value of N is in the range from 9 to 11 correlates well with the transition onset location in two-dimensional flows. The predictions of the approach showed good agreement with transition experimental data obtained in a low-disturbance environment such as quiet wind tunnels[3] and under flight conditions.[4] In the case of flow over roughness elements, the predictions of the e^N method agreed reasonably well even with relatively noisy wind-tunnel transition data.[5,6] Bushnell and Reshotko[7] pointed out that "at supersonic speeds, roughness is such an overriding transition bypass that the research can be conducted in conventional, noisy, tunnels."

The dependence of the predicted transition onset location on the value of N can be quantified by considering the sensitivity of the e^N method. The sensitivity of the e^N method is denoted by σ_N and defined as the rate of change of correlated transition Reynolds number $(Re_x)_N$ with respect to N divided by the correlated transition Reynolds number. Therefore,

$$\sigma_N = \frac{1}{(Re_x)_N}\frac{\mathrm{d}(Re_x)_N}{\mathrm{d}N} \tag{1}$$

where

$$Re_x = U^*_\infty x^*/\nu^*_\infty \tag{2}$$

and U^*_∞ is the dimensional freestream streamwise velocity, ν^*_∞ is the dimensional freestream kinematic viscosity, and x^* is the dimensional distance measured from the leading edge. The value $(Re_x)_N$ is the smallest Reynolds number value (sweeping over all frequencies) at which the N factor reaches the value N. For example, in incompressible flow over a smooth flat plate and using $N = 9$, the value of σ_N is 0.168. This implies that the predicted value of $(Re_x)_N$ will vary by about ±16.8% if the correlating N factor was chosen to be 10 or 8 instead of 9. In this work, we evaluate the sensitivity σ_N for the case of flow over a roughness element that might cause the flow to separate.

We consider a two-dimensional incompressible flow around a single smooth two-dimensional hump on a flat plate. We consider a two-parameter family of symmetric hump shapes given by

$$y = y^*/L^* = (h^*/L^*)f(z) = hf(z) \tag{3}$$

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