Engineering Notes

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Drag Reduction Due to Riblets on a GAW(2) Airfoil

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Nomenclature

C_{DT} = total drag coefficient = drag force/$q_\infty * c$
C_p = pressure coefficient
c = airfoil chord
h = riblet height
h^+ = $(hu_\tau)/\nu$
p = static pressure
p_∞ = freestream static pressure
q_∞ = freestream dynamic pressure
u_τ = friction velocity
x = distance along the airfoil chord
y = distance normal to tunnel axis
α = angle of attack
β = clauser pressure-gradient parameter = $(\delta^*/\tau_w)(\mathrm{d}p/\mathrm{d}x)$
$\Delta C_{DT}/C_{DT}$ = $(C_{DT\,rib} - C_{DT\,smooth})/C_{DT\,smooth}$
δ^* = boundary-layer displacement thickness
ν = kinematic viscosity
τ_w = wall shear stress

Introduction

THE study of turbulent drag reduction by use of riblets has been an area of significant research during the past decade.[1,2] Riblets with symmetric v grooves with adhesive-backed film manufactured by the 3M Company (U.S.) have been widely used in earlier studies. The effectiveness of riblets in reducing the drag of a simple two-dimensional configuration is fairly well established now.[1,2] Although there has been some effort[3–5] to assess the effectiveness of riblets on airfoils, the results reported by Sundaram et al.[3] on a NACA 0012 airfoil at low speeds have been particularly noteworthy. Their studies[3] showed that both total and viscous drag reduction increased monotonically with an angle of attack up to 6 deg; it was also shown[3] that the higher drag reduction resulted primarily from the airfoil upper (or suction) surface, suggesting increased effectiveness of riblets in adverse pressure gradients. In a subsequent study by Subaschandar et al.,[6] who extending the work of Sundaram et al.[3] to higher angles of attack (by using the same NACA 0012 model and the same wind tunnel), it was observed that the drag reduction decreased rapidly beyond $\alpha = 6$ deg with virtually no drag reduction at $\alpha = 12$ deg.

The present study is an attempt to assess the total drag reduction that is due to riblets on a cambered airfoil up to high angles of attack at low speeds. The 13% thickness General Aviation Wing [GAW(2)] airfoil section was chosen because of its strong relevance in many applications. Furthermore, it was expected that the results would provide a basis for comparing riblet effectiveness on an infinite swept wing with the GAW(2) profile currently in progress at our laboratory.

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Experiments

Facility and Model

The experiments were conducted in the 300 × 1500 mm boundary-layer wind tunnel as in the previous study.[3] The airfoil model, having a chord of 600 mm and a span of 300 mm, was mounted vertically in the test section. Since the major interest in this study was to assess the total drag reduction with α, the model was not instrumented with static pressure ports.

Measurements

The tests were carried out at a freestream velocity of 30 m/s, providing a chord Reynolds number of 1×10^6. The boundary layer developing on the top and the bottom surfaces were tripped at 10% chord from the leading edge by a sandpaper strip (24 grade and 30 mm wide). The riblet film manufactured by 3M was applied between $0.12c$ and $0.96c$ on both the surfaces, providing a riblet length of 510 mm. Total drag was determined from pitot-static measurements in the wake by use of the method of Jones as described by Schlicthing.[7] The reference configuration for determining drag reduction was the smooth airfoil with the same transition trip, but without the smooth vinyl sheet (0.1 mm thick), which is often used to account for the riblet backing sheet.

Selection of Riblets

In the present study, the measurements have been made with riblet sheets with $h = 0.076$ mm. Figure 1 shows the streamwise variation

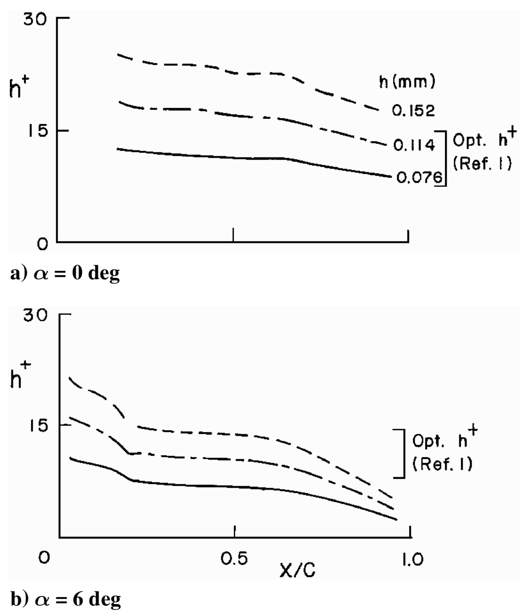

Fig. 1 Variations of h^+ on airfoil upper surface.

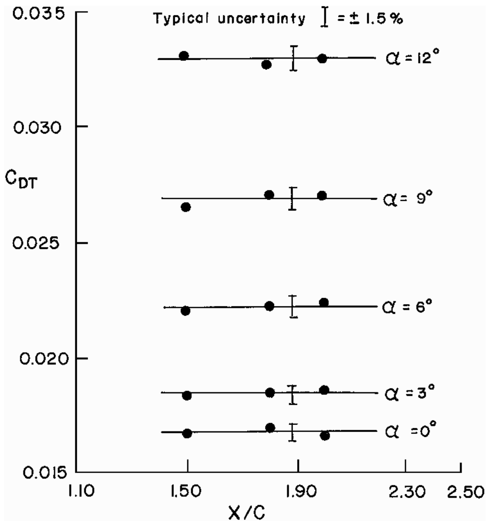

Fig. 2 Streamwise variation of total drag coefficient.

of h^+ for the airfoil upper surface for three values of h: 0.152, 0.114, and 0.076 mm. Information of wall skin friction required for estimating h^+ was obtained by use of a lag-entrainment integral boundary-layer code[8] with C_p distributions obtained with an airfoil potential flow code,[9,10] As may be seen in Fig. 1a, a riblet with $h = 0.076$ mm is a very good choice for the airfoil upper surface at $\alpha = 0$ deg; optimizing h^+ for the upper surface is important as it contributes more to the viscous drag reduction than the airfoil lower (or windward) surface.[3] At $\alpha = 6$ deg, the h^+ variation is still in the drag reduction regime (Fig. 1b). The lower surface h^+ varied between 9 and 5 (not shown in Fig. 1), which is also in the drag reduction regime.[1] Furthermore, the same riblet geometry with $h = 0.076$ mm is being currently used in the swept wing experiment with GAW(2) section at the National Aerospace Laboratories, India.

Accuracy of the Measured Data

Uncertainty in the measured drag, estimated with the methodology of Kline and McClintock[11] and with repeatability taken into account, is as follows:

$$\Delta C_{\mathrm{DT}} = \pm 0.015 C_{\mathrm{DT}} (20\text{–}1)$$

Two-Dimensionality

Two dimensionality of the mean flow in the experiments was assessed with the well-known two-dimensional momentum integral technique in the wake. Pitot profiles in the wake were measured at three streamwise locations ($x/c = 1.5$, 1.8, 2.0). Figure 2 shows the variations of the measured total drag coefficient (C_{DT}) plotted against the streamwise distance in the wake. It may be observed that, in the entire range of α tested, the variations of the measured total drag are within $\pm 1.5\%$, which is also the estimated uncertainty in C_{DT}. These results suggest good mean-flow two dimensionality over the entire range of α investigated.

Results and Discussion

Results of percentage total drag reduction $\Delta C_{\mathrm{DT}}/C_{\mathrm{DT}}$ with airfoil incidence are shown in Fig. 3; also shown in the figure is the variation of the Clauser pressure-gradient parameter (β) with α. At each α, β is estimated midway in the adverse pressure-gradient zone on the upper surface of the airfoil ($0.5 < x/c < 1.0$); surface pressure distributions obtained from the potential flow code[9,10] are utilized for the calculation of the average pressure gradient and for the estimation of δ^* and τ_w by use of the turbulent boundary-layer code.[8] The results show increased total drag reduction with α up to 6 deg, beyond which there is a rapid decrease in drag reduction with virtually no drag reduction at $\alpha = 12$ deg. These results bear a strong similarity to those obtained by Sundaram et al.[3] on a NACA 0012 airfoil model under very similar test conditions, which are also

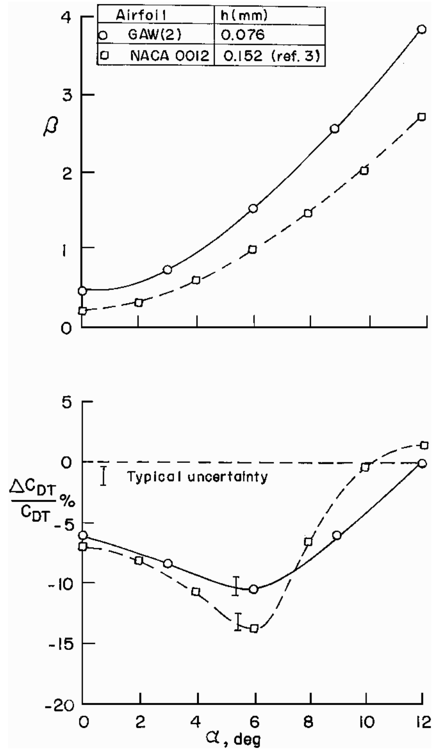

Fig. 3 Drag reduction by use of riblets on a GAW(2) airfoil.

shown in Fig. 3. It is interesting to note that the drag reduction is maximum at $\alpha = 6$ deg, although the riblet height ($h = 0.076$ mm) chosen is not the optimum at $\alpha = 6$ deg (Fig. 1); these results, once again, indicate increased effectiveness of riblets in adverse pressure gradients as long as the riblet chosen is in the drag reduction regime.

Conclusions

The results show conclusively, once again, that drag reduction due to riblets increases initially with incidence even on a cambered airfoil; the total drag reduction is as high as 10% at $\alpha = 6$ deg, implying an even larger viscous drag reduction. This trend is qualitatively similar to the results obtained on a NACA 0012 airfoil model under very similar test conditions.[3,6] These results, once again, demonstrate the increased effectiveness of riblets in adverse pressure gradients up to a certain value of β, beyond which the effectiveness is reduced, presumably because of the strong deceleration of the boundary layer, which leads to separation on the airfoil upper surface. It would be very useful to examine the validity of the above conclusions at much higher Reynolds numbers in future studies.

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Theodorsen's Propeller Performance with Rollup and Swirl in the Slipstream

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Introduction

THEODORSEN' S classic theory,[1] elegant and efficient as it is for the design of optimal propellers under specified conditions, suffers from an unrealistic high average static pressure in the slipstream. This high pressure has its impact on the expressions for predicted thrust, power, and efficiency. In earlier papers[2,3] this author has pointed out that the high pressure is inherent to the model with rigid vortex sheets in the slipstream. It is unrealistic to maintain the rigidity down to the Trefftz plane. The high pressure is eased by allowing rollup of the vortex sheets.

Theodorsen[1] models the propeller wake as a rigid backward moving (multiple) helical vortex sheet. Far downstream, in the region of the Trefftz plane, where the slipstream is supposed to be in equilibrium with its surroundings, the sheets move with the constant velocity w (in the following referred to in dimensionless form $\bar{w} = w/V$). A rigid vortex sheet, assumed to be force free, is not in equilibrium with its surroundings. Rollup ensures that the static pressure in the wake tends toward ambient pressure or lower. In the rolled-up model, the sheets start rolling up as soon as they leave the propeller blades. In the vicinity of the propeller the rollup has proceeded so little that the sheets are considered to have their original shape for the most part. The flow is still in development. For the velocities induced at the propeller, the development downstream is at first considered to be of minor importance. The design of the propeller is performed using the induced velocities at the propeller pertaining to the spiraling rigid sheets, uninfluenced by the rollup.

In Ref. 2 a rough implementation of the rollup has been presented to demonstrate its impact on the prediction of thrust and power coefficients and on efficiency. In that implementation, the average static pressure over the slipstream cross section was the ambient pressure. In a recent paper Ribner[4] directed attention to the fact that swirl reduces the interior pressure of the slipstream below ambient and that, therefore, the momentum equation (10) in Ref. 2 is a flawed equation. In the improved modification of the theory, presented in the following sections, using a more specified model of the slipstream incorporating rollup and swirl, the effects are taken into account in the momentum and energy balance and in the resulting expression for the efficiency.

In an example, referring to the eight-bladed propfan mentioned by Ribner in Ref. 4, the efficiency as predicted by the present theory is only 1.5% below the measured value of 82.3%. This is twice as close to the measured value as the prediction of the classical theory (see Ribner[4]). This result is interpreted as support of the present improved theory.

Modification of the Theory from Rigid to Rolled Up

Role of Edge Forces

When considering Theodorsen's[1] helicoidal slipstream at a distance from the propeller, it is worthwile to discuss the implicit consequence of the rigidity of the sheets. The singular edge forces on the rigid sheets, although everywhere normal to the propeller axis, play a fundamental role in keeping the slipstream together. In a sense they counterbalance the high pressure in the central region. In the two-dimensional model used as an example by Schouten,[3] it is clear at once that the effect of letting the sheets roll up is that the high pressure in the central region disappears. Abandoning the edge forces implies abandoning the high pressure in the central region.

In a three-dimensional model, things are complicated by the rotation of the propeller and the swirl in the slipstream. As long as only axial and radial velocities are involved, the simple two-dimensional reasoning applies. The complications come from the tangential velocity components v_θ in the slipstream. These components require a radial pressure gradient in the slipstream taking care of the curvature of the streamlines in the crossplane. In Theodorsen's[1] rigid-sheet model, the edge forces take care of this aspect as well as of balancing the high pressure inside the slipstream.

The edge forces are unrealistic (they do not exist in a free slipstream) and so is the high pressure in Theodorsen's model.

Low Static Pressure in the Slipstream with Swirl

We restrict the discussion to a model where far downstream all gradients in the axial direction are negligibly small. The swirl in the slipstream goes with a radial pressure gradient subject to the equilibrium condition

$$\frac{\mathrm{d}p(r)}{\mathrm{d}r} = \varrho\frac{v_\theta^2(r)}{r}, \qquad p(r) = \int_0^{R_s} \varrho\frac{v_\theta^2(r)}{r}\,\mathrm{d}r \tag{1}$$

The distribution of swirl velocity $v_\theta(r)$ governs the static pressure in the slipstream. In combination with an (arbitrary) axial velocity distribution, the distribution of **total head** follows from

$$p_0(r) = p(r) + (\varrho/2)\left[v_z^2(r) + v_\theta^2(r)\right] \tag{2}$$

The condition at the edge of the slipstream is that the static pressure is the ambient pressure p_a. The positive outward pressure gradient (1) then implies that the static pressure in the slipstream has its maximum value p_a at the edge. Inside the slipstream, the pressure $p(r) \le p_a$, with a minimum at the axis. Any tangential velocity distribution has its own radial pressure distribution. In constructing the equilibrium model we are free to allow any axial velocity distribution provided it goes with a distribution of total head as described by Eq. (2).

Development of Rigid Helicoid Sheet

We consider a slipstream model (see Fig. 1) that, at the propeller and close behind it, is Theodorsen's rigid helicoidal sheet model. The rollup of the sheets results far downstream in a simple averaged

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