

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

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Nomenclature

- base drag coefficient, $[C_{p,r}(r/c)]$
- total drag coefficient
- pressure coefficient. $(p - p_0)/q$
- $C_{p,b}$ - base pressure coefficient, $(p_b - p_0)/q$
- c - airfoil chord
- h - riblet height
- p_0 = local static pressure
- p_∞ = freestream static pressure
- p_∞ = freestream dynamic pressure = trailing-edge thickness
- u_τ - friction velocity
- x = distance along the chord
- y = distance normal to tunnel axis = angle of attack
- $CD_{61,1r} \sim CD_{61,1r} \sim \nu$ - 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 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 fuse of giblets in separated flows, either from the point of view of drag reduction or separation control.^{3,4} Recently, Krishnan et al.⁵ showed that riblets actually increase the base drag (about 8.7% 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 sheers 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), the effect could be favorable on an airfoil with a blunt trading 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 X 1500 ntm boundary-layer tunnel. The GAW(2) airfoil model, with a r of

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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 3×10^6 . 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 0.1 and 0.96c on both the top and bottom surfaces. Streamwise variations of h^+ calculated using an integral turbulent boundary-layer code 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 case 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. 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 and taking into account repeatability are

$$\Delta C_D = \pm 0.0035 C_D, \quad \Delta C_L = \pm 0.015 C_L$$

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 ($x/c = 10, 2.5, \text{ and } 3.01$) were measured for determining the total drag. Excellent constancy of drag coefficient (within the estimated uncertainty) was observed.

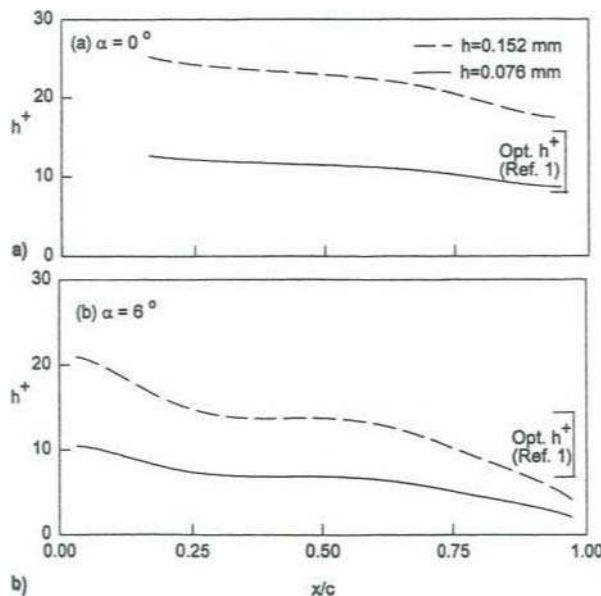


Fig. 1 Variations of h^+ on upper surface of GAW(2) airfoil.

served to suggest good mean flow two dimensionality in the experiments."

Results and Discussions

Surface Pressure Distributions

The measured surface pressure distributions on the airfoil, both with and without the riblets, revealed that the effects of riblets on C_A distributions were very small (as in many earlier studies), 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. 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

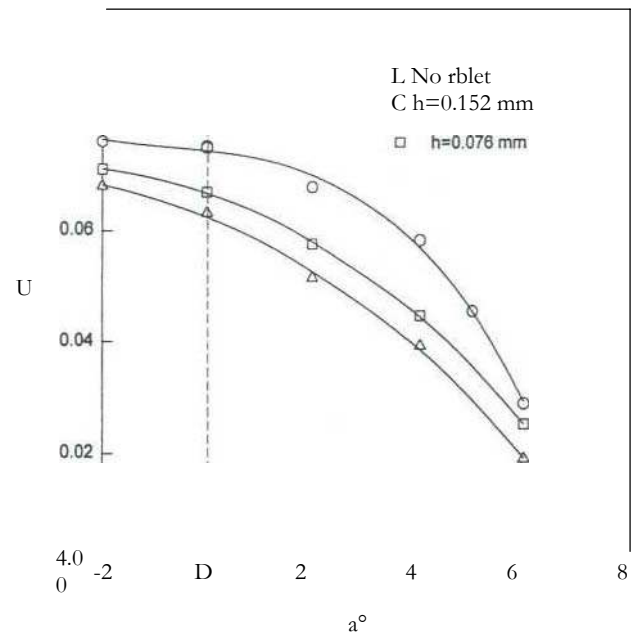


Fig. 2 Variation of base pressure coefficient with incidence.

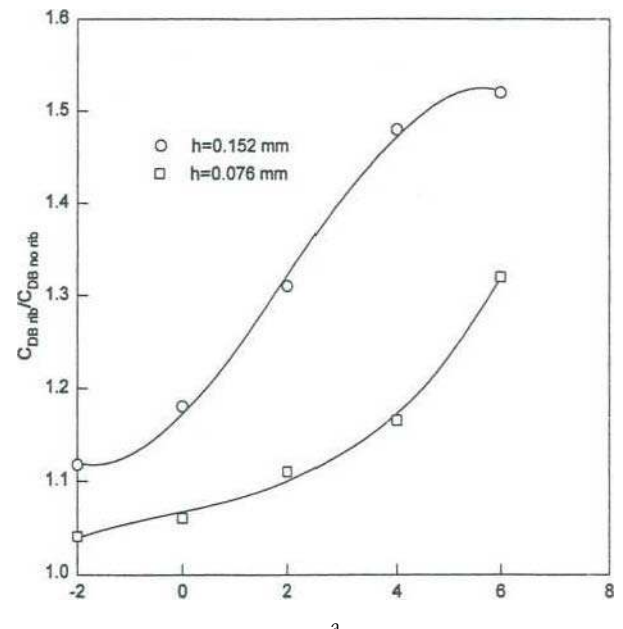


Fig. 3 Variation of normalized base drag with incidence.

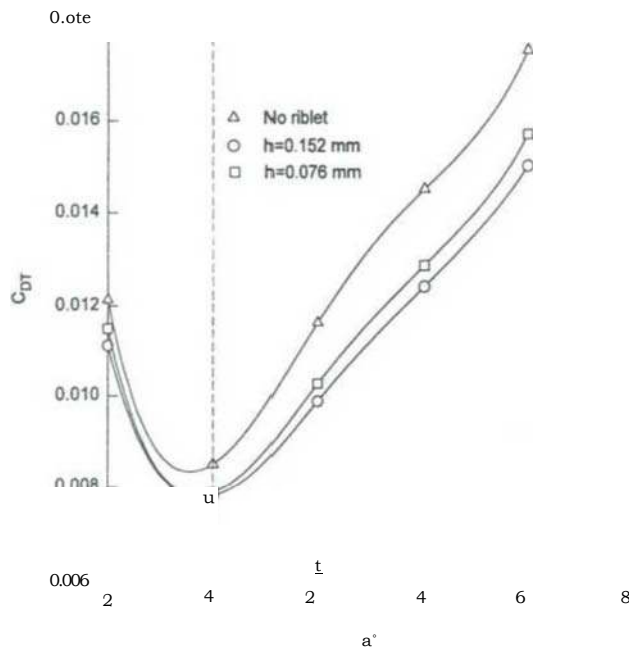


Fig. 4 Variation of total drag coefficient with incidence.

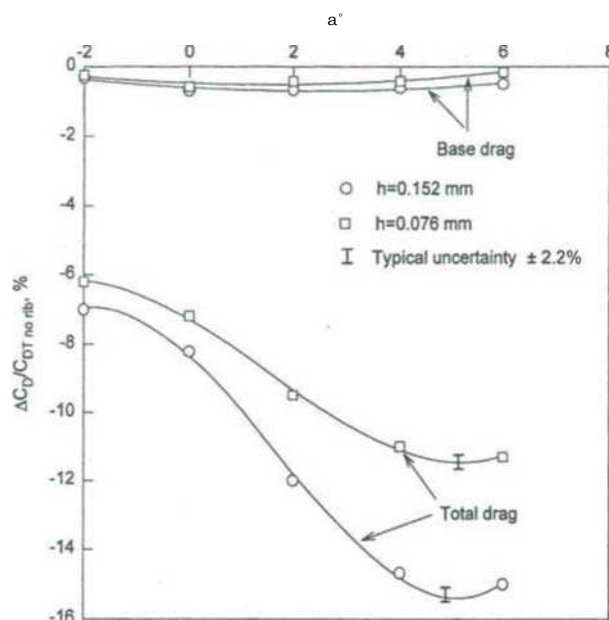


Fig. 5 Total drag and base drag reductions with incidence.

base drag coefficient with riblets relative to no riblets is shown plotted in Fig. 3. The increase in base thrust is as high as 5090 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.¹ and Subaschandar et al.,² 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 fair $h = 0.152$ mm, is nearly constant with re.

Possible Flow Mechanisms

Having observed the increase in base pressure because a riblets, it is appropriate to speculate on possible flow mechanisms that may be responsible for the same. Measurement, 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, h is well known, e.g., Refs. 1, 3, and 7. that riblets lead to lower boundary-layer displacement thickness (S^*) and, therefore, the effective base height (including u^* effect) is smaller compared with the smooth airfoil, and an increase in base pressure can be expected. In the context of base flow dynamics, it is generally known that the base pressure depends on the development of the free shear layer, which in turn depends as the initial boundary-layer conditions just ahead of the base; Earlier studies³ revealed that the near-wall flow is strongly affected by riblets, which includes a reduction in turbulent intensities (as much as 10-20%) and Reynolds shear stresses, e.g., about 15% in the experiments of Walsh⁴ and Suzuki and Kasagi.⁵ 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 (effectively) lower velocity along the dividing streamline of the shear layer and, hence, a higher base pressure 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 is 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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