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Development of the Wake of an Airfoil with Riblets

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Abstract

TESTS were conducted on a NACA 0012 airfoil with riblets at a freestream Reynolds number of 2.5×10^5 in the Texas A&M University indraft wind tunnel. The riblets used in the investigation were of symmetric v-groove type with the heights of 0.0229, 0.076, and 0.152 mm. Measurements of the mean velocity profiles, turbulence, and integral quantities in the near and intermediate wakes indicated that the growth of the wake of an airfoil with riblets was similar to that of a clean airfoil. It was also observed that even at a distance of 600 momentum thicknesses downstream of the trailing edge wake equilibrium had not been reached for any of the configurations tested; however, riblet effectiveness was indicated by a marked decrease in the level of maximum shear stress, especially for the 0.152 mm riblets.

Contents

Previous investigations[1-4] of riblets, which are streamwise grooves of extremely small dimension for use in reducing turbulent skin-friction drag, have indicated that the optimum riblet configuration was that of the symmetric v-shaped riblets of heights of approximately equal to 12, as expressed in law of the wall coordinates. Measurements[3,4] have shown that an 8–13% reduction of drag could be achieved for flat plates and symmetric airfoils at zero angle of attack, respectively. Although the mechanism of this reduction is not yet fully understood, researchers[4] have surmised that it is due to a reduction in the Reynolds shear stress over the airfoil, which not only reduces the local shear stress but also reduces the momentum transport within the boundary layer.

Because of the potential for riblets as a method to reduce the drag of aerodynamic surfaces, the primary objective of this investigation was to determine if the application of riblets, which results in the modification of the wall boundary layer, affected the development of the wake of a symmetric airfoil. It was expected that the effects of the surface modifications (i.e., riblets) on the wall layer would be seen in the wake in the form of changes in the wake parameters as compared to the wake of the same airfoil with an unmodified wall boundary layer. Furthermore, previous investigations[5-8] of wake flows have shown that the pressure distribution over the aft part of streamlined bodies is dictated by the interaction of the boundary layer and the wake.

Hot film x-probe measurements were made in the near and intermediate wake regions of a NACA 0012 airfoil, 152.4 mm chord, at zero angle of attack in the Texas A&M University 46×46-cm low-speed indraft wind tunnel. The tests were conducted at a reference Reynolds number of 2.5×10^5, which corresponds to a freestream velocity of 23 m/s. The test setup and experimental procedures have been documented in Ref. 4. The riblet geometries tested were of the vinyl symmetric v-grooved type and ranged in heights from 0.0229 to 0.152 mm. Friction velocity, determined from the mean velocity profiles measured near the trailing edge of the airfoil (95% of chord), showed that the heights of the riblets in law of the wall coordinates h^+ were 1.5, 5, and 10 for 0.0229-, 0.76-, and 0.152-mm riblets, respectively.

Figures 1 and 2 show the nondimensional mean velocity defect in the wake where $W = U_\infty - U$ and $W_o = U_\infty - U_{\text{centerline}}$, U being the velocity in the streamwise direction for the clean airfoil and the 0.152-mm riblet, respectively. The horizontal axis indicates the distance y away from the wake centerline nondimensionalized by the half-wake width, which is defined as the y location where $U = \frac{1}{2}(U_\infty - U_{\text{centerline}})$. The longitudinal distances x away from the trailing edge of the airfoil are given in percentage chord length c. Also shown in the figures is the expression for the asymptotic mean velocity profile developed by Ramaprian et al.[5] Although the initial development of these profiles is different for each configuration, the mean velocity profiles begin to reach local similarity by $x/c \approx 17\%$. Integration[4] of the velocity profiles at this location resulted in a half-wake momentum thickness of ≈ 40, which has been shown[5,6] as the location of the beginning of the intermediate wake region. The mean velocity profiles agree rather well with the asymptotic profile, except for some small discrepancies near the outer edge. This indicates that the mean velocity profiles for both cases, and similarly for the other cases, begin to establish a near-asymptotic profile in the intermediate wake region.

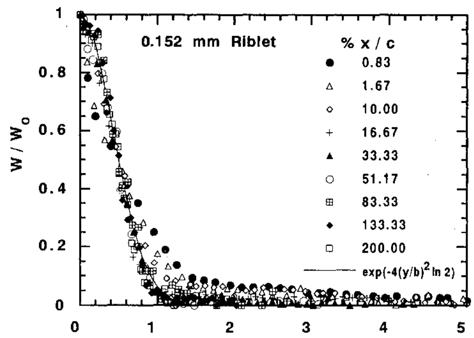

Fig. 1 Wake velocity defect profile—clean airfoil.

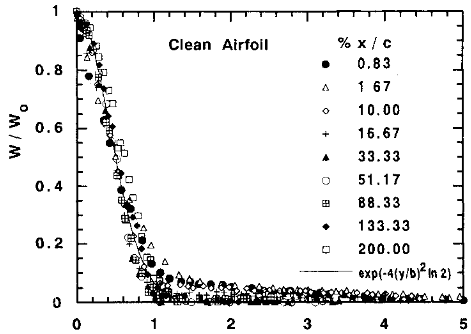

Fig. 2 Wake velocity defect profile—$h^+ = 10$ riblet.

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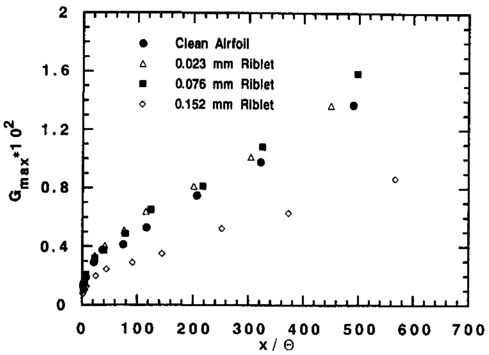

Fig. 3 Streamwise development of shear stress in the wake.

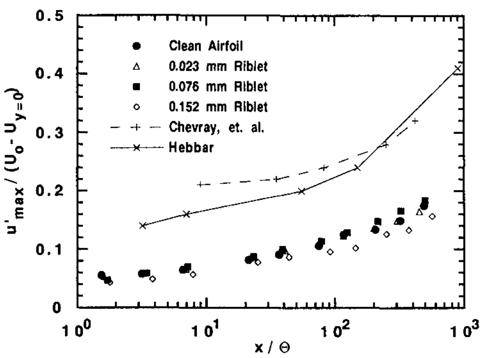

Fig. 4 Streamwise development of wake turbulence intensity.

As the flow moves far downstream from the trailing edge, i.e., in the far wake region, the structure of both the mean-flow and the turbulence parameters is expected to attain universal distributions independent of trailing-edge conditions. Sreenivasan and Narasimha[7] predicted that the equilibrium form of the half-wake width $b/\sqrt{x\Theta}$ and the maximum wake deficit $W_o/U(\sqrt{x/\Theta})$, where Θ is the half-wake momentum thickness, would asymptotically approach the values of 0.30 ± 0.005 and 1.63 ± 0.02, respectively. Using this criteria, an evaluation of the data at the last measurement station, two chord lengths downstream from the trailing edge, is presented in Table 1. The data show that the maximum wake defect and half-wake width have not reached similarity for any of the configurations tested. It should be noted that this criterion has been questioned by the detailed experiments of Wygnanski et al.,[8] which show that the approach to equilibrium is more dependent on the end conditions of the wake generator and the test facility and, therefore, the pressure gradients encountered during the test. The lack of similarity in the wakes for all of the configurations may be due to rapid expansion of the boundary layers over the airfoil as they merge into the wake and travel downstream and the presence of the favorable pressure gradient in the fixed wall test section.

Ramaprian et al.[5] showed that the maximum nondimensional shear stress G_{max} should approach the value of 0.0487 in the far wake. As can be seen in Fig. 3, this value has not yet been reached, even at distances of 600 momentum thicknesses downstream of the trailing edge. Also, a significant difference in the rate of growth of G_{max} between the $h^+ = 10$ riblet and the other configurations is observed. The maximum longitudinal turbulence intensity u'_{max} normalized by the centerline velocity deficit is presented in Fig. 4. The figure shows again

Table 1 Calculated equilibrium parameters

Configuration	$W_o/U_o\sqrt{x/\Theta}$	$b/\sqrt{x\Theta}$
Clean airfoil	2.46	0.172
0.023-mm riblet	2.18	0.202
0.076-mm riblet	2.07	0.167
0.152-mm riblet	2.14	0.249

that the fluctuating parameters have not attained equilibrium, which is indicated by the independence of these parameters from the downstream distance. Presented for comparison are the results of Chevray and Kovasznay[9] and Hebbar,[6] which overshoot the equilibrium value of 0.27.[10] The lack of similarity of the values in Table 1 and Figs. 3 and 4 are attributed to the growth of the boundary layer along the test section walls and the associated pressure gradient.

Although local similarity was seen in the mean velocity profiles, wake equilibrium had not been reached for any of the configurations tested. However, riblet effectiveness in modifying the development of the wake turbulence parameters can be seen by the reduction of the maximum nondimensional shear stress and longitudinal turbulence intensity in the wake for the 0.152-mm riblet. The reduction in the maximum shear stress for the $h^+ = 10$ riblet shows the effect of the riblets in reducing the shear stress that is developed over the airfoil. Walsh[3] reported that maximum drag reduction for flat plates occurred for riblets of heights on the order of 12, which compares well with the present results. The decreases in the maximum shear stress and longitudinal turbulence intensity in the wake of the airfoil reflect the effectiveness of the riblets in reducing the momentum transport to the surface of the airfoil.

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