Effect of Riblets on Turbulence in the Wake of an Airfoil

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Abstract

MEASUREMENTS were made in the near and intermediate wake regions of a NACA 0012 airfoil with three different riblet sizes at a freestream Reynolds number of 2.5×10^5. The riblets tested were a symmetric v-groove type of heights 0.0229, 0.076, and 0.152 mm, respectively. To ensure turbulent flow on the airfoil, a transition strip was applied at 10% of the chord. Wake velocity profiles and turbulence parameters were measured with a temperature compensated hot-film x-probe. Riblet effectiveness was indicated by marked decrease in turbulence levels in the wake. Integration of the wake mean velocity profiles indicated a net reduction in drag of up to 13.3%, which was possibly caused by the combined effect of decreased turbulent shear stress and lower momentum exchange near the surface due to a viscosity-dominated region in the riblet valleys.

Contents

Riblets, which are streamwise grooves of very small dimensions, are currently being investigated as a promising method for the reduction of turbulent skin friction drag of airfoils, nacelles, and aircraft fuselages. Detailed measurements of Walsh and Weinstein[1] and Walsh [2,3] have shown that symmetric riblets of heights of 12, expressed in law of the wall coordinates,[4] are capable of reducing turbulent skin friction drag on flat plates by as much as 8%; however, the mechanism of this reduction is yet to be fully understood. Investigators[5] have surmised through flow visualization techniques that the effect of riblets is to severely retard the flow in the valley of a riblet, thus creating a viscosity-dominated region where the local skin friction is greatly reduced.

All previous data related to riblets correspond to the measurements made with arrays of riblets applied to the flat plats placed in a flow with zero longitudinal pressure gradient. The measurements reported in this paper were made in the near and intermediate wake regions of a symmetric airfoil with riblets applied on both sides. Since the small size of riblets prohibit measurements within the valley of riblets with the smallest available hot-film probe, it was assumed that upstream history could be extrapolated by analyzing the wake parameters that would be influenced by the downstream propagation of the effects of riblets. To verify the effectiveness of riblets, measurements of wake of an airfoil with riblets to that of an airfoil without riblets were quantitatively compared.

All tests were conducted in the Texas A&M University 46×46 cm, low-speed, low-turbulence, indraft wind tunnel with a longitudinal turbulence intensity of less than 0.25%. The tests were conducted at a reference Reynolds number of 2.5×10^5, which corresponds to a freestream velocity of 22–24 m/s. The test model consisted of a NACA 0012 airfoil of 152.4-mm chord length mounted in the tunnel at zero angle of attack. Since riblets are effective only in turbulent flow, transition of the boundary layer on the airfoil was fixed by a 0.28-mm thick trip strip at 10% x/c. Surface flow visualization was conducted to ensure a fully attached and turbulent boundary layer at the point of transition. The riblet geometries tested were of the vinyl symmetric v-groove type and ranged in heights from 0.0229 to 0.152 mm. Surface integrity of the riblets was checked by micrographs produced by the Texas A&M University scanning electron microscope. Micrographs of the riblet configurations tested are shown in Fig. 1. Except for some contamination due to dust, the riblets appear to be very clean and symmetric. A hot-film x-probe mounted on a two-dimensional traversing system[4] was used to measure the mean velocity profiles, turbulence intensities, and Reynolds stresses in the near and intermediate wake regions. The entire width of the wake was traversed at each measurement station starting from 1.3 mm from the airfoil trailing edge to two chord lengths downstream. The wake mean velocity profiles were integrated to obtain the momentum thickness at each station. Friction velocity was calculated from the boundary-layer profiles measured near the airfoil trailing edge ($x/c \sim 0.95$) with a hook-type boundary-layer pitot probe with flattened tip. This value of friction velocity as measured for each riblet configuration separately was used for the calculation of riblets height in the law of the wall coordinates and resulted in h^+ of 1.5, 5, and 10 for 0.0229, 0.076, and 0.152 mm riblets, respectively.

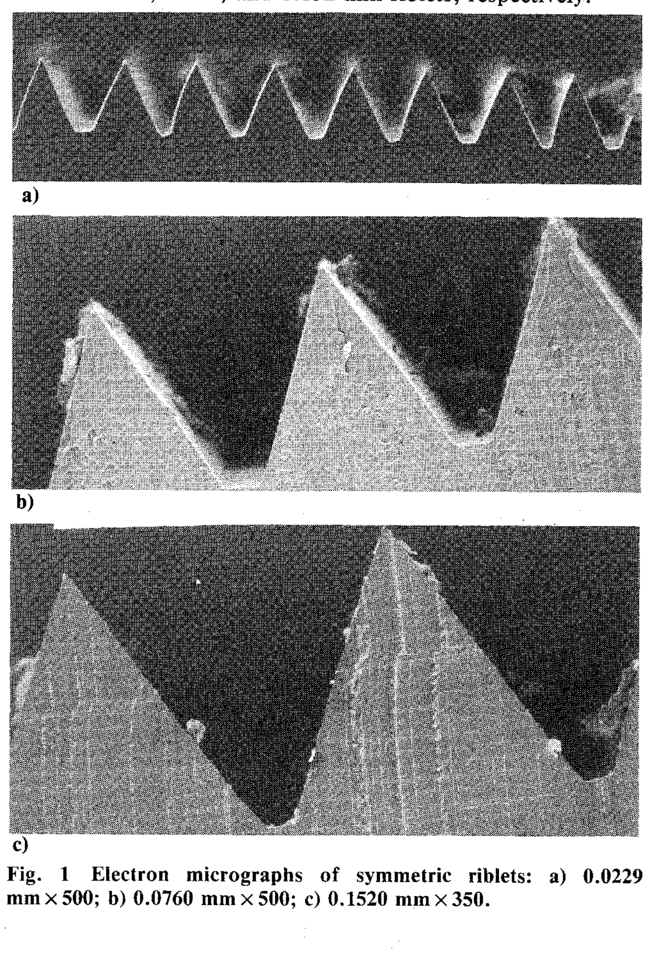

Fig. 1 Electron micrographs of symmetric riblets: a) 0.0229 mm × 500; b) 0.0760 mm × 500; c) 0.1520 mm × 350.

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Table 1 Maximum longitudinal turbulence intensity

Configuration	$\langle u \rangle_{max}/U_0 \times 10^2$						
(x/c), %[a]	0.83	1.67	3.33	10.0	33.3	88.3	200
Clean airfoil	3.42	3.49	3.42	3.31	2.86	2.33	1.94
0.023-mm riblet	3.39	3.53	3.49	3.42	2.88	2.13	1.68
0.076-mm riblet	3.20	3.56	3.67	3.38	2.74	2.28	1.71
0.152-mm riblet	2.78	2.82	2.92	2.90	2.22	1.84	1.41

[a]Distance from trailing edge.

Table 2 Maximum normal turbulence intensity

Configuration	$\langle u \rangle_{max}/U_0 \times 10^2$						
(x/c), %[a]	0.83	1.67	3.33	10.0	33.3	88.3	200
Clean airfoil	1.99	2.07	2.10	1.99	1.49	1.31	1.23
0.023-mm riblet	1.99	2.09	1.99	1.96	1.53	1.33	1.20
0.076-mm riblet	1.97	2.09	2.15	1.85	1.38	1.25	1.14
0.152-mm riblet	1.61	1.54	1.64	1.38	1.05	0.88	0.76

[a]Distance from trailing edge.

Table 3 Maximum turbulent kinetic energy

Configuration	$\mathrm{TKE}_{max}/U_0 \times 10^2$						
(x/c), %[a]	0.83	1.67	3.33	10.0	33.3	88.3	200
Clean airfoil	9.80	10.16	10.02	8.93	6.27	4.32	3.04
0.023-mm riblet	9.74	10.30	10.10	9.68	6.29	3.74	2.80
0.076-mm riblet	8.91	10.12	11.01	9.04	5.49	3.96	2.76
0.152-mm riblet	6.11	6.46	6.50	5.45	3.31	2.34	1.53

[a]Distance from trailing edge.

Table 4 Maximum Reynolds shear stress

Configuration	$-\overline{uv}_{max}/U_0^2 \times 10^4$						
(x/c), %[a]	0.83	1.67	3.33	10.0	33.3	88.3	200
Clean airfoil	4.95	5.62	5.35	4.83	2.99	2.27	1.69
0.023-mm riblet	5.37	5.44	5.66	5.35	3.19	2.00	1.45
0.076-mm riblet	4.85	5.51	5.77	4.82	2.80	1.95	1.37
0.152-mm riblet	3.28	3.48	3.40	2.45	1.56	1.12	0.70

[a]Distance from trailing edge.

Table 5 Airfoil drag coefficients

Configuration	c_D	$\Delta c_D/c_{D_{C.A.}}$, %
Clean airfoil	0.0150	N/A
0.023-mm riblet	0.0139	7.3
0.076 mm riblet	0.0146	2.7
0.15 2mm riblet	0.0130	13.3

Variation of the freestream velocities remained within 5%, except for the measurements in the wake of the 0.0229-mm riblet where the variation was as much as 8%. The overall experimental error was estimated to be not more than $\pm 1\%$ for mean velocity U, $\pm 3\%$ for the longitudinal and normal turbulence intensities $\langle u \rangle$ and $\langle v \rangle$, respectively, and as high as $\pm 12\%$ for the Reynolds shear stress $-uv$.

Tables 1 and 2 list the peak longitudinal (streamwise) and normal turbulence intensities measured at several wake stations for all the configurations tested. The variation of the peak turbulence intensities in the wakes for each configuration shows that in the region immediately behind the trailing edge marked overshoots occur for both components. The overshoots, similar to ones that were observed by Ramaprian et al.[6] and Hebbar,[7] are primarily associated with the vortical interaction of the boundary layers immediately behind the trailing edge. This interaction initiates separation or vortex shedding behind the trailing edge and is thought to be caused by a combination of the merging boundary layers at the trailing edge (which has an included angle of 20.5 deg), the presence of an adverse pressure gradient, and a small finite thickness (0.279 mm for the clean airfoil) at the trailing edge. The sudden interaction of the fluctuation components at the trailing edge results in extra production of these components. As the boundary layers at the trailing edge of the airfoil merge into a wake, the changeover from wall turbulence to free turbulence is indicated by the relation of the turbulence intensities. It is at this point where the difference between the longitudinal and normal components begins to decrease and nearly become equal in the far-wake region. For this investigation, however, distinct differences still exist at a distance of two chord lengths downstream.

A comparison between the magnitudes of the turbulence intensities for all the riblet configurations indicates that the riblets reduced the amount of turbulence intensity present in the boundary layer on the airfoil; the most significant difference was with the $h^+ = 10$ riblet as compared to the clean airfoil configuration.

Table 3 and 4 list the peak values for the turbulent kinetic energy (TKE) and Reynolds shear stress in the wake. These parameters developed similarly to the development of the longitudinal and normal turbulence intensities such that there are overshoots near the trailing edge before relaxing further downstream. Again, noticeable differences can be seen in the magnitudes of TKE and $-$uv between the riblets and the clean airfoil configuration; the maximum difference was with the $h^+ = 10$ riblet.

The wake mean velocity profiles of all four configurations displayed no significant differences and a standard development of wake was observed. However, integration of the mean velocity profiles at the last measurement station for the half-wake momentum thickness indicated changes in the drag coefficient C_D for the airfoil. The values of C_D for each of the configurations are listed in Table 5. As can be seen, the $h^+ = 10$ riblet reduced the C_D of the airfoil by the substantial amount of 13.3%. Although this reduction is higher than the previously reported values, [1-3, 5,] it should be noted that the $h^+ = 10$ is within the range of heights of riblets for which some reduction is expected. The net reduction in the drag coefficient for the ribletted airfoil configurations was possibly due to a reduction in the skin-friction drag for these configurations. The decrease in skin-friction drag resulted from a combination of the viscosity-dominated region deep within the riblet valley, as shown by Hooshmand et al.,[5] and the reduced turbulence intensity in the flow above this region to which the remaining riblet surface is exposed. By definition, the local shear stress is a function of the velocity gradient near the wall and the Reynolds shear stress. Therefore, any reduction in $-\overline{uv}$ not only has a direct effect on reducing the local shear stress but also has a coupling effect on the mean velocity profile due to reduced momentum transport within the boundary layer. Thus the integrated effect of reduced local shear stress on the airfoil resulted in reduced net drag.

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