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NEAR WAKE STUDIES OF AN AIRFOIL WITH MICRO-GROOVES

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ABSTRACT

Measurements were made in the near and intermediate wake regions of a NACA 0012 airfoil with and without micro-grooves (M.G.) at a freestream Reynolds number of 2.5×10^5. *The M.G. were the symmetric v-grooved type, .152 mm in hieght. Experiments were conducted in the TAMU suction type, open return low speed wind tunnel. 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 the help of a temperature compensated hot film x-probe. The growth of the wake was found to be similar for the clean airfoil and the airfoil with M.G., however M.G. effectiveness was indicated by a marked decrease in turbulence levels in the wake.*

INTRODUCTION

Investigations of micro-grooves (M.G.) began in the early 70's with the work of Kennedy et al. (1973), who showed that small longitudinal fins placed on a flat plate produced a reduction in the average shear stress over the whole perimeter. Continuing work on M.G. technology, Walsh (1982) made measurements of the skin friction on a flat plate with a very sensitive drag balance. By narrowing the range of the viscous heights of the M.G. to less than 30, Walsh found consistent drag reductions of 8 percent occurred with the use of the symmetric v-shaped M.G. of h+ = 12. Based on water tunnel tests, Bacher and Smith (1986) proposed that the M.G. effectively reduced the surface shear stresses by decreasing the momentum exchange due to the formation of streamwise vortices near the surface and beneath the turbulent layer.

Wallace and Balint (1987) published a comprehensive study of previously taken M.G. data and presented more recent results of Hooshmand et al. (1983). In all the cases reviewed the turbulence intensities, streamwise and normal, as well as Reynolds stresses, normal and shear, were shown to decrease with the use of M.G.. It was surmised that the effect of the M.G. is to severely retard the flow in the valley, thus creating a viscosity dominated region where the local skin friction is greatly reduced. Because M.G. increase the wetted surface to planform area ratio by as much as a factor of 4, the net drag reduction has been limited to 8 percent. In conclusion, Wallace and Balint (1987) stated that the M.G. shield the surface from much of the turbulent momentum transport resulting in smaller velocity gradients at the bounding surface.

Current Objectives

Investigations of the flow conditions in the wake of a flat plate or airfoil have been done because the pressure distribution over the aft part of streamline bodies is dictated by the interaction between the boundary layer, the wake, and the external flow. Data retained in these types of investigations aid in the successful prediction of the performance of streamlined bodies as well as aid in the development of turbulence models which satisfactorily predict the flow fields of practical configurations such as those found over airfoils at moderate angle of attack. Recently, the work of Chen and Patel (1989) showed some advancement in the area of turbulence modeling by using the Reynolds-averaged Navier-Stokes equations in conjunction with a two-layer turbulence model. The numerical solutions produced for an elongated axisymmetric body displayed the essential features of theory but failed to describe some of the details of the flow field. Numerical methods and turbulence models such as this could not be evaluated without the existence of an extensive data base on turbulent boundary layers and interacting wakes.

The size and scale of the M.G. tested in this investigation made it impossible to measure flow properties within the M.G. valleys therefore the primary concern of this investigation was to determine if the effects of the M.G. on the surface boundary layer propagate into the developing near and intermediate wake regions of a symmetric airfoil. It was assumed that the upstream history can be extrapolated by analyzing the downstream effects. These effects would be seen in the profiles of the mean velocities, turbulence intensities, and Reynolds stresses in the wake. The results of the airfoil with M.G. were compared to the results of the same airfoil without M.G..

TEST FACILITY AND EXPERIMENTAL PROCEDURE

All tests were conducted in the Texas A&M University 46 cm × 46 cm low speed, low turbulence, suction type wind tunnel with a longitudinal turbulence intensity of less than 0.25 percent. The test model consisted of a NACA 0012 airfoil of 152.4 mm (6 in.) chord length. The airfoil was mounted in the forward half of the test section at zero angle of attack. Transition of the boundary layer on the airfoil was fixed by a .28 mm thick trip strip placed at 10% x/c. The M.G. geometry tested was of the vinyl symmetric v-grooved type, .152 mm (.006") in height.

The tests instrumentation consisted of a TSI model 1241-20 end flow type "x" probe with a nominal sensor resistance of 5.75 and 6.65 ohms and was used with an over heat ratio of 1.5. All of the data from the hot film probe was temperature compensated. Free stream velocity was measured with the help of a pitot static tube. More information on instrumentation can be found in Caram (1989).

The upstream reference Reynolds number was 2.5×10^5 corresponding to a velocity of 22-24 m/s (75-80 ft/s). Before each test, the tunnel, as well as the hot film probe, was allowed to run for some time (usually 30 minutes) to attain steady state conditions.

Measurements of the flow properties were made in the near and intermediate wake and the entire width of the wake was traversed. Detailed measurements of the two dimensional profiles of the mean velocity, turbulence intensity, and Reynolds stresses were taken at preselected streamwise stations located along the centerline of the test section and varied from 1.3 mm from the trailing edge to two chord lengths downstream (Fig. 1).

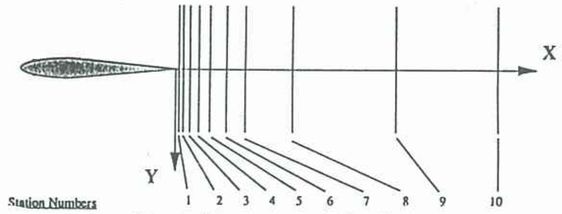

Fig. 1 Measurement Stations.

RESULTS AND DISCUSSION

Variation of the freestream velocities remained within 5%. The overall experimental error has been estimated to be no more than ±1% for the mean velocity measurements. For $< u >^2$, the maximum error was not more than ±5%; where as for $-\overline{uv}$ the maximum error was calculated to be as high as ±12%. Also, a 99% level of confidence in mean velocity measurements is assumed for a standard deviation of 3σ, where $\sigma = .0367U$ at the point of maximum turbulence.

Static pressure measurements along the wall indicated a slightly favorable longitudinal pressure gradient which is typical of a constant cross sectional area test section. Boundary layer measurements at the trailing edge resulted in a Θ_{TE} of .86 mm and .69 mm for the clean airfoil and the airfoil with the .152 mm M.G., respectively. The Θ_{TE} for the M.G. configuration corresponded to a viscous height of h+=10.

Wake symmetry was considered quite good with maximum difference in mean velocity on either side being less than 5%. Measurements of the entire wake were made for each streamwise station; however because of symmetry only the measurements on one side of the wake are reported.

The streamwise development of the mean velocity profiles in the wake for the cases of the clean airfoil and h+=10 M.G. are presented in half wake form in Figs. 2 and 3. It can be seen that for both cases only the center portion of the flow changes with downstream distance as the flow accelerates rapidly with the disappearance of the wall shear stress while the outer portion remains unchanged. At $x/c \approx 17\%$ ($x/\Theta \approx 40$) the profile begins to change over from a boundary layer type profile to more like a wake profile. Due to the absence of any additional turbulence production and the presence of the wall pressure gradient the profiles widen gradually. The region where the profiles retain the boundary layer shape is known as the near wake region and the distance downstream for which it exists given in the present data compares well for that given by Ramaprian et al. (1982) and Hebbar (1986), $x/\Theta = 25$ for flat plates and 50 for airfoils, respectively. From this region the wake flows into the intermediate wake region where the wall shear forces begin to dissipate outward.

The intensities of the longitudinal(streamwise) and normal components of the velocity fluctuations in the wake are seen in Figs. 4, 5 and 6, 7 for the clean airfoil and h+=10 M.G., respectively. Two distinct patterns for both cases can be seen to develop with dividing limit again being at $x/\Theta \approx 40$ for $H_{TE} \approx 1.61$. Note that Hebbar (1986) and Chevray and Kovasznay (1969) reported these values to be 50/1.54 and 30/1.44, respectively. In the near wake region the point of maximum intensity moves away from the axis of symmetry or the zone of maximum

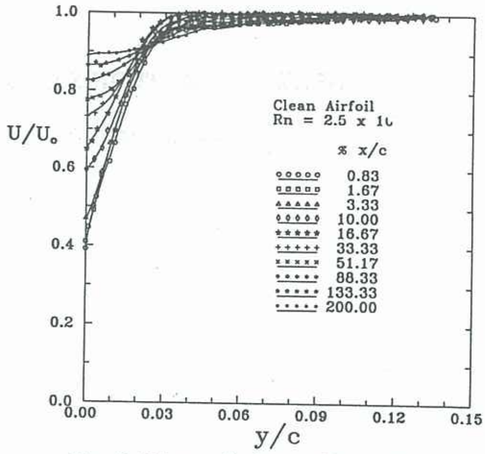

Fig. 2 Mean velocity profiles in the wake- clean airfoil.

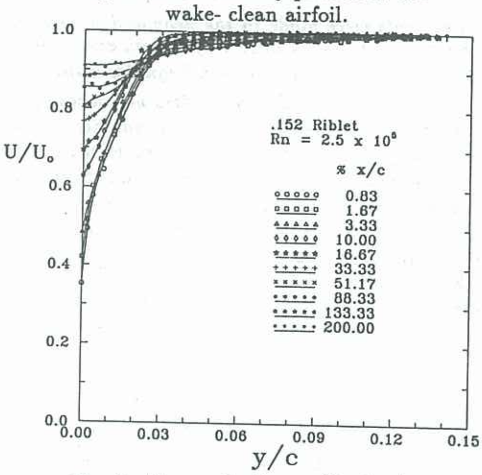

Fig. 3 Mean velocity profiles in the wake- h+=10 M.G..

shear. In both cases the magnitude of the longitudinal component of turbulence is 1.5 times greater than that of the normal component in the near wake region which is expected because of the restraining effect of the wall on the normal component.

As the boundary layers at the trailing edge of the airfoil merge into a wake, the change over from wall turbulence to free turbulence is clearly seen by the restructuring of the turbulence intensity profiles. It is at this point where the difference in the longitudinal and normal components begins to decrease and should become nearly equal in the far wake region. For this investigation however, distinct differences still exist between the two components even at the last measurement station which is a distance of two chord lengths downstream.

The distributions of turbulent kinetic energy, Figs. 8 and 9, and Reynolds shear stress, Figs. 10 and 11, in the wake for the clean airfoil and h+=10 M.G., respectively, show similar trends as those seen in the previous figures of turbulence intensity. Reynolds normal stresses showed similar trends and can be seen in Caram (1989). As before, the restructuring of the profiles occurs with the change over from wall turbulence to free turbulence in the wake.

In the region immediately behind the trailing edge marked overshoots occur in the distributions of all the turbulence parameters recorded (Figs 4-11). The overshoots, similar to the ones which were observed by Ramaprian et al. (1982) and Hebbar (1986), and 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 trialing edge and is thought to be caused by a combination of

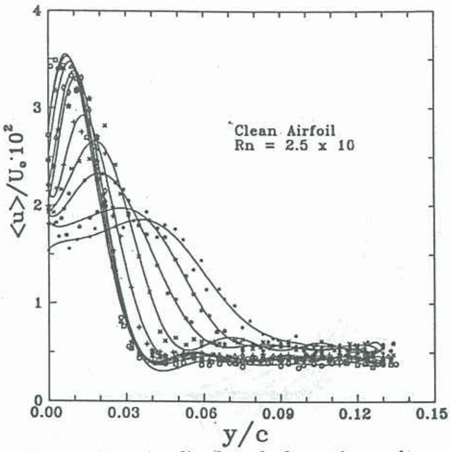

Fig. 4 Longitudinal turbulence intensity in the wake- clean airfoil.

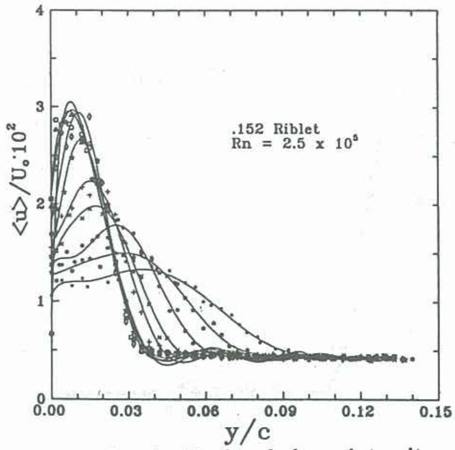

Fig. 5 Longitudinal turbulence intensity in the wake- h+=10 M.G..

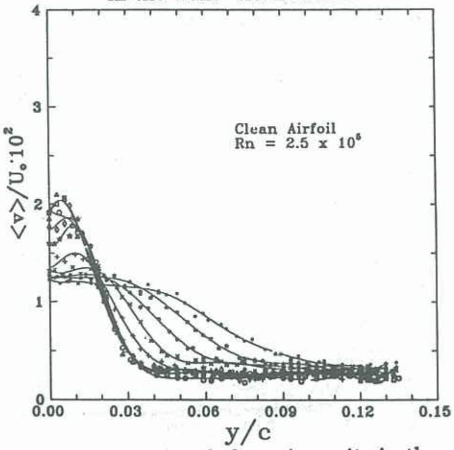

Fig. 6 Normal turbulence intensity in the wake- clean airfoil.

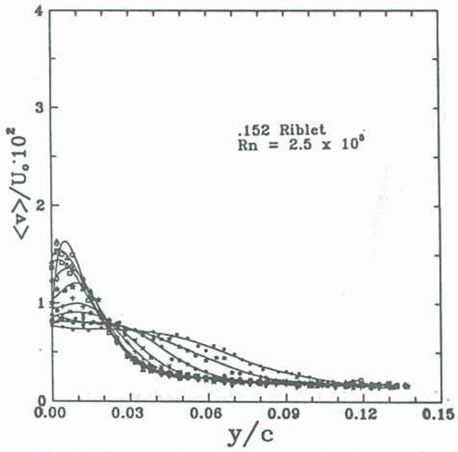

Fig. 7 Normal turbulence intensity in the wake- h+=10 M.G..

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 (.279 mm for the clean airfoil) at the trailing edge. The sudden interaction of the fluctuating components at the trailing edge results in extra production of these components in the near wake region before relaxing further downstream.

A closer examination of the turbulence parameters in Figs. 4-11, show significant differences in the magnitudes of the parameters related to the h+=10 M.G. as compared to the clean airfoil configuration. The figures showing the turbulent kinetic energy and Reynolds shear stress show decreases in these parameters of up to 35% for the h+=10 M.G..

CONCLUSION

Mean velocity and turbulence measurements have been taken in the wake of a symmetric airfoil with and without M.G., .152 mm in height. Although the M.G. array increased the thickness of the trailing edge which lead to more vortical action, no significant changes could be seen in the development of the near and intermediate wake regions. For each of the configurations change over from wall turbulence to free turbulence occurred at $x/\Theta \approx 40$. This transition was indicated by distinct differences in the mean velocity and turbulence parameter profiles as they reacted to the sudden disappearance of the wall shear stress at the trailing edge. The transition was preceded by initial overshoots in the near wake region due the vortical action and pressure gradient at the trialing edge.

Riblet effects were seen to propagate into the wake and were most noticable in the decreases in the magnitudes of the turbulence parameters, especially those of the Reynolds shear stresses and turbulent kinetic energy. This indicates that the M.G. reduce the turbulent momentum transport to the surface of the airfoil which decreases the amount of turbulent shear stress acting on the surface.

Acknowledgments

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NOMENCLATURE

c = chord length
h = physical height of the M.G.
$h+$ = heights of M.G. in law of the wall variables
$s+$ = spacing of M.G. in law of the wall variables
TKE = turbulent kinetic energy
$= \frac{1}{2}(<u>^2 + <v>^2 + <w>^2)$
U = longitudinal mean velocity
U_o = freestream velocity
u = turbulent velocity in the x direction
v = turbulent velocity in the y direction
w = turbulent velocity along the span
x = downstream distance from the trailing edge
y = normal distance from the wake centerline
Θ = half wake momentum thickness as defined by
$= \frac{1}{2}\int_{-\infty}^{+\infty} \frac{U}{U_o}(1 - \frac{U}{U_o})dy$

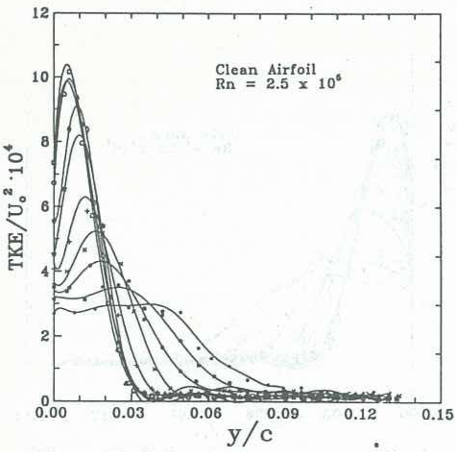

Fig. 8 Turbulent kinetic energy in the wake- clean airfoil.

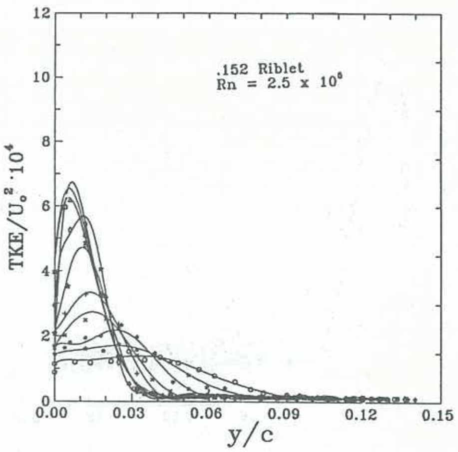

Fig. 9 Turbulent kinetic energy in the wake- h+=10 M.G..

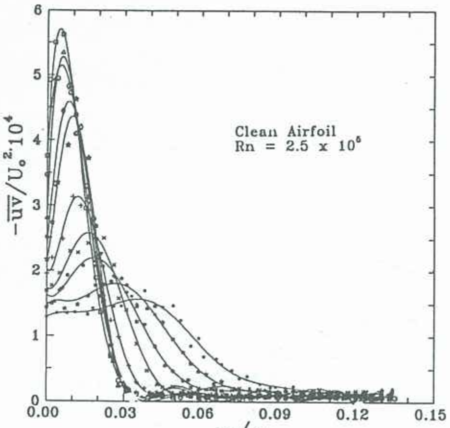

Fig. 10 Reynolds shear stress in the wake- clean airfoil.

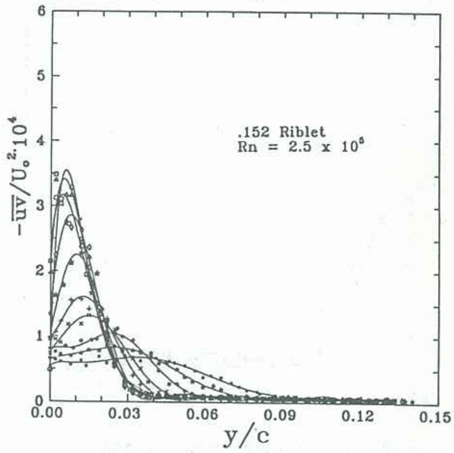

Fig. 11 Reynolds shear stress in the wake- h+=10 M.G..

Θ_{TE} =trailing edge momentum thickness
ρ = density
τ_{TE} = wall shear stress
τ = Reynolds shear stress = $-\rho\overline{uv}$
<> = r.m.s values

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