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Turbulent Boundary-Layer Flow over a Rotating Flat-Plate Blade

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AND

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Turbulent boundary layers on rotating blades have not been studied as extensively as laminar flows, although turbulence is common in practical applications, such as propellers and helicopter rotors. This Note is concerned with a set of calculated results for the incompressible turbulent flow over a steadily rotating flat-plate blade, for flow conditions that in the laminar case were found by Dwyer and McCroskey[1] to produce strong three-dimensional effects, such as centrifugal pumping and an increase in the shear stress at the wall. One of the main points of interest here is the extent to which certain qualitative features of laminar and turbulent flows are alike, whereas the quantitative details are significantly different.

The calculations described in this Note were performed using the recent method of Nash,[2] modified by the inclusion of the Coriolis and centrifugal terms in the two mean-flow momentum equations, following Ref. 1. The assumptions concerning the shear stress were left unchanged. These assumptions are that the shear stress can be determined from the empirically modified turbulent kinetic-energy equation, formulated by Bradshaw et al.,[3] for two-dimensional flow, together with the additional assumption that the local shear-stress vector acts in the direction of the local mean rate of strain. Otherwise, two-dimensional turbulent physics is assumed to apply.

Following the notation of Ref. 1 (shown here in Fig. 1), the calculations were started at initial chordwise x stations such that a laminar boundary layer growing from the leading edge would have attained a momentum thickness Reynolds number of 380. At this point "transition" to an initial turbulent velocity profile, with $Re_\theta = 380$ and $Re_\delta = 3000$, was assumed to occur. This starting procedure was found to be effective in reducing the sensitivity of the results to variations of local unit Reynolds number, $\Omega z/\nu$. The range of Reynolds numbers considered was from 3.5×10^6 to 5×10^8, based on the maximum distance from the leading edge; this range covers both marine and aeronautical applications.

One of the most important results from the previous laminar investigation[1] was that the three-dimensional departures from two-dimensional flow, or "strip theory" results, correlated uniquely with the parameter x/z. Furthermore, the chordwise component of the surface shear stress was found to provide a good basis for indicating the over-all significance of crossflow and rotational effects. Therefore, the ratio of the component of the wall shear stress in the x direction to the local "strip theory" value is shown in Fig. 1 as a function of x/z. All of the turbulent results were found to collapse essentially to the single curve shown. Just as in the laminar case, the wall shear increases with increasing x/z, although the rate of increase is considerably less in the present case.

There is a subtlety associated with Fig. 1 that deserves further consideration. Unlike the laminar results, the increase in the turbulent shear stress coincides almost exactly with the results of a simple-minded locally two-dimensional flow based on the total external velocity at each point; that is, a nonrotating flat-plate boundary layer which has a local external velocity equal to $(U_e^2 + W_e^2)^{1/2}$ and no boundary-layer crossflow relative to the local potential-flow streamline. This is consistent with the small crossflow in the actual three-dimensional boundary layer. Figure 2 shows the variation of the wall crossflow angle, i.e., the angle between the surface streamlines and the inviscid-flow streamlines. Even at the lowest Reynolds numbers,§ this angle is less than 3° for values of x/z up to 0.8. For the hovering flat plate, of course, the potential-flow streamlines are circular arcs.

A further illustration of the nature of the crossflow is provided by Fig. 3, which shows the velocity profiles in the radial direction rather than spanwise. The fluid close to the wall, whether laminar or turbulent, is centrifuged radially outward. The quantitative differences can be explained by recalling that turbulent flow near a wall has a much smaller tangential momentum defect and larger shear stress gradients than laminar flow; therefore, it is not surprising that the centrifugal pumping effect should be an order of magnitude smaller for the turbulent case. It is interesting to note that in either case the radial velocity increases approximately linearly

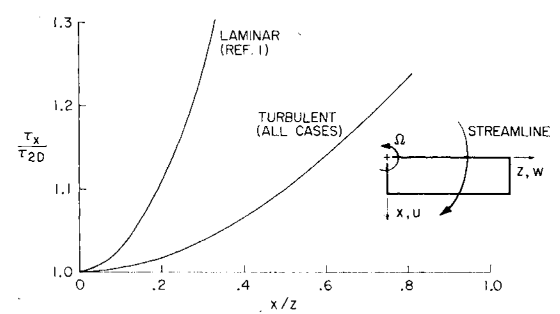

Fig. 1 Chordwise wall shear-stress distribution on a rotating flat-plate blade.

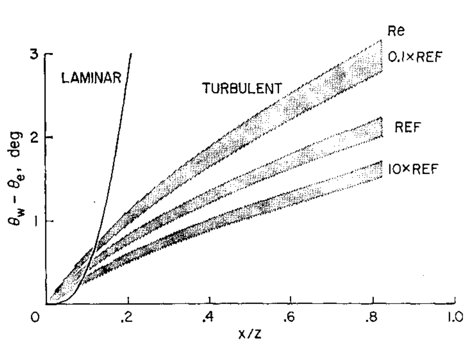

Fig. 2 Surface streamline direction relative to the local inviscid flow.

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§ Unlike the shear stress ratio in Fig. 1, the flow direction exhibits a slight systematic dependence upon Reynolds number. The reference Reynolds numbers, $\Omega xz/\nu$, were based upon $\Omega = 23$ rad/sec, 17 ft $\leq z \leq$ 25 ft, $0 < x \leq 13.7$ ft, and $\nu = 1.56 \times 10^{-4}$ ft²/sec.

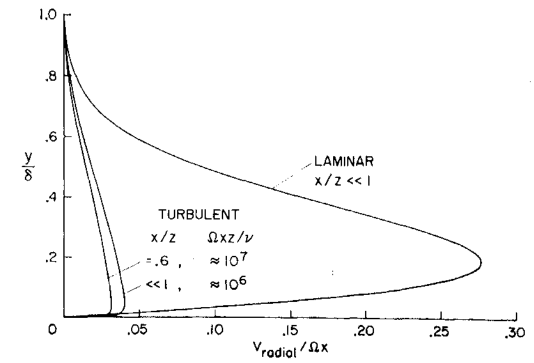

Fig. 3 Radial velocity profiles on a rotating flat-plate blade.

with Ωx; this is the reason for the choice of the abscissa in Fig. 3. A slight decrease in the maximum value of $V_r/\Omega x$ with increasing x/z is predicted by laminar theory,[1] and this also occurs in the turbulent case.

The main conclusion to be drawn from the foregoing remarks is that the turbulent flow on a rotating flat plate is a boundary layer with small crossflow and behaves much as though it were locally two-dimensional, with the appropriate local dynamic pressure and Reynolds number of the local external flow. In other words, the Coriolis and centrifugal effects of rotation appear to be negligible when the problem is cast in potential streamline coordinates. This situation is, of course, quite different from the laminar case, even though the qualitative physical features and parameters are the same.

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Turbulent Boundary-Layer Separation at Low Supersonic Mach Numbers

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Nomenclature

AR = step span-to-height aspect ratio
C_{p2} = plateau pressure coefficient
h = step height
L = distance from leading edge of the flat plate to the face of the step
M_1 = Mach number of flow approaching the separation shock wave
x_s = separation distance measured from the face of the step to the point where separation occurs
$\bar{X}$ = modified separation distance measured from the face of the step to the point where the centerline pressure begins to rise
δ_s = boundary-layer thickness at point of separation

Turbulent boundary-layer separation is a flow phenomena that has been extensively studied both experimentally and theoretically. Its technical importance is well known and it is not necessary here to describe its many practical applications. Zukoski[1] has recently published a summary of experimental studies of turbulent boundary-layer separation in front of a forward-facing step. Based on these experimental results, he suggests a number of very simple empirical relations to describe various separated flow parameters, including separation distance x_s and plateau pressure coefficient C_{p2}. Although Zukoski's correlations were based on a considerable amount of data, it was obvious that very little information is available for the very important low supersonic Mach number case of $M_1 < 2$.

Because of this lack of data and in order to determine the limit of applicability of Zukoski's correlations, a series of wind-tunnel tests has been conducted at the Applied Gasdynamics Institute of the DFVLR at Porz-Wahn, Germany. The tests were performed in a blowdown wind tunnel having a 60 × 60 cm rectangular test section. Mach numbers ranged from 1.24 up to 2.96 with the emphasis being on the lower (1.24–1.75) Mach numbers. Reynolds numbers were between 0.35×10^6/cm and 0.7×10^6/cm. Using a boundary-layer rake, the boundary-layer thickness in the region of separation could be accurately measured. Natural transition to fully turbulent flow occurred well upstream of separation for all cases. Boundary-layer thickness at the point of separation ranged from 2.75 to 3.75 mm.

The model consisted of a 50 × 50 cm flat plate and a series of forward-facing steps which were mounted at L = 350 mm for all cases studied. The steps were of various sizes having widths of from 100 to 480 mm and heights from 5 to 30 mm. Step span-to-height aspect ratios ranged from AR = 3.3 to AR = 96. Centerline and spanwise pressure distributions were obtained and schlieren photographs were made for each test condition. A series of oil-flow photographs of the separated region was also made.

Because of the relatively large size of the model and the corresponding tunnel blockage at transonic freestream Mach numbers, it was necessary to introduce an angle of attack of 6° at supersonic freestream Mach numbers in order to study cases where Mach number was less than 1.47. Data obtained with and without angle of attack are distinguished in this note by closed and open symbols, respectively. Further details of the test method are given in Ref. 2.

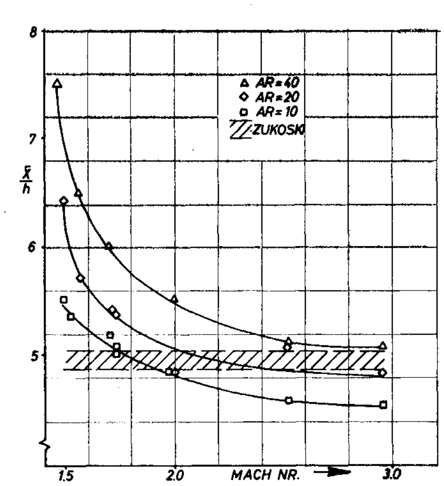

Fig. 1 Effects of Mach number on modified separation distance.

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