layer around the airfoil mounting region, the variation of δ^* in the suction region can be reduced to a minimum and the inviscid flow outside the boundary layer is now practically parallel to the sidewall to form a true two-dimensional testing condition.

Suction Ahead of Model

The common method of boundary layer control is to reduce the boundary layer thickness by suction ahead of the airfoil. This method is less effective in controlling the δ^* development as the boundary layer recovers rapidly downstream from the suction area and reverts to the flat plate type. Thus it reacts to the pressure field generated by the airfoil in a similar manner to the case without suction, discussed in the previous section, and large variations of δ^* around the model area result from this. The reduction of initial thickness of the boundary layer appears mainly as a scale effect (Reynolds number effect). The recovery of the boundary layer downstream of the suction region is demonstrated in Fig. 3. The suction area is located at $x/c = 2.7$ ahead of the model leading edge.[8] The growth of δ^* and the variation of form factor H for cases with suction and without suction are shown in the figure. The conditions of the external flow are the same as the case discussed above. The recovery of the suction cases is shown by the rapid increase of form factor H to the value of the flat plate a short distance downstream from the suction boundary, and the δ^* grows at a rate close to that without suction.

The scale effect due to the change of initial boundary layer thickness has been reported by Bernard-Guelle.[8] He showed that the normal force and the quarter-chord pitching moment decrease as the initial thickness of the boundary layer increases. As shown in Fig. 2, the rapid growth of δ^* at the rear part of the airfoil without suction would undoubtedly induce higher pressure at the upper surface of the airfoil and consequently reduce the normal force and the pitching moment. The pressure induced by the bulging boundary layer can be considered as a small perturbation to the external inviscid flow. Thus the integrated effect of the induced pressure and the boundary layer thickness δ can be correlated linearly. The normal force correlation can then be written as

$$\frac{C_n}{C_{n_0}} = 1 - \frac{C}{\sqrt{1-M_\infty^2}}\left(\frac{2\delta}{b}\right)$$

where C_{n_0} is the value of C_n with zero δ and b is the width of the test section. The constant C is determined from the data of Ref. 8 and has a value of 1.5, except in the strong interaction region. When the shock on the airfoil is strong, the side wall boundary layer separates after interacting with the shock and the initial thickness has little effect on the flow downstream.

In summary, by applying suction at an area of the sidewall around the model one can actively control the boundary layer growth and consequently the inviscid flow outside the boundary layer can be made practically parallel to the side wall. Without suction, the large variation of the displacement thickness, especially at the rear portion of the airfoil upper surface, causes severe interference to the inviscid flow and distorts the uniformity of the two-dimensional test conditions. Suction applied ahead of the model is much less effective in controlling the boundary layer development, as the boundary layer recovers rapidly after the suction area and responds to the pressure field in a manner similar to that without suction.

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Experimental Investigation of the Two-Dimensional Asymmetrical Turbulent Wake Behind a Blade

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Nomenclature

b	= lateral distance between two points of the same actual turbulence intensity
B	= profile width at $T_{e,m} = 0.5$
C	= blade chord
R	= Reynolds number
T_e	= actual turbulence intensity, $T_e = \lvert\bar{u}'\rvert / \bar{U}$
$T_{e,m}$	= normalized actual turbulence intensity, $T_{e,m} = T_e / T_{e,\max}$
$T_{e,\max}$	= maximum actual turbulence
U_0	= freestream velocity
$\bar{U}$	= mean longitudinal velocity
$\lvert\bar{u}'\rvert$	= time average of the modulus of longitudinal turbulence component
X	= streamwise distance measured from the blade trailing edge
Y	= lateral distance

Introduction

THE flow in the two-dimensional wake has received wide interest of many investigators in the last few decades. The major part of these studies is experimental, restricted to

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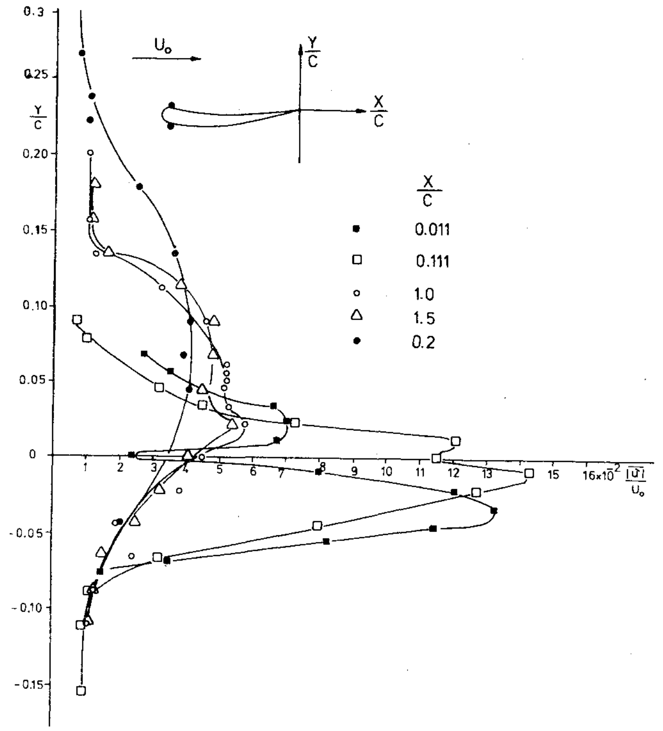

Fig. 1 Turbulence distribution in two-dimensional wake behind 10C4/30C50 blade section, $U_0 = 31.4$ m/s, $R = 3.77 \times 10^5$.

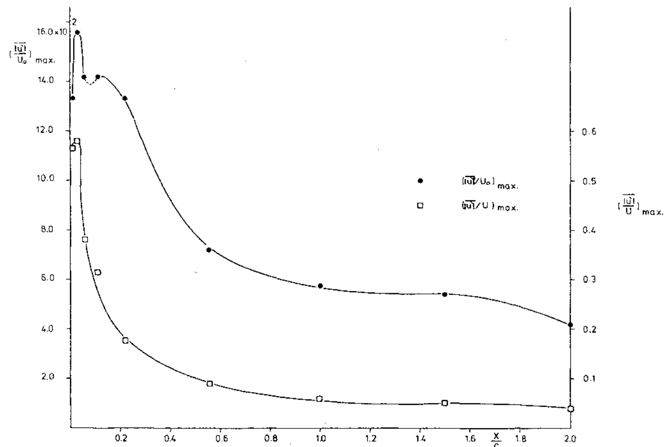

Fig. 2 Streamwise variations of maximum value of turbulence intensity, $U_0 = 31.4$ m/s, $R = 3.77 \times 10^5$.

symmetrical wakes. Recently, the case where there is an essential assymentry in the wake flow has been studied by few investigators. Mugridge[1] examined the structure of turbulence in the wake of a symmetrical airfoil operating at low angles of attack. His results indicated that the broad band turbulence spectrum can be described in terms of a Strouhal number based upon the momentum thickness of the wake.

Palmer and Keffer[2] investigated the two-dimensional asymmetrical turbulent wake generated by pairs of cylinders of unequal diameters. They found that the mean velocity defect was significantly skewed toward the small cylinder portion of the wake. The maximum level of turbulence intensity occurs on the large cylinder side of the flow while the maximum absolute value of Reynods stress is larger on the other side. The shedding vortices remained persistent and identifiable as separate structures downstream of the cylinders. Ahmad and Luxton[3] investigated the asymmetrical wake of a cylinder in a weak uniformly sheared external flow. They found that there is a tendency for the wake to grow faster on the high velocity side than on the low velocity side.

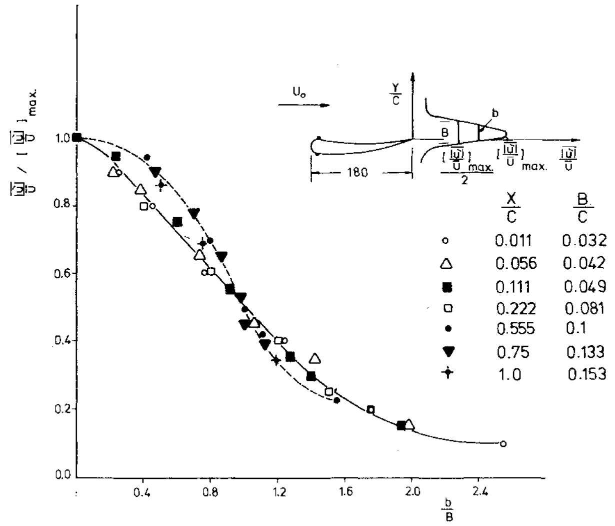

Fig. 3 Turbulence distribution relative to local velocity in two-dimension wake near trailing edge behind 10C4/30C50 blade section, $U_0 = 31.4$ m/s, $R = 3.77 \times 10^5$.

Also, they concluded that the turbulence structures on the two sides of the wake appeared to behave independently.

In the present work, the results of turbulence measurements of the asymmetrical turbulent "near wake" of the cambered airfoil 10C4/30C50, British convention, are presented and discussed. A theoretical analysis of the same problem was given by Ghazi.[4]

Apparatus

The present work was carried out using a low-speed wind tunnel having a working section of 0.4×0.4 m. The wind tunnel velocity ranged 0.5-32 m/s. The freestream turbulence level was less than 0.4%. The test model was the British conventional profile (10C4/30C50), with a chord length of 0.18 m and a span of 0.4 m. It was fastened to the tunnel side walls with a provision to change the angle of attack. A 0.5 mm wire was used as turbulence generator at 10 mm from the leading edge on both sides of the blade. The turbulence characteristics were measured by the linearized, Disa 55D01, hot wire anemometer. The hot wire was mounted on a traverse mechanism capable of moving the probe in both the lateral and streamwise directions.

Results and Discussions

Turbulence velocity profiles $|\bar{u}'|$ were measured at different streamwise locations, ($X/C = 0.011$, 0.056, 0.111, 0.222, 0.555, 0.75, 1, 1.5, and 2) where X is the streamwise distance measured from the trailing edge and C is the blade chord. The profiles of the normalized turbulence intensity $|\bar{u}'|/U_0$ against the normalized lateral distance Y/C are shown in Fig. 1 for $R = 3.77 \times 10^5$. The distribution of turbulence intensity is asymmetrical and has two peaks at the lower and upper parts of the wake. It is noticed that the higher peak is always located in the lower (suction) side of the wake. These asymmetrical turbulence intensity profiles are attributed to the different flow histories of the two sides of the wake. These peaks are smoothed off with streamwise propagation of the wake until they finally combine in one peak at $X/C > 1.5$.

The maximum of both the turbulence intensity and the actual turbulence intensity, defined by $T_e = |\bar{u}'|/\bar{U}$, were found to vary with streamwise location X/C as shown in Fig. 2. A sharp increase in both curves is noticed very close to the trailing edge. This is attributed to the high mixing in this region.

The actual turbulence intensity T_e is normalized by its maximum value at the considered X station, i.e., $T_{e,m} = T_e / T_{e,\max}$. The lateral distance between the two sides of the actual turbulence intensity profile having the same T_e is denoted by b, whereas B is the profile width at $T_{e,m} = 0.5$. Figure 3 is a plot of $T_{e,m}$ vs b/B. It should be noticed that these normalized profiles fall in two groups. The first one, represented by the solid curve, corresponds to $0.011 < X/C < 0.222$, whereas the dashed curve corresponds to $X/C > 0.222$. It was noticed that the two groups are related to the static pressure distribution in the streamwise direction. The first group lies in the positive pressure gradient regime, whereas the second group lies in the negative pressure gradient regime.

Conclusions

The present work reveals some important characteristics of the asymmetrical wake flow behind a plate. The following main conclusions can be derived:

1) The distribution of turbulence at any streamwise location is asymmetrical and has two peaks at the upper and the lower sides of the wake, which tend to be smoothed into one peak relatively far from the trailing edge.

2) The actual turbulence intensity normalized by its maximum falls on two curves for the two regions of the wake having positive and negative static pressure gradient.

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