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Technical Notes

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Reynolds Number Dependence of the Freestream Turbulence Effects on Turbulent Boundary Layers

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Introduction

TURBULENT boundary layers over turbomachinery blades are characterized by high freestream turbulence intensities and low Reynolds numbers. The theoretical developments and the experimental measurements of these effects in zero pressure gradient low-speed flows are given in Refs. 1-3 and 4-12, respectively. It has been known for some time that in the accounting of the effects of freestream turbulence the intensity alone does not control the effect.[1] Instead, it is the combined effect of the intensity (u/U_e) and the dissipation length scale ratio (L_e/δ) that is important. Here, u is the root-mean-square of longitudinal velocity fluctuation in the freestream, U_e the freestream speed, L_e the longitudinal dissipation length scale of the freestream turbulence, and δ the boundary-layer thickness. A definition of the freestream turbulence parameter (FSTP) f [$=(u/U_e)/(L_e/\delta+2)$] that combines those effects has been given in Refs. 4 and 5. Hancock[4] arrived at the parameter empirically after examining experimental data. A slightly different form of f has also been recently suggested that appears to collapse some of the data somewhat better.[6]

In Refs. 4 and 5, it is shown that the fractional increase in skin friction ($\Delta c_f/c_{f0}$) due to the effects of freestream turbulence depends on f only. [Here c_f is coefficient of skin friction $\tau_w/(\frac{1}{2}\rho U_e^2)$ where τ_w is the wall shear stress and ρ the density; Δc_f is the change in c_f from boundary-layer value in low freestream turbulence at the same Re_θ; subscript 0 denotes values for negligible freestream turbulence; and Re_θ is the momentum thickness (θ) Reynolds number $U_e\theta/\nu$ where ν is kinematic viscosity.] However, Blair[7] (also see Refs. 3 and 8) showed later on that the effect reaches an asymptotic level approximately for $Re_\theta > 2000$ whereas it displays a Reynolds number dependence for $Re_\theta < 2000$. He has empirically arrived at a damping factor β defined as

$$\beta = [1 + 3e^{-(Re_\theta/400)}] \tag{1}$$

to account for the low Reynolds number effects. The fractional increase in skin friction is then a function of ($f\beta$). Castro[6] has pointed out that this works better at large values of f (~ 0.02) and has proposed an alternative empirical function of f and β.

In all works so far, it is implied that the freestream turbulence parameter f and the boundary-layer Reynolds number (Re_θ) effects always interact monotonically. In other words, before saturation, as the Reynolds number is increased, the effect of freestream turbulence on a variable always either increases or decreases. Here, published experimental data have been analyzed to examine the relationship between f and Re_θ.

Results

Figure 1 shows a compilation of recent data (1980s) on the Reynolds number variation of Clauser's velocity profile shape parameter G

$$= \int_0^\delta \left(\frac{U_e - U}{U_\tau}\right)^2 dy \Bigg/ \int_0^\delta \left(\frac{U_e - U}{U_\tau}\right) dy$$

in zero pressure gradient, smooth flat wall turbulent boundary layers.[8,13-16] The data sets are characterized by documentation of zero pressure gradient and tunnel cross sections of large aspect ratio (> 1.0). Unlike that at higher Re_θ, the value of G is not a constant at the lowest Reynolds numbers but can be expressed by the following relationship:

$$G = 7.0[1 - e^{-(Re_\theta/425)}] \tag{2}$$

Interestingly, the damping part of Eq. (1) that was obtained empirically is very close to Eq. (2). Hence, in this work, β has been modified to

$$\beta = [1 + 3e^{-(Re_\theta/425)}] \tag{3}$$

The strength of the wake component ($\Delta U/U_T$), which is the maximum deviation in the mean velocity profile from the log-law in wall layer variables, is a function of Re_θ below about 5000. At a constant Re_θ, it decreases first rapidly and then slowly as FSTP increases from zero. From the sparse measurements[4,6] of $\Delta U/U_\tau$ vs Re_θ (< 2500) at $0.005 \leq f \leq 0.02$, the variation of the wake component fraction with f has been

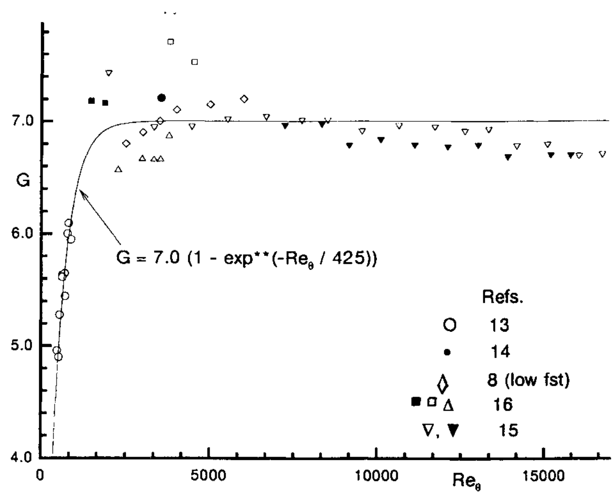

Fig. 1 Low Reynolds number effect on Clauser's shape parameter G.

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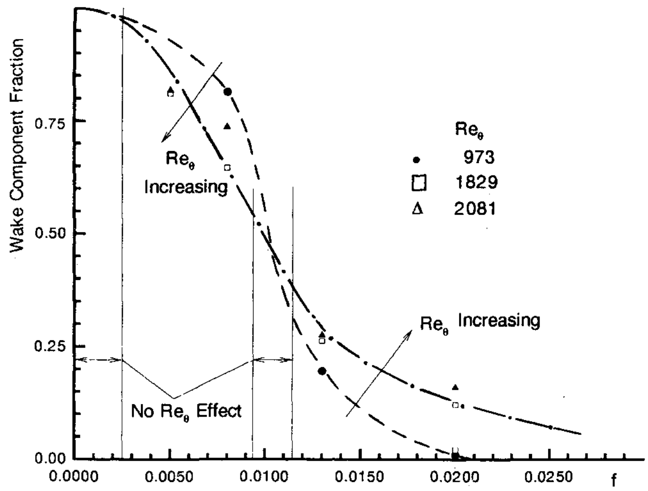

Fig. 2 Fractional reduction in wake component due to the effect of freestream turbulence parameter. Basic data from Refs. 4 and 6.

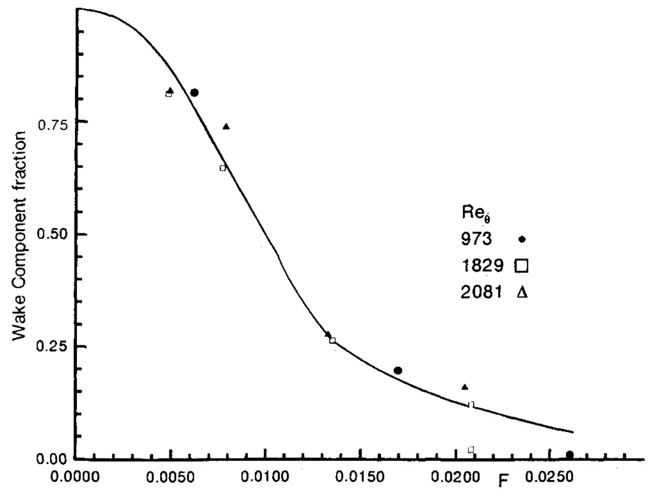

Fig. 3 Correlation in Fig. 2 replotted after including variable Reynolds number effect.

plotted in Fig. 2 at constant Reynolds numbers. The wake component fraction at a constant Re_θ is defined as the ratio of the values of $\Delta U/U_\tau$ at a positive value of f to that at $f\approx 0$ that is given by the well-known asymptotic data compilation due to Coles. Most published data of the depletion of the wake component with freestream turbulence do not contain the measurements of L_e/δ, and therefore they could not be used. Although the data in Fig. 2 are unavoidably rather limited, the two fitted lines at $Re_\theta \sim 1000$ and ~ 2000 indicate a reversal in the Reynolds number trend with increasing f having intervening regions of no Reynolds number effect. It turns out that Castro[6] had an inkling of this. While examining the variation of u^2/U_τ^2 with Re_θ at a fixed y/δ within a turbulent boundary layer, he observed, "It appears that the addition of freestream turbulence significantly reduces the Reynolds number effects on u^2/U_τ^2 and there is even a suggestion that at the highest value of FSTP [0.02, Fig. 10(c)] the effect is reversed." (Here U_τ is friction velocity.) His further observation, "It is interesting that the modification proposed by Blair to account for low Reynolds number effects is quite good for the highest values of FSTP (0.02) but clearly underestimates the effects at lower levels of free-stream turbulence," is also suggestive that Blair's[7] Reynolds number modification at low FSTP is in the wrong direction. Therefore, if indeed there is a reversal in the Reynolds number effect, then that shown in Fig. 2 should disappear if Blair's low Reynolds number modification of f is retained for high values of f but it is reversed at low values of f. This has been achieved in Fig. 3 where, based on the mean lines in Fig. 2, it has been assumed that

$$F = f\beta \text{ for } f > 0.01$$
$$F = f/\beta \text{ for } f < 0.01 \tag{4}$$

As is to be expected, the mean line in Fig. 3 now is close to the high Reynolds number line in Fig. 2.

The low Reynolds number dependence of the influence of freestream turbulence can therefore be better described by incorporating the variable Reynolds number dependence marked in Fig. 2. For skin friction, the modifications are described as follows:

$$f_\beta = f\beta^n \tag{5}$$

where

$n = -1$ for $f > 0.0115$
$n = 0$ for $f \le 0.0025$ and $0.0095 \le f \le 0.0115$
$n = 1$ for $0.0025 < f < 0.0095$

The boundaries of f in Eq. (5) are abrupt, and a gradual distribution (probably sinusoidal) would be more accurate.

Figure 4 is a compilation of data on the fractional increase in skin friction due to freestream turbulence where the variable dependence on Reynolds number has been taken into account in the aforementioned manner. A straight line through the origin and ±5% band lines are also included.

Discussion

Very little seems to be known about the mechanism that influences the behavior of freestream turbulence at low Reynolds numbers. There is experimental evidence that freestream turbulence can have a selective coupling with the near-wall turbulence via the Stokes layer excitation.[17] In Fig. 4, it is not clear why some of the very low Reynolds number data points do not follow the trend. Errors in skin friction measurement and low aspect ratio (~ 1) of the tunnel might be more important[6] at $Re_\theta < 1000$ whereas the nature of transition (trip sensitivity) is likely to be less important as f increases from zero. In any case, here all data from Ref. 6 have been plotted, including those having a saturated effect of freestream turbulence and those at the lowest possible Reynolds numbers (which Castro[6] has called transitional; he omitted both of these categories of points in his final correlation). Although the mean

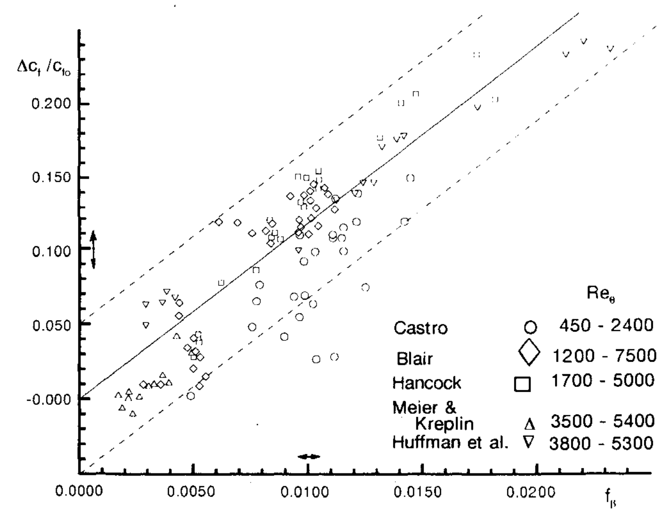

Fig. 4 Correlation of fractional increase in skin friction after including variable Reynolds number effect. Dashed lines indicate a ±0.05 $\Delta c_f/c_{f0}$ scatter band about the solid line. The arrows indicate uncertainties.

trend in Fig. 4 seems linear and through the origin, in the literature, several individual data sets suggest[5] the following: 1) a nonlinear trend and 2) a drag reduction as $f \rightarrow 0$. Such a behavior would be reminiscent of riblets.[18] However, the scatter in Fig. 4 is too large to resolve these possibilities. Further research with pressure gradients and curvature should be carried out to determine the applicability of the flat plate results to the turbomachine flow problem.

Conclusions

The published experimental data on the influence of freestream turbulence on turbulent boundary layers have been examined to determine the effect of Reynolds number on such influence. Two manifestations of the effect of low Reynolds numbers on the outer layer are observed. First, the Clauser's shape parameter G is Reynolds number dependent at very low Reynolds numbers. Second, the reduction in the wake component due to freestream turbulence undergoes a *reversal* in the Reynolds number dependence depending on the value of the freestream turbulence parameter. Hancock's freestream turbulence parameter has been modified using these observations. This has led to a new correlation of the fractional increase in skin friction due to freestream turbulence.

Acknowledgment

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Analysis of Damping in Composite Laminates

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I. Introduction

AMONG the virtues of fiber-reinforced composite materials are relatively high-damping characteristics, an attractive feature for vibration control in lightweight structures. This enhanced damping capacity originates from the viscoelastic behavior of the constituent components, usually the matrix, but in some cases also the fibers. Other sources of damping resulting from damaged or debonded composites and large vibration amplitudes are not considered here.

Viscoelastic materials under steady-state vibration can be characterized by complex stiffness and compliance coefficients,[1] manifested by the experimentally observed phase lag between stress and strain. According to the viscoelastic correspondence principle, these complex coefficients may be used directly in the equations of elastic analysis. The dynamic behavior, including damping, can therefore be characterized according to laminate theory.[2] This approach has been used to evaluate the damping capacity of composite laminates based on experimental data from beam bending and torsion experiments (see, e.g., Refs. 3 and 4). The damping capacity has also been analyzed using a strain-energy approach according to the analysis of Ungar and Kerwin,[5] whereby the components of the dissipated energy are assigned to be a fraction of the corresponding components of the strain energy (see, e.g., Refs. 6-8). As will be seen later, the difficulty with this approach is that these strain-energy components are not independent in the context of the material constitutive relation, which is in contrast with the array of independent springs of the analysis of Ungar and Kerwin.[5] Thus, the manner in which the method is applied has implications with regard to its accuracy for general states of strain.

In the present study, these two approaches are compared to address the apparent discrepancy between them and to evaluate the significance of this discrepancy for a typical composite laminate material. For problems of uniaxial stress, beam bending, and pure shear, addressed by the studies described earlier, the two formulations give essentially the same results. Herein, more general states of strain are considered for which a relative difference in specific damping capacity of up to 8% is obtained.

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