Freestream Turbulence Effects on Wake Properties of a Flat Plate at an Incidence

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The effect of freestream turbulence on the characteristics of a turbulent wake developed from the trailing edge of a flat plate at angles of attack of −3, 0, and 6 deg is discussed. Correlations based on analytical and experimental considerations are developed to predict the mean characteristics of a turbulent wake at an incidence in the freestream turbulence environment. The analytical approach is based on the Navier-Stokes mean-momentum and continuity equation. The experimentation was carried out in a subsonic wind tunnel using cross-wire anemometry. Experimental data of the flat plate at three incidences and three turbulence levels (0.40, 5.23, and 7.23%) from self-similarity considerations are presented to predict the semiempirical correlations for the wake velocity defect, length scale, wake velocity profile, shape factor, and eddy viscosity. The effect of pressure gradient on various parameters is also discussed. It is concluded that the wake velocity defect and shape factor decrease while the length scale and eddy viscosity increase when there is an increase in freestream turbulence.

Nomenclature

a,b	= constants in Eq. (2)
C	= chord of the flat plate
C_d, C_{d_0}	= drag coefficient in the presence and absence of freestream turbulence, respectively
f	= velocity profile function
H	= shape factor
K	= constant in Eq. (2)
K_1, K_2	= constants in Eqs. (2) and (6), respectively
L_0	= length scale, Fig. 1
m	= constant representing pressure gradient effect
R	= Reynolds number $(\bar{U}_1 C/\nu)$
R_T	= turbulent Reynolds number
T	= turbulence level $(\sqrt{\overline{u^2}}/\bar{U}_1)$
$\bar{U}$	= mean velocity component along axial direction
$\bar{U}_1$	= inlet average velocity in test section
$\bar{U}_0$	= velocity scale $(\bar{U}_e - \bar{U}_c)$, Fig. 1
$\bar{U}_c$	= mean velocity at wake centerline, Fig. 1
$\bar{U}_e$	= outer edge velocity $(\propto x^{-m})$
x,y	= distances along axial and normal axes, respectively
x_0	= virtual origin
X,Y,Z	= axial, normal, and lateral axes, respectively, Fig. 1
α	= angle of attack
$\bar{\alpha},\beta$	= constants in Eqs. (1) and (4), respectively
δ_1	= displacement thickness
η	= similarity variable $(y/L_{0_p}\phi_2$ or $y/L_{0_s}\phi_2)$
θ	= momentum thickness
ν	= kinematic viscosity
ν_T	= eddy viscosity $(\propto U_0 L_0 \phi_1 \phi_2)$
ϕ_1, ϕ_2	= turbulence parameters in Eq. (5); $\phi_1 = [(x/C) + (x_0/C)]^{\bar{\alpha}T/2}$, $\phi_2 = [(x/C) + (x_0/C)]^{-\beta T/2}$

Subscripts and Superscripts

c	= centerline values
e	= edge values
ℓ	= leading-edge values
t	= trailing-edge values
∞	= freestream values
$\bar{(\ )}$	= mean values

Introduction

TURBULENCE is considered an important factor in noise generation from multistage turbomachinery. The wake of a blade following the first row of blades is affected by the turbulence of the shear layers generated from the wake of the stationary or rotating row of blades upstream. The nature of this freestream turbulence depends upon the axial distance between rotor and stator, angle of incidence of the blades, radial location, curvature, solidity, stage loading, etc. The development of the boundary-layer, heat-transfer, and wake characteristics in the freestream turbulence environment are dependent upon the freestream turbulence. Thus, the knowledge of freestream turbulence on wake behavior can be beneficial in better understanding turbomachinery performance and noise generation in aircraft and marine propulsors.

An extensive literature search of the effect of freestream turbulence on boundary layer and heat transfer has been given by Pal.[1] With the exception of a few remarks made by Eagleson et al.,[2] indicating that the wake recovery rate increases with the increase in turbulence level, there is little information to date that describes the effect of freestream turbulence on wakes. Some of the properties of cylinder wakes have been studied by Komoda[3] and Ahmed et al.[4] Recently, Refs. 1, 5, and 6 have illustrated, theoretically and experimentally, the behavior of wakes in the presence of freestream turbulence. It has been concluded that freestream turbulence enhances wake mixing, growth rates, turbulence intensities, and Reynolds stress, and reduces the shape factor. The qualitative and quantitative effects of freestream turbulence on wake characteristics based on Refs. 1-7 are summarized by Pal.[8]

This paper examines the effect of freestream turbulence on the characteristics of a wake at −3, 0, and 6 deg angles of attack for three inlet turbulence levels. Correlations based on analytical and experimental considerations are developed to

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predict the characteristics of a turbulent wake at an incidence in the freestream turbulence environment. The effect of pressure gradient on various parameters in freestream turbulence environment has also been incorporated.

Experimental Equipment, Method, and Instrumentation

An open circuit wind tunnel with a test section cross section of 45.72×45.72 cm^2 was used in the experiments (Fig. 1). The test model consisted of a flat plate made of precision ground, nondistorting stainless steel, with dimensions of $45.72 \times 14.92 \times 0.238$ cm^3. The plate was mounted firmly in the wind tunnel in an X-Y plane (Fig. 1), such that the wake produced from its trailing edge varied in the X-Z plane. Measurements were taken at -3 and 6 deg angles of attack.

The freestream turbulence was generated by two grids.[5] The square grid produced a freestream turbulence level of 5.23% at the leading edge of the flat plate. A freestream turbulence level of 7.23% at the leading edge of the flat plate was generated by a circular grid. The third level of freestream turbulence (0.40%) was obtained without any grid. Measurements were taken using cross-wire anemometry in the X-Y' plane and were transferred to the X-Y plane with the appropriate transformation. The measurement method is described in Refs. 1 and 8.

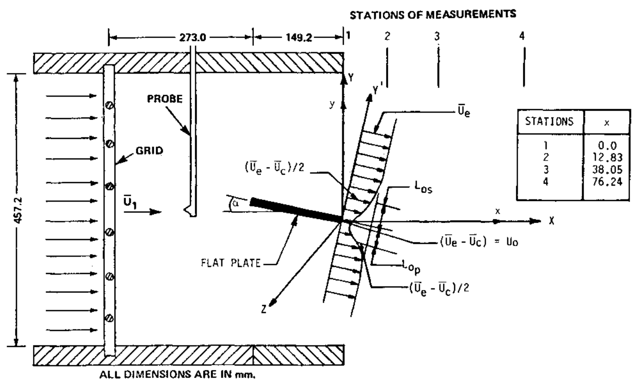

Fig. 1 Experimental setup.

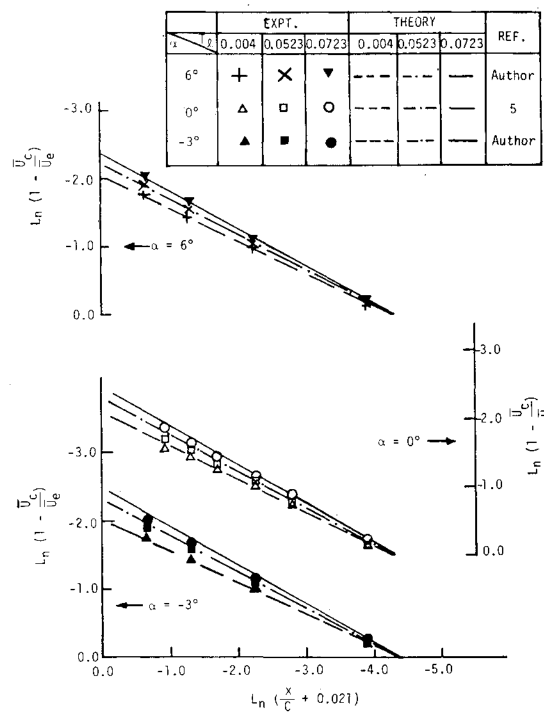

Fig. 2 Logarithmic variation of wake centerline velocity with downstream distance.

The flow Reynolds numbers, based on the average velocity in the test section and the chord length, were 2.45×10^5, 2.03×10^5, and 2.38×10^5 at turbulence levels of 0.40, 5.23, and 7.23%, respectively. The corresponding average mean velocities were 25.47, 21.12, and 24.78 m/s.

Experimental Results and Comparisons with Predictions

The data are presented in dimensionless form using C and $\overline{U}_e$ as dimensional parameters, with C the chord length of the flat plate and $\overline{U}_e$ the local mean velocity at the outer edge of the wake.

Freestream Turbulence Level

The freestream turbulence level at the leading edge was found to be 0.40% for no grid, 5.23% with a square-bar grid, and 7.23% with a circular-rod grid (Fig. 2 of Ref. 8). At the beginning of the wake (trailing edge of the flat plate), the freestream turbulence level was 0.4% for no grid, 2.56% with a square-bar grid, and 4.0% with a circular-rod grid. A detailed description of turbulence parameters ϕ_1 and ϕ_2 is given in Ref. 8.

Mean Velocity Profile

Mean velocity profiles were measured at two angles of attack (-3 and 6 deg), three turbulence levels, and four axial locations. The profiles for -3 deg angle of attack for three turbulence levels are given in Figs. 3a-c of Ref. 8; the corresponding profiles for 6 deg angle of attack are given in Ref. 9. The corresponding profiles for 0 deg angle of attack are given in Refs. 1 and 5. From these figures it can be seen that the mean velocity profiles become asymmetrical about the wake centerline because of the angle of attack and symmetrical at 0 deg angle of attack, even when the freestream turbulence is present. Near the trailing edge, at $x/C = 0$ and $\alpha \neq 0$, the characteristics of the boundary-layer behavior are maintained. The boundary-layer thickness is greater on the suction surface than on the pressure surface. These surfaces become reversed at a positive angle of attack. The asymmetry in the mean velocity profile about the wake centerline is reduced with an increase in axial distance from the trailing edge of the flat plate, and is at its maximum at the trailing edge.

Wake Recovery Rate

The logarithmic variation of the mean velocity at the wake centerline for three incidences and three turbulence levels is presented in Fig. 2. The increase in freestream turbulence level increases the wake recovery rate. This is shown in Fig. 2 and can be stated by[8]:

$$1 - (\overline{U}_c/\overline{U}_e) = KC_d^{1/2}[(x/C) + (x_0/C)]^{-(1+\bar{\alpha}T-m)/2} \tag{1}$$

where

$$K = K_1/(a + b\phi_{2_t}) \tag{2}$$

The values of K_1, a, and b were 2.7, 0.76, and 1.0, respectively. K, x_0/C, and $\bar{\alpha}$ (for the present case) were 1.534, 0.021, and 4.0, respectively.

The change in the exponent (velocity power law) is indicated by the change in the freestream turbulence level from 0.4 to 4.0% at different angles of attack. At two angles of attack and three turbulence levels, the value of $(1-m)/2$ varied from 0.445 to 0.496. Even in this case of a mild pressure gradient, the value of $\bar{\alpha}$ was 4.0. This is consistent with the trends predicted in earlier investigations.[1-3,5] The constant K in Eq. (1) is dependent upon the value of ϕ_2 at the trailing edge. The coefficient of drag in the absence of

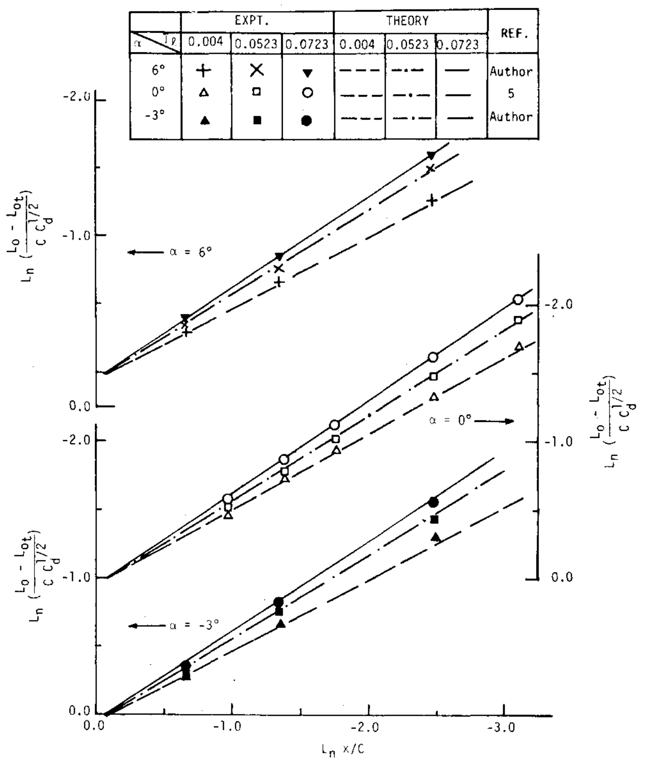

Fig. 3 Logarithmic variation of length scale with downstream distance.

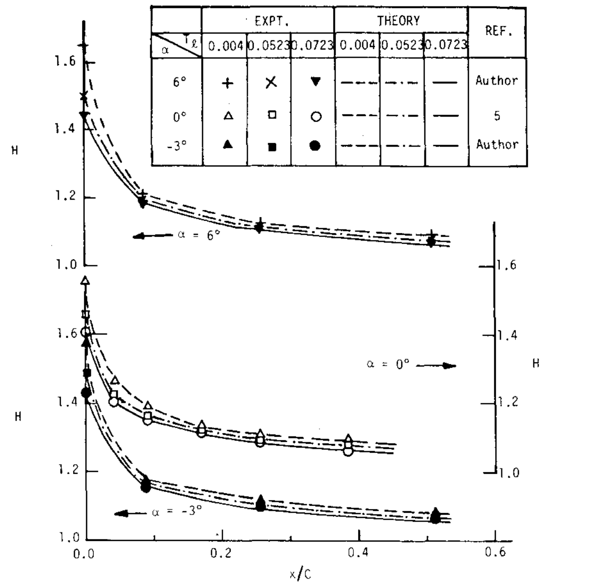

Fig. 4 Variation of shape factor with downstream distance.

freestream turbulence and at 0 deg angle of attack was found to be 0.0064. The value of the drag coefficient in the absence of freestream turbulence was obtained from experimental results. In the presence of freestream turbulence the drag coefficient was obtained from the modified correlation of Ref. 10 and is stated as

$$C_d = C_{d_0}(1 + 4.8T) \tag{3}$$

Figure 2 leads to the following observations about the wake centerline velocity:

1) The effect of freestream turbulence on wake centerline velocity is predominant only in the near-wake region, $x/C < 0.3$, and is predominant even in the presence of angle of attack.

2) The velocity defect at the wake centerline decreases to about 35% for $x/C < 0.1$.

3) The wake velocity power index is dependent upon the freestream turbulence level and pressure gradient. The nature of the effect of freestream turbulence is similar to the favorable pressure gradient effect.

4) The constant of proportionality in Eq. (1) depends upon the turbulence parameter for the length scale at the trailing edge.

Length Scale (Half-Wake Width)

The logarithmic variation of half-wake width with downstream distance for three freestream turbulence levels and with three angles of attack is shown in Fig. 3. An increase in freestream turbulence increases the length scale in the downstream direction. This increase can be stated by:

$$\frac{L_0 - L_{0_t}}{CC_d^{1/2}} = 1.05\left(\frac{x}{C}\right)^{(1+\beta T + m)/2} \tag{4}$$

where $L_0 = L_{0_s} + L_{0_p}$; L_0 is the summation of the length scales of the suction and pressure sides and L_{0_t} the value of L_0 at the trailing edge of the flat plate. The length scale on the suction side is greater than that on the pressure side at an angle of attack, ($\alpha \neq 0$ deg), and both become equal at 0 deg angle of attack. The value of β obtained from the experimental data is 8.27 and is consistent with the earlier investigation.[5] The prediction of the growth law is in agreement with experimental data in the presence of freestream turbulence and angle of attack.

A few important observations about length scale can be made from Fig. 3.

1) The length scale power index is strongly dependent upon the freestream turbulence level. The nature of the freestream turbulence effect is similar to that of the adverse pressure gradient effect.

2) Freestream turbulence acts more strongly at the wake edges than at the wake centerline. This nearly doubles the exponent for the growth of the length scale when compared to the exponent value for the recovery of the mean velocity at the wake centerline.

3) The increase in freestream turbulence enhances the growth of the wake.

From Eqs. (1) and (4), the following observations can be drawn:

a) Equations (1) and (4) tend to flat plate and cylinder wake equations, when $m \to 0$ and $T \to 0$ or when $m = \bar{\alpha}T$ and $m = -\beta T$, respectively.

b) When $m > 0$ and $m > \bar{\alpha}T$ (adverse pressure gradient), the wake centerline velocity recovers more slowly than that in case a. This is typical of compressors and airfoils.

c) When $m > 0$ and $m < \bar{\alpha}T$ or $m < 0$ (favorable pressure gradient), the wake centerline velocity recovers faster than that in case a.

Similarity

By substituting the wake velocity profile in the presence of freestream turbulence,

$$(\bar{U}_e - \bar{U})/U_0\phi_1 = f(y/L_0\phi_2) \tag{5}$$

It was theoretically shown[8] that

$$f = \exp(-K_2 R_T \eta^2/2) \tag{6}$$

where $R_T = U_0 L_0 \phi_1 \phi_2 / \nu_T$ and K_2 is a constant dependent upon angle of attack. This indicates that the velocity profile shape is given by a Gaussian function.

An attempt is made to reduce the velocity profiles given in Figs. 3a-c of Ref. 8 to a single curve as shown in Figs. 7a-c of Ref. 8, respectively. $L_{0_p}\phi_2$ and $L_{0_s}\phi_2$ are the length scales for the pressure and suction sides, respectively, and $U_0\phi_1$ is the velocity scale. L_{0_p} is the distance from the wake centerline to a point in the normal direction and along the pressure side where the velocity defect is 50% of the velocity scale $U_0 = \overline{U}_e - \overline{U}_c$. L_{0_s} is the corresponding distance toward the suction side. The similarity profiles for 6 deg angle of attack are given in Ref. 9. Figures 7a-c of Ref. 8 show that the similarity profiles are well described and lie between the functions $[1-(\eta/2)^{1.5}]^2$ and $\exp(-\eta^2/2)$, where $\eta = y/L_{0_p}\phi_2$ or $y/L_{0_s}\phi_2$, respectively, for the pressure or suction side. Asymmetry about the wake centerline in the similarity profiles is reduced when compared to the asymmetry in the mean velocity profile about the wake centerline, due to the appropriate normalization. The ratio of $U_0L_0\phi_1\phi_2/U_{e_t}C$ is found to be nearly constant at all axial locations beyond $x/C > 0.05$ (Fig. 8 of Ref. 8). This constant ratio confirms the similarity assumptions made during the development of the theoretical analysis. As a result, it is concluded that eddy viscosity increases with the increase in freestream turbulence.

Profile Parameters

The variation of shape factor H for variable angle of attack with downstream distance from the trailing edge of a flat plate is shown in Fig. 4. The shape factor, defined as

$$H = \frac{\delta_1}{\theta} = \int_{-\infty}^{\infty}\left(1-\frac{\overline{U}}{\overline{U}_e}\right)\mathrm{d}y \Big/ \int_{-\infty}^{\infty}\frac{\overline{U}}{\overline{U}_e}\left(1-\frac{\overline{U}}{\overline{U}_e}\right)\mathrm{d}y$$

with the substitution of Eq. (5), and rearranging,[8] takes the form

$$\frac{1-(1/H)}{1-(1/H_t)} = \frac{\phi_1}{\phi_{1_t}}\left(1+\frac{x/C}{x_0/C}\right)^{-\frac{1}{2}(1+\bar{\alpha}T-m)} \qquad (7)$$

Displacement thickness increases with downstream distance for the adverse pressure gradient and decreases for the favorable pressure gradient. The behavior of momentum thickness is similar to that of displacement thickness for $x/C \geq 0.1$. The theoretical curves [Eq. (7)], together with the experimental data, are plotted for various turbulence levels and pressure gradient values, in Fig. 4, with good agreement. From the comparison, the increase in freestream turbulence reduces the shape factor and the adverse pressure gradient increases the shape factor. The effect of the favorable pressure gradient on the shape factor is similar to the effect of an increase in the freestream turbulence level. An increase of the angle of attack increases the shape factor.

Conclusions

The investigation on the effect of freestream turbulence on wake behavior with the pressure gradient leads to the following conclusions:

1) Mean velocity profiles are observed to be asymmetrical about the wake centerline when the wake is influenced by the pressure gradient and freestream turbulence.

2) Similarity in the mean velocity profile is maintained to a good extent when the profiles are normalized with respect to the turbulence parameters.

3) The wake centerline velocity recovers faster with the increase in freestream turbulence. The nature of the effect of freestream turbulence on wake centerline velocity defect is similar to the favorable pressure gradient effect.

4) The increase in freestream turbulence increases the length scale. The nature of this effect on length scale is similar to that of the adverse pressure gradient effect.

5) The turbulence parameters (ϕ_1 and ϕ_2) behave opposite in character, tend to unity for the far wake ($x/C > 1.0$), and are independent of pressure gradient and angle of attack effects.

6) The shape factor reduces with the increase in freestream turbulence. An increase of the angle of attack increases the shape factor, even in the presence of freestream turbulence.

7) Eddy viscosity increases with the increase in freestream turbulence.

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