Technical Notes

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Turbulence Intensities in the Near-Wake of a Semielliptical Afterbody

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Nomenclature

R = model radius, 31.12 mm
r = local radius of model
V = velocity
v' = velocity fluctuation
X = axial distance from base (positive = downstream, negative = upstream)
Y = radial distance from centerline

Subscripts

∞ = freestream condition

Introduction

BOUNDARY-layer separation from a body moving through a real fluid is usually due to an abrupt change in surface geometry or a sufficiently strong adverse pressure gradient. Such adverse pressure gradients may be caused by wall curvature. Both types of flow separation may be found on vehicles such as cars, trucks, trains, planes, and other high-speed transportation systems. At the rear of these vehicles where separation is most likely to occur, the free shear layers which are formed pass on downstream to form the wake of the vehicle. The flow separation and the subsequent wake greatly influence the drag and stability of a vehicle.

Numerous investigators have studied boundary-layer separation for many years, and comprehensive reviews of the classical references may be found in Schlichtin[1] and Chang.[2] Much of the work for incompressible flows has been directed at two-dimensional geometries as opposed to axisymmetric and three-dimensional flows. An investigation by Yi and Przirembel[3] dealt with separation from an axisymmetric, curved afterbody. This study concentrated on the boundary layer, its properties, the separation process, and the criteria for separation. Recently, Merz et al.[4] have reported the mean flow characteristics in the near-wake behind the same curved afterbody. To complete the description of this particular flowfield, the turbulence characteristics in the near-wake need to be determined. Consequently, a comprehensive experimental investigation was undertaken to determine these characteristics.

Specifically, the near-wake behind the ellipsoidal afterbody used by Yi and Przirembel[3] and Merz et al.[4] was surveyed with a hot-wire anemometer system. Figure 1 shows a schematic of the important flowfield components. The attached boundary layer continues to grow as the mean pressure increases and the velocity decreases. Finally, the flow separates near the trailing edge of the body, forming a small recirculation region. The free shear layer is realigned with the main stream and then accelerates rapidly. Further downstream, the far-wake with its familiar similarity profile is established and the mean velocity recovery continues with the centerline turbulence decaying slowly.

The data presented, along with the previous results of Yi and Przirembel[3] and Merz et al.[4] provide a complete description of this flowfield and represent the most extensive set of information available on this flow. They will serve as the basis for the development and evaluation of analytical solutions.

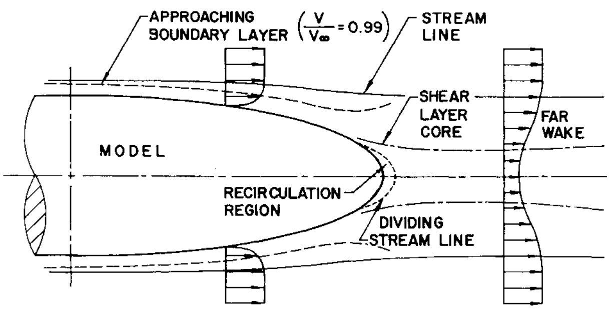

Fig. 1 Schematic of flowfield.

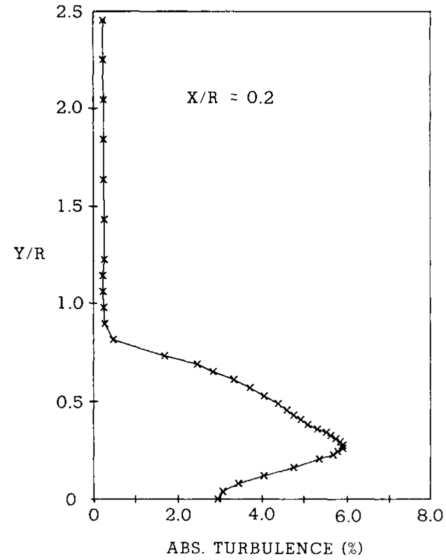

Fig. 2 Typical absolute turbulence intensity profile.

Received July 15, 1985; revision received March 10, 1986.

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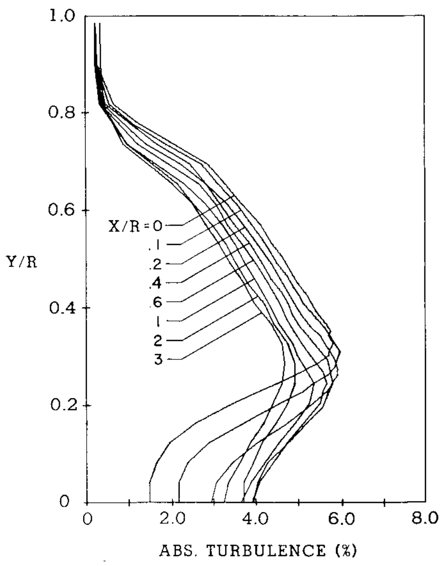

Fig. 3 Near-wake absolute turbulence intensities.

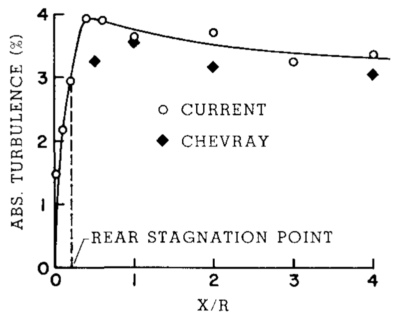

Fig. 4 Centerline absolute turbulence intensity.

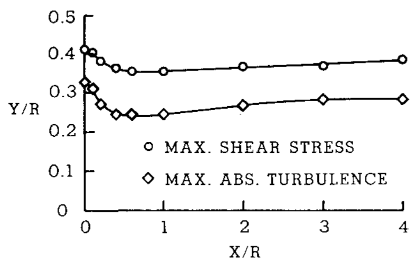

Fig. 5 Maximum turbulence and shear stress locations.

Experiment

This experiment was conducted in the Rutgers low turbulence subsonic wind tunnel. It is an open-circuit induction facility with a closed test section (30.5 cm × 45.7 cm). A cylindrical forebody which was 1.52 m long and 6.22 cm in diameter was suspended on the tunnel centerline by two sets of bronze straps. The straps and suspension system for the forebody were located in the tunnel plenum chamber where they would produce minimal disturbances to the flow. A semielliptical body of revolution with an axis ratio of 4 to 1 was attached to the end of the cylindrical forebody in the test section.

The near-wake was surveyed with a number of hot-wire probes. However, for the major portion of this study, 55F11 straight probes from DISA's "Golden Line" series were used. Due to their unique geometrical arrangement, these probes are particularly free from support prong disturbances and are insensitive to yaw angle changes. The signal from the hot-wire probe was processed by a DISA solid-state constant-temperature universal anemometry system (55D00) with a signal linearizer (55D10). Except for the tip of the probe, the entire measurement system is located outside of the test section. A traversing mechanism allowed the probe position to be determined to within ±0.013 mm.

The tests were conducted at a freestream velocity of 47.25 m/s with a corresponding Reynolds number of 3.08×10^6/m and a Mach number of 0.14. The stagnation pressure at the entrance to the contraction was just below atmospheric pressure while the stagnation temperature was 295°K ± 3.3°K. The test section had a static pressure of −1.28 kPa gage and a freestream turbulence intensity of 0.2%. Measurements prior to the installation of the centerbody showed no measurable axial static pressure gradient in the test section. This is due to a very slight divergence of the test section walls in the axial direction. The boundary layer on the centerbody was turbulent, fully developed and could be adequately described by a 1/7 power-law profile. Further details on the experimental setup, the approaching boundary layer and the mean flow characteristics may be found in Refs. 3 and 4.

Results

Turbulence intensity is usually presented as the root-mean-squared value of the fluctuating velocity component divided by the mean freestream velocity. An alternate approach is to use the local mean velocity to normalize the root-mean-squared value of the velocity fluctuation. This gives a local or relative measure of the turbulence at a point in a flowfield. Since both methods are useful and yield certain information, data are presented using both approaches.

To avoid confusion, different terminology will be used for the two methods.

Absolute turbulence intensity:

$$\sqrt{\overline{v'^2}}/\bar{V}_\infty \tag{1}$$

Relative turbulence intensity:

$$\sqrt{\overline{v'^2}}/\bar{V} \tag{2}$$

The absolute turbulence intensity provides information on the variation of turbulence on an absolute scale at each point in the flowfield. It may be used for direct comparison with the work of other investigators. On the other hand, the relative turbulence intensity indicates the degree of turbulence locally at a point. Since the relative turbulence level would become infinite when the local mean velocity goes to zero, it can be used as an indication of a stagnation point. Such a point occurs in the realignment process in the near-wake behind a bluff body.

Figure 2 shows a typical profile of the absolute turbulence intensity through the near-wake shear layer while Fig. 3 presents the variation throughout the near-wake. Note the difference in Y scale between the two plots. At the outer edge of the shear layer the absolute turbulence level decreases monotonically. On the other hand, near the centerline it increases rapidly up to approximately $X/R = 0.6$ and then decreases slowly. This is shown in Fig. 4. The peak absolute turbulence intensity on the centerline is 4% and occurs between $X/R = 0.4$ and 0.6 which is just downstream of the rear stagnation point which occurs at $X/R = 0.2$. Reasonable agreement with the results of Chevray[5] was obtained. His measurements in the far-wake indicated a slow decay of the absolute turbulence level. At $X/R = 10$ he found a turbulence level of 3.3% and as far downstream as $X/R = 36$ the intensity was still 2.7%.

Each of the profiles in Fig. 3 exhibit a maximum turbulence level. The radial location of this maximum varied with axial distance from the model tip and is shown in Fig. 5 along with the variation in location of the maximum shear stress as determined from the velocity profiles[4]. The maximum shear stress occurs between $Y/R = 0.3$ and 0.4. At all axial locations the point of maximum turbulence was consistently located ap-

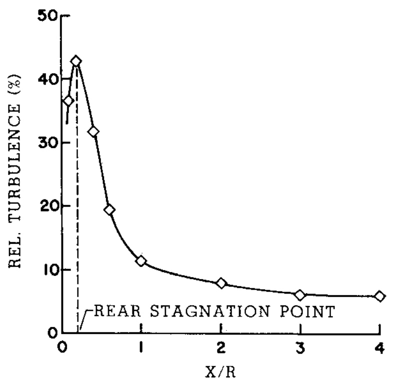

Fig. 6 Centerline relative turbulence intensity.

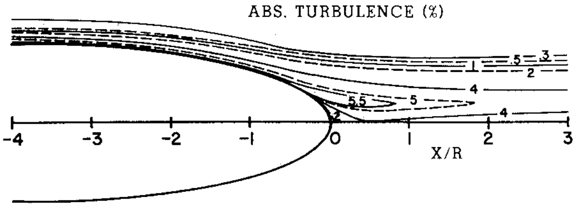

Fig. 7 Absolute turbulence intensity map.

proximately $Y/R = 0.1$ below the point of maximum shear stress.

As mentioned previously, the relative turbulence intensity can provide some useful information. On a relative scale, turbulence levels as high as 60% were observed around the separation bubble; on an absolute scale, the turbulence level was only 6%. Care must be exercised when quoting these large values of relative turbulence since they occur in regions where the local mean velocity is small.[6] A plot of the centerline relative turbulence level against axial distance downstream from the model tip is shown in Fig. 6. A peak in the relative turbulence is found at $X/R = 0.2$, the rear stagnation point as determined by other methods.[4] Downstream of the rear stagnation point the relative turbulence intensity declines rapidly due to the increase in centerline velocity. The peak in the relative turbulence curve can be used to indicate the rear stagnation point while a look at Fig. 4 shows that the absolute turbulence intensity cannot be used to find the rear stagnation point.

Combining the results in the near-wake with the data of Yi and Przirembel[3] for the approaching boundary layer on the model, a map of the absolute turbulence intensity may be constructed for the entire flowfield. This is shown in Fig. 7. It can be seen that the absolute turbulence intensity in the boundary layer remains nearly constant along the streamlines. This is also true in the outer edges of the free shear layer. A turbulent core is formed in the central part of the free shear layer. Within the separation bubble, the turbulence is small.

Conclusions

The turbulent near-wake of a semielliptical afterbody has been investigated experimentally using a hot-wire anemometer system. A complete map of the absolute turbulence intensity has been obtained. It shows a maximum turbulence level of approximately 6% in a small core region just adjacent to the separation bubble. On the near-wake centerline, the maximum absolute turbulence intensity was 4%; it occurred just downstream of the rear stagnation point. The absolute turbulence in the wake decays slowly, persisting to distances well in excess of 10 model radii downstream of the model tip. At all axial locations in the near-wake, the point of maximum turbulence was located $Y/R = 0.1$ below the point of maximum shear stress in each velocity profile.

On a relative scale, the turbulence intensity is much larger throughout the near-wake than on an absolute scale. Turbulent fluctuations in excess of 60% of the local mean velocity were observed in and around the separation bubble. The relative turbulence intensity can be used to indicate the presence of a stagnation point. It successfully located the rear stagnation point in the near-wake at $X/R = 0.2$.

The information presented in this paper on turbulence intensities, when coupled with the previous work of Yi and Przirembel[3] and Merz et al.[4] provides a complete description of the flowfield about a semielliptical afterbody. The results will be useful in developing and evaluating analytical solutions for the flowfield.

References

[1]Schlicting, H., *Boundary Layer Theory*, 7th ed., McGraw-Hill, New York, 1979.

[2]Chang, P. K., *Separation of Flow*, Pergamon Press, New York, 1970.

[3]Yi, C. H. and Przirembel, C. E. G., "Incompressible Turbulent Boundary Layer Separation from a Curved Axisymmetric Body," *Developments in Mechanics, Proceedings of the 13th Midwestern Mechanics Conference*, Univ. of Pittsburgh, Pittsburgh, PA, Vol. 7, Aug. 1973, pp. 203-216.

[4]Merz, R. A., Yi, C. H., and Przirembel, C. E. G., "The Subsonic Near-Wake of an Axisymmetric Semielliptical Afterbody," *AIAA Journal*, Vol. 23, Oct. 1985, pp. 1512-1517.

[5]Chevray, R., "The Turbulent Wake of a Body of Revolution," *Transactions of the ASME, Journal of Basic Engineering*, Series D, Vol. 90, June 1968, pp. 275-284.

[6]Simpson, R. L., "Interpreting Laser and Hot-Film Anemometer Signals in a Separating Boundary Layer," *AIAA Journal*, Vol. 14, Jan. 1976, pp. 124-126.

Incremental Multigrid Strategy for the Fluid Dynamic Equations

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I. Introduction

OVER the past few years, the author has developed implicit schemes for the numerical solution of the Navier-Stokes and lambda-formulation Euler equations, mostly for the case of steady flows. The basic framework that underlies the development of these numerical methods[1-4] follows. The governing equations are discretized in time by a two-level implicit Euler time stepping and linearized using the Taylor series and the incremental (delta) approach of Beam and Warming.[5] The large, block-pentadiagonal, linear system that results at every time step is reduced to a series of smaller block-tridiagonal systems by approximate factorization[1-3] or simple directional mutilation.[4] These smaller systems are solved very efficiently by means of standard block-tridiagonal Gaussian elimination.[6] The solution is then updated and the process is repeated until a satisfactory convergence criterion is met.

A positive feature of this approach is that a deferred-correction strategy[7] can be implemented in a very easy and

Presented as Paper 85-1517 at the AIAA Computational Fluid Dynamics Conference, Cincinnati, OH, July 15-17, 1985; received Oct. 24, 1985; revision received May 5, 1986.

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