Interaction Between Boundary Layer and Wakes of Different Bodies

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Measurements of mean velocity and Reynolds stresses have been made when the wakes of a streamlined body and a bluff body interact with the boundary layer on a flat wall. The streamlined body is the NACA 0012 airfoil, and the bluff body is a rectangular cylinder. The two bodies have the same drag and are placed such that at the initial station behind the wake-producing body, the lower edge of the wake in the two cases is at the same height above the bottom wall. It is found that though at the initial station the bluff-body wake is narrower and shallower than the airfoil wake, the level of turbulent fluctuations is higher in it, which causes faster mixing, and the velocity profile becomes monotonic earlier in the bluff-body case. Thus, for the same drag, the mixing is faster with a bluff body than with a streamlined body.

Nomenclature

H = shape factor factor, δ^*/Θ
u', v', w' = root mean square values of velocity fluctuations along x, y, and z directions, m/s
U = mean velocity, m/s
U_e = velocity in the freestream, m/s
$u'v'$ = kinematic Reynolds shear stress, m^2/s^2
x, y, z = Cartesian coordinates
δ^* = displacement thickness, m
Θ = momentum thickness, m

I. Introduction

On wings with a multielement airfoil, the wake from one element flows over the element immediately downstream and interacts with the boundary layer on the latter surface. This provided the initial motivation for the study of the interaction between the wake and the boundary layer, so that optimum shapes of airfoil, slat, and flap could be obtained. However, the interaction between the wake and the boundary layer is now recognized as an important phenomenon of basic interest in the study of turbulent flows, and several experimental studies have been carried out on various aspects of it. Goradia[1] attempts to calculate the lift and drag of an airfoil with flap, taking into account the mixing of the wake and the boundary layer over the upper surface of a flap. These calculations were based on the wall-jet studies of Goradia and Colwell.[2] Omar et al.[3] present the velocity profiles when the wake of a slat mixes with the boundary layer on the main wing. But this investigation is mainly aimed at obtaining maximum lift by optimizing parameters like slat deflection and the gap between the slat and the main wing.

Detailed experimental investigation of the mixing of the boundary layer on a flat plate with the wake of another flat plate kept at three boundary-layer heights is reported by Pot.[4] Distributions of mean velocity U and the rms values of the fluctuating quantities u', v', w' and $u'v'$ are presented. Angrilli et al.[5] have investigated the interaction between the boundary layer and the wake of a circular cylinder. They find that as the cylinder approaches the solid boundary, the vortex-shedding frequency of the cylinder increases. Bario et al.[6] have measured the mixing of the wake, from a small airfoil, with the boundary layer on a big airfoil located behind the small airfoil at an angle of 7 deg. Though some interesting measurements are presented, it is felt that they have considered too many parameters at the same time and interpretation of the results is difficult. Olson and Orloff[7] use the Laser Doppler Anemometer to study the wake of an airfoil passing over the boundary layer on a flap. The layer is very thin, and the interaction appears to begin only beyond the trailing edge of the flap. Brune and Sikavi[8] present detailed measurements of the wake of a slat interacting with the boundary layer on the upper surface of an airfoil kept at angles of attack of 9, 12, and 15 deg. Up to 30% of the airfoil chord, a potential flow region separates the slat wake and the boundary layer. However, the two have not merged; i.e., kinks in the velocity profile are seen, even at 90% of the airfoil chord where the flap begins. Sundaram and Yajnik[9] have studied the mixing of the wake from the NACA 0012 airfoil kept at zero angle of attack, with the boundary layer on a flat plate. They have measured the skin-friction coefficient, U, u', v' and $u'v'$. Zhou and Squire,[10] Savill and Zhou,[11] and Zhou and Squire[12] undertook a systematic study of the interaction between the boundary layer on a flat plate with wakes of airfoil at different angles of attack and a flat plate. They have measured distributions of U, u', v' and $u'v'$ but assumed the $w' = v'$. However, an examination of Pot's data[4] shows that this is not quite true. While comparing the interaction of the boundary layer with the wakes from a thick airfoil and a flat plate with similar drag, they find that[10] the wake from the flat plate mixes less rapidly than does the wake from an airfoil. Investigation of Tulapurkara et al.[13] indicates that the interaction is faster when the wake is produced by a bluff body (a square cylinder) than when it is produced by a streamlined body (an airfoil). But that was not the main aim of their investigation, and the drags of the streamlined body and the bluff body were widely different. Now, it is expected that the interaction process, though dependent on the structure of turbulence in the wake, would also depend on 1) the distance separating the boundary layer and the wake at a station immediately behind

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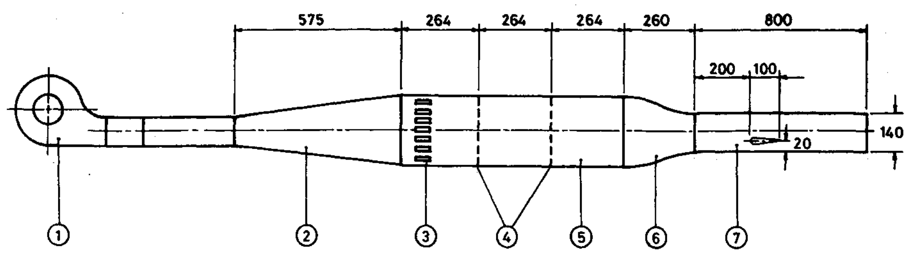

Fig. 1 Experimental setup.

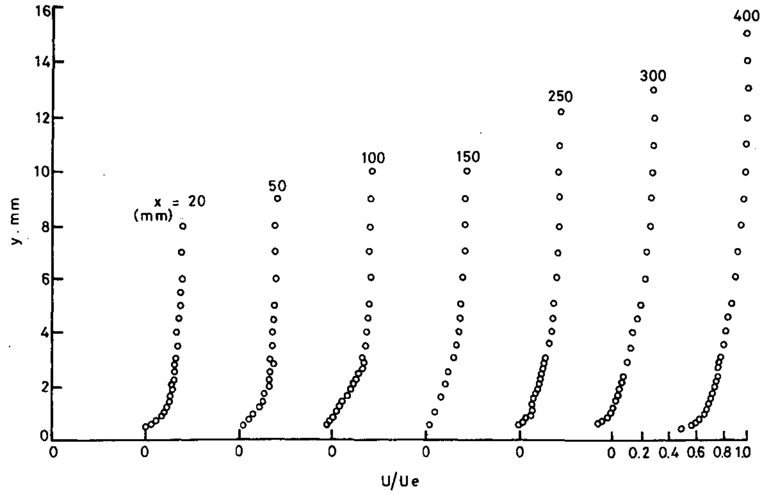

Fig. 2 Velocity profiles in the boundary layer on the lower wall.

the wake-producing body, and 2) the gross features of the wake. Hence, in the investigation reported in this article, the turbulent fluctuations in the interaction region are measured when 1) the streamlined body and the bluff body are placed such that the lower edge of the wake in the two cases is at the same height above the plate on which the boundary layer develops, and 2) the sizes of the two bodies are such that their drags are equal. This latter requirement is also useful from a practical point of view in that it yields information on the rapidity of interaction with bodies having the same drag. The details regarding experimental setup, measuring technique, and wake-producing bodies are described in Sec. II. The characteristics of the boundary layer and the wakes are presented in Sec. III, which is followed by the discussion of the interaction in Sec. IV.

II. Experimental Setup and Measuring Technique

A. Experimental Setup

The experimental setup is shown in Fig. 1. The centrifugal blower is driven by a 2-hp motor and delivers about 15 cubic meters of air per minute. The diffuser has an area ratio of 1:4 and a semiangle of 6 deg. The settling chamber that follows the diffuser has 1) a honeycomb of cell width 10 mm and depth 50 mm, and 2) two nylon screens with a wire diameter of 0.36 mm, mesh width of 1.25 mm, and a settling chamber 264 mm long. The contraction has a circular cross section of 250 mm at the inlet and a square cross section of side 140 mm at the exit, the contraction ratio being 2.5:1. The test section has a cross section of 140 × 140 mm and is 800 mm long.

The velocity distributions at various stations in the test section were almost uniform over the cross section, except in the boundary layers on the walls. The velocity in the test section near the exit of contraction was 13.1 m/s and increased to 14.0 m/s near the exit to the test section. The slight favorable pressure gradient results because the test section has a constant area of cross section. The models are kept such that their trailing edge is at 300 mm from the entry to the test section. Thus, the change in freestream velocity over the portion where measurements are taken is from 13.5 to 14 m/s. The freestream turbulence level in the test section is about 0.7%.

B. Measuring Technique

The mean velocity was generally measured using pitot and static tubes of 1-mm outer diameter. The pressures were measured using FCO12 micromanometers made by M/s. Furness Control of the United Kingdom. The manometer has a resolution of 0.01 mm of water, and its accuracy is 0.5% of the measured value.

The turbulent fluctuations were measured using a two-channel constant temperature hot-wire anemometer system (56C01) supplied by DANTEC. The probes used are standard normal wire and X-wire probes, the sensor being 5μm tungsten wire of 1.2-mm length. The turbulence quantities u', v', w' and $u'v'$ were obtained by placing the X-wire probe in the X-Y and X-Z planes. The response equations for a linearized mode of operation given by Champagne and Sleicher[14] were used to calculate the u', v', w' and $u'v'$. The values of u' obtained by placing the X-probe in the X-Y and X-Z planes were generally within 5% of each other.

C. Models

The aim of the present investigation is to examine the differences in wake/boundary-layer interactions when the wake develops 1) from two turbulent boundary layers on the airfoil, and 2) from a separated flow behind a bluff body. For the first case, the wake can be easily generated by a stream-

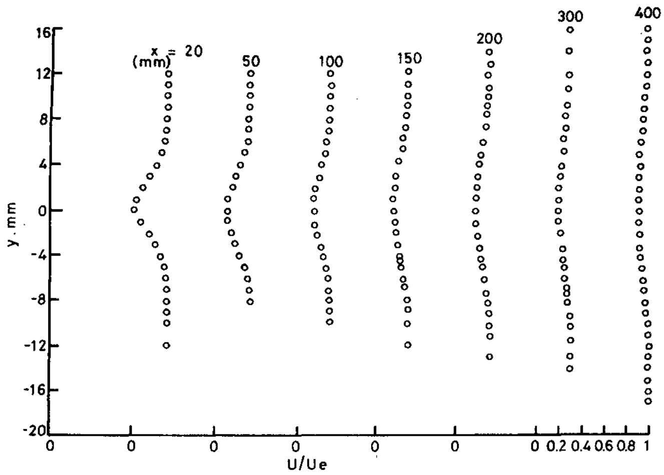

Fig. 3 Velocity profiles in the wake of airfoil (NACA 0012).

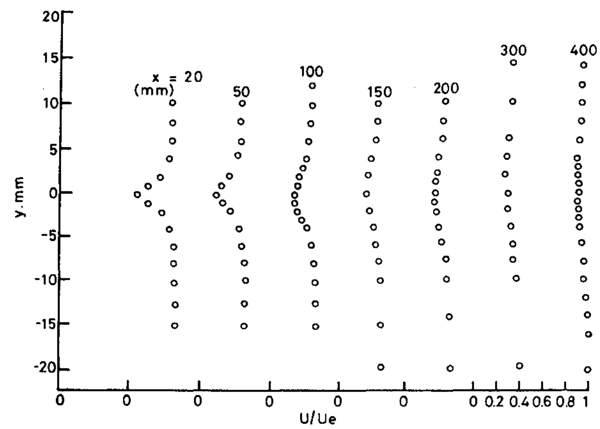

Fig. 4 Velocity profiles in the wake of a bluff body.

lined body. The symmetrical NACA 0012 airfoil of 100-mm chord at zero angle of attack was chosen for this purpose. Trip wires of 0.8-mm diameter were attached at 35% of chord from the leading edge on the upper and lower surfaces of the airfoil. This location of the trip wire was chosen because, to be efficient as a tripping device, the wire should be in the region of adverse pressure gradient. The boundary layers at the trailing edge on the top and bottom sides had shape factor H of 1.5, and the Reynolds number, based on the momentum thickness of 0.65 mm, was 602. The momentum thickness of the wake Θ at a station 300 mm behind the trailing edge of the airfoil was 1.27 mm; the momentum thickness of the wake slightly decreased with distance due to the mild favorable pressure gradient in the test section. It was decided that the bluff body to be used for producing the second type of wake should be of rectangular or square shape. This was done with a view to facilitate predictions of flow using existing computer codes that can handle rectangular geometry. A square 1.6-mm cylinder would have given a Θ of 1.27 mm, but such a small-sized cylinder, which can span the test section width of 140 mm, could not be fabricated accurately. Hence, it was decided to use a rectangular cylinder. Taking guidelines from the data given in Hoerner[15] and Bearman and Trueman,[16] various rectangular cylinders were tried. A 2.5 × 8-mm cylinder was found to give, in the far wake, almost the same value of Θ as the wake of the airfoil.

III. Boundary Layer on the Wall and the Wakes

The airfoil and the bluff body are mounted in the test section such that their trailing edges are 300 mm from the entry to the test section. The x coordinate is taken as zero at this station. The velocity profiles on the lower wall of the test section at $x = 20$, 50, 100, 150, 200, 300, and 400 mm are shown in Fig. 2. The boundary layer has a thickness of 7 mm at $x = 20$ mm and grows to about 12 mm at $x = 400$ mm. The shape factor H of the profiles is about 1.36. The profiles show the existence of log law, and the values of the skin-friction drag coefficient C_f obtained using the Preston tube and Clauser plot were found to be almost equal. Due to the presence of the slight favorable pressure gradient in the test section, the value of C_f changes from 0.0047 to 0.005 over the distance covered in the measurements. These results indicate that the boundary layer on the wall was a fully developed turbulent boundary layer.

The velocity profiles of the wake behind the airfoil are shown in Fig. 3. These measurements were done using pitot and static tubes. The wake was fully developed and could be predicted accurately using a computational scheme based on the k-ϵ model of turbulence.[17]

The velocity profiles of the wake behind the rectangular cylinder are shown in Fig. 4. The flow behind a bluff body takes a longer distance to develop, and the momentum thickness Θ increased from a value of 0.82 mm to 1.27 mm when x varied from 20 to 300 mm. Beyond this station Θ was almost constant. It is seen from Fig. 4 that up to 100 mm, the bluff body has a smaller velocity defect and half-width. But at $x = 300$ mm, the values of these parameters are almost equal for the bluff body and the streamlined body.

IV. Interaction Studies—Results and Discussion

To study the interaction between the boundary layer and the airfoil wake, the airfoil was kept 20 mm from the wall.

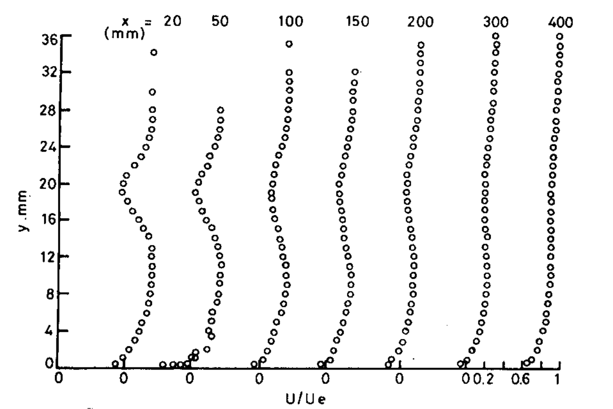

Fig. 5 Velocity profiles in the airfoil wake and boundary-layer interaction.

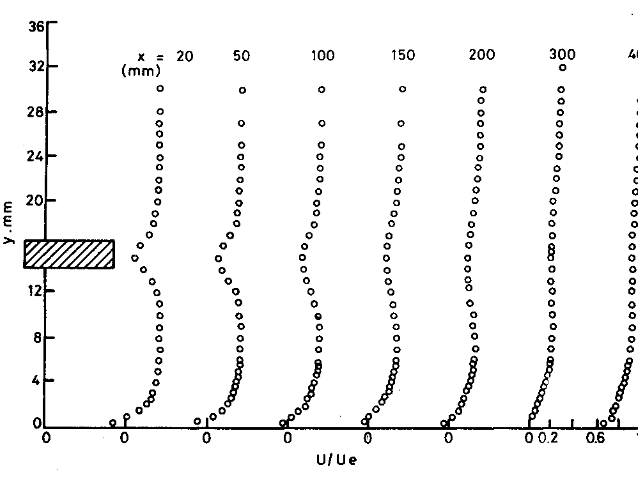

Fig. 6 Velocity profiles in the bluff-body wake and boundary-layer interaction.

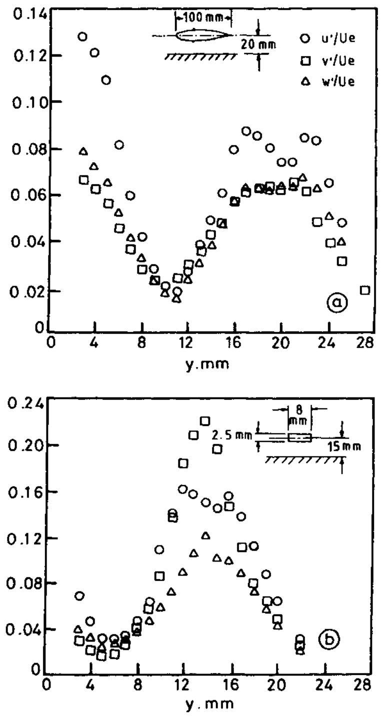

Fig. 7 Distributions of normal stresses at $x = 20$ mm.

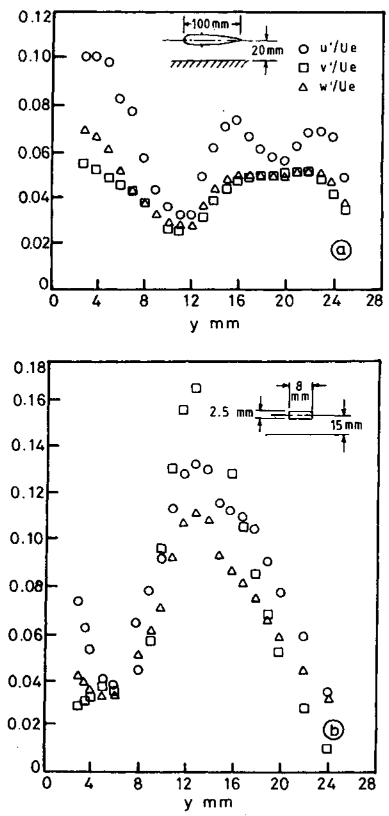

Fig. 8 Distributions of normal stresses at $x = 50$ mm.

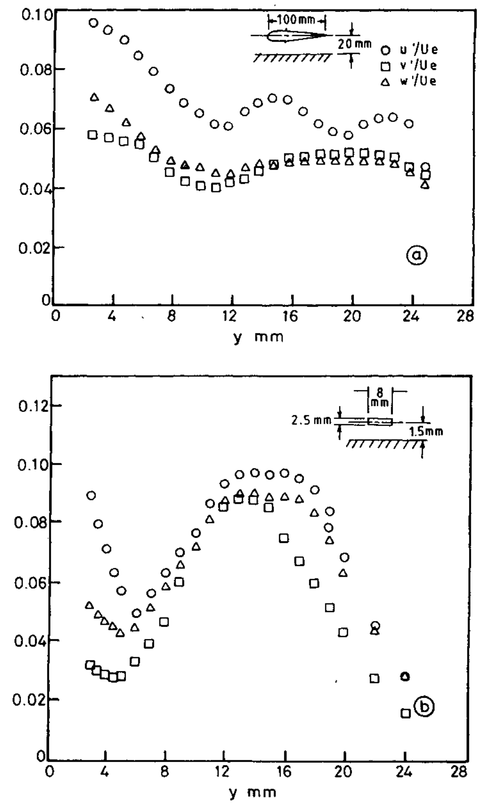

Fig. 9 Distributions of normal stresses at $x = 100$ mm.

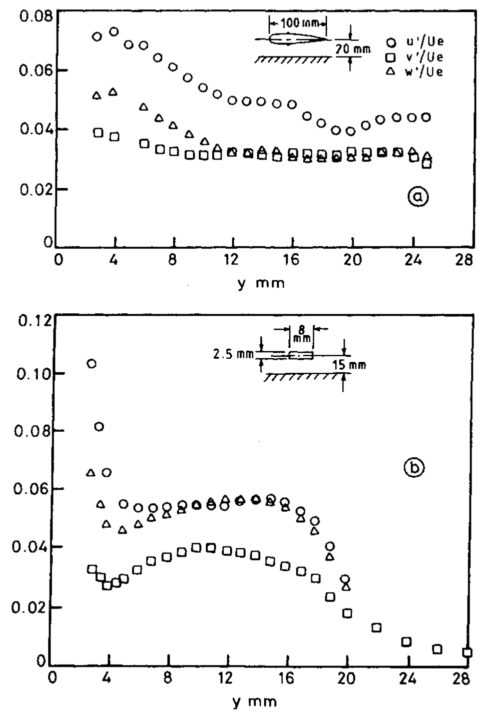

Fig. 10 Distributions of normal stresses at $x = 200$ mm.

The velocity profiles are shown in Fig. 5. It is seen that at $x = 20$ mm, the lower edge of the airfoil wake is about 12 mm from the wall. The bluff body was placed such that the lower edge of its wake was also 12 mm from the wall. This required that the center of the bluff body be 15 mm from the wall. The velocity profiles for the interaction with the bluff-body wake are shown in Fig. 6.

Comparing the velocity distributions in Figs. 2, 5, and 6, it is noticed that at $x = 20$ mm, the presence of the bluff body does not seem to affect the boundary layer on the wall. However, the presence of airfoil causes some thickening of the boundary layer. Its thickness is about 10 mm, as compared with 7 mm for the undisturbed boundary layer. This thickening is evidently due to the deceleration to which the boundary layer is subjected under the rear half of the airfoil. Such thickening of the boundary layer is noticed also in the data of Sundaram and Yajnik.[9] Perhaps this thickening could be avoided by placing the airfoil farther away from the wall, as

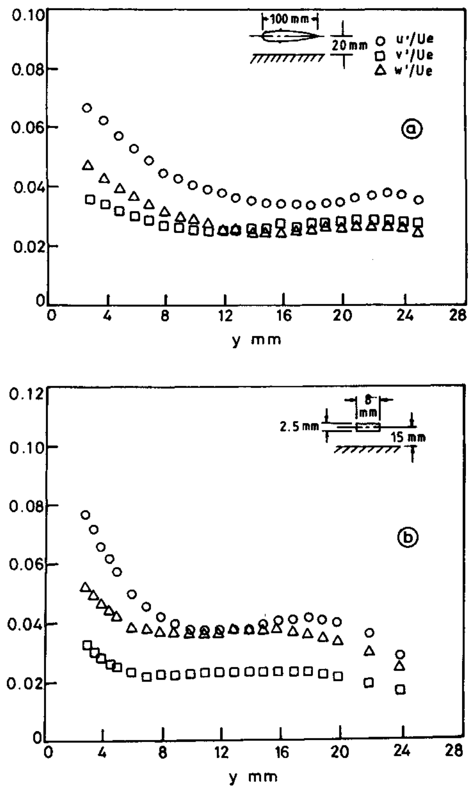

Fig. 11 Distributions of normal stresses at $x = 300$ mm.

done by Zhou and Squire.[12] But the interaction would be, as in their case, too slow and may not reveal anything new. In practical situations, where the slat is kept at a distance of 4–5% of the airfoil chord, the presence of the slat alters the boundary layer on the main wing.

Looking at the velocity profiles at other stations, it is found that though at the initial station ($x = 20$ mm) the bluff-body wake is narrower, shallower, and farther away from the boundary layer than the airfoil wake, the velocity profiles for the bluff-body case become monotonic at $x = 300$ mm, and the same happens for the airfoil case at $x = 400$ mm. This suggests that the interaction and growth of the shear layer depend not only on the initial velocity profile in the neighborhood of the bluff body but also on the fluctuating quantities. The distributions of u', v', and w' for the two cases are shown in Figs. 7–12. The usual practice is to plot u', v', and w' in separate diagrams.[4,9,12] However, it is felt that the present way of plotting normal stresses at a station in one figure gives better insight into the phenomenon. For the sake of comparison, the variations in the two cases are shown one below the other. Velocity profiles at $x = 20$ mm (Figs. 5 and 6) show that there is a region of uniform velocity between the boundary layer and the wake. This region is referred to as the region of potential flow. However, Fig. 7 shows that the region between the boundary layer and the wake, where the levels of u', v', and w' are small, is narrower than the potential flow region. Thus, the interaction between the fluctuating quantities begins earlier than the mean velocity. At $x = 20$ mm, the levels of u', v', and w' in the outer part of the shear layer are higher for the bluff-body case than for the case of a streamlined body. This leads to faster interaction in the former case. Up to $x = 200$ mm, the levels of u', v' and w' in the outer part of the shear layer continue to be higher for the bluff-body case than for the streamlined-body case. At $x \geq 300$ mm, the levels in the two cases are nearly equal. A similar trend, though at a much slower pace, is seen in the data of Zhou and Squire.[10] Considering these changes in u', v' and w' along with those in the velocity profile suggests that the higher level of fluctuation in the bluff-body case causes faster interaction in the beginning, and the velocity profile tends to become monotonic faster. But this results in lower velocity gradients, and the level of fluctuations also decreases faster in the bluff-body case. Finally, when the interactions are complete, the level of fluctuations is almost the same in the two cases.

Figures 7–12 show that in the portion of the shear layer near the wall, $u' > w' > v'$ for both cases. This is typical of boundary-layer behavior and indicates that the inner region of the boundary layer is not significantly altered by the interaction. It is noticed that the maximum values of u', v' and w' near the wall are generally higher for the airfoil case. This increase is likely to be due to the adverse pressure gradient to which the boundary layer under the airfoil is subjected (see Fernholz,[18] p. 68).

The distributions of $u'v'$ for the two cases are shown in Figs. 13 and 14. For the bluff-body case, the shear stress does not change sign for $x \geq 300$ mm (Fig. 13). The same behavior is shown in the airfoil case for $x \geq 400$ mm (Fig. 14). The fact that the velocity profile also becomes monotonic at $x = 300$ and 400 mm, respectively, for the two cases may suggest the use of the eddy viscosity concept to predict the interaction. But it is not likely to be correct in the initial phases of interaction where, especially for the bluff-body case, the

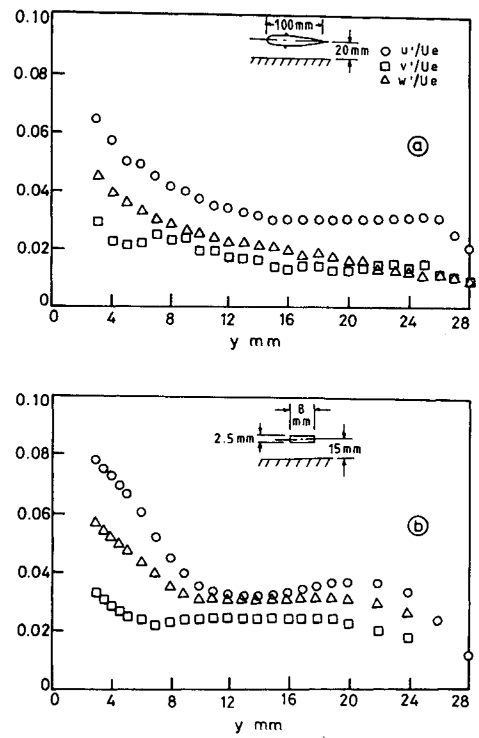

Fig. 12 Distributions of normal stresses at $x = 400$ mm.

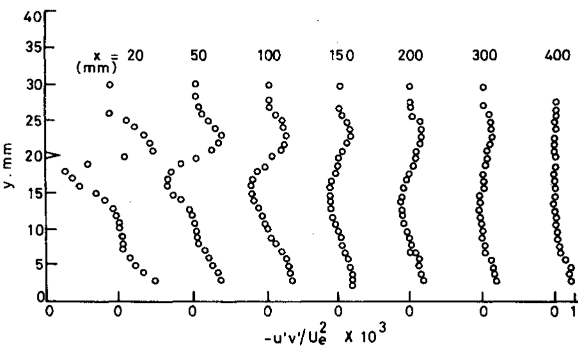

Fig. 13 Distributions of shear stress—streamlined body.

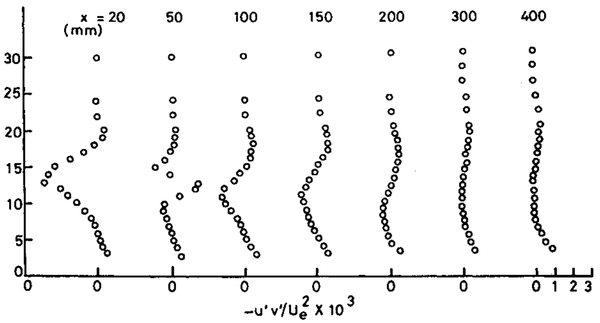

Fig. 14 Distributions of shear stress—bluff body.

stresses are not small, even when the velocity gradient is zero in the potential flow region.

V. Conclusions

The study of the interactions between the boundary layer and the wakes of a streamlined body and a bluff body shows that for the same drag a bluff body causes faster interaction in the sense that the velocity becomes monotonic earlier. This is caused by the higher level of the fluctuating quantities behind the bluff body. However, as the velocity profile becomes monotonic, the velocity gradients in the shear layer decrease, and the velocity fluctuations also decrease faster for the bluff-body case. When the interactions are complete, the levels of fluctuations are nearly the same in both cases.

Acknowledgment

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References

[1]Goradia, S. H., "Confluent Boundary Layer Flow Development with Arbitrary Pressure Distribution," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, 1971.

[2]Goradia, S. H., and Colwell, G. T., "Parametric Study of a Two-dimensional Turbulent Wall-jet in a Moving Stream with Arbitrary Pressure Gradient," *AIAA Journal*, Vol. 9, Nov. 1971, pp. 2156–2165.

[3]Omar, E., Zierten, T., Hahn, M., Szpizo, E., and Mahal, A., "Two-dimensional Wind Tunnel Tests of NASA Supercritical Airfoil with Various High-lift Systems—Volume II-Test Data," NASA CR-2215, Sept. 1973.

[4]Pot, P. J., "Measurements in a Two-dimensional Wake and in a Two-dimensional Wake Merging into a Boundary Layer," National Lucht-en Ruimtevaart Laboratorium, the Netherlands, Data Rept. TR-79063 U, 1979.

[5]Angrilli, F., Bergamaschi, S., and Cosalter, V., "Investigation of Wall-Induced Modifications to Vortex Shedding from a Circular Cylinder," *Transactions of ASME—Journal of Fluids Engineering,* Vol. 104, Dec. 1982, pp. 518–522.

[6]Bario, F., Charney, G., and Papailiou, K. D., "An Experiment Concerning the Conference of Wake and a Boundary Layer," *Transactions of ASME—Journal of Fluids Engineering,* Vol. 104, March 1982, pp. 18–23.

[7]Olson, L. E. and Orloff, K. L., "On the Structure of Turbulent Wakes and Merging Shear Layers of Multi-element Airfoils," AIAA Paper 81-1238, 1981.

[8]Brune, G. W. and Sikavi, D. A., "Experimental Investigation of the Confluent Boundary Layer of a Multi-element Low-Speed Airfoil," AIAA Paper 83-0566, Jan. 1983.

[9]Sundaram, S. and Yajnik, K. S., "Measurements on the Merging of the Wake of NACA 0012 Airfoil with a Turbulent Boundary Layer," National Aeronautical Laboratory, Bangalore, India, TM-FM-8801, 1988.

[10]Zhou, M. D. and Squire, L. C., "The Interaction of a Wake with a Boundary Layer," *IUTAM Symposium on Structure of Complex Turbulent Flows*, edited by R. Dumas and L. Fulachier, Springer-Verlag, Berlin, 1983. pp. 376–387.

[11]Savill, A. M. and Zhou, M. D., "Wake/Boundary Layer and Wake-Wake Interactions—Smoke Flow Visualization and Modelling," *Proceedings of the Second Asian Congress on Fluid Mechanics*, Science Press, Beijing, 1984. pp. 743–752.

[12]Zhou, M. D. and Squire, L. C., "The Interaction of Wake with a Turbulent Boundary Layer," *Aeronautical Journal*, Vol. 89, 1985, pp. 72–81.

[13]Tulapurkara, E. G., Ramjee, V., and Rajasekar, R., "Experimental Investigation of Wake and Boundary Layer Interaction," *Journal of the Aeronautical Society of India*, Vol. 40, 1988, pp. 45–53.

[14]Champagne, F. H. and Sleicher, C. A., "Turbulence Measurements with Inclined Hot-Wires, Pt. 2—Hot-wire Response Equations," *Journal of Fluid Mechanics*, Vol. 28, Pt. 1, 1967, pp. 177–182.

[15]Hoerner, S. F., "Fluid Dynamic Drag," published by author, 1965.

[16]Bearman, P. W. and Trueman, D. M., "An Investigation of Flow Around Rectangular Cylinders," *Aeronautical Quarterly*, Vol. 23, 1972, pp. 229–239.

[17]Rajasekar, R., "Experimental and Theoretical Investigation of Some Aspects of Wake-Boundary Layer Interaction," M.S. Thesis, Indian Institute of Technology, Madras, India, May 1988.

[18]Fernholz, H. H., "External Flows," *Turbulence,* edited by P. Bradshaw, Springer-Verlag, Berlin, 1978, p. 68.