Development of Airfoil Wake in a Longitudinally Curved Stream

V. Ramjee,* E. G. Tulapurkara,† and R. Rajasekar‡
Indian Institute of Technology, Madras, India

Measurements of mean velocity and longitudinal turbulent fluctuations in the wake of an airfoil are carried out in a straight duct and in two curved ducts. The velocity profiles of the wake in the curved ducts are asymmetric. The thickness of the shear layer is higher on the inner side than on the outer side. The inner side is the portion of the flow between the centerline of the curved duct and the wall nearer to the center of the curvature. The intensity of the longitudinal turbulence fluctuations is enhanced on the inner side of the flow and not appreciably affected on the outer side of the flow between the centerline and the outer wall of the curved duct.

Introduction

THIN shear flows with significant streamline curvature arise in many situations of practical interest. The field of turbomachinery provides many examples, such as the flow over compressor and turbine blades. Another familiar example is that of the multi-element wing of an airplane in which the wake of the leading-edge slat develops in a curved flow.

The effect of curvature on turbulent boundary layer has been studied by some investigators.[1-6] So and Mellor[1] made elaborate measurements of mean and fluctuating velocities in a turbulent boundary layer over a convex wall and a concave wall. The surfaces were steeply curved with $\delta/R = 0.1$, where δ is the boundary-layer thickness and R is the radius of curvature of the wall. They found that the law of the wall was similar to the flat plate log-law, but the outer layer showed a considerable departure from the flat plate profiles. The turbulence was suppressed when the wall had convex curvature and enhanced when it was concave. Ramaprian and Shivaprasad[2] have made elaborate measurements in the boundary layer, with $\delta/R = 0.01$ on both convex and concave walls. They find that the large eddies were suppressed in a flow on a convex wall. Muck et al.[3] and Hoffman et al.[4] have made a number of studies on the effect of the curvature. Bradshaw[5] has suggested an analogy between the buoyancy and streamline curvature and proposed the curvature Richardson Number. He has also given a relationship between mixing length and curvature. Prabhu et al.[6] have made a detailed study of the effect of curvature on turbulent boundary layer, with δ/R ranging from -0.08 to $+0.125$, where the negative sign indicates concave curvature and the positive sign convex curvature. They find that the intercept in the log-law (i.e., constant B) decreases with increase in the parameter (δ/R) on a convex wall.

Castro and Bradshaw[7] have measured the development of a shear layer directed toward a sharp 90-deg bend. The effect is like subjecting the shear layer to a convex curvature in a certain region and then removing the curvature. The turbulence quantities decrease in the region affected by the curvature and then return to the plane shear layer values after an overshoot.

The effect of curvature on the development of a wake is currently being investigated. Savill[8] has investigated the wake of a circular cylinder directed around a 90-deg corner. The wake that lies in the central part of the flow can be considered as subjected to a curved flow. The diameter of the circular cylinder d is 9.5 mm, and the Reynolds number based on the diameter is 6500. He has measured the three normal stresses and two shear stesses in the wake. There are differences in the variations of the turbulent quantities on the two sides of the centerline. Nakayama[9] has investigated the effect of curvature and the pressure gradient on the small defect far wake of a circular cylinder of diameter 1.6 mm with Reynolds number of 1550. He measured mean velocity and some turbulence quantities in the range of $x/d = 300$–500. He finds that the Reynolds stresses are strongly influenced by streamline curvature and pressure gradient. However, it is difficult to separate the effects of curvature and pressure gradient. Hence, an investigation has been undertaken to study the development of wake in ducts of constant curvature. Savill[8] and Nakayama[9] studied the wake of a circular cylinder in a curved flow. In the present study, the development of the wake of a symmetric airfoil is studied in a straight duct and in two curved ducts of different radii of curvature R, namely $R = 350$ mm and $R = 700$ mm. Mean velocity and longitudinal turbulence intensity are measured up to four chord lengths behind the airfoil.

Experimental Setup and Measuring Technique

The experimental setup is shown in Fig. 1. The centrifugal blower is driven by a 2-hp motor. The blower is connected to a diffuser and then to a settling chamber. Two nylon screens and a honeycomb are provided. The test section has a cross section of 140×140 mm and is 600 mm long. The velocity in the test section is about 15 m/s, and the freestream turbulence level is about 0.5%. The longitudinally curved ducts are attached at the end of the straight duct. An NACA 0012 airfoil with a chord c of 100 mm at zero angle of attack is kept vertically such that the trailing edge is at a distance of 100 mm ahead of the curved section. The development of the wake from it in the curved flow is studied by measuring the mean velocity U and the longitudinal turbulence intensity u' using a hotwire probe with 5 μm diameter and DISA 56C01 constant temperature anemometer. Radial traverses of the hotwire probe were done at $x/c = 1.5$, 2.0, 2.5, 3.0, 3.5, and 4.0, where x is measured from the trailing edge of the airfoil. Care was taken to traverse the probe in a radial direction. To align the probe along a radius, two radial lines were drawn—one each on the top and bottom sides of the duct. The probe traversing mechanism is rotated till the probe holder lies along the chosen radial line. The top side of the duct is made of a transparent sheet, and the lines on the top and bottom sides help in avoiding error due to parallax. The half width of the wake b at a station 100 mm behind the airfoil ($x/c = 1$) is about 10 mm. Thus, at the entry to the curved duct, the value of the ratio b/R is 0.0286, where $R = 350$ mm.

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*Professor, Department of Applied Mechanics.
†Assistant Professor, Department of Aeonautical Engineering.
‡Project Associate, Department of Aeronautical Engineering.

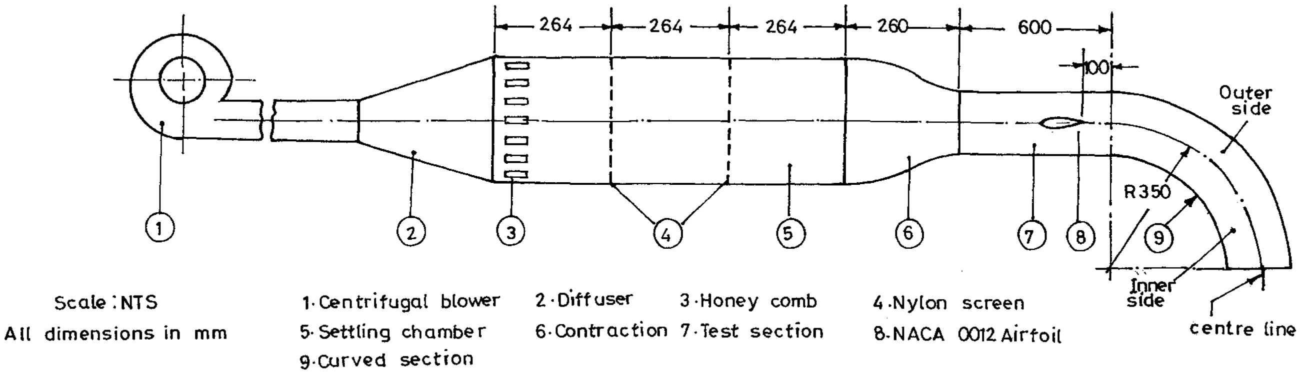


Fig. 1 Experimental setup.

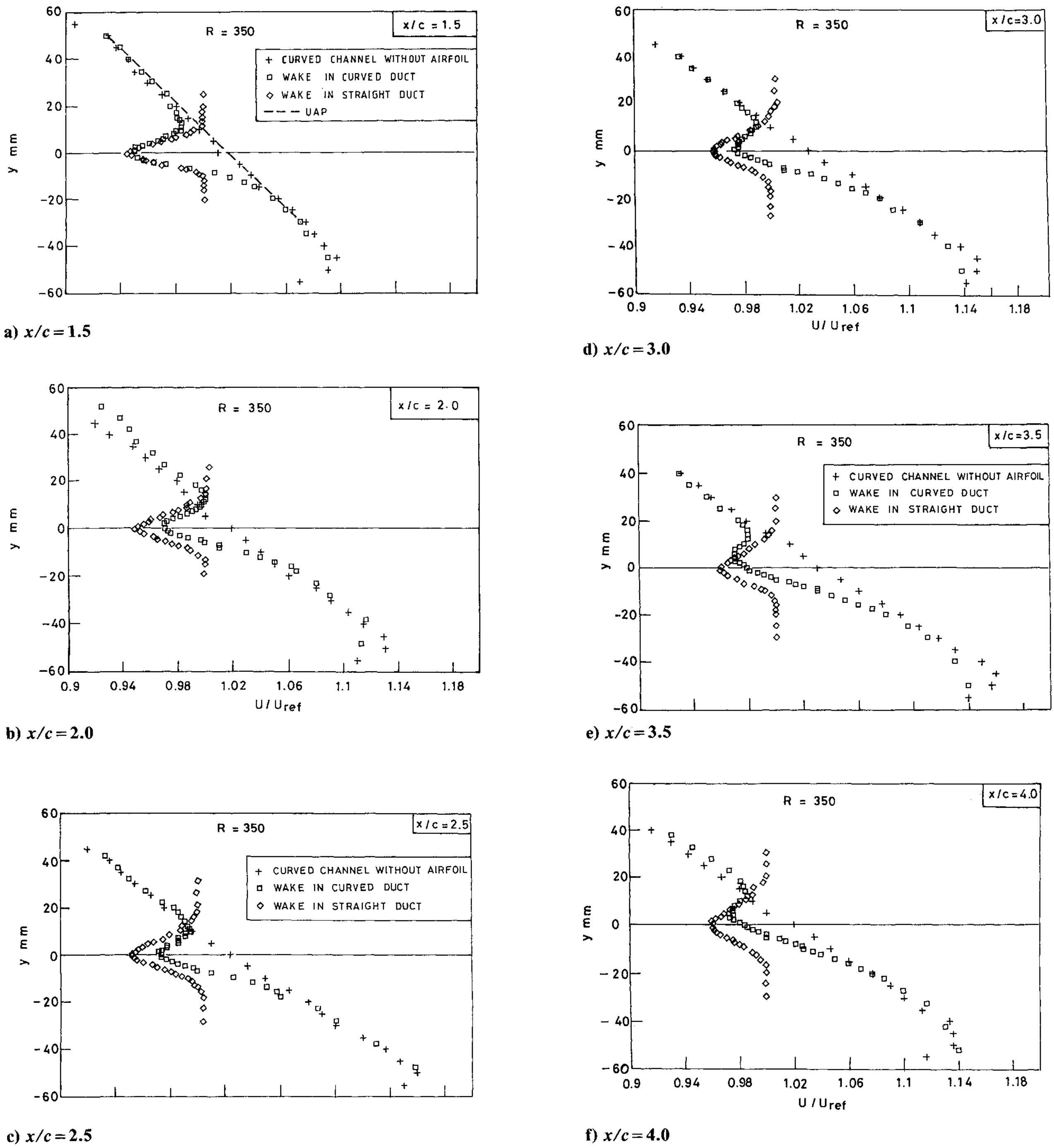


Fig. 2 Mean velocity profiles ($R = 350$).

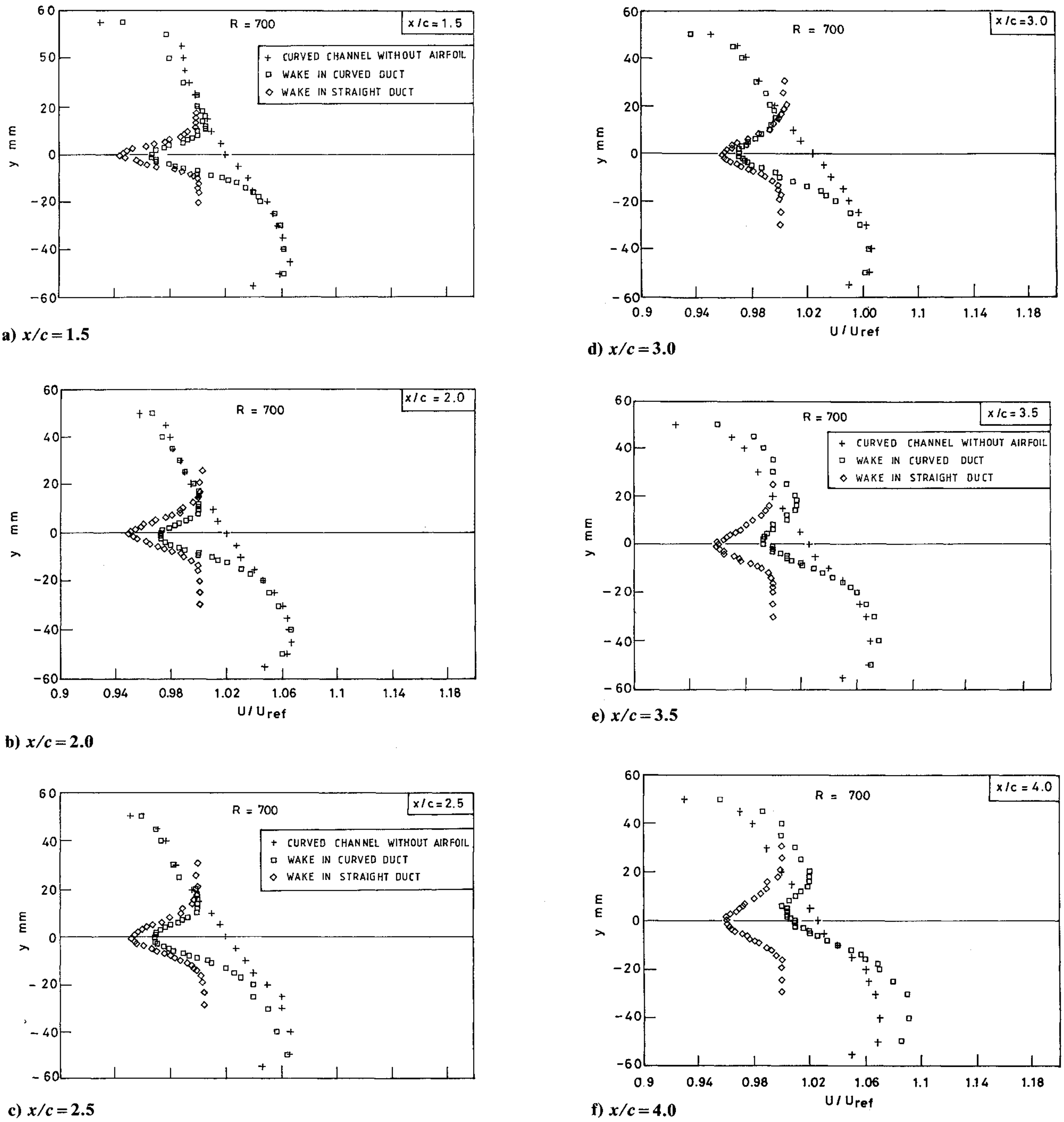
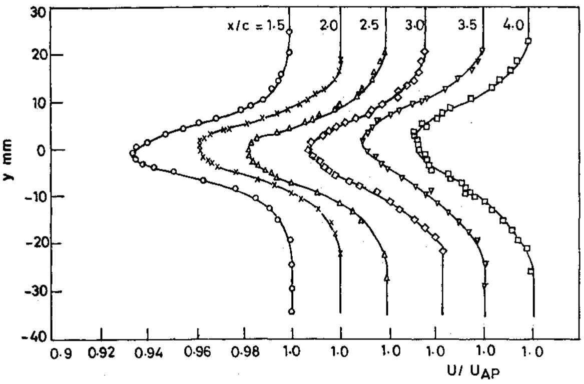


Fig. 3 Mean velocity profiles ($R = 700$).

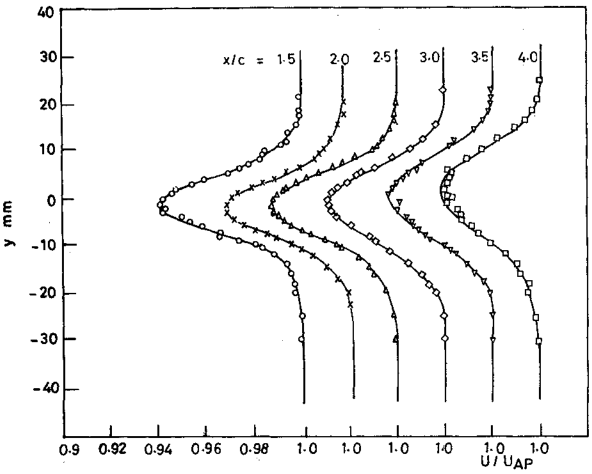
To check the upstream influence of the curved duct in the test section, the mean velocity distribution without the airfoil was measured at the station where the airfoil trailing edge was kept. The velocity distribution outside the wall boundary layers was found to be almost uniform. Thus, the upstream influence of the curved duct is negligible in the straight test section at the station where the airfoil trailing edge lies. When there was no airfoil, the boundary layer on the wall had a thickness of 15 mm at this station. To check the two dimensionality, the measurements were done in the wake at 35 mm above and below the centerline of the duct at $x/c = 4.3$. These distributions of mean velocity and that at the centerline were within $\pm 2\%$ of each other. Thus, the flow in the center part of the duct can be treated as two dimensional up to the last measuring station ($x/c = 4$). Briley and McDonald[10] call such a region a potential core. Wake development was also studied in another curved duct with a radius of curvature $R = 700$ mm. In this curved duct also, the flow turns through 90 deg. Since the radius of curvature of this duct is twice that of the first duct, the curvature parameter (b/R) is half of the previous one. To enable a comparison of wake development in a curved duct with that in a straight duct, the mean velocity and the longitudinal turbulence intensity were measured in a straight duct at $x/c = 0.5$, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0.

Results and Discussion

The mean velocity U and the longitudinal turbulence intensity u' were measured at $x/c = 1.5$, 2.0, 2.5, 3.0, 3.5, and 4.0 with and without the wake-producing airfoil in the two curved ducts. In the absence of the wake-producing body, the mean velocity in the curved section, outside the boundary layers on the walls, approximately follows a straight line (Figs. 2a-2f and 3a-3f). This velocity can be referred to as potential flow velocity. The quantity U_{ref} in Figs. 2a-2f and 3a-3f is the reference velocity measured in the straight test section at a station one chord ahead of the airfoil. It is seen that the value of

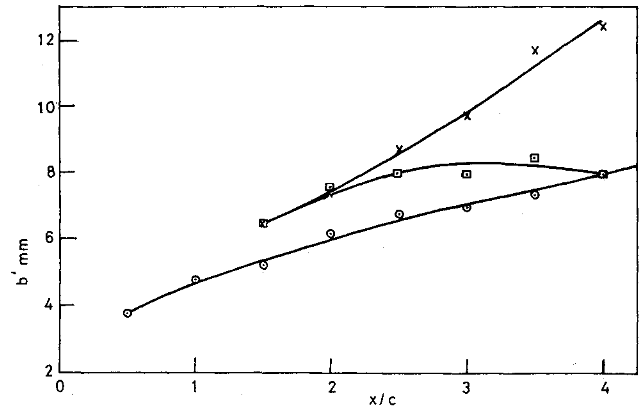


a) $R = 350$

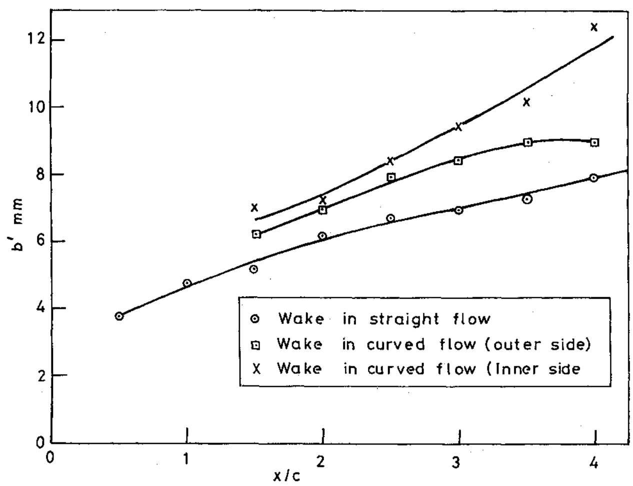


b) $R = 700$.

Fig. 4 Velocity profiles plotted as *U/UAP*.



a) $R = 350$



b) $R = 700$

Fig. 5 Variation of half width *b*.

the mean velocity at the edge of the boundary layer is more on the inner wall than on the outer wall; the inner wall is the wall closer to the center of curvature, and the outer wall is the one farther from it. Figures 2a-2f and 3a-3f show the velocity distributions when the wake develops in the curved section. The development of the wake in a straight duct is also indicated in the same figures. It is seen that the wake in the curved flow is not symmetric about the centerline of the curved duct. The thickness of the shear layer on the inner side is more than that on the outer side; the inner side of the flow here refers to the flow between the centerline of the duct and the inner wall, and the outer side of the flow is between the centerline and the outer wall of the duct.

To examine the differences between the wakes developing in curved flow and in straight flow, the wake defect profiles are plotted as follows. The wake defect at a radial station can be defined as the difference between the velocities at that point without the wake and with the wake. Calculation of the wake defect would have been simple if the velocity outside the wake were the same as the potential flow velocity. However, the velocity outside the wake is slightly different than the potential flow velocity. Perhaps this is necessary to conserve the mass flux. To obtain the wake defect, the velocity distribution without the wake is obtained by drawing a line joining the points outside the wake (dashed line in Fig. 2a). This velocity will be denoted by UAP. Then the wake defect w is $(UAP - U)$. Figures 4a and 4b show the variations of U/UAP with y for $R = 350$ mm and $R = 700$ mm, respectively. It is seen that the maximum wake defect occurs near the centerline of the duct. Let half width b' be the value of y at which the wake defect equals half of its maximum value. It is observed that b' is not the same on the two sides of the wake. Its values are shown in Figs. 5a and 5b. The variation of the maximum wake defect w_0 for the wakes in straight flow and curved flow is shown in Fig. 6. It is seen that the wake defect w_0 is more in curved flow than in straight flow. In addition, with $R = 350$ mm, w_0 is higher than when $R = 700$ mm. Thus, the effect of curvature is more when b/R is higher. Since the half widths b' of the wake are different on the inner and outer sides, an average value of the half width (b_{avg}) is plotted in Fig. 7. It is seen that the average half width is higher in a curved flow than in a straight flow.

To understand the significance of both b_{avg} and w_0 being more for a wake in a curved flow than in a straight flow, the displacement thickness δ^* was calculated for the curved wake using the following equation:

$$\delta^* = \int_{-\delta}^{\delta} \left(1 - \frac{U}{UAP}\right) dy$$

where δ is sufficiently large so that $U = UAP$ is attained on both sides of the wake. Figure 8 shows the variation of δ^*. It is seen that δ^* increases with x/c for a wake in a curved flow, whereas it decreases with downstream distance for a wake in a straight flow. This suggests that the curvature also affects the entrainment due to the wake. A similar trend was also noticed by Savill.[8]

Figures 9a-9f show the variations of the longitudinal turbulent fluctuations u'/U with y. The values of u'/U for the wake developing in a straight flow are also indicated in the figures. It is seen that the values of u'/U are enhanced on the inner side and are not appreciably affected on the outer side. Nakayama[9] also gets similar results for a small defect wake.

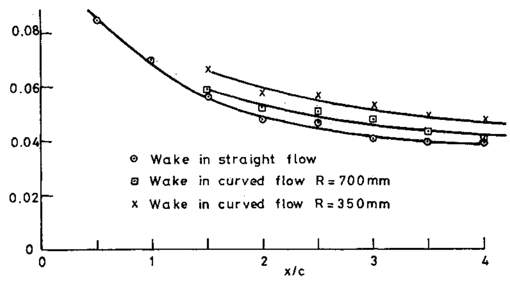


Fig. 6 Maximum wake defect w_o.

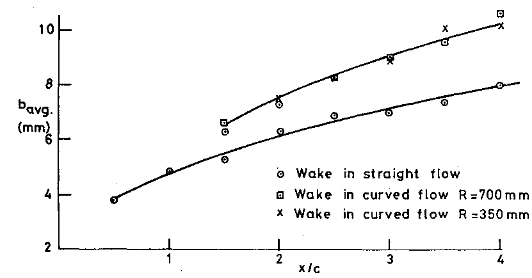


Fig. 7 Average half width b_{avg}.

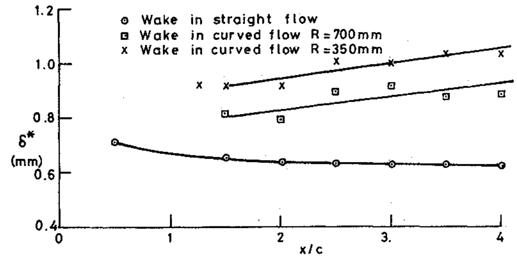


Fig. 8 Displacement thickness δ^*.

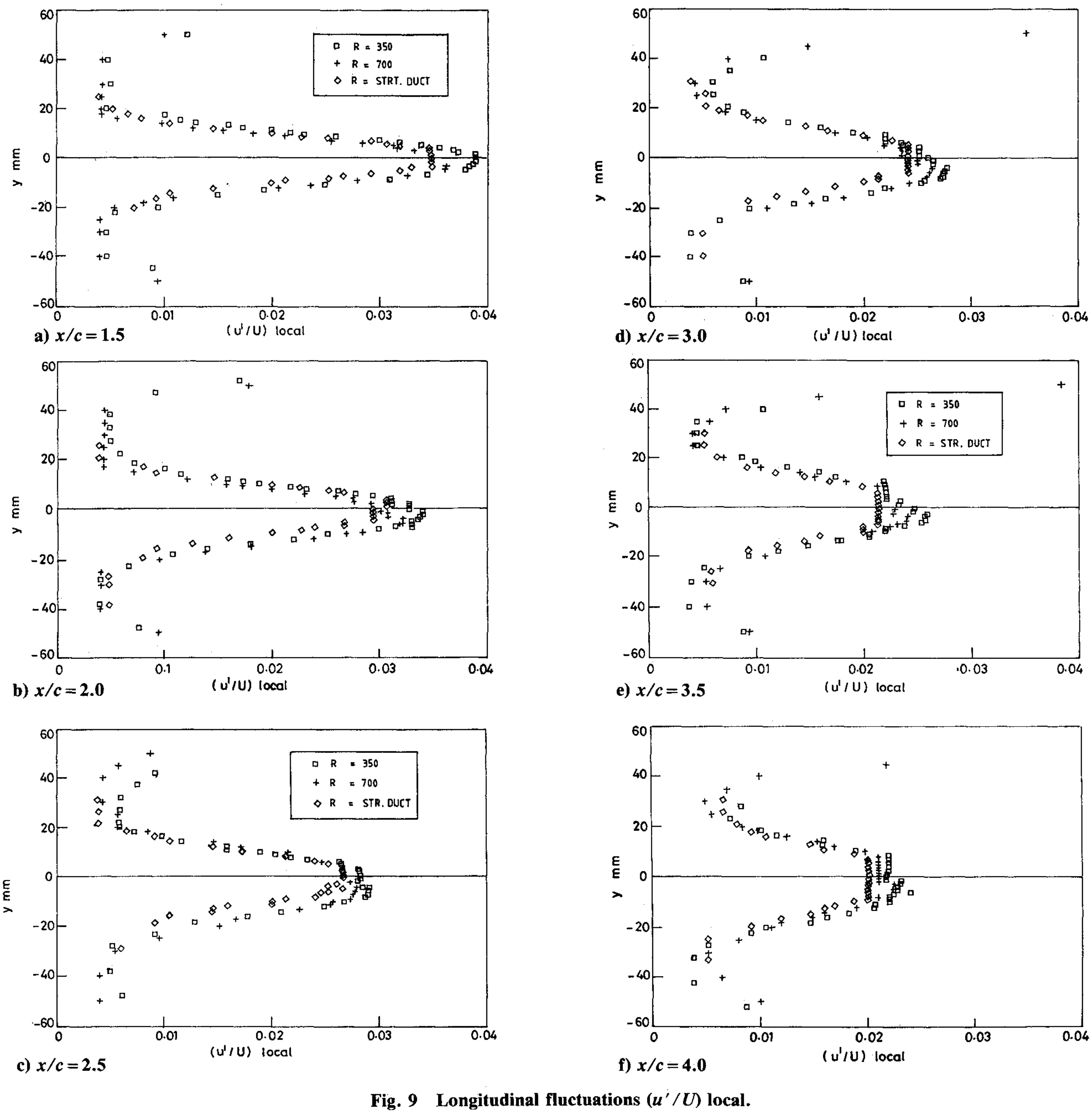


Fig. 9 Longitudinal fluctuations (u'/U) local.

Basing his work on the solution of the simplified form of the governing equations, he shows that, in the inner half, u' increases, v' deceases, and q^2 decreases, where q^2 is the turbulent kinetic energy. The present investigation indicates similar trends, but this needs to be investigated in detail.

Conclusions

Based on the development of the wake of an airfoil in a straight duct and in two curved ducts of radius of curvature $R=350$ mm and $R=700$ mm, the following observations can be made.

1) The mean velocity profile of the wake is asymmetric. The half width of the wake is more on the inner side of the curved duct than on the outer side. The wake defect w_0 is larger in a curved duct than in a straight duct and is also larger when b/R is higher.

2) The intensity of the longitudinal turbulent fluctuations are increased on the inner side of the curved duct. There is not much change on the outer side.

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