Velocity Correlation Structure in the Turbulent Near Wakes of Bluff Bodies

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Two-point space correlations of streamwise fluctuations have been measured in the turbulent near wakes of two-dimensional bluff body models like 90-deg wedges, circular and rectangular cylinders in the Reynolds number range of 2×10^4 to 10^5. Two single hot-wire probes operated by constant temperature anemometers were used for this purpose. The data show that the streamwise, lateral, and spanwise extents of eddies, in general, are larger in the free shear layer region compared to the centerline region of the turbulent near wakes. Integral scales increase with distance downstream. In particular, the streamwise and lateral integral scales increase linearly with distance after about 1.5 times the diameter or base height of the model. For 90-deg wedge models of different BR up to 25%, the correlation curves show similarity when length scale is nondimensionalized with the base height. The correlation curves for one BR models of different bluffness also indicate approximately similar trends. Hot-wire traces show intermittency between laminar and turbulent states in the region of free reattachment point for all two-dimensional models.

Nomenclature

BR	= blockage ratio
C_{pb}	$= (p_b - p_\infty)/\frac{1}{2}\rho U_\infty^2$ = base pressure coefficient
d	= diameter or base height
e	= hot-wire voltage fluctuation
$\hat{L}_{X_i}$	$= \int_0^\infty R_{uu}(\hat{X}, \hat{X}_i)\, d\hat{X}_i$ = dimensionless integral scale
p_b	= base pressure
p_∞	= freestream static pressure
$R_{uu}(\hat{X},\hat{X}_i)$	$= \langle u(\hat{X})u(\hat{X}+\hat{X}_i)\rangle / \langle u^2(\hat{X})\rangle^{1/2}\langle u^2(\hat{X}+\hat{X}_i)\rangle^{1/2}$
u	= streamwise velocity fluctuation
U_∞	= free stream velocity
X	$= Xi + Yj + Zk$
$\hat{X}_i$	$= X_i/d$
ρ	= density of the fluid
$\hat{\lambda}_{X_l}$	= streamwise wavelength as the distance between the first two peaks of $R_{uu}(\hat{X},\hat{X}_l)$
τ	= time delay
$\langle\ \rangle$	= ensemble average

Subscripts

1	= station 1
2	= station 2
i	= 1,2,3

Superscripts

$(\hat{\ })$	= dimensionless lengths made nondimensional with d

I. Introduction

REVIEW papers by Morkovin,[1] Marris,[2] Roshko,[3] Berger and Wille[4] provide an excellent introduction to the variety of incompressible flow phenomena which appear in the near wake region of a bluff body as a function of Reynolds number. Similarity characteristics of mean flow properties in the turbulent near wakes have been investigated experimentally by Calvert[5] for axisymmetric models and by Sullerey et al.[6] for two-dimensional bluff body models. The present work is a report of data on streamwise velocity correlation structure measured in the turbulent near wakes of two-dimensional bluff body models.

At Reynolds number of about 10^4, the turbulent near wake of a bluff body is a region of high turbulence intensities coupled with unsteadiness of flow due to vortex shedding. The mean flow recirculation region extends to about 2-diam downstream of the base, forming a bubble-like cavity as shown by the broken lines (zero streamline) in Fig. 1 for a wedge. The static pressure varies in this bubble-like region with the minimum appearing on the centerline at about 1 diam downstream of the base. Turbulent vortices are formed one at a time in the recirculation region and are shed alternately from the upper and lower sides of the model. Since the high-intensity turbulence in this region is anisotropic and inhomogeneous, the measurements of mean flow properties like static pressure, mean velocity and turbulence intensities using conventional probes and techniques are susceptible to errors. As pointed out by Hinze,[7] Siddon,[8] Becker and Brown,[9] the estimation of these errors requires a knowledge of eddy sizes in the recirculation region. Furthermore, to get more insight into the turbulence structure in the near wakes, data on two-point velocity correlations are desirable.

The objective of the present experiments was to measure two-point velocity correlations of streamwise fluctuations in the three orthogonal coordinate directions by means of two single hot-wire probes traversed in the recirculation region of three bluff body two-dimensional models. These wooden models each of 5% blockage ratio were a circular cylinder, a 90-deg wedge, and a rectangular cylinder with a width to height ratio of 0.6. Blockage ratio (BR) also was varied up to 25% in the case of the 90-deg wedge, and considerble data on space correlations were obtained for the 25% BR model of a 90-deg wedge.

II. Apparatus and Experimental Procedure

The experiments were conducted at one wind speed of 10 m/sec in an open-circuit low-speed wind tunnel of test section size 0.6×0.6×3 m. The turbulence level measured with a single hot wire was about 0.2% at this wind speed. Based on the diameter or base height of models, the Reynolds numbers turned out to be 2×10^4 for 5% BR models and 10^5 for a 25%

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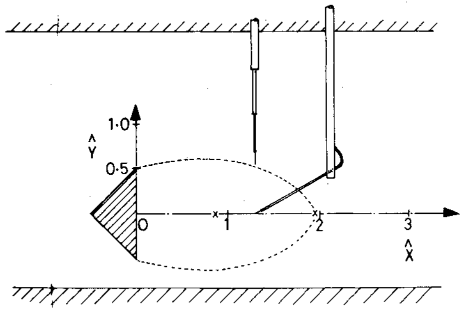

Fig. 1 Geometry of turbulent near wake.

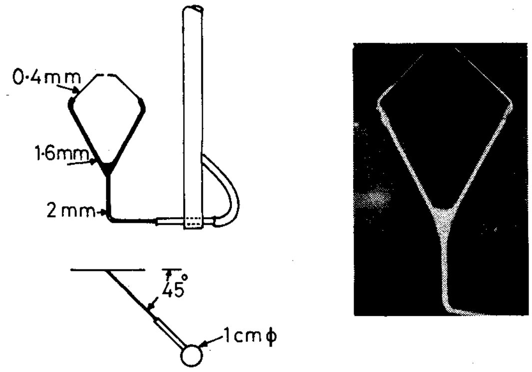

Fig. 2 Pentagon-shape probe.

BR wedge. The bluff body models were located at a downstream distance of 120 cm from the test section inlet and were instrumented with suitably spaced pressure taps of 1.5-mm diam for base pressure measurements.

Wollaston platinum wires of diam 12.5μ and 1.5-3 mm etched lengths were soft soldered to relatively thick stem hot-wire probes whose schematic views are shown in Figs. 1 and 2. The pentagon-shape hot-wire probe shown in Fig. 2 was found particularly suitable as an upstream probe for streamwise correlation measurements with little interference to the downstream hot-wire probe.

A three translational degrees-of-freedom traversing mechanism was used to traverse one of the hot-wire probes in the three coordinate directions. This traversing mechanism was fitted with three reversible 5-digit mechanical counters which provided the Cartesian coordinates of the moving probe with an accuracy of 0.125, 0.05, and 0.05 mm in the streamwise, spanwise, and vertical directions, respectively. The traverses were made monotonically in one direction to minimize backlash errors.

The instrumentation included two DISA 55 A01 constant temperature hot-wire anemometers, a DISA 55 A06 correlator, and a Tektronix dual-trace 545 B oscilloscope. A cathetometer of accuracy 0.01 mm was used to position the probes initially and to measure small vertical distances between the two hot wires.

Correlation Measurements in Inhomogeneous Turbulence

The two-point space-time velocity correlation coefficient in a turbulent flow is defined as[7,10]

$$R_{u_1 u_2}(X_1,X_2,\tau)=\frac{\langle u_1(X_1,t)u_2\ (X_2,t+\tau)\rangle}{\langle u_1^2(X_1)\rangle^{1/2}\langle u_2^2(X_2)\rangle^{1/2}}$$

where X_1 and X_2 are the position coordinates of two points in the flowfield; u_1 and u_2 are the fluctuating velocity components at points X_1 and X_2, respectively; and τ is the time delay. The symbol $\langle\ \rangle$ in the preceding expression indicates the ensemble average. For the present investigation where streamwise velocity fluctuations u were measured without time delay the preceding definition simplifies to the form

$$R_{uu}(X_1,\ X_2)=\frac{\langle u(X_1)\ u(X_2)\rangle}{\langle u^2(X_1)\rangle^{1/2}\langle u^2(X_2)\rangle^{1/2}}$$

or

$$R_{uu}(X,\ X_i)=\frac{\langle u(X)u(X+X_i)\rangle}{\langle u^2(X)\rangle^{1/2}\langle u^2(X+X_i)\rangle^{1/2}}\ ;\ i=1,2,3$$

where $X=Xi+Yj+Zk$ denotes the Cartesian coordinate of the fixed probe, and X_1, X_2, X_3 are the distances traversed by the moving probe measured with respect to X in the streamwise, lateral, and spanwise directions, respectively.

Hinze[7] has developed the following expression for the correlation coefficient in terms of hot-wire voltage fluctuations e_1 and e_2 corresponding to the two points X and $X+X_i$ by assuming a linearized relation between instantaneous velocity and voltage fluctuations:

$$R_{uu}(X,X_i)=\frac{\langle(e_1+e_2)^2\rangle-\langle(e_1-e_2)^2\rangle}{4\langle e_1^2\rangle^{1/2}\langle e_2^2\rangle^{1/2}}$$

This is valid for inhomogeneous turbulent flow and for unequal hot-wire sensitivities. In case of homogeneous turbulent flow with unequal hot-wire sensitivities, the foregoing expression takes a simpler form.

For an inhomogeneous turbulent flowfield, the shape of the correlation curve $R_{uu}(X_1,\ X_2)$ will depend not only on (X_2-X_1), but also on X_1. Since the turbulent near wakes for all of the present models are symmetric about the centerline of the wake, the fixed probe has been traversed on the centerline corresponding to $Y/d=\hat{Y}=0$, and in the upper free shear layer at $\hat{Y}=0.54$ at the midspan station $Z=0$. The fixed probe has been located, in general, at $X/d=\hat{X}=0.5$, 1.10, 1.5, and 2.0 so as to restrict our attention to the recirculation region.

III. Results and Discussion

The coordinate system adopted for presenting the data is shown in Fig. 1. An indication of two dimensionality of the near wake mean flow is obtained by plotting base pressure coefficient C_{pb} as a function of dimensionless spanwise coordinate $\hat{X}_3$. This is shown for four models in Fig. 3, where C_{pb} is observed to be constant within about 5% for the central three diameters of 25% BR models, and for the central five diameters of 5% BR models. The magnitudes of C_{pb} for different models as well as their variation trend with bluffness and blockage are in good agreement with the data of Sullerey et al.[6]

A. Correlations

Typical Correlations for a 25% BR 90-deg Wedge

Because of its large base height of 15 cm and consequent relative accuracy of positioning the probes, detail measurements of correlation coefficients were carried out first

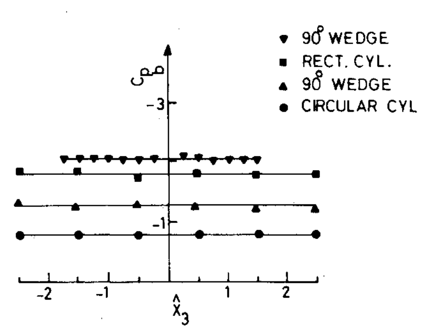

Fig. 3 Base pressure coefficient C_{pb} distribution for different models.

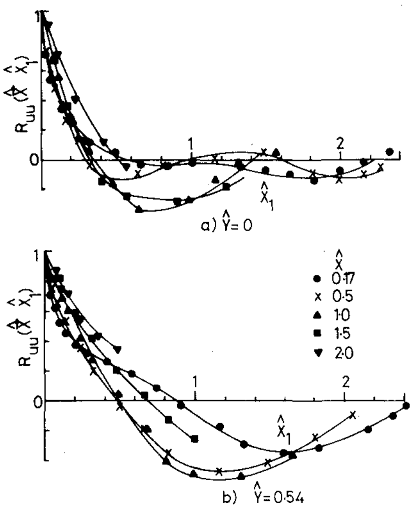

Fig. 4 Streamwise correlation $R_{uu}(\hat{X},\hat{X}_1)$ vs $\hat{X}_1$ for a 25% BR 90-deg wedge.

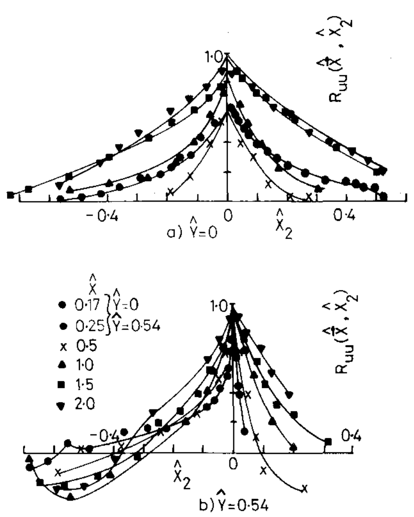

Fig. 5 Lateral correlation $R_{uu}(\hat{X}, \hat{X}_2)$ vs $\hat{X}_2$ for a 25% BR 90-deg wedge.

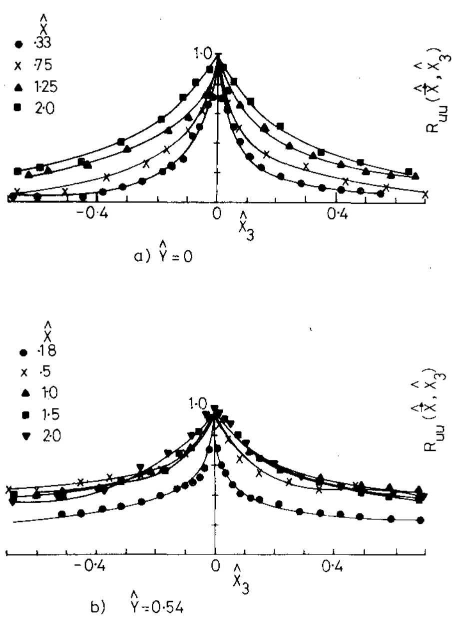

Fig. 6 Spanwise correlation $R_{uu}(\hat{X}, \hat{X}_3)$ vs $\hat{X}_3$ for a 25% BR 90-deg wedge.

in the turbulent near wake of this model. A small sample of these typical correlation curves is presented in Figs. 4-6.

Fig. 4a shows the plot of $R_{uu}(\hat{X},\hat{X}_1)$ vs $\hat{X}_1$ for five values of fixed probe locations $\hat{X}$ along the centerline of the wake $\hat{Y}=0$. The shape of the correlation curve corresponding to $\hat{X}=0.17$, $\hat{Y}=0$ indicates that the u fluctuations in the recirculation region are anticorrelated on either side of the low-pressure trough region. Farther downstream, corresponding to fixed probe locations of $\hat{X}=0.5$ and 1, an eddy of streamwise wavelength of about 1.5 diam seems to appear which grows in length further downstream. In the free shear layer region, $\hat{Y}=0.54$, the streamwise wavelengths clearly are longer than those on the centerline region as shown in Fig. 4b.

The lateral correlation curves, $R_{uu}(\hat{X}, \hat{X}_2)$ vs $\hat{X}_2$ at $\hat{Y}=0$, and 0.54 are shown for five $\hat{X}$ locations in Figs. 5a and 5b. The symmetry nature of $R_{uu}(\hat{X}, \hat{X}_2)$ about $\hat{Y}=0$ is evident in Fig. 5a. Apparent small deviations from symmetry are within the experimental errors. The data corresponding to $\hat{Y}=0$ also indicate that the eddy lateral extent first decreases up to about the low-pressure trough location and then increases for values of $\hat{X}$ farther downstream. In the free shear layer region at $\hat{Y}=0.54$, the lateral correlation curves are distinctly asymmetric. For $\hat{X}_2>0$, the correlation curves in Fig. 5b spread out monotonously as $\hat{X}$ increases, indicating the increase in eddy lateral size in the interface region. For $\hat{X}_2<0$, the eddy lateral size seems to decrease with $\hat{X}$ at first, possibly up to the low-pressure trough location, and then increases for larger values of $\hat{X}$ farther downstream. The out-of-phase nature of u fluctuations due to alternate vortex shedding is clearly evident for $\hat{X}\geq 1.0$ locations in Fig. 5b, and is in agreement with Robert's observations.[11]

The symmetry of spanwise correlation curves $R_{uu}(\hat{X}, \hat{X}_3)$ vs $\hat{X}_3$ is observed in Figs. 6a and 6b as expected at both $\hat{Y}=0$, and 0.54. The spanwise correlation extents are also longer in the free shear layer region than at $\hat{Y}=0$, just as for $R_{uu}(\hat{X}, \hat{X}_1)$. Furthermore, Fig. 6b shows that the spanwise correlation extents in the free shear layer region increase very slowly for $\hat{X}\geq 0.5$.

Typical Correlations for 90-deg Wedges of Different BR

These correlations are shown in Figs. 7-9. Except for the fixed probe location $\hat{X}=0.5$, the correlation curves $R_{uu}(\hat{X}, \hat{X}_1)$ vs $\hat{X}_1$ for different BR models coincide with one another. This is true for both the centerline and the free shear layer regions of the turbulent near wake. Similar trends in correlation data $R_{uu}(\hat{X}, \hat{X}_2)$ vs $\hat{X}_2$, and $R_{uu}(\hat{X}, \hat{X}_3)$ vs $\hat{X}_3$ for different BR models at $\hat{X}=1.0$, 2.0, and $\hat{Y}=0$, 0.54 are observed in Figs. 8 and 9.

Typical Correlations for Different Models of 5% BR

The lateral and spanwise correlation curves for circular and rectangular cylinders were found to be more or less similar to those of a wedge, and therefore are not presented. The streamwise correlation curves $R_{uu}(\hat{X}, \hat{X}_1)$ vs $\hat{X}_1$ for the three bluff body models, however, did not coincide on a single curve because the λ_{X_1} for different models was found to be different as shown in a later figure.

B. Integral Scales

The dimensionless integral scales were computed by graphical integration of the correlation data of Figs. 7-9 using the following relation:

$$\hat{L}_{X_i}(\hat{X})=\frac{L_{X_i}}{d}=\int_0^\infty R_{uu}(\hat{X}, \hat{X}_i)\, d\hat{X}_i;\; i=1,2,3$$

For convenience in computing, the upper limit infinity in the integral was replaced by that location of $\hat{X}_i$ where the $R_{uu}(\hat{X}, \hat{X}_i)$ crossed the abscissa for the first time. In cases

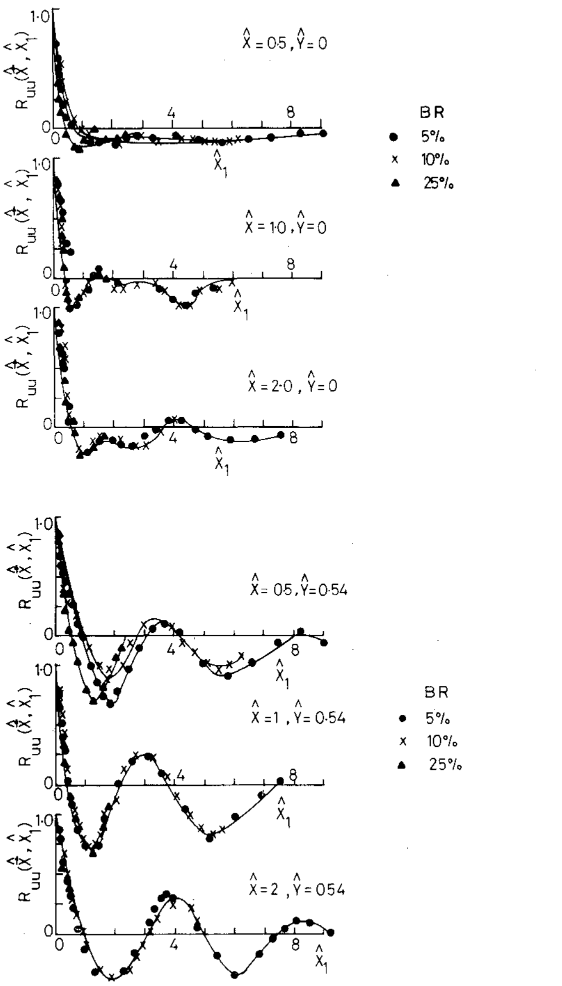

Fig. 7 Streamwise correlation $R_{uu}(\hat{X},\hat{X}_I)$ vs $\hat{X}_I$ for 90-deg wedges of different BR.

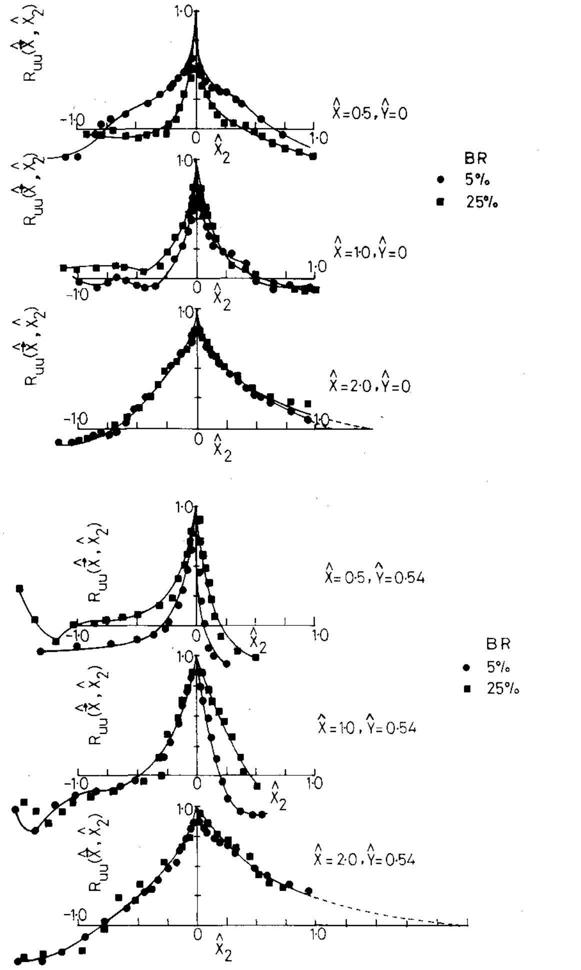

Fig. 8 Lateral correlation $R_{uu}(\hat{X}, \hat{X}_2)$ vs $\hat{X}_2$ for 90-deg wedges of different BR.

where data were insufficient, the correlation curves were extrapolated to intersect the $\hat{X}_i$ abscissa coordinate. This is indicated by broken lines in Figs. 7-9. The correlation curves $R_{uu}(\hat{X}, \hat{X}_I)$ vs $\hat{X}_I$ in Fig. 7 show strong oscillations due to the presence of turbulent Karman vortex street. In these cases, a dimensionless streamwise wavelength $\hat{\lambda}_{X_I} = \lambda_{X_I}/d$ has also been estimated as the axial nondimensional distance between the first two positive peaks of the correlation curves $R_{uu}(\hat{X}, \hat{X}_I)$.

Figure 10 shows the variation of $\hat{\lambda}_{X_I}$, $\hat{L}_{X_i}$; $i=1,2,3$ with distance downstream $\hat{X}_I$ up to $\hat{X}_I = 2.0$ for wedge models of different BR. Flagged symbols in the plot of $\hat{L}_{X_2}$ vs $\hat{X}_I$ indicate the integral scales corresponding to the upper part $(\hat{X}_2 > 0)$ of the correlation curves in Fig. 8. It is clear that eddy sizes are larger in the free shear layer region compared to the centerline region of the turbulent near wakes. The present data also show that $\hat{L}_{X_2}$ and $\hat{L}_{X_I}$ are about the same magnitude while $\hat{L}_{X_3}$ is several times greater than either $\hat{L}_{X_2}$ or $\hat{L}_{X_I}$. Thus, one can visualize large-scale, almost circular cross-section eddies in the X Y plane with an elongated extent in the spanwise Z direction.

Similar trends are observed for the integral scales in the turbulent near wakes of different models of 5% BR as shown in Fig. 11. Data of Fiedler and Wille,[12] who reported results of similar measurements on a truncated vertical circular cylinder, also are shown. A comparison shows that, while the present data for $\hat{L}_{X_I}$ and $\hat{L}_{X_2}$ are in reasonable agreement with Fiedler and Wille's data,[12] those of $\hat{L}_{X_3}$ differ by a large factor. The reason for these differences in L_{X_3} is the finite cylinder span in Ref. 12 compared to the two-dimensional cylinder in the present case. Figure 11 also indicates that the streamwise $\hat{L}_{X_I}$ and lateral $\hat{L}_{X_2}$ integral scales increase linearly with distance downstream after about 1.5 diam, in fair agreement with Fiedler and Wille's data.[12]

C. Intermittency Near the Free Reattachment Point

While carrying out the present experiments it was observed that the signal from a hot wire located on the centerline of the recirculation region about two base diameters downstream of the base showed the flow alternating between laminar and turbulent states. As mentioned by Bloor,[13] such intermittency was to be expected in the interface region of the turbulent near wake boundary. In the axisymmetric wakes behind disks and spheres, such intermittency on the centerline of the turbulent wake has also been reported in the far wake $\hat{X} = 200$ by Wang and Baldwin,[14] and in the region of $\hat{X} > 9$ by Gibson et al.[15] and Riddhagini et al.[16] In fact Gibson et al.[15] have suggested that a central continuous turbulent region for the sphere wake is at most confined to a small recirculation region just behind the sphere apparently for $\hat{X} \leq 9$.

In the present experiments, on the other hand, intermittency was observed on the centerline of the two-dimensional bluff body near wakes near $\hat{X} \simeq 2$. Evidence by means of two concurrent hot-wire traces is presented in the sequence of pictures shown in Fig. 12. The geometry of the setup for recording these traces is shown in Fig. 1. The upper trace in each picture is from the hot wire located at $\hat{Y} = 0.54$, while the lower trace is from the hot wire located on the centerline of the wake $\hat{Y} = 0$. In each picture, the value of $\hat{X}$ is the same for both the hot-wire signals, and increasing velocity is positive upwards. Both traces in Fig. 12 have approximately equal sensitivity which remains unchanged for all pictures.

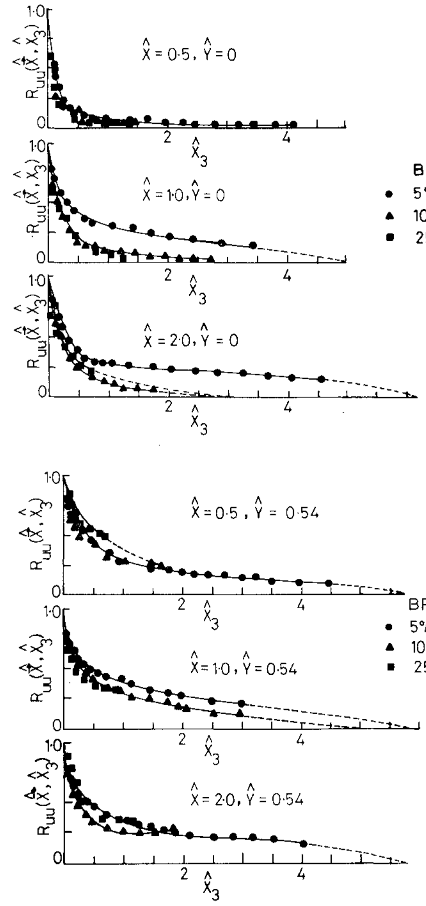

Fig. 9 Spanwise correlation $R_{uu}(\hat{X}, \hat{X}_3)$ vs $\hat{X}_3$ for 90-deg wedges of different BR.

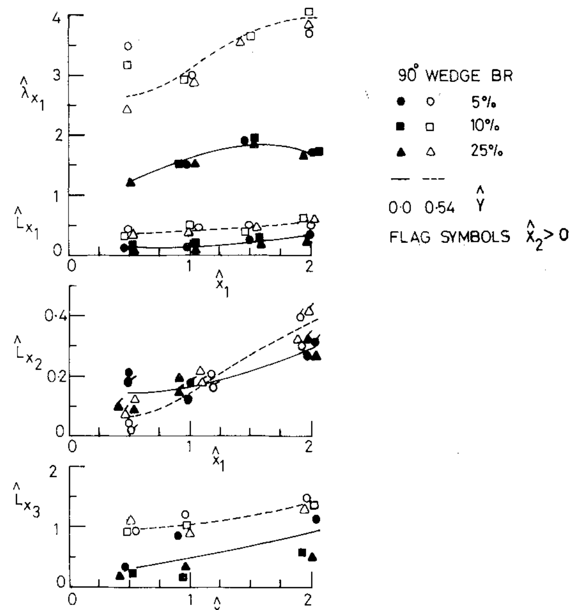

Fig. 10 Nondimensional integral scales for 90-deg wedges of different BR.

The sweep rate is 10 msec/cm and the horizontal length of a trace corresponds to 10 cm.

The upper trace corresponding to $\hat{X}=0.04$ in Fig. 12 shows that the separating boundary layer from the 25% BR 90-deg wedge contains high-frequency instability waves of the type mentioned by Bloor.[13] The lower trace, on the other hand, shows completely turbulent flow. As the wake width increases

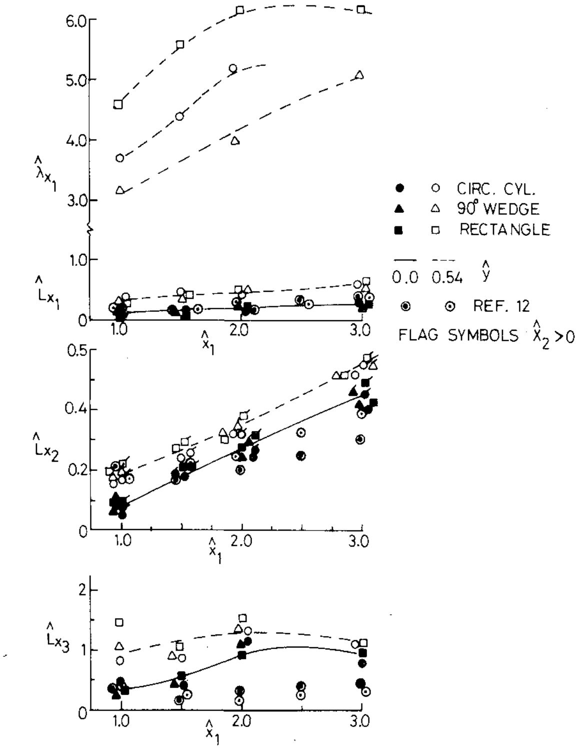

Fig. 11 Nondimensional integral scales for different models of 5% BR.

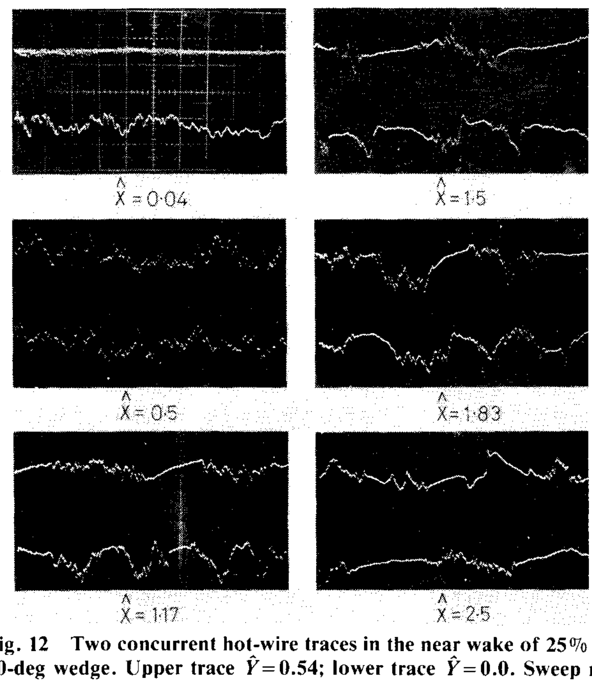

Fig. 12 Two concurrent hot-wire traces in the near wake of 25% BR 90-deg wedge. Upper trace $\hat{Y}=0.54$; lower trace $\hat{Y}=0.0$. Sweep rate 10 msec/cm.

for a value of $\hat{X}=0.5$, both of the hot wires are immersed in turbulent flow. At $\hat{X}\simeq 1.0$, which is the approximate location of low-pressure trough and the maximum wake width (Sullerey et al.[6]), short patches of laminar flow appear on the lower trace. For larger values of $\hat{X}$ the hot wire corresponding to the upper trace is in the region of diffuser-type outer flow, and the interface intermittency superimposed on the vortex shedding oscillations is evident. At the same time the lower trace displaying the signal from the centerline of the wake shows longer and longer regions of laminar flow alternating with turbulent flow. A crude estimate of the intermittency factor at $\hat{X}=2.0$ is about 0.5.

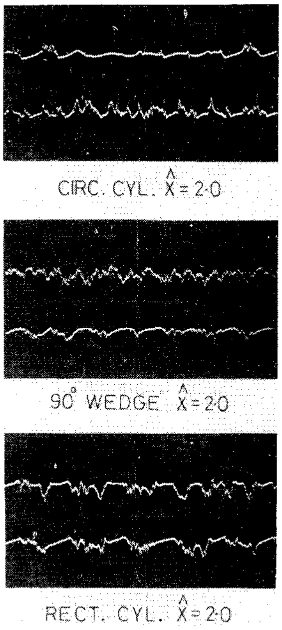

Fig. 13 Two concurrent hot-wire traces in the near wakes of 5% BR models. Upper trace $\hat{Y}=0.0$; lower trace $\hat{Y}=0.54$.

A streamwise traverse of a single hot wire located on the centerline of the wake showed that for this high BR model the intermittency persisted up to about $\hat{X} \simeq 6.0$, after which the flow was fully turbulent. It may be noted from Fig. 12 that laminar regions are in general higher momentum flow regions compared to turbulent regions, both on the centerline as well as on the interface. Similar evidence of intermittency for 5% BR models of rectangular and circular cylinders, and 90-deg wedge at $\hat{X} \simeq 2.0$ is presented in Fig. 13.

IV. Concluding Remarks

The present data on streamwise velocity correlation structure in the turbulent recirculation region of two-dimensional bluff bodies show that the streamwise, lateral, and spanwise extents of eddies are larger in the free shear layer region than on the centerline of the recirculation region. Eddy dimensions, in general, increase with distance downstream. The correlation curves for 90-deg wedges of different BR up to 25% show similarity when the length scale is nondimensionalized with the base height. A typical eddy shape in the recirculation region is approximately circular in the XY plane and is elongated in the spanwise Z direction. Insofar as the vortex formation and growth in the recirculation region is a dynamic phenomenon, space time-delay correlations are expected to provide more insight into the velocity correlation structure.

While the hot-wire traces presented in the foregoing provide evidence that the intermittency exists near the free reattachment point of the recirculation region of two-dimensional bluff bodies, it is important to measure the intermittency factor quantitatively. As demonstrated by Corrsin and Kistler,[17] who used an analog method of measuring the intermittency factor, and also by Kaplan and Laufer,[18] who employed digital data processing techniques, it is not an easy problem to measure the correct intermittency factor. The difficulty arises in the correct detection of the start and the end of turbulent regions. More definitive results are required to know the extent of persistence of intermittency on the centerline of the wake further downstream of the free reattachment point.

Acknowledgment

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