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The Structure of a Turbulent Wake behind
a Cruciform Circular Cylinder*
(1st Report, The Mean Velocity Field)

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The mean velocity field of a turbulent wake behind a cruciform circular cylinder which is composed of two sufficiently long circular cylinders is examined experimentally. The measurements were performed for the surface pressure distributions on the cruciform circular cylinder and the mean velocity profiles in the wake at a number of downstream stations in a wide range of $x/d = 3$ to 594 .

It is revealed that the decay rate of centerline velocity defect is considerably slower, while the rate of growth of the half-width for the $y=z$ plane of the present wake is very close to that of a two-dimensional wake. In the center region of the wake of the cruciform shape, secondary flows are observed and the magnitude of the flow is measured. The drag coefficient of the cruciform circular cylinder almost agrees with that of the equivalent two-dimensional circular cylinder.

Key Words: Turbulence, Wake, Cruciform Body, Mean Velocity, Drag

1. Introduction

A flow around a cruciform circular cylinder, which consists of two effectively long circular cylinders with the same diameter, seems to be peculiar having no generality, but it can be considered that this flow field gives one of the basic flow patterns concerning the flow around the heat exchanger, the damping screen and various on-shore and off-shore structures. We have recognized the significance of a research on the three-dimensional flow field appearing often in practice through an experiment⁽¹⁾ of a flow around an artificial reef model. The purpose of this paper is to make clear the mean flow property of a turbulent wake in a wide range from the vicinity of the cruciform circular cylinder to far downstream flow region.

So far many investigations⁽²⁾⁽³⁾ on two-dimensional and axisymmetric wakes have been performed, and it is well known that the streamwise development of these two types of the wakes is different, for instance, Reynolds number based on both the maximum velocity defect and the half-width is constant for the two-dimensional wake but proportional to the $-1/3$ power of the streamwise distance for the axisymmetric wake. Although there exist a number of

prediction methods for these flows, a well-established one is yet unavailable⁽⁴⁾. The investigations on the three-dimensional wake in a free stream are hardly found, although there are some studies⁽¹³⁾⁽¹⁴⁾ on the three dimensional wake with respect to the drag coefficient and the effect of both the tunnel-wall blockage and the boundary interference, except for one by Kuo-Baldwin⁽⁵⁾ who examined the wake of an elliptic plate, and YxahoBa⁽⁶⁾ who investigated the wakes of a short length circular cylinder and a cruciform circular cylinder with the finite length. It is reported that the decay rate of the velocity defect on the wake center line of the cruciform circular cylinder with the finite length coincides with that of the axisymmetric wake. This result means that the three-dimensional wake behind an obstacle with the finite length resembles the axisymmetric wake in a far downstream region.

The present investigation deals with the wake of a cruciform circular cylinder of which the length is effectively infinite, so that the present wake exhibits three-dimensionality near the wake center as the result of the interference due to the cylinders, while it approaches the two-dimensional wake at a location away from the center region.

In this paper the measurements of the development of the mean velocity field, the characteristic scale of the present wake, the identifying method of the specific region based on the interference of the cylinders and both the pressure distribution and the drag coefficient acting on the cylinder are reported.

Nomenclature (see Fig.1)

x : distance in the streamwise direction
from the origin of a cruciform
circular cylinder

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- y, z : distances along two-cylinder axes from the origin
 y' : distance along the $y = z$ plane from the origin
 U, V, W : mean velocity components in the x , y and z directions, respectively
 U_1 : free stream velocity
 U_d : mean velocity defect ($=U_1 - U$)
 U_{d0} : mean velocity defect on the x axis (maximum velocity defect)
 U_{d2} : maximum velocity defect in the two-dimensional wake region
 $b_{y'}$: half-width for the $y = z$ plane
 b_2 : half-width for the two-dimensional wake region
 $l_y, l_{y'}$: length scales defined by Townsend, Eqs. (2), (3)
 d : diameter of the cruciform circular cylinder
 θ : angle measured clockwise from the front stagnation point
 p' : local static pressure
 p_a : atmospheric pressure
 p : local surface pressure on a circular cylinder
 p_0 : free stream pressure at $x = -207$ mm upward of the cruciform circular cylinder
 C_d : local drag coefficient, Eq. (5)
 C_D : mean drag coefficient of the cruciform circular cylinder, Eq. (9)

2. Experimental Apparatus and Techniques

The wind tunnel used in the present experiment has a contraction exit of 0.4 m square, as shown in Fig. 2. The working section made of transparent acrylic resin plate is about 4 m long, whose cross-sectional area is enlarged in the downstream direction by the amount of the boundary layer displacement thickness, and one of the side walls is an adjustable roof to give a zero pressure gradient. The intersecting cruciform circular cylinder consists of two sufficiently long brass cylinders 5 mm diameter and 400 mm length, and it is mounted stationarily in the mid test section against the free stream at the section of 365 mm downstream from the entrance of the working section. The circular cylinder with y axis has a hole of 0.5 mm diameter to measure the pressure distribution on the cylinder surface. The pressure distribution was measured by rotating the cylinder with y axis and then displacing the pressure hole in the spanwise slice relative to the cylinder with z axis, with attention paid to the contact part between both cylinders. The distribu-

Fig. 1 Configuration of flow field and coordinate system

tions of mean velocities U and static pressures p' were measured with a pitot-static tube of 2.5 mm outer diameter. The main measurement of the mean velocity was carried out at 8 stations in the range of $x/d = 15$ to 475, in the range of $|y/d|, |z/d| \leq 30$. The mean velocities V, W were measured by a five-hole pressure probe of 2.4 mm outer diameter which was made of five stainless tubes of 0.8 mm outer diameter. The yaw angle of flow was determined by the pressure difference method using a calibration curve examined in advance. The measurement of V - and W - components was limited to the upstream region where the magnitude of the secondary current was relatively appreciable. In order to confirm the existence of the secondary flows a windmill was used with three blades which were made of a scotch tape with 7 mm length, 6 mm width and 0.2 mm thickness. The rotating speed (rpm) of the windmill was measured by counting the intermittent signals which were given when the blade passed through between a luminous diode and a photo transistor. Only in the measurement by use of the windmill, a cruciform circular cylinder of 10 mm diameter was mounted in the free stream ($R_d = 8 \times 10^3$), taking account of the dimension of the windmill. Reynolds number $R_d = U_1 d / \nu$ was kept constant at 4×10^3 in almost all measurements, the turbulence intensity of the free stream being about 0.35 % at the exit of the contraction. The difference between the basic velocity at the location, several times diameters upward from the cruciform cylinder, and the free stream velocity U_1 was within ± 1 %.

3. Experimental Results and Discussion

3.1 Overall flow field

At first, in order to understand the feature of the cruciform circular cylinder wake, the mean velocity defect profiles on both the $y = z$ plane (left hand side) and the $z = 0$ plane (right hand side) are shown in Fig. 3. The velocity defect profiles on the $z = 0$ plane show a kind of saddle-back shape which has a peak value at the vicinity of $y/d = 8$ in a relatively upstream region. In the range of $x/d > 100$, however, these profiles take a monotonous shape that shows a maximum value at the wake center and gradually approaches the two-dimensional value with an increasing y/d . On the other hand, the velocity defect profiles on the $y = z$ plane take a maximum value at the wake center and decrease monotonously to zero with an increasing y'/d . As described above, the

Fig. 2 Wind-tunnel used for the present experiment

velocity profiles on both the $y=z$ plane and the $z=0$ plane do not agree with each other and are different from the velocity profile of the axisymmetric wake near the wake center even in the far downstream region of $x/d \geq 300$. Both profiles on the $y=z$ plane and the $z=0$ plane however seem to become a proper shape respectively in the far downstream region, therefore a kind of self-preservation may be expected.

Fig.4 shows a streamwise variation of the pressure coefficient, $C_p = 2(p' - p_a) / \rho U_0^2$. The static pressure distribution in the free stream is about constant. On the other hand, at the wake center in the range of $x/d \leq 100$ occurs a recovery process from the negative value behind the cruciform circular cylinder to the constant value in the free stream. In the downstream region from this section, C_p is about constant within an experimental scatter of $\pm 0.5\%$.

3.2 Contours of the mean velocity

Fig.5(a) to (c) show the contours of the mean velocity defect in the y - z plane at the sections of $x/d = 30.5$, 90.5 and 298.5 respectively. These results were obtained from the measurements at 609 to 1524 points in the cross section. The whole aspect of these profiles indicates that the symmetric crisscross shape remains stable even in the far downstream region, whereas a two-dimensional wake grows continuously at a sufficiently long distance from the wake center. Therefore, the identifying region of the cruciform circular cylinder wake is encircled with the two-dimensional wake regions. The streamwise enlargement of this specific region changes gradually, and hence is different from that of the whole flow field of the present wake. At the section of $x/d = 30.5$, the velocity defect profile takes a maximum value of $U_d/U_1 = 0.17$ at the wake center, and takes the same value as the wake center maximum value in the vicinity of $|y/d| = |z/d| = 8$ on the y and z axes. The present wake, therefore, has a so-called eye of iso-

Fig.3 Mean velocity defect profiles for the $y=z$ plane (left hand side) and the $z=0$ plane (right hand side)

Fig.4 Streamwise variation of the static pressure coefficient

vels at these positions on both cylinder axes and the velocity defect profile shows a kind of saddle-back shape. In addition, in the corner region of the cruciform circular cylinder wake, isovels distort towards the wake center along the $y=z$ plane, therefore it is evident that there exist a secondary current which agrees with that found in the corner region of the duct flow. At $x/d = 90.5$, the value of U_d/U_1 at the wake center decreases to 0.11, but isovels still show the saddle-back shape on both cylinder axes that is found in the upstream region. The distortion of the isovels in the corner region of the crisscross shape is still observed. Furthermore, in the far downstream section of $x/d = 298.5$ the velocity defect becomes small and isovels become gentle.

Fig.5 Contours of the mean velocity

Though not shown in the figure, an eye of isovels was observed until the section of $x/d = 150.5$.

The existence of the saddle-back profile is not limited only to the present flow field, and this trend is also recognized in the cases of an elliptic plate wake by Kuo-Baldwin⁽⁵⁾ and rectangular jets by Sforza et al.⁽⁷⁾ and Sfeir⁽⁸⁾. This characteristic shape for the elliptic plate wake, however, disappears in the downstream region at a distance of about 80 times the equivalent diameter of an ellipse and at about 30 times the short axis of a rectangular orifice for the rectangular jet, and so the variation of these flow fields is fairly rapid compared with the present wake.

Next, in order to confirm the existence of the secondary flow conjectured from the distortion of isovels in the corner region, the measurements of the directional angle of the mean velocity by means of a five-hole pressure tube were performed. Fig. 6 shows the secondary flow vectors obtained from the V- and W- components of the mean velocity at $x/d = 30.5$. It is clear from this figure that this secondary current distorts the isovels towards the wake center along the $y = z$ plane and has a maximum value of about 4 % of U_1 on the $y = z$ plane. This distortion of isovels, however, decays as the flow field develops towards downstream.

Futhermore, both the directions and the number of revolutions of the small windmill were measured at $x/d = 12$ in order to understand the whole aspect of the secondary flow.

Fig. 6 Secondary flow vectors

Fig. 7 Number of revolutions of the windmill

These results are shown in Fig. 7. The features of the secondary currents agree quite well with those estimated from the distortion of isovels and the velocity vectors described above. In other words, there exist the vortices which are symmetric with respect to the geometrically symmetric planes of the flow field and their direction turns inwards on the bisector. This secondary flow is regarded as a secondary current of the second kind classified by Prandtl. Applying the equation which Gessner⁽⁹⁾ has proposed on the occurrence of the secondary flow to the $y = z$ plane for the present wake, we have obtained satisfactory results that the flows point towards the wake center on the $y = z$ plane.

Now, let's estimate the profile function of velocity defect based on the experimental results in the range of $x/d \geq 300$. Supposing that the velocity profile approaches the two-dimensional profile at the locations of both large value of y and z , and approximately becomes an axisymmetric profile near the wake center, and considering a well known solution for both two-dimensional and axisymmetric wakes and the boundary conditions at the wake center ($y = z = 0$), the following equation is obtained,

$$f = \frac{1}{2+\gamma} (e^{-(\alpha/2)\eta^2} + e^{-(\alpha/2)\zeta^2}) + \frac{\gamma}{2+\gamma} e^{-(\alpha/2)(\eta^2+\zeta^2)} \dots\dots(1)$$

where $f = U_d/U_{d0}$, $\eta = y/l$, $\zeta = z/l$, and α and γ were determined from the experimental results on the local cross section.

Fig. 8 shows the comparison of Eq. (1) with the experimental results at the section of $x/d = 475$ that is the last location measured in the present experiment. In this figure, $l = b_y/\sqrt{2}$, and α is decided as $f = 0.5$ when $y/b_y = 1$ on the $y = z$ plane and γ is also decided as $\gamma = C_1 l y/d$ ($C_1 = -0.075$ from the experimental results). It is clear that

Table 1 Values of α and γ for Eq. (1)

x/d	α	γ
298.5	1.93	-0.67
386.5	1.88	-0.63
475.0	1.82	-0.58

Fig. 8 Comparison of Eq. (1) with the experimental result

Eq.(1) agrees reasonably well with the experimental results over the entire $y-z$ plane. Hence, it seems that Eq.(1) represents the velocity profile of the cruciform circular cylinder wake when choosing suitably the local constant values of α and γ . The constant values of α and γ chosen for the range of $x/d \geq 298.5$ are shown in table 1. Meanwhile the analytic solution of the self-preservation Reynolds equation did not agree with the experimental results.

3.3 Scales and flow field

Let's examine both the characteristic velocity and the length scales in the present wake.

Fig.9 shows the streamwise variation of U_{d0} and U_{d2} , and the straight line in the figure is determined by applying the method of least squares to the experimental data. U_{d0} decays as $x^{-0.37}$ in a wide range of $x/d \geq 30$. The rate of the decay is definitely slower than those of the two-dimensional and the axisymmetric wakes. In the upstream region to $x/d = 30$, U_{d0} decays monotonously from $U_{d0}/U_1 = 1$ at $x/d \approx 6$ which is equivalent to the boundary of separation bubble. On the other hand, U_{d2} decays as $x^{-0.45}$ beyond $x/d = 30$. The rate of the decay agrees

Fig.9 Velocity scale

Fig.10 Development of half-width

Fig.11 Length scale

with that in the two-dimensional circular cylinder wake by authors⁽¹⁰⁾. In the upstream region, U_{d2} decays monotonously from $x/d \approx 3$ which is equivalent to the boundary of separation bubble, but the tendency of the decay is slightly different from that of U_{d0} .

The result that the decay rate of U_{d0} is slower than that of U_{d2} indicates that the rate of the spread for the identifying region of the cruciform circular cylinder wake encircled with the two-dimensional wake region is small compared with that of the two-dimensional wake as previously described. The velocity defect on the center line in the cruciform circular cylinder wake with the finite length of aspect ratio 8 measured by YxaHoBa⁽⁶⁾ decays as nearly $x^{-2/3}$ in the region to $x/d = 40$, and so this wake has a similar property to the axisymmetric wake. Therefore, the structure of the present wake behind the cruciform circular cylinder of which the length is effectively infinite is different from YxaHoBa's wake, and approaches a new three-dimensional wake structure asymptotically.

Fig.10 shows the streamwise variation of the half-width. The half-width for the $y=z$ plane $b_{y'}$ increases as $x^{0.48}$ in a wide range of $x/d \geq 8$, and agrees quite well with that of the two-dimensional wake. b_2 increases as $x^{0.49}$ in the range of $x/d \geq 30$. Therefore, b_2 and U_{d2} almost take the same value as that of the two-dimensional wake.

Fig.11 shows the length scales proposed by Townsend⁽³⁾ which are exactly determined for the $y=z$ plane (the y' axis) and the $z=0$ plane (the y axis). The length scale are defined as

$$l_y^2 = \int \left(\frac{\partial U}{\partial y} \right) y^2 dy / \int \left(\frac{\partial U}{\partial y} \right) dy, \dots \dots \dots (2)$$

$$l_{y'}^2 = \int \left(\frac{\partial U}{\partial y'} \right) y'^2 dy' / \int \left(\frac{\partial U}{\partial y'} \right) dy', \dots \dots \dots (3)$$

As shown in the figure $l_{y'}$ increases as $x^{0.46}$ in the range of $x/d \geq 8$, and almost agrees with both the exponent and the magnitude of the half-width $b_{y'}$. Meanwhile l_y is larger than $l_{y'}$ by about three times, but has the same power as $l_{y'}$ in the range of $x/d \leq 30$. Up to $x/d = 300$ beyond $x/d = 30$, l_y has a constant value, hence the length scale for the $z=0$ plane hardly increases. Then,

Fig.12 Identifying region due to the interference between two cylinders

beyond about $x/d = 350$, $l_{y'}$ becomes larger than l_y . A reversal of the length scales with respect to the typical two axes is also observed in the cases of the three-dimensional flow field such as the elliptic plate wake by Kuo-Baldwin⁽⁵⁾ and the rectangular jet by Sforza et al.⁽⁷⁾.

In the next place, let's estimate the interfering region which expresses the characteristics of a three-dimensional structure due to the intersecting circular cylinder. Since the present wake can be split into the two-dimensional wake region at the locations with a large value of y and z , and the three-dimensional region near the wake center as previously described, these regions may be distinguished by the location of the velocity gradient in radial direction from the wake center. Fig.12 shows the identifying region encircled with Townsend's length scales in all the radial directions at the section of $x/d = 475$. Then, the scales were calculated using the velocity profile function(1), because of the experimental uncertainty. The extent of the interference region is almost equal in the range of $x/d \geq 298.5$, and this configuration distorts towards the wake center on both y and z axes. Isovels of $U_d/U_{d0} = 0.5$ shown in the figure are close to the outline of the interference region.

3.4 Similarity for the symmetric plane

The similarity of the mean velocity defect profile on both the $y=z$ plane and the $z=0$ plane is described below. Fig.13 shows the velocity profile for the $y=z$ plane.

Fig.13 Similarity of mean velocity for the $y=z$ plane

Fig.14 Similarity of mean velocity for the $z=0$ plane

The solid line is an empirical equation proposed by Townsend⁽¹¹⁾ for the two-dimensional wake;

$$\frac{U_d}{U_{d0}} = \exp[-0.6619 \left(\frac{y'}{b_{y'}}\right)^2 \{1 + 0.0465 \left(\frac{y'}{b_{y'}}\right)^4\}] \quad \dots\dots\dots (4)$$

The dotted line indicates Eq.(1) with constant values of α and γ at $x/d = 475$. The velocity profiles are quite similar in all the range of $x/d \geq 90.5$, and agree quite well with both Eq.(1) and Eq.(4). Furthermore, this similarity profile also agrees with that of the axisymmetric wake by Chevray⁽¹²⁾. On the other hand, Fig.14 shows the velocity defect profiles for the $z=0$ plane. These profiles are very complicated in the entire region, but in the far downstream region of $x/d \geq 298.5$ they become almost similar and agree with Eq.(1) with a suitable value of α . Therefore, the mean velocity profiles of the present wake seem to become similar beyond about $x/d = 300$, but can not be expressed using a solution of the self-preservation as previously described. The profile for the two-dimensional region can be represented by Eq.(4) of Townsend.

3.5 Surface pressure distribution around the circular cylinder and drag coefficient

It is expected that the pressure distribution on the cruciform circular cylinder surface is closely related to the surrounding flow field, and that this profile has a characteristic tendency. Fig.15 shows the distribution of the pressure coefficients $C_p = (p - p_0)/(1/2)\rho U_0^2$ on the surface of a circular cylinder at constant y/d . The solid line in the figure shows the experimental result of the two-dimensional circular cylinder wake by authors⁽¹⁰⁾. At the constant plane of $y/d = 0.6$ very close to the z axis cylinder, the variation of C_p becomes gentle as θ increases. θ is measured clockwise from the front stagnation point. The angle of

Fig.15 Pressure distribution on the circular cylinder surface

$C_p = 0$ moves to near $\theta = 50$ deg., since C_p is directly affected by the z axis. In addition, the angle of the minimum pressure almost coincides with that of the two-dimensional cylinder, but both the minimum pressure coefficient and the back pressure coefficient are fairly high. In other words, it is supposed that the pressure in the separation bubble near the intersection of two cylinders is high. This phenomenon seems to be closely related to the secondary flows in the corner region of the present wake described above. Such a tendency at the plane of $y/d = 1$ has a close resemblance to that of $y/d = 0.6$ plane. At $y/d = 2$, the variation of C_p is the largest. Although the C_p distribution up to the angle of the minimum C_p agrees with that of the two-dimensional cylinder, both the minimum and the back pressure coefficient are fairly smaller than those of the two-dimensional cylinder. At the planes of large y/d , the C_p distributions become similar to that of the two-dimensional cylinder again. Since the angle of the minimum pressure occurs in the vicinity of $\theta = 75$ deg. at all y/d planes, it is likely that the flow on the cylinder separates in the state of laminar flow.

Fig. 16 shows the spanwise variation of the following local drag coefficient C_d , calculated from the surface pressure distribution,

$$C_d = \frac{1}{2} \int_0^{2\pi} C_p(y, \theta) \cos \theta d\theta, \quad (5)$$

$$C_p(y, \theta) = \frac{p(y, \theta) - p_0}{\rho U_0^2 / 2}$$

The experimental result ($C_d = 1.0$) for the two-dimensional cylinder by authors is also shown as a dotted line in Fig. 16. At $y/d = 0.6$, the value of C_d is different from that of the two-dimensional cylinder, due to a specific distribution of the cylinder surface pressures. C_d takes the maximum value of 1.04 at $y/d = 1.5$ as guessed from the tendency of the pressure distribution at the location of $y/d = 2$. As y/d increases, the value of C_d decreases and takes the minimum value of 0.95 in the range of $y/d = 4 \sim 6$, and then it gradually approaches the value of the two-dimensional cylinder as y/d increases. The area average of C_d for the cruciform circular cylinder is 0.97, which is almost the same as that of the two-dimensional cylinder.

In the next place, let's estimate the mean drag of the cruciform circular cylinder by applying the law of momentum to the control volume surrounding the present flow field as shown in Fig. 17. It is considered that both the control volume and the cruciform circular cylinder are geometrically

symmetric. Eq. (6) given below can be assumed for the plane ③ in Fig. 17.

$$U = U_1(1 - \epsilon), \quad (\epsilon > 0), \quad \dots\dots\dots(6)$$

where ϵ is the ratio of the defect flow rate to the whole flow rate. Considering the momentum balance, the drag is expressed as Eq. (7),

$$D = \rho U_1^2 \left\{ \iint_{\text{plane ②}} \frac{U}{U_1} (1 - \frac{U}{U_1}) dy dz - \epsilon \iint_{\text{plane ③}} (1 - \frac{U}{U_1}) dy dz \right\}. \quad \dots\dots\dots(7)$$

Therefore, the drag can be obtained by integrating Eq. (7) in the cross plane ② to the main flow direction. Since $\epsilon \neq 0$ in the far downstream region, Eq. (7) can be reduced to,

$$D = \rho U_1^2 \left\{ \iint_{\text{plane ②}} \frac{U}{U_1} (1 - \frac{U}{U_1}) dy dz \right\}. \quad \dots\dots\dots(8)$$

The mean drag coefficient of the cruciform circular cylinder is defined as follow:

$$C_D = D / (1/2) \rho U_1^2 A. \quad \dots\dots\dots(9)$$

where A is the shadow area projected on the y - z plane of the cruciform circular cylinder. Fig. 18 shows C_D calculated from Eq. (9) using the experimental results. C_D takes approximately a constant value in the range of $x/d \geq 90.5$, which means the momentum defect is well preserved in the streamwise direction. C_D has a value of about 1.0, which almost agrees with the area average of the local drag coefficient obtained from the pressure distribution on the cylinder surface and also with the value of the two-dimensional cylinder. The result that the values of C_D evaluated by the two different methods agree with each other to some degree means that C_D thus obtained is fairly reliable.

Fig. 17 Control volume model

Fig. 16 Local drag coefficient

Fig. 18 Drag coefficient of the cruciform circular cylinder

4. Conclusions

The mean velocity profile of a wake behind a cruciform circular cylinder and the surface pressure distribution around it were measured. From these results the following are revealed.

(1) It is confirmed that the entire mean velocity profile of the cruciform circular cylinder maintains a crisscross shape up to the downstream cross section of $x/d = 475$ which is the last one measured in the present experiment. In the corner region of cruciform circular cylinder wake, isovels distort towards the wake center along the $y=z$ plane, because there exists a secondary flow with the magnitude of about 4 % of free stream velocity which is directed towards the wake center on the $y=z$ plane and outwards on the cruciform circular cylinder axis.

(2) The velocity scale, U_{d0} , of the cruciform circular cylinder wake decays as $x^{-0.37}$. The rate of the decay is smaller than those in the two-dimensional and the axisymmetric wakes. The length scales, l_y and b_y , on the $y=z$ plane increase in proportion to $x^{0.5}$, while the streamwise variation of the length scale, l_y , on the $z=0$ plane is not monotonous.

(3) The velocity profiles on the $y=z$ plane show similar profiles to those of the two-dimensional and the axisymmetric wakes in the downstream region of $x/d \geq 90.5$. The velocity profiles on the $z=0$ plane show a kind of saddle-back shape in the upstream region, but become monotonous in the downstream region of $x/d \geq 298.5$. From these results, it can be considered that the whole mean velocity field become similar beyond about $x/d = 300$.

(4) Although the local drag coefficient calculated from the pressure distribution on the cruciform circular cylinder surface depends on the spanwise location, the area average of C_d is 0.97, which almost coincides with that of the two-dimensional cylinder.

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