Three-Dimensional Jet Issuing from the Cruciform Nozzle*

(4th Report, Statistical Characteristics)

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Statistical characteristics of a three-dimensional jet issuing from a cruciform nozzle have been examined experimentally to clarify the features of the present flow field due to the secondary flows. In the extent of $x/d \geq 50$ where the mean velocity profile U/U_{ox} shows the similarity, the ratio of the integral length scales L_u/L_v on the x axis assumes a constant value. In the relatively upstream portion, both the skewness factors $S(u)$ and $S(v)$ show a negative value, while both the flatness factors $F(u)$ and $F(v)$ take a positive value. The turbulent large eddy structure conjectured from the space-time correlation is significantly different at each location throughout the cross section.

Key Words: Turbulence, Jet, Cruciform Nozzle, Probability Density Function, Space-Time Correlation, Power Spectrum

1. Introduction

In previous paper⁽¹⁾⁻⁽³⁾, mean flow and turbulent flow structures of a three-dimensional jet issuing from a cruciform nozzle were investigated; the transport process of kinetic energy was also clarified. From these results, it was revealed that secondary flow played an important role in the present flow field and made the rate of strain anisotropic, and that the profiles of each term in the energy equation exhibited distinguished shapes corresponding to the magnitudes of local mean velocity and turbulent intensity. Considering the result that the turbulent eddy structure was affected by this secondary flow, it is presumed that the space-time correlation, probability density

function and spectral energy transfer are also influenced. From the above, it seems to be very important to investigate the statistical characteristics to clarify the features of the present flow field.

Regarding previous turbulent jets associated with these statistical characteristics, studies of two-dimensional jets by Bradbury⁽⁴⁾ and Everitt and Robins⁽⁵⁾, axisymmetric jets by Wygnanski and Fiedler⁽⁶⁾ and Riberio and Whitelaw⁽⁷⁾, and square jet by Nakamura et al.⁽⁸⁾ have been conducted. Furthermore, Tsutiya et al.⁽⁹⁾⁽¹⁰⁾ and Marsters and Fortheringham⁽¹¹⁾ showed the mean flow and turbulent flow properties of rectangular jets in which the secondary flow was the same as in the present flow field. Nevertheless, there is no discussion of secondary flow in the studies mentioned above. On the other hand, in the study of cruciform jet⁽¹²⁾, Quinn and Marsters presumed that the curvature of the streamlines trigger transverse pressure gradients which cause bulging of the mean streamwise velocity contours and consequently generate secondary motions of Prandtl's first kind, similar to their results for a rectangular jet⁽¹³⁾. However, the feature of secondary flow has not yet been clarified experimentally.

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From these points of view, in the present paper, the structure of the flow field deformed by secondary flow has been investigated using the results of autocorrelation, probability density function, space-time correlation and spectral energy density function. Characteristics of the present flow field have also been clarified.

The majority of the nomenclature used in previous papers^{(1)~(3)} has been given in the discussion; new symbols are explained in the following:

- x, y, z : Cartesian coordinates system; x distance in the direction of free stream; y, z distance along two-nozzle axes from the origin
- x, y', z' : Cartesian coordinates system rotated clockwise by 45 degrees with respect to the x axis
- R_{uu}, R_{vv}, R_{ww} : Autocorrelation coefficients of fluctuating velocity components in the x, y and z directions, respectively
- $R_{v'v'}, R_{w'w'}$: Autocorrelation coefficients of fluctuating velocity components in the y' and z' directions, respectively
- L_u, L_v : Integral length scales of fluctuating velocity components u and v , respectively
- k : Wave number [cm^{-1}]
- $E_{uu}(k)$: One-dimensional power spectral density function of u -fluctuating velocity component

Subscripts

- q : Location of the largest value of turbulent kinetic energy on the y axis
- q' : Location of the largest value of turbulent kinetic energy on the y' axis
- ox : On the jet centerline (on the x axis)
- o : Location of quasi two-dimensional region ($y/d=0, z/d=60$)
- m : Moving probe on the y axis
- m' : Moving probe on the y' axis

2. Experimental Apparatus and Technique

Equipment, experimental Reynolds number ($Re = 8000$) and range measurements in this research were the same as those reported in previous papers^{(1)~(3)}. For the measurement of turbulent quantities, DISA constant-temperature hot wire anemometers and linearizers (DISA 56C17 and 56N21) with X -type and I -type probes (1 mm long and 5 μm in diameter) were used.

Calculations of statistical quantities, e.g., autocorrelation function, probability density function and power spectral density function at a fixed position in the flow field, were performed using data from the X -

type probe. On the other hand, calculation of the space-time correlation between two separate points was executed using data from two I -type probes. Signals from both X -type and I -type probes were recorded on an analogue data recorder (TEAC XR510) with a cutoff frequency of 10 kHz. These signals were re-played and digitized, and then input into a personal computer (HP9000 MODEL330) to calculate statistical quantities.

For calculation of the probability density function, 6.5 seconds of data were A/D converted with a sampling frequency of 10 kHz and analyzed on the personal computer. (The accuracy of calculation was estimated to be sufficient to obtain good results from preliminary experiments.) The same method was used for that of the autocorrelation function and the power spectral density function except that the output signal was low-pass filtered at 20 kHz to obtain a resolution up to 10 kHz because the dissipative scales are thought to be very small.

On the other hand, for the space-time-correlation analysis, a data length of 6.5 seconds for 2 channels was used.

3. Experimental Results and Discussion

3.1 Autocorrelation and turbulence scales

The autocorrelation function of fluctuating velocity u at an arbitrary point in the flow field is defined as follows:

$$R_{uu} = \overline{u(t)u(t+\tau)} / \{\overline{u^2(t)u^2(t+\tau)}\}^{1/2} \quad (1)$$

In the same way, autocorrelation functions of fluctuating velocity components v and v' in the y and y' directions are described by R_{vv} and $R_{v'v'}$, and those of w and w' in the z and z' directions by R_{ww} and $R_{w'w'}$, respectively. On the other hand, integral length scales of fluctuating velocity u and v are given by

$$L_u = U^* \cdot \int_0^\infty R_{uu}(\tau) d\tau \quad (2\cdot a)$$

$$L_v = U^* \cdot \int_0^\infty R_{vv}(\tau) d\tau \quad (2\cdot b)$$

where U^* is convection velocity. In this report, U^* is replaced by the local mean velocity $U^{(14)}$ for convenience. Zero-crossing time can be adopted as the upper bound of integral. Figure 1 shows the streamwise variation of both L_u and L_v normalized by nozzle width d on the x axis. First, the streamwise variation of L_u/d will be discussed. The value of L_u/d takes a constant value until $x/d=20$, then increases as $(x/d)^{0.90}$ as far as $x/d \geq 30$. The position where L_u/d begins to increase agrees with that of the largest value of turbulent intensity on the x axis. Next, the value of L_v/d decreases until $x/d=30$ and takes a minimum value there, then increases as $(x/d)^{0.91}$ in the downstream direction. Here, the relationship between the

location of the minimum value of L_v/d and that of secondary flow directional to the jet center region remains unexplained. The development rate of both L_u/d and L_v/d agrees with that of half-width b'/d on the y' axis mentioned in previous paper⁽¹⁾. Furthermore, the ratio of L_u/L_v takes a constant value of 2.2 as far as $x/d \geq 50$, where the mean velocity profile was found to be similar. It is supposed that large eddies are stretched in the x direction.

Figures 2(a) and (b) show the profiles of the spanwise variation of autocorrelation coefficients (R_{uu} , R_{vv} and $R_{v'v'}$, R_{ww} and $R_{w'w'}$) on both the 1 and

Fig. 1 Streamwise variation of integral scales

(a) On the y axis ($x/d=20$)

(b) On the y' axis ($x/d=20$)

Fig. 2 Profiles of autocorrelation coefficients on both the y and y' axes

y' axes at $x/d=20$ where the present flow field is significantly affected by the secondary flow. Figures 3(a) and (b) also show the autocorrelation coefficients at $x/d=100$ where profiles of both mean velocity and turbulent quantities are similar, as described in previous paper⁽¹⁾⁽²⁾. At first, considering the profiles on the y axis at $x/d=20$, the values of the zero-crossing time of all profiles of R_{uu} , R_{vv} and R_{ww} increase as y/l . The zero-crossing-time value of R_{ww} profile becomes larger than that of R_{vv} with increasing y/l , although the profiles near the jet center region are almost the same. On the other hand, the profiles on the y' axis show the same tendency as that described on the y axis. In the region of larger y'/l' value, however, the profile of $R_{v'v'}$ is almost similar to the $R_{w'w'}$ profile. Comparing the zero-crossing-time of profiles on the y axis with those on the y' axis, it can be found that they are both very similar in the jet center region, while those on the y' axis are much larger than those on the y axis in the region far away from the jet center. Next, as for the results at $x/d=100$, all the profiles on both the y and y' axes show a tendency similar to those at $x/d=20$, but the magnitudes of zero-crossing-time at $x/d=100$ are much

(a) On the y axis ($x/d=100$)

(b) On the y' axis ($x/d=100$)

Fig. 3 Profiles of autocorrelation coefficients on both the y and y' axes

larger than those at $x/d=20$. This result indicates that the present flow field is still developing. It is very interesting that profiles of autocorrelation coefficients in the self-preserving region⁽¹⁾ are very similar to those in the upstream region where the secondary flow plays a significant role in the flow structure.

To investigate the variation in the scale of large eddy, streamwise variations of integral scales on both the y and y' axes are shown in Fig. 4, where only integral scale L_u of fluctuating velocity component u exhibits a typical eddy scale. In this figure, L_u is normalized with the half width b_m or $b'^{(1)}$ for comparison with the length scale in the present flow field. First, profiles on the y axis will be discussed. The profile of L_u/b_m at $x/d=20$ is relatively unchanging throughout the cross section. Profiles of L_u/b_m at both $x/d=50$ and 100 , however, abruptly change to increase near the jet center line, and then take the largest values at $y/l=0.9$ and 0.5 , respectively, subsequently approaching an almost constant value with increasing y/l . The location of the largest value of L_u/b_m corresponds to that where the Reynolds shear stress also shows the largest value. As for the results on the y' axis, all the profiles at $x/d=20, 50$ and 100 increase from the value on the jet center line and assume different maximum values at any of the respective locations. These locations are in agreement with those where the triple velocity correlation $\overline{v'u^2}$ (Reynolds shear stress flux⁽³⁾) also reaches its maximum value. From these results it may be found that the magnitude of integral length scales is closely related to the location where the turbulent kinetic energy transport, caused by the energy-containing eddy, contributes a significant gain.

3.2 Probability density function and its moment

Probability density function $P(u)^{(15)}$ of fluctuating velocity u in the x direction is defined as:

$$P(u) = \lim_{\Delta u \rightarrow 0} [P_{\text{rob}}\{u < u(t) < u + \Delta u\} / \Delta u] \quad (3).$$

Probability density functions of fluctuating velocity components v and v' , w and w' are defined in the same

Fig. 4 Streamwise variation of integral scales L_u on both the y and y' axes

way. Figures 5(a) and (b) show the probability density function profiles of $P(u/\sqrt{u^2})$, $P(v/\sqrt{v^2})$ and $P(v'/\sqrt{v'^2})$, $P(w/\sqrt{w^2})$ and $P(w'/\sqrt{w'^2})$ on both the y axis (right-hand side) and y' axis (left-hand side) at $x/d=20$ and 100 , respectively. First, the results on the y axis at $x/d=20$ will be discussed. The location of the largest value of $P(u/\sqrt{u^2})$ near the jet center region ($y/d=0, 1.0$) is situated in the region of $u/\sqrt{u^2} > 0$. Profiles of $y/d=2.0$ shows an almost Gaussian distribution. Profiles of both $P(v/\sqrt{v^2})$ and $P(w/\sqrt{w^2})$ are also almost Gaussian throughout the entire cross section. As for the results on the y' axis, profiles of both $P(u/\sqrt{u^2})$ and $P(v'/\sqrt{v'^2})$ near the jet center region are shifted toward the region of $u/\sqrt{u^2} > 0$ and $v'/\sqrt{v'^2} > 0$, and with increasing y'/d , the location of the largest value moves definitively from $u/\sqrt{u^2}=0$ and $v'/\sqrt{v'^2}=0$ to $u/\sqrt{u^2} < 0$ and $v'/\sqrt{v'^2} < 0$. The

(a) On the y (right-hand side) and y' (left-hand side) axes ($x/d=20$)

(b) On the y (right-hand side) and y' (left-hand side) axes ($x/d=100$)

Fig. 5 Probability density function profiles on both the y and y' axes

distortion of those profiles increases, and that of u profile is larger than that of v profile. On the other hand, profiles of $P(w'/\sqrt{w'^2})$ are hardly distorted throughout the entire cross section. The probability density distributions of an axisymmetric jet given by Riberio and Whitelaw⁽⁷⁾ are similar to the Gaussian distribution near the jet center line, and the location where the largest values of those distribution are taken shifts toward the negative region with increasing radial distance. Comparison with the results of the present study reveals a large difference in shape between them. Therefore, the turbulent structure of the two jets is different. Next, the results at $x/d=100$ will be examined. Each profile for the fluctuating velocities of u , v and w on the y axis shows the same tendency as that at the upstream section ($x/d=20$) and so do the probability density distributions for u , v' and w' on the y' axis. From the above, it is found that the peak values of the probability density distributions on both the y and y' axes become smaller in the far downstream section. It can be inferred that this feature is related to the deformation of flow field caused by the secondary flow. On the other hand, all the profiles of the probability density function shift toward the negative region owing to entrainment with ambient fluids around the jet edge.

Subsequently, the third moment, namely the skewness factor, $S(u)$ and the fourth moment, namely the flatness factor, $F(u)$ ⁽¹⁶⁾ of fluctuating velocity component u defined in the following equations will be examined. The skewness factor is considered as the significant parameter in the discussion concerning the coherent structure of the turbulent boundary layer⁽¹⁷⁾

$$S(u) = \int u^3 P(u) du / \left[\int u^2 P(u) du \right]^{3/2} \quad (4)$$

$$F(u) = \int u^4 P(u) du / \left[\int u^2 P(u) du \right]^2 \quad (5)$$

where the values of skewness factor and flatness factor of Gaussian profile are zero and 3, respectively. In the same way, for the other fluctuating velocity components v and v' , w and w' , equations similar to Eqs. (4) and (5) can be used to define the skewness factor and flatness factor.

Figures 6 and 7 show the profiles of both the skewness and flatness factors of fluctuating velocity components (u , v and v' , w and w') on both the y and y' axes, respectively, at $x/d=20, 50$ and 100 . First, the profiles of the skewness factor will be discussed. Near the jet center region, the profile of $S(u)$ at $x/d=20$ indicates the negative value, and those of $x/d=50$ and 100 also take small, but negative values. The position of the largest value of $S(u)$ lies outward compared with those of the turbulent intensity and Reynolds shear stress, and corresponds to that of the positive

largest value of the working term W_{m1} as described in a previous paper⁽³⁾. Profiles of $S(u)$ take zero in the region of large value for y/l because the feature of the flow field in that region is similar to that of a two-dimensional jet. Next, $S(v)$ shows a slightly different profile compared with that of $S(u)$ due to the influence of the secondary flow at $x/d=20$. At the sections $x/d=50$ and 100 , the profiles of $S(v)$ show an almost Gaussian profile throughout the entire cross section. Profiles of $S(w)$ show the Gaussian value in all sections. As for the profiles on the y' axis, the value of $S(u)$ increases from a negative value at the jet center to a positive value with increasing y'/l' in all sections. The trend of these profiles is closely related to the entrainment near the edge of a free jet and is very similar to that of the axisymmetric jet studied by

Fig. 6 Streamwise variation of skewness factor on both the y and y' axes

Fig. 7 Streamwise variation of flatness factor on both the y and y' axes

Wyganski and Fiedler⁽⁶⁾. The profiles of $S(v')$ increase from almost zero at the jet center and take their largest values at $y'/l' = 1.65$ with increasing y'/l' , and then decrease monotonically. However, it should be noted that both the intermittency of flow field and the signal-to-noise ratio influence on the present data in the region showing a decreasing trend. Comparing the profiles of $S(v')$ for the present flow field with those of the axisymmetric jet, we find that they are similar to each other in profile, but are different in magnitude within the extent of $y'/l' = 1.2$. The profiles of $S(w')$ take almost zero near the jet center region in all sections. With increasing distance from the jet center, $S(w)$ increases for the profiles at $x/d = 20$, conversely decreasing at $x/d = 50$ and 100. The relationship between the development of the present flow field and the results mentioned above remains unexplained.

Next, the profiles of the flatness factor on the y axis will be examined. Near the jet center, all the profiles of $F(u)$, $F(v)$ and $F(v')$, $F(w)$ and $F(w')$ indicate larger values than 3 for Gaussian profile at $x/d = 20$. From the result of a previous paper⁽³⁾, it is supposed that the outward development of the present jet near the jet center is smaller because of the secondary flow in the direction of the jet center region on both the y and z axes. In the far downstream region, owing to the disappearance of the potential core region, the tendency mentioned above is not observed. At both sections of $x/d = 50$ and 100, all the profiles show little variation in value and are similar to a Gaussian profile throughout the entire spanwise region. Next, the results on the y' axis will be discussed. All the profiles of $F(u)$, $F(v')$ and $F(w')$ near the jet center at $x/d = 20$ take the same values larger than 3 as those of the y axis, and then increase rapidly with y'/l' after decreasing once. In the downstream region of $x/d = 50$ and 100, all the profiles take values of about 3 near the jet center and increase suddenly with y'/l' due to the intermittency of the flow behavior. This tendency agrees with the result of the axisymmetric jet studied by Wygnanski and Fiedler⁽⁶⁾ shown in Fig. 7, except in the jet center region.

3.3 Space-time correlation coefficients

The space-time correlation function between two points is defined as follows⁽¹⁶⁾:

$$Ru_i u_j(x_d, y_d, z_d, \tau) = \frac{u_i(x, y, z, t) \cdot u_j(x + x_d, y + y_d, z + z_d, t + \tau)}{\{u_i^2(x, y, z, t) \cdot u_j^2(x + x_d, y + y_d, z + z_d, t + \tau)\}^{1/2}} \quad (6)$$

where x_d , y_d and z_d show the distances between the fixed probe and the moving probe in the x , y and z directions, respectively, and τ is the time delay. The distances between them in the y' and z' directions are

expressed by y'_d and z'_d , respectively.

Figure 8 illustrates the profiles of space-time correlation coefficients for the time delay $\tau = 0$ when the fixed probe is located at the jet center ($y/d = z/d = 0$) of each section and the moving probe moves in both the y and y' directions, respectively. The spanwise distances y and y' are nondimensionalized by Townsend's length scales l and l' , respectively. The profiles of $Ru_{ox} u'_m$ on the y axis coincide with a single curve in the region of $x/d \geq 100$ where turbulent intensity profiles show the similarity. Therefore, it is recognized that the transport process of turbulent momentum flux due to the streamwise fluctuating velocity component becomes similar. Here, the location of $y/l = 0.6$, where correlation coefficients take zero value, corresponds to the location of the largest value of the outward secondary flow. The result mentioned above indicates the relationship between the variation of large eddy scales and the magnitude of the secondary flow. On the other hand, the tendency of the profiles on the y' axis is similar to those on the y axis. Compared with the profiles (nondimensionalized with l and l') of the two-dimensional jet given by Everitt and Robins⁽⁵⁾ shown in Fig. 8, it is recognized that the correlation scales for the present flow field are indeed smaller than those of Everitt and Robins. These differences originate in the selection of scale lengths used here.

For the case in which the fixed probe is located in the quasi-two-dimensional region ($y/d = 0$, $z/d = 60$) and the moving probe moves in the y direction, the tendency of the space-time correlation coefficient, which is not shown, was almost similar to that of the two-dimensional jet shown in Fig. 8.

Furthermore, the profiles of space-time correlation coefficients for time delay $\tau = 0$, when the fixed probe is positioned at the location of the largest value of the turbulent kinetic energy on the y' axis and the moving probe moves in the y' direction, are shown in Fig. 9. The spanwise distance y'_d is normalized by l' . At first, in the region of $y'_d/l' \geq 0$, it is found that all

Fig. 8 Streamwise variation of space-time correlation coefficients on both the y and y' axes (Fixed probe is located at $y/d = z/d = 0$)

the profiles have similar shapes and so eddy structures show the similarity in the region $x/d \geq 100$. In the region $y'_d/l' < 0$, the shifts in correlation profiles become narrower with increasing downstream distance up to $x/d=100$. Therefore, it is found that the further downstream, the more the shape of correlation coefficients is entirely subject to the restriction of symmetry of flow near the jet center. From the results mentioned above, the shifts in correlation coefficients in the outer region are twice compared with those in the inner region of the downstream region. This suggests a difference in the diffusion transport process between the inner region and the outer region.

Subsequently, we will investigate the contour plot of the space-time correlation obtained in the case in which the fixed probe is located at the representative location and the moving probe moves on the representative slice shown in Table 1.

The results are shown only in the positive region of time delay τ because the profiles are symmetrical with respect to the plane of $\tau=0$. Figure 10(a) shows the contour plots on both the y and y' axes at $x/d=20$ for each case shown in Table 1. Time delay τ is nondimensionalized by U_{0x} and nozzle width d . Considering the result that an outward secondary flow exists on both the y and y' axes, it is found that shapes of the large eddy in both streamwise and spanwise directions are similar to each other. However, the eddy size in the streamwise direction is 2.5 times as

Table 1 Location of each probe

	Fixed probe location	Main axis of moving probe
a	$y/d = z/d = 0$	On the y axis and the y' axis
b	$y/d = 0, z/d = 60$	On the slice of $z/d = 60$
c	Maximum point of $(1/2)q^2$ on the y axis	On the y axis
d	Maximum point of $(1/2)q^2$ on the y' axis	On the y' axis

Fig. 9 Streamwise variation of space-time correlation coefficients on the y' axis (Fixed probe is located at the position of largest value of turbulent kinetic energy)

(a) On both the y and y' axes

(b) Quasi two-dimensional region

(c) Location of the largest value of turbulent kinetic energy on the y axis

(d) Location of the largest value of turbulent kinetic energy on the y' axis

Fig. 10 Contour plot of space-time correlation coefficients at each representative location ($x/d=20$)

large as that in the spanwise direction. Figure 10(b) shows the contour plot in a quasi two-dimensional region for case (b) shown in Table 1. The eddy size for case (b) is almost the same as that for case (a) in the spanwise direction, while it is three times larger in the streamwise direction. This suggests that the eddy size for case (b) is elongated compared with that for case (a).

Figure 10(c) shows the contour plot at the location of the largest value of turbulent kinetic energy on the y axis. Mean velocity component V has a positive value at this location, but has large negative values in the region of large value of y/d . It is considered from these results that the outward development of the present flow field on the y axis is suppressed by the inward component of V ; this effect does not arise in the contour plot. Furthermore, considering the evidence that the eddy size in the spanwise direction is almost equal to that in case (a), otherwise the streamwise direction value is twice as large, it is found that the contour plot is also stretched in the streamwise direction at this location.

Figure 10(d) shows the contour plot at the location of the largest value of turbulent kinetic energy on the y' axis. The fixed probe is located in the region where V' component always indicates a positive value. The profile inclines outwards the jet outer

region with increasing streamwise distance, and this indicates the spreading of the present jet corresponding to the variation of V' component. This result can be explained by a large quantity of momentum being transported by a turbulent fluctuating velocity in the direction perpendicular to the inclination of the contour plot. Here, the angle of inclination to the x axis is about 8.6° from the contour plot. On the other hand, the development angle of Townsend's length scale l' to the x axis⁽¹⁾ in the present flow field is about 11° , so it is recognized that near the jet exit section, the development rate of the mean flow field is larger than that of the turbulent flow field as evaluated from the shape of the large eddy.

Subsequently, we will investigate the space-time correlation coefficients at $x/d=100$. The contour plots on both the y and y' axes shown in Fig. 11(a) are almost identical. Compared with the shape in Fig. 10(a), it can be found that the shapes of the contour plots are almost the same, and that the eddy size is 3.5 times as large. This suggests that the present flow field develops with increasing streamwise distance. Figure 11(b) shows almost the same shapes as those of Fig. 10(b), while the development rate of the eddy size is a little larger than that for case (a) shown in Table 1. The profile of Fig. 11(c) slants towards the region of $y_d/d > 0$ and is also inclined outwards the jet

(a) On both the y and y' axes

(b) Quasi-two-dimensional region

(c) Location of the largest value of turbulent kinetic energy on the y axis

(d) Location of the largest value of turbulent kinetic energy on the y' axis

Fig. 11 Contour plot of space-time correlation coefficients at each representative location($x/d=100$)

outer region in the streamwise direction. The profile of Fig. 11(d) is almost the same as that of Fig. 10(d), indicating stretching in the direction of the jet development due to the V' component in the x - y' plane. The angle of inclination to the x axis is almost 11° , that is, the same degree as the development rate of l'/d . Comparing this result with that at $x/d=20$, it is found that the development rate at $x/d=100$ is larger and the entrainment with ambient fluids is more active in the far downstream region. Here, the inclination angle of jet development at $x/d=50$ is also about 11° . As for the spanwise development of large eddy size, the magnitude of the eddy size in the region of $y'/d > 0$ is about twice as large as that of $y'/d < 0$. This result supports the results of Fig. 9. Furthermore, the magnitude of the eddy size in the streamwise direction in the region of $\tau \geq 0$ is 2.5 times as large as in the region of $\tau < 0$.

3.4 One-dimensional power spectral density function

Figure 12 shows the streamwise variation of one-dimensional power spectral density function $E_{uu}/\overline{u^2}$ on the x axis. Here, only results of fluctuating velocity u in the x direction are investigated. Measurements were taken at 8 sections from $x/d=20$ to 200. In the present flow field, the potential core region exists within $x/d=10^{(1)}$, so the value of nondimensional turbulent intensity u_{rms}/Ue (Ue is the nozzle exit velocity) on the x axis continues to increase in the range between $x/d=20$ and 30. In this range, it is found that the cascade process, that is, the energy of large eddies are continuously transformed into small eddies. In the region of $x/d \geq 50$, there exists a definite inertial sub-range and an extent of this sub-range becomes larger, increasing with streamwise distance. Profiles of both $E_{vv}/\overline{u^2}$ and $E_{ww}/\overline{w^2}$ closely resemble as that of $E_{uu}/\overline{u^2}$.

Figures 13(a) and (b) show the spanwise variation of one-dimensional power spectral density function $E_{uu}/\overline{u^2}$ on both the y and y' axes, respectively, at $x/d=20$. Throughout the entire range of the y axis, no inertial sub-range where $E_{uu}/\overline{u^2}$ is proportional to $k^{(-5/3)}$ can be found. The $E_{uu}/\overline{u^2}$ profile at the location of $y/d=1$, where the V component takes the largest

Fig. 12 Streamwise variation of power spectral density function on the x axis

value, is a little different from those at other locations. Thus, the secondary flow effect on the wave number range cannot be ascertained. The profiles on the y' axis shown in Fig. 13(b) also indicate a plateau in the small wave number range near the jet center, and do not show a decreasing rate proportional to $k^{(-5/3)}$ in the large wave number range. However, a narrow range of the inertial sub-range exists at $y'/l'=1.02$ and 1.36 as shown in Fig. 13(b).

Subsequently, Figures 14(a) and (b) show the one-dimensional power spectral density profiles on both the y and y' axes at $x/d=100$. The profiles on the y axis decrease in proportion to $k^{(-5/3)}$ throughout the wave number range. The outward component of V takes the largest value at $y/l=0.47$, but the influence of secondary flow vector on the power spectral density

(a) On the y axis

(b) On the y' axis

Fig. 13 Spanwise variation of power spectral density function ($x/d=20$)

(a) On the y axis

(b) On the y' axis

Fig. 14 Spanwise variation of power spectral density function ($x/d=100$)

profiles is not evident in the same way as that of $x/d = 20$. Furthermore, the profiles on the y' axis also indicate the existence of an inertial subrange throughout the range and this subrange is wider than that of $x/d = 20$.

4. Conclusions

(1) The ratio of integral length scales L_u/L_v on the x axis is constant in the region of $x/d \geq 50$ where the profiles of U/U_{0x} indicate similarity. The profiles of L_u on the y and y' axes vary with the development of flow field. The location of the largest value of L_u on the y' axis agrees with that of $\overline{v'u^2}$ (Reynolds shear stress flux).

(2) In the relatively upstream section, skewness factors $S(u)$ and $S(v)$ take negative values; conversely, flatness factors $F(u)$ and $F(v)$ take positive values due to the significant influence of the secondary flow. In the far downstream section, values of skewness factor and flatness factor approach those of a Gaussian profile.

(3) The eddy structure of the present cruciform jet are conjectured from the contour plots of space-time correlation coefficients. It is clarified that large eddies at each representative location show their own distinctive structure, and that the contour plot of the locations where turbulent kinetic energy takes the largest value is stretched in the direction of flow development in the x - y' plane.

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