

Evaluating Scales by using Slotted Correlation in Cylinder flow

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Abstract The slotted correlation method for the post-processing of laser Doppler anemometer (LDA) data is applied to obtain the autocorrelation and turbulent scales at the in-cylinder flow of an IC engine. The slotted correlation method can provide correlation of turbulence from random time sampling data like as LDA measurement. The experiment is performed in the steady cylinder flow through the cylinder head. The cylinder head is designed for an SI engine with two intake valves and two exhaust valves. The transparent cylinder was made by acrylic with bore of 75 mm and length of 100 mm. The experiments are made by means of sucking the air from the bottom of the cylinder by the blower. The experiments are conducted by single- or dual- valve open conditions with 8 mm valve lift under -1470Pa suction gauge pressure in order to simulate the air flow motion through the intake ports in the actual operating condition. In these conditions, mean velocities at the cross section are about 7.0m/s for dual-valve open condition, and about 4.0m/s for single-valve open condition. The LDA consists on a fiber sending optics, a photomultiplier and a burst spectrum analyzer (BSA). From the results, comparison between conventional FFT and slotted correlation method shows a little difference in the turbulent scales. The FFT results show the tendency of overestimation compared with the slotted correlation results. This tendency becomes remarkable when the LDA data rate is low. The time scale of turbulence by FFT is gradually decreased with data rate. The slotted correlation results provide stable value of the turbulent scales along the data rate except for very low data rate region. Using the time scale by the slotted correlation, the applicable range of the Taylor's hypothesis becomes wider than that of FFT. For analysis of the cyclic flow, a combination method of FFT and slotted correlation methods is also proposed. In the method, the FFT method is applied for dividing flow motion into mean/bulk flow motion which includes the cyclic flow and turbulence fluctuation. The proposed method is useful for calculating the time scale.

1. Introduction

In the improvement of the internal combustion engine, the flow inside the cylinder becomes more important to get better quality of the air-fuel mixture. New trend of technique of the gasoline engine is gasoline direct injection system and that of the Diesel engine is pre-mixed and/or homogeneous charge compression ignition (PCCI/HCCI) system. For the systems, the authors have performed the measurements of gasoline type spray (Ismailov et al., 1999), those of Diesel spray (Long et al, 1998), instantaneous fuel flow rate analysis (Ishima et al., 2005) and characterization on total engine performance (Ishima et al.,2003). These new combustion systems need not only special spray but also organized in-cylinder flow. Since the in-cylinder flow is highly turbulence and has cyclic motion, it is better to evaluate information from statistic data and detail turbulence structure. The statistic data are presented by the mean and rms velocities. The detail of turbulence is discussed by the temporal- and spatial-scales and correlations.

In this kind of research field, a laser Doppler anemometer (LDA/LDV) is one of the strong tools. The LDA is non-intrusive measurement technique and it has high spatial and temporal resolution. The authors applied the LDA to measure a grid turbulence, a vortex shedding from cylinder (Nomura et al., 2004b), a flow around a square obstacle (Nomura et al., 2002a, 2002b) and in-cylinder flow (Nomura et al., 2004a). In the studies, auto-correlation was calculated from the LDA

data with FFT. From the auto-correlation, the spatial correlation was estimated by Taylor's hypothesis (Hinze, 1975; Tennekes and Lumley, 1972). The two-point measurements were also carried out in the studies in order to calculate the spatial correlation directly (Nomura et al., 2004b). These results are compared with particle image velocimetry (PIV) data. The results show that the two-point measurements present almost the same tendency and values of the length scales as that of PIV data. The Taylor's hypothesis is useful for calculating the length scale estimation when the turbulence is small enough. In the in-cylinder flow, since the turbulence is high, the length scale measured by LDA with Taylor's hypothesis is much smaller than that of PIV.

However, the difficulty in the LDA data processing is random sampling in time axis depending on signal arrival. Normally, the FFT can be applied when the data has a constant time interval. Then, the series of the authors' studies have to have a reconstruction in time. Recently, a slotted correlation method was proposed for calculating the correlation by some researchers (Nobach, 2002; Gaster and Roberts, 1977; Mayo et al., 1974; van Maanen and Tummers, 1996). The slotted correlation method can provide the correlation from discrete time data like as LDA, directly.

The purpose of this study is to show an effectiveness of the slotted correlation method. The experiment is carried out in the flow inside the modeled engine cylinder. The auto-correlation and time scale are calculated by the FFT and the slotted correlation method. The length scale is calculated by Taylor's hypothesis. The data are also compared with that of PIV, which can supply the spatial correlation and the length scale directly.

2. Calculation of flow parameters

The LDA data is discrete in the temporal axis. When each velocity represents $u(t)$, the statistic data can be obtained by;

$$U = \frac{1}{N} \sum_{i=1}^N u(t) \quad (1)$$

$$u'(t) = u(t) - U \quad (2)$$

$$u'_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N (u'(t))^2} \quad (3)$$

where U is mean velocity, u_{rms} is rms velocity and t is time. The auto-correlation is defined as

$$R(\tau) = \frac{u'(t) \times u'(t + \tau)}{u'^2_{rms}} \quad (4)$$

In this paper, two methods are tested for obtaining the auto-correlation. The first one is the FFT and the second one is the slotted correlation method. The authors have been using FFT for the correlation analysis to turbulent flows (Nomura et al., 2002a, 2002b). The FFT provides frequency components as;

$$U(f) = \int_0^{\infty} u(t) e^{-j2\pi f t} dt \quad (5)$$

where j is imaginary unit and f is frequency. After obtaining $U(f)$, mean motion and frequency are divided by frequency range. The mean motion is treated as

$$U'(f) = 0 \text{ when } f > f_{cut} \quad (6)$$

where f_{cut} is cut off frequency. The mean velocity can be calculated with the inverse FFT;

$$U(t) = \int_0^{\infty} U'(f) e^{j2\pi f t} df \quad (7)$$

Using $U(t)$, the fluctuation $u'_f(t)$ can be re-defined as

$$u'_f(t) = u(t) - U(t) \quad (8)$$

The power spectrum $S(f)$ is calculated by using FFT to $u'_f(t)$;

$$X(f) = \int_0^{\infty} u_f'(t) e^{-j2\pi f t} dt \quad (9)$$

$$S(f) = \lim_{T \rightarrow \infty} \frac{X(f)X^*(f)}{T} \quad (10)$$

where $X(f)$ and $X^*(f)$ are conjugate complex number. From the power spectrum, the auto-correlation is calculated as;

$$R(\tau) = \int_0^{\infty} S(f) e^{j2\pi f \tau} df \quad (11)$$

$$\rho(\tau) = \frac{R(\tau)}{R(0)} \quad (12)$$

The FFT needs constant time interval data. This is difficulty to apply it to LDA data. The authors' group performed with "timer-mode" in counter type signal processor (DISA: 55L90a), which is supply the constant time interval data in the previous work (Nomura et al., 2004a). In the present study, a burst spectrum analyzer (BSA; Dantec 57N10) is applied. Since the BSA supplies random sampling data, a zeroth-order reconstruction (sample-and-hold method) is applied to obtain the constant time interval data for FFT. The slotted correlation method can calculate auto-correlations directly from the BSA data.

The slotted correlation method is proposed for calculating the correlations from the randomly sampled data in time (Nobach, 2002; Gaster and Roberts, 1977; Mayo et al., 1974; van Maanen and Tummers, 1996).

$$\rho(\tau) = \rho(k\Delta\tau) = \frac{\sum_{i=1}^N \sum_{j=1}^N u'_i u'_j b_k(t_j - t_i)}{\sqrt{\left(\sum_{i=1}^N \sum_{j=1}^N u_i^2 b_k(t_j - t_i) \right) \left(\sum_{i=1}^N \sum_{j=1}^N u_j^2 b_k(t_j - t_i) \right)}} \quad (13)$$

$$b_k(t_j - t_i) = \begin{cases} 1 & \text{for } \left| \frac{t_j - t_i}{\Delta\tau} - k \right| < 0.5 \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

where u'_i and u'_j are obtained by equation (2). As regards $b_k(t_j - t_i)$, some definitions are proposed and the equation which is used by Mayo and Benedict is applied here.

From the auto-correlation, time scale L_t is defined as;

$$L_t = \int_0^{\infty} \rho(\tau) d\tau \quad (15)$$

In the study, the time scale is obtained as the time where the auto-correlation value is equal to 0.37 ($\approx 1/e$). Using Taylor's hypothesis, length scale L_z is calculated by using time scale and mean velocity W ;

$$L_z = L_t \times W \quad (16)$$

In the study, the spatial correlation is supplied directly by PIV because it is area measurement. The spatial correlation is

$$L = \int_0^{\infty} R(r) dr, \text{ where } R(r) = \frac{1}{N} \sum_{i=1}^N \frac{u'_i(\xi) \cdot u'_i(\xi+r)}{u'_{rms}(\xi) \cdot u'_{rms}(\xi+r)} \quad (17)$$

In the study, L is obtained by the same method of the time scale L_t .

3. Experimental apparatus

3.1 Engine cylinder model (Nomura et al., 2004a)

The testing system and measurement method are the same as the previous study (Nomura et al., 2004a). Figure 1 shows a test cylinder and engine head. The head is a four valves SI engine model. In the head, two intake ports have the different geometries. It has the transparent cylinder made by the acryl with bore of 75mm and length of 100mm. In the bottom of the test rig, there is an outlet box with windows and mirror. The LDA measurement is carried out by using the window and mirror. The experiments are made by means of sucking air from the bottom of the cylinder by a blower. The inlet conditions are single- or dual- valve open conditions with 8mm valve lift under -1470 Pa suction gauge pressure in order to simulate the actual air flow motion through the intake ports. In these conditions, mean velocity at the cross section is about 7.0m/s for dual-valve open condition, and about 4.0m/s for single-valve open condition.



Fig. 1 Steady flow test rig for measurements.

3.2 Laser Doppler anemometer (LDA)

Figure 2 shows the experimental set-up with LDA system. Table 1 shows the specification of the LDA. The LDA system consists of a He - Ne gas laser (NEC: GLS3200, 25mW), a fiber probe, a receiving optics, a photomultiplier (Dantec: 55X08) and a BSA (Dantec: 57N10). A transmitter lens is 300mm in focal length and beam crossing full angle is 7.73 degrees. The LDA sending optics has double Bragg cell system. The frequency shift is varied from 4 to 6 MHz. The measurement was made under the forward scattering one-dimensional mode with 30 degrees of offset angle. The intersection volume size of beams was $95.4\mu\text{m} \times 1.6\text{mm}$ however real measuring volume size was estimated as $95.4\mu\text{m} \times 370\mu\text{m}$ under the condition of 30 degrees scattering angle. The seeding particles were water mists of which mean size was about $7\mu\text{m}$.

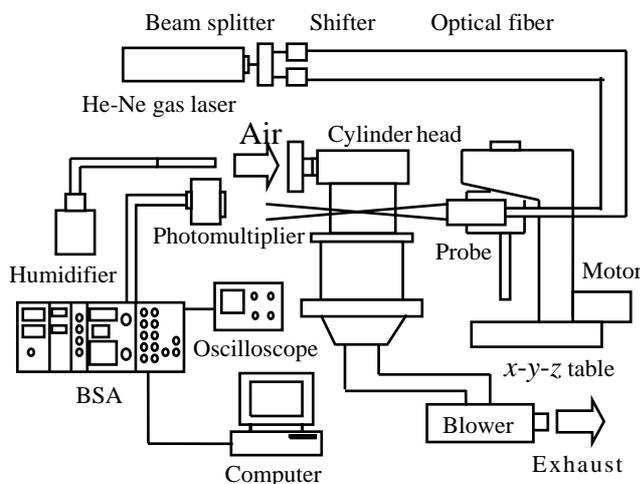


Fig. 2 Experimental set-up for laser Doppler anemometer.

Table 1 Specification of LDA

Laser source	He-Ne
Wavelength (nm)	632.8
Full beam angle (degree)	7.73
Calibration factor (m/s/MHz)	5.21
Mean diameter of waist (μm)	95.4
Measuring volume length (mm)	1.6
Measuring volume width (μm)	95.4
Shift frequency (MHz)	4 - 6

Figure 3 shows the measuring positions of LDA. The origin was set on the center and the top of the cylinder. The coordinate axes were set to x - axis of the radial direction and z - axis of the cylinder axis direction. The measurements were made on 6 sections and the measuring points of axial direction were set from $z = 20\text{mm}$ to $z = 70\text{mm}$ with 10mm interval. Moreover, the radial measuring points were 5mm interval from a center of the cylinder.

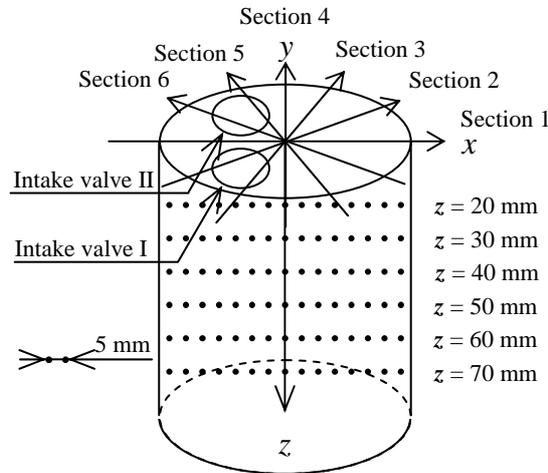


Fig. 3 Measuring points for LDA.

3.3 Particle image velocimetry (PIV)

For the PIV measurement, the test rig was the same as the LDA measurement. Table 1 shows the specification of PIV. The PIV system consists of an Nd:YAG laser (New Wave Research: Model SOLO III-15), a high-resolution CCD camera (KODAK: MEGAPLUS ES-1.0), a PIV processor (DANTEC: Flow Map 2000) and a personal computer. The laser beams were transformed into light sheets using a cylindrical lens. The high-resolution CCD camera with 1008×1018 pixels positioned in a direction normal to the laser sheet. The CCD camera was synchronized with laser pulses and it took two images corresponding to the laser pulses. Each image was divided into the interrogation areas of 32×32 pixels with $50\% \times 50\%$ overlapping. The measuring area is selected as $80\text{mm} \times 80.8\text{mm}$ and actual interrogation area is $2.5\text{mm} \times 2.5\text{mm}$. From each pair of images, two-dimensional vector maps were obtained using a cross correlation method.

Table 2 Specification of PIV

Laser source	Nd : YAG
Laser wavelength (nm)	532
Laser power (mJ)	50
CCD Camera (pixel)	1008 x 1018
Interrogation area (pixel)	32 x 32
Actual Interrogation area (mm)	80 x 80.8
Pulse interval (μs)	10
Over lap (%)	50 x 50

4. Results and discussions

4.1 Velocity map (Nomura et al., 2004a)

The detail of the mean velocity distribution is already reported in the previous paper (Nomura et al., 2004a), then the velocity vector map is briefly described here. Figure 4 shows mean velocity of the measurement section 1 ($y = 0 \text{ mm}$). The velocity vector pattern is measured by LDA and PIV. The condition is dual intake valves opened. Both of the velocity patterns are almost the same each other but there are some differences. A large vortex is located at $x = 0 \text{ mm}$ and $z = 40\text{mm}$. The

vortex is clearly shown in the PIV data but it is unclear in the LDA data. Near the region of the cylinder wall, the LDA has large velocity but the PIV has small velocity. The PIV has large error in near region of the cylinder wall because of reflex light from the wall. Figure 5 shows PIV result with single valve (intake valve II) opening condition. The flow becomes complicated compared with dual valve opening condition. There are two vortices in the plane.

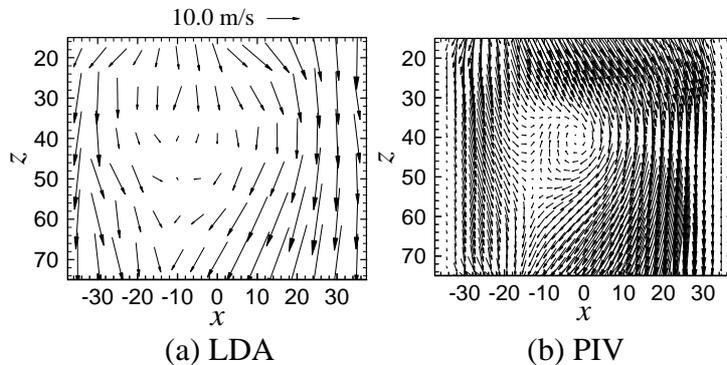


Fig. 4 Mean velocities of LDA and PIV at center plane of $y = 0$ mm under both valve open condition.

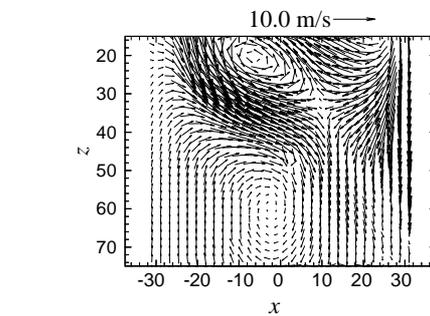


Fig. 5 Mean velocity measured by PIV at the $y = 0$ mm plane under single valve open condition.

4.2 Comparison between FFT and slotted correlation method

Figure 6 shows integral time scales estimated by FFT and slotted correlation method. The vertical axis is length scale with FFT and the horizontal axis is that of slotted correlation method. The result includes both of single- and dual-valve opening conditions. Many points are on the line that indicates that both of the length scales are the same value each other. However, it is clearly shown that the FFT has the tendency of the overestimation.

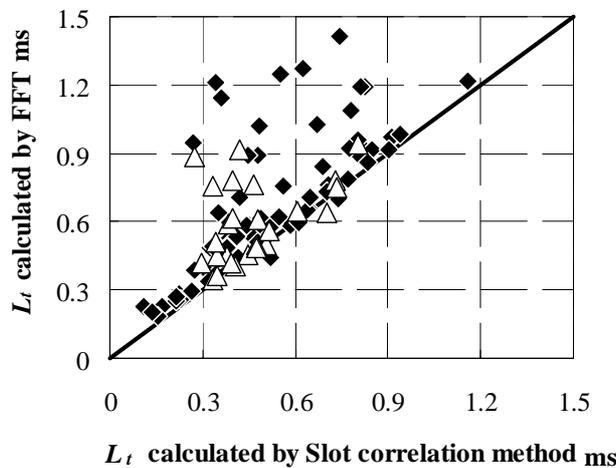


Fig. 6 Integral time scale estimated by slotted correlation methods and FFT method.

Figure 7 shows the comparison between the length scale results by FFT and slotted correlation. In the figure, L_{SLOT} and L_{FFT} are the time scales obtained by slotted correlation and FFT, respectively. The results include both conditions of the single- and dual-valve opened and all of the measuring positions. In the figure, the vertical axis is the ratio of the L_{SLOT} and L_{FFT} and horizontal axis is sampling frequency which is same as the data rate. In the high data rate, the ratio of the time scales becomes to close to about 0.9. This means the time scale by FFT is larger than that of slotted correlation. When the sampling frequency becomes less than 4 kHz, the ratio is gradually decreasing. This means the sampling frequency affects the accuracy of the estimation on the time scales.

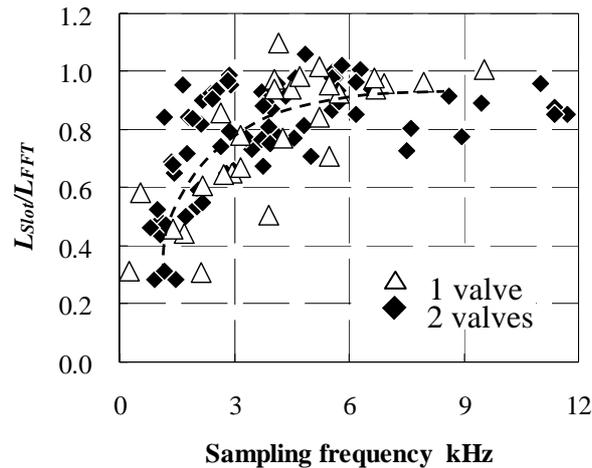


Fig. 7 Ratio of length scales by FFT and slotted correlation method

Figure 8 shows the influence of the substantial sampling frequency on the length scales. The data was obtained at $x = 20$ mm, $y = 0$ mm and $z = 40$ mm. The FFT result is decreasing with the sampling frequency. The slot correlation indicates the large value in the lowest sampling frequency and after the value is stable. This result points out that the FFT result is sensitive to the sampling rate and the slot correlation method is almost independent from the data rate.

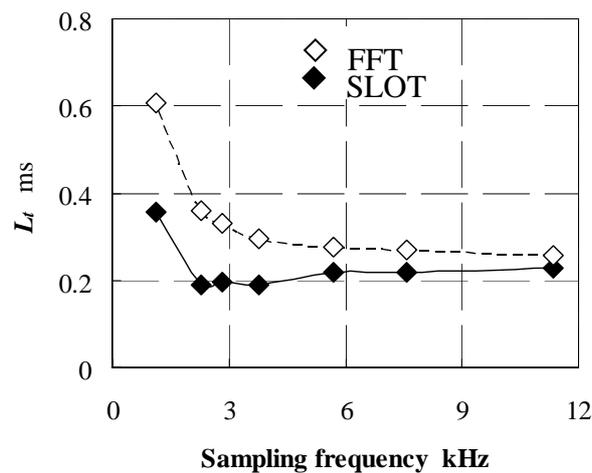


Fig. 8 Influence of sampling frequency on length scale.

Figure 9 shows the previous result of comparison between length scales by the LDA and the PIV (Nomura et al., 2004). The L_z of LDA was calculated by using FFT data and Taylor's hypothesis. There are large differences in the results. Using the slotted correlation method, the length scales are re-calculated here. Figure 10 shows the comparison between the length scales of the LDA and the PIV data. Figure 10 (a) is the result of 2 valves opening condition and Fig.10 (b) is that of 1 valve opening condition. The condition of 2-valve opened, the data is almost the same as the PIV data except for those around $x = 0$ mm. The 1valve open condition has large difference in the whole measuring positions. Although there are still differences in the LDA and the PIV data, both of the data becomes to close to the PIV data compared with those of the conventional FFT. This means the correlation calculated by the slotted correlation method becomes to be estimated in good accuracy. Then, the applicable range of the Taylor's hypothesis becomes wide when using the slotted correlation method. The difference in the results in the 2-valves opening condition is caused by almost zero velocity in mean value and large fluctuation. Under the condition of the small velocity and large fluctuation, the length scales cannot be estimated correctly due to the

limitation of the Taylor's hypothesis. In the results of 1-valve opening condition, the length scales are almost half value of that of PIV. There are several possibilities of the reason why there were differences. It is natural that the flow motion is quite complicated and then the Taylor's hypothesis cannot be applied. The other possibility is PIV error in calculating the length scales. Because the interrogation area of the PIV is set to 2.5 mm x 2.5 mm, the size seems to be almost the same size as turbulent eddies. This will be resulted in errors for the estimation of the length scales from the PIV data. The influence of the size of the interrogation has to continue to be investigated.

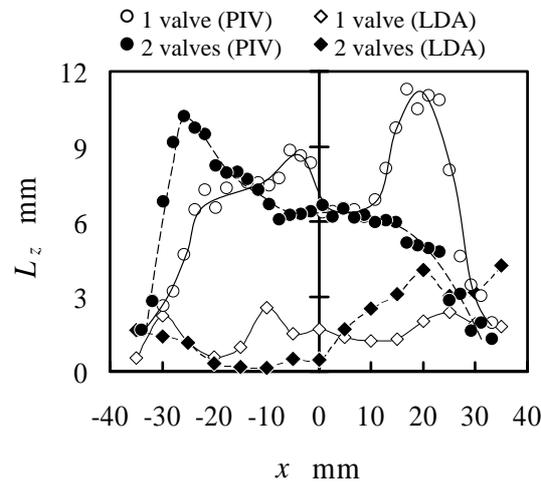


Fig. 9 Comparisons of integral length scale distributions between PIV and LDA at the center plane of $y = 0$ mm (Nomura et al., 2004).

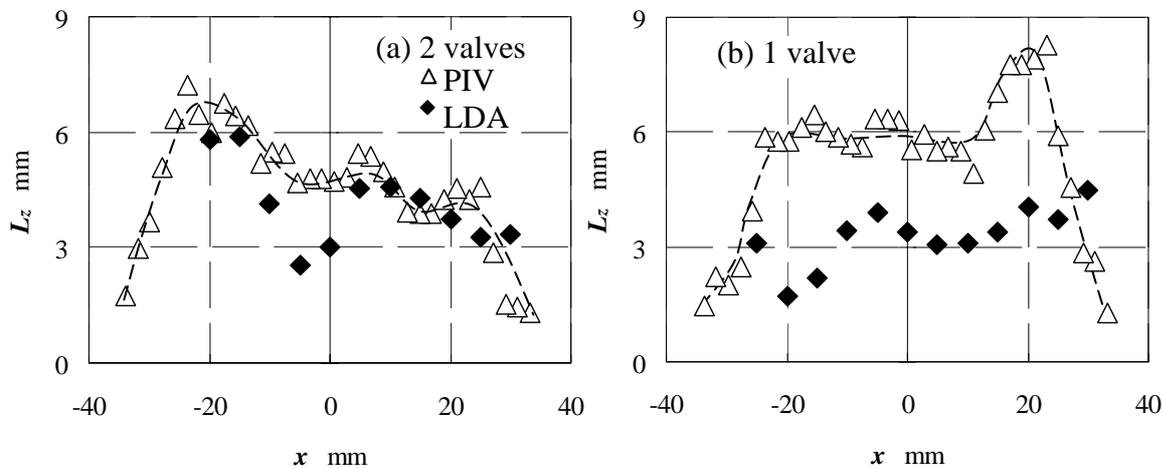


Fig. 10 Comparisons of integral length scale distributions between PIV and LDA with slotted correlation at the center plane of $y = 0$ mm.

4.3 Combination of FFT and slotted correlation method

From above discussion, the slotted correlation method is useful to calculating the auto-correlation and turbulent scales. When it will be applied to the cyclic motion, i.e. in-cylinder flow of actual internal combustion engine, definition of the mean flow becomes difficult. The slotted correlation method normally uses the fluctuation $u'(t)$ with the equation (2). In the actual internal combustion engine, the instantaneous in-cylinder flow can be divided into ensemble averaged mean velocity, cycle-to-cycle variation of bulk velocity and turbulence (Heywood, 1988). The treatment causes the difficulty to use equation (2) in the slotted correlation method. In this section, the fluctuation $u'_f(t)$ of the equation (8) is using for estimating the auto-correlation. In other words, a

combination of FFT, which divides the mean velocity and the fluctuation, and the slotted correlation method, which presents the auto-correlation, is proposed here.

Figure 11 shows the auto-correlations with various cut off frequency by using combination method and only FFT. The measuring position is $x = 35$ mm, $y = 0$ mm and $z = 40$ mm. The data rate is about 7 kHz. There is no difference in the tendency and the value in the results. When the cut off frequency is 300 Hz, the distribution shape of correlation curve is different from the others. As for a trial, the dominant frequency is estimated for the in-flow through the inlet valve relates with valve diameter 27.3 mm and bulk velocity of the inlet port of 30m/s. Using Strouhal number 0.21, the dominant frequency is estimated as about 230 Hz. This is a possibility why the auto-correlation with 300 Hz cut-off frequency is different from the others.

Figure 12 shows the auto-correlation at low data rate position in the cylinder. The measuring position is $x = 5$ mm, $y = 0$ mm and $z = 40$ mm. The tendencies are the same each other but values has difference. Again, the FFT result shows overestimations in the auto-correlations.

Figure 13 shows comparisons of the time scales under both data rate conditions. The time scales are independent from the estimating method when the data rate is enough high. The cut off frequency is almost no effect for the length scale. With the low data rate condition, the value of the slotted correlation method is smaller than that of the FFT. When the cut off frequency becomes small, the time-scale greatly increases in the result of only FFT. On the other hand, the slotted correlation method is stable to the cut off frequency although the auto-correlation shape of the 300 Hz cut-off frequency is different from the other data as shown in Fig. 11(a) and Fig. 12(a). It is indicated from the results that an exact establishment of the cut-off frequency is not requested when the slotted correlation method is applied.

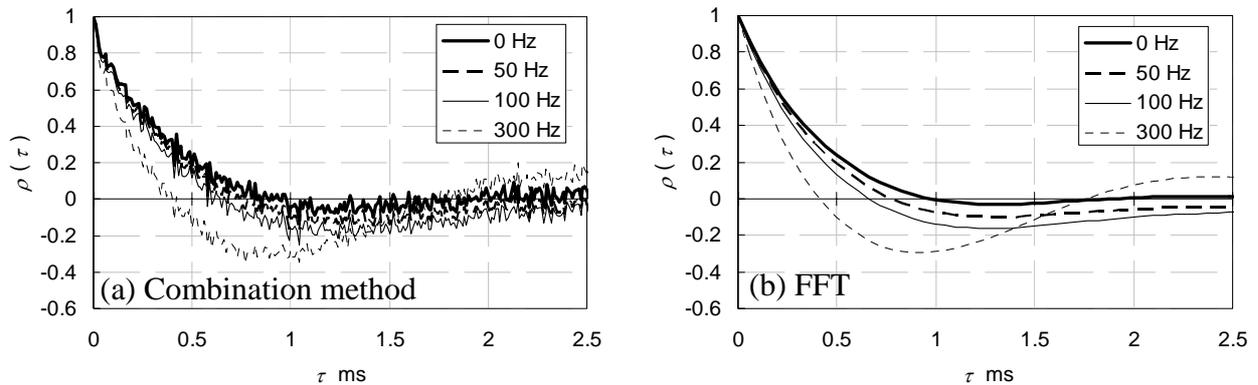


Fig. 11 Variation on auto-correlation with various cut off frequency by combination method (a) and only FFT (b) under high data rate condition.

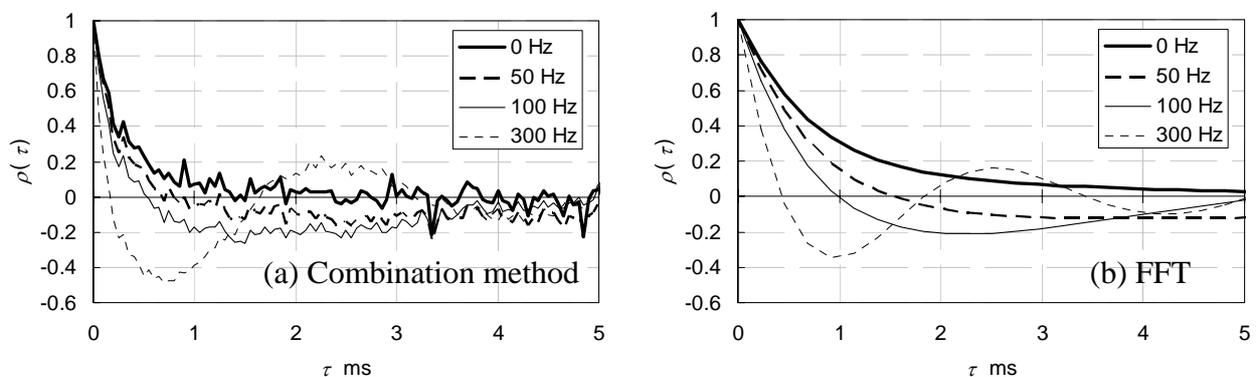


Fig. 12 Variation on auto-correlation with various cut off frequency by combination method (a) and only FFT (b) under low data rate condition.

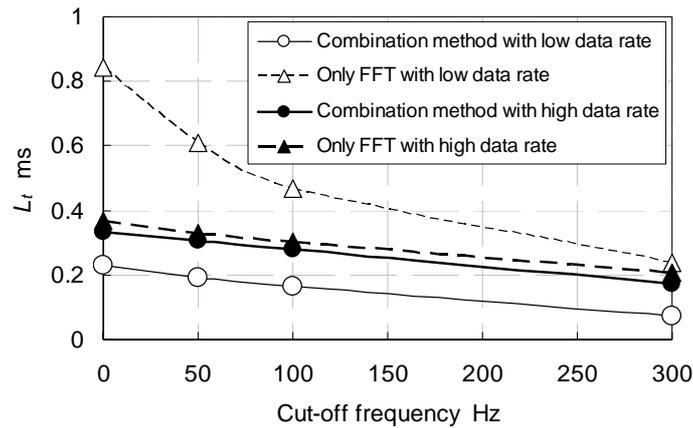


Fig. 13 Effect of the cut-off frequency on time scale.

4. Concluding remarks

The slotted correlation method developed for LDA data analysis is tested at the steady turbulent in-cylinder flow. Comparison results between the slotted correlation method and conventional FFT method show following conclusions.

1. The slotted correlation method is stable to the all data rate condition.
2. Using the slotted correlation method, the applicable range of the Taylor's hypothesis becomes wider.
3. To discriminate the turbulence components from the cyclically fluctuating bulk velocity at the flow like I. C. engine cylinder, the new combination of the FFT and the slotted correlation method is proposed. The effectiveness of the method is demonstrated.

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