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A LABORATORY STUDY OF THE EFFECT OF ACOUSTIC DOPPLER VELOCIMETER SAMPLING FREQUENCY AND SAMPLING VOLUME ON MEASUREMENTS

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Abstract: Acoustic Doppler velocimeters (ADVs) are popular devices for the measurement of velocity in hydraulic engineering applications. It has been found that ADVs accurately predict the mean velocity; however their turbulence measurements are affected by noise. It is expected that turbulence measurements using ADVs are further influenced by user adjustable ADV parameters, such as the sampling frequency and sampling volume. These parameters affect how the ADV calculates velocities (which depend upon temporal and spatial averaging of the received signals). Given this, an experimental study focusing on the performance of ADVs operating at different sampling rates and sampling volumes has been conducted to determine the effect on the turbulence statistics. The velocity field of a turbulent axisymmetric jet with a Reynolds number of 10,000 issued into a background of quiescent water was measured using an ADV. Measurements of the mean and RMS (root mean square) velocities at different sampling frequencies and sampling volumes were conducted and compared with those of other measurement techniques. The results show that mean velocities were not influenced by variations in the sampling frequency nor the sampling volume. On the other hand, the RMS velocities were damped as the sampling frequency decreased (resulting in more pings being averaged) or when the sampling volume increased (resulting in the velocity being averaged over more scattered particles). The present results offer insight into the choice of proper sampling frequency and sampling volume size for ADV measurements of turbulent flows.

1 INTRODUCTION

Acoustic Doppler velocimeters (ADVs) are relatively new instruments, which have been employed for the measurement of velocity, both in the field and the laboratory. The operating principle of ADVs involves the transmission of acoustic pulses and the subsequent reception of the backscattered signal from the sampling volume to obtain velocity estimates for the particles suspended therein. The probe consists of a transmitter and three or four receivers, which are symmetrically arranged around the transmitter. The sampling volume is located approximately 50 mm below the probe, which minimizes the interference of the probe with the flow. The velocity measured by the coherent demodulation approach will be along the bisecting angle between the transmitter and receiver (Nortek 2004) (also known as the beam velocity), which is subsequently converted into a Cartesian coordinate system by means of a transformation matrix.

The advantages of ADVs include their robustness, their ability to make three-dimensional velocity measurements, their practicality for use in non-clean environments, having minimal interference with the flow (due to the distance between the device and sampling volume), and their portability. These make ADVs a suitable instrument for many types of velocity measurements, particularly ones in the field. Despite these advantages, ADVs are nevertheless susceptible to certain errors. Although ADV measurements have been found to be accurate in terms of mean velocities and the Reynolds shear stresses, (Lohrmann et al. 1994; Voulgaris & Trowbridge 1997; Hurther & Lemmin 2007; Dombroski & Crimaldi 2007), the accuracy of their predictions of RMS velocities and the turbulent kinetic energy have been questioned (Voulgaris & Trowbridge 1997; Hurther & Lemmin 2007; Nikora & Goring 1998; Khorsandi et al. 2012). The reason is attributed to the fact that ADV measurements are subject to random spikes and Doppler noise (Voulgaris & Trowbridge 1997; Hurther & Lemmin 2000; Goring & Nikora 2002; Garcia et al. 2005; Doroudian et al. 2010, Khorsandi et al. 2013).

The principle of ADV operation involves averaging a number of pings prior to computing the outputted velocity estimate (which is referred to as the sample). With the understanding that the Doppler noise is the main contributor to the uncertainty in turbulent flow measurements (McLelland and Nicholas 2000; Khorsandi 2012), it is expected that the process of temporal and spatial averaging affects the RMS velocities by damping both the true signal and Doppler noise. Temporal averaging is not expected to affect the mean statistics since the Doppler noise is unbiased, and also because of the commutative nature of the averaging operator in the pre- and post-averaging domains. However, spatial averaging over the sampling volume can influence the mean velocities, especially where velocity shear is not negligible. Moreover, temporal and spatial averaging may both also affect the precision of measurements of RMS velocities as a result of the damping of fluctuations.

Statistical intuition would lead one to conclude that when the integral time and length scales of the flow, which are representative of the time and length scales over which the pings are correlated, become comparable with the size of the sampling interval and/or volume, respectively, the damping of RMS velocities may not be negligible. There may therefore exist a compromise between reduction of noise at the expense of an attenuation in the signal's fluctuations. Therefore, it is necessary to determine the reliability of ADV measurements and how they might be improved. Here we attempt to study mean and turbulence statistics measurements made by ADVs at two sampling frequencies of 25 Hz and 200 Hz (the maximum user adjustable sampling frequency) and two sampling heights of 9.1 mm and 3.1 mm (corresponding to the sampling volumes of 0.26 cm^3 and 0.09 cm^3, respectively), which are the maximum and minimum user adjustable heights, respectively.

2 EXPERIMENTS

The experiments were carried out in a 1 m by 1.7 m by 0.54 m (upstream) concrete basin connected to a 6 m long flume filled with water, open to the ambient air at the top, and located in the Hydraulics Laboratory of the Department of Civil and Environmental Engineering at Amirkabir University of Technology. An axisymmetric turbulent jet of circular cross-section was emitted into the upstream basin, parallel to the flume direction. The jet issued from a copper tube, which was 10 mm in diameter and fed from a constant head reservoir. The Reynolds numbers of jet ($Re=U_JD/\nu$, where U_J is the mean velocity at the jet nozzle, D is the diameter of jet nozzle, and ν is the kinematic viscosity of the water) was 10,000.

The velocity field was measured by a Nortek Vectrino 10-MHz acoustic Doppler velocimeter. The manufacturer's accuracy is given to be 0.5% of the sampling range, selected herein to be ±10, ±30 or ±100 cm/s (depending on the position in the flow), and chosen to span the entire range of measured velocities. The sampling rate was 25 Hz and 200 Hz (the maximum) and the sampling height of the ADV was set to its largest (9.1 mm) and smallest (3.1 mm) to evaluate the effect of these user-adjustable parameters on the measurements. Talcum powder was added to the water to increase the signal to noise ratio of the ADV. During the measurements, the axis of the jet was oriented along the x-direction of the ADV probe. The u, v and w velocities reported herein are along the x-, y- and z-directions of the probe, respectively.

3 RESULTS

The effect of sampling frequency on measurements will be discussed first. During these measurements, the sampling height was constant and set to its largest (9.1 mm). Profiles of axial mean velocity (normalized by the centerline mean velocity, U_{cl}) measured at $x/D = 75$ (where x is the downstream distance) using two sampling frequencies of 25 Hz and 200 Hz are plotted in figure 1 (in a manner consistent with self-similarity). The shapes of the profiles compare generally well with the flying hot-wire anemometry (FHWA) measurements by Panchapakesan & Lumley (1993), the laser Doppler anemometry (LDA) measurements by Darisse et al. (2015) and the constant-turbulent viscosity theory of Pope (2000). Although the magnitude of the ADV mean flow tends to be slightly underestimated close to the edge of the jet, there is a consistency in the results near the centerline. Near the axis of the jet (0 < r/x < 0.05), the present measurements are in excellent agreement with FHWA data of Panchapakesan & Lumley (1993), with deviations of less than 2%. Also note that measurements using different sampling frequencies are in good agreement with each other, which suggests that the mean statistics are effectively independent of the instrument's sampling frequency.

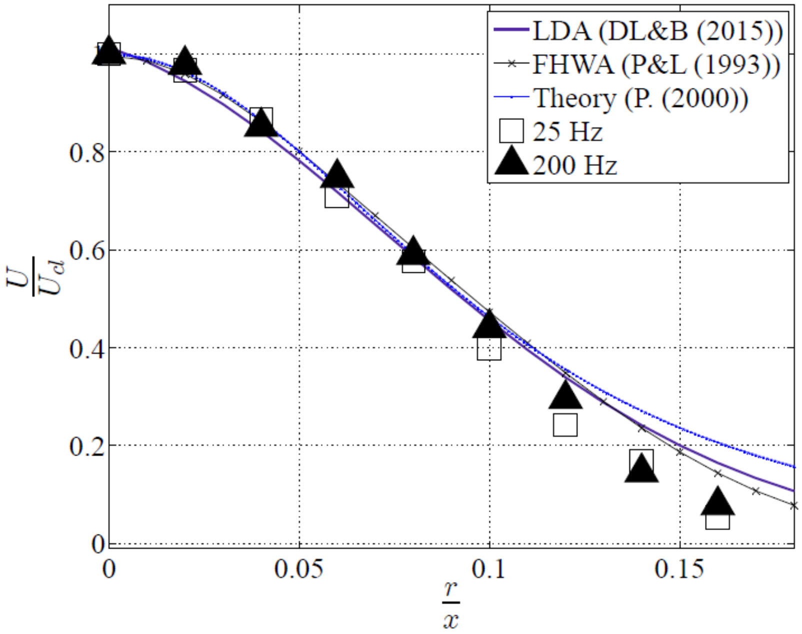

Figure 1: Normalized axial mean velocity measured at different sampling frequencies (at x/D = 75), and compared with other studies.

The downstream decay of mean axial velocity over the range 30 ≤ x/D ≤ 105 measured using different sampling frequencies is shown in figure 2. The expected linear growth of the reciprocal of the centerline velocity normalized by the nozzle exit velocity is observed over the range 30 ≤ x/D ≤ 80 for both sampling frequencies, although small deviations for x/D ≥ 90 also exist, which are presumably due to the small jet velocities at those far-downstream locations. Consistent with the axial mean velocity profile, the similarity between the measurements using various sampling frequencies confirms that the mean statistics are effectively independent of the instrument's sampling frequency. The data have a constant slope, with its inverse, the decay rate (B), defined by $\mathrm{U_{cl}/U_j = B[(x - x_0)/D]^{-1}}$, where x_0 is the virtual origin and depends on the initial conditions (Pope 2000). Another parameter of interest is the spreading rate (S), defined as $\mathrm{S = r_{1/2}/(x - x_0)}$, where $\mathrm{r_{1/2}}$ is the half-width of the jet, given by the radial distance at which the velocity falls to half of its maximum centerline value at a given downstream distance. Table 1 shows the values of B, $\mathrm{x_0}$ and S obtained using the method of least squares using the aforementioned two equations fitted to data sampled at different sampling frequencies. The value of B and $\mathrm{x_0}$ were calculated using the data over the range 30 ≤ *x*/D ≤ 80, and the value of S corresponds to the measurements at x/D = 75. Good agreement is observed between the results of present work and the ADV measurements of Khorsandi et al. (2012), the stationary hot-wire anemometry (SHWA) measurements by Wygnanski & Fiedler (1969), the FHWA by Panchapakesan & Lumley (1993), and the LDA by Hussein et al. (1994). Note that the ADV measurements of Khorsandi et al. (2012) were measured using a different apparatus with different background conditions, and their agreement with the present measurements serves to validate the accuracy of ADV measurements herein for the mean flow.

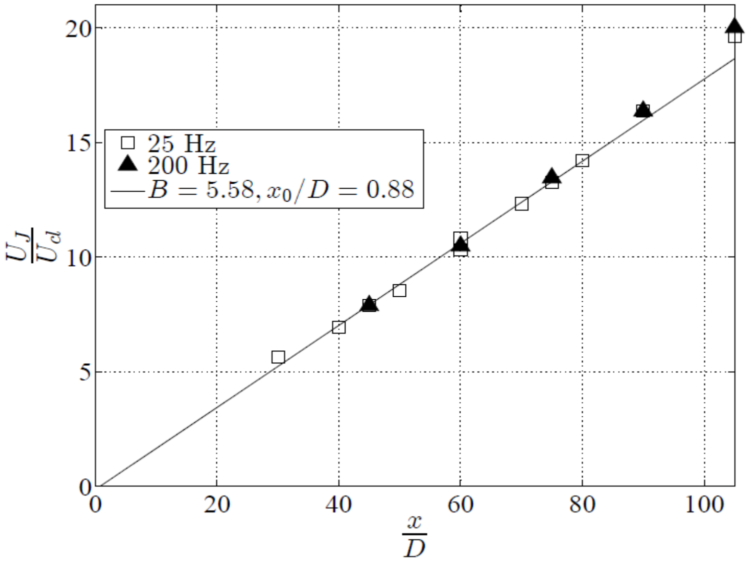

Figure 2: Variation of the (inverse of the) centerline axial mean velocity with downstream distance. The data is fit to the explicit function: $U_{cl}/U_j = B[(x - x_0)/D]^{-1}$

Table 1: Comparison of the evolution of turbulent axisymmetric jet studies.

	Present Study (25Hz & 200 Hz)	KM&G (2012) ADV (25Hz)	W&F (1969) SHWA; x/D<50	P&L (1993) FHWA	HC&G (1994) LDA
Re	10000	10600	100000	11000	95500
x_0/D	0.88	5.5	3	0	4
B	5.58	5.43	5.7	6.06	5.8
S	0.089	0.099	0.084	0.096	0.094

Figure 3 plots the variation of the axial velocity variance for various sampling frequencies normalized by the square of the mean velocity along the centerline of the jet. Overall, one observes that the sampling frequency of 200 Hz tends to overestimate the axial RMS velocities (u_{rms}), when compared to those measured with a 25-Hz sampling frequency in the present study, and with other measurement techniques, including FHWA by Panchapakesan & Lumley (1993) and the LDA data of Hussein et al. (1994).

Another important observation is that the difference between the data acquired with the 25 Hz and 200 Hz sampling frequencies in figure 3 decreases with increasing downstream distance. This is due to a reduction in the turbulence, which is accompanied by an increase in the integral time scale (and therefore, dropping the ratio of sampling interval to the integral time scale, hereafter called the SI/ITS), and an overall increase in the correlation coefficient reported by the instrument.

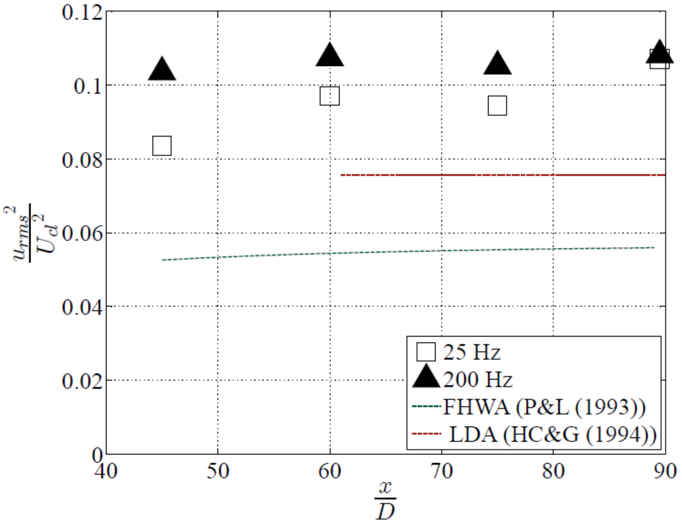

Figure 3: Variation of axial velocity variance normalized by the squared centerline mean velocity measured at different sampling frequencies in this study, and compared with others.

The normalized lateral and vertical centerline velocity variances plotted as a function of the downstream distance are shown in figure 4. Similar to the axial velocity variance, the lateral velocity variances are overestimated, especially at higher sampling frequencies. The difference between various sampling frequencies also drops at the farthest downstream locations. All of the aforementioned observations are best explained in terms of the growth in the SI/ITS, as discussed for u_{rms}^2. We note that the noise in the x- and y-directions is similar due to the transformation matrix, and so are the correlation coefficients reported by the instrument, thus the similarity in the observed trends for these two moments is not unexpected.

Also apparent from the measurements is the significant deviation of the v_{rms}^2 measurements, in spite of the fact that they must be identical to those of w_{rms}^2, due to axisymmetry of the flow. This observable deviation is due to the increased noise in the v_{rms}^2 measurements, and the damping of w_{rms}^2. Furthermore, it is clear that the difference between w-measurements for different sampling frequencies is not significant over the range of downstream distances considered, in contrast to the evolutions of u_{rms}^2 and v_{rms}^2. This observation further indicates that the major source of error for w-measurements differs from that for the u- and v-measurements.

Figure 5 depicts the profiles of the normalized axial velocity variance measured at two sampling frequencies, and compared with the LDA data of Darisse et al. (2015) and the FHWA data of Panchapakesan & Lumley (1993). Overall, the general shape of the profile is comparable with other measurement techniques, but the ADV's 200 Hz sampling frequency results in an increase in the measured statistics in comparison with other techniques, as well as the 25-Hz sampling frequency. On the other hand, the steadily decreasing difference between the measurements at two sampling frequencies when moving towards the outer regions of the jet is due to the reduction in SI/ITS.

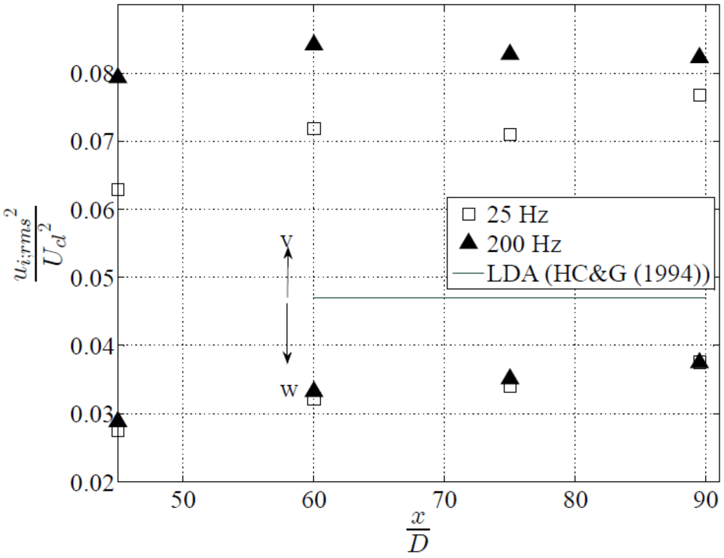

Figure 4: Variation of the lateral and vertical velocity variances normalized by the squared centerline mean velocity for different sampling frequencies, and compared with the FHWA data of Panchapakesan & Lumley (1993).

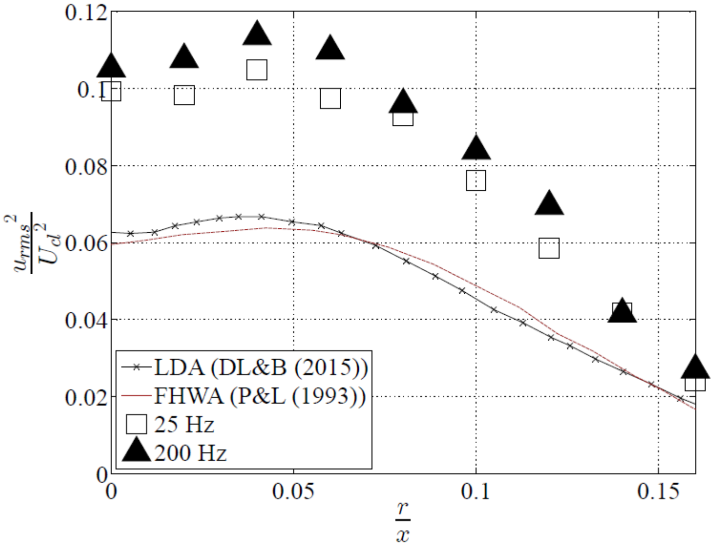

Figure 5: Radial profiles of normalized axial velocity variance measured at different sampling frequencies, and compared with other studies.

The profile of the normalized Reynolds shear stress is presented in figure 6. The overall shape of profile is comparable for both the FHWA and LDA data, with increased levels of agreement by moving away from the peak. In contrast to the claims in the literature that the noise does not affect the Reynolds shear stresses (e.g., Hurther & Lemmin (2000); Voulgaris & Trowbridge (1997)), it can be argued that the Reynolds shear stress contains substantial noise on the grounds of the observable deviations of the measurements from those using other techniques. In addition, the ADV's 200-Hz sampling frequency results in an increase in the measured statistics in comparison with the 25-Hz sampling frequency.

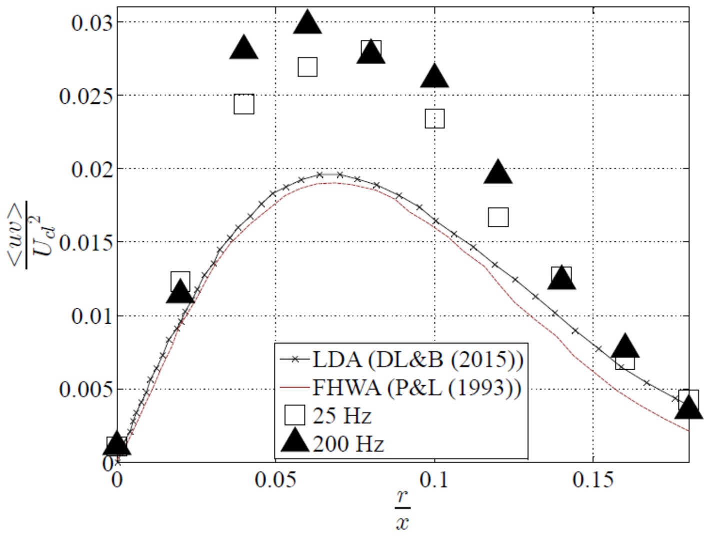

Figure 6: Radial profile of the normalized Reynolds shear stress measured at different sampling frequencies, and compared with other studies.

The effect of the size of sampling volume on measurements is evaluated next. During these measurements the sampling frequency was constant and set to 25 Hz. The self-similar profiles of axial mean velocity measured using two sampling heights of 9.1 mm and 3.1 mm are plotted in figure 7. The shapes of the profiles agree well with those of the other studies. Despite the variations of the mean velocity shear across the profiles, no significant difference is observed between the mean velocities measured at the two sampling volume sizes. This suggests that the mean statistics are effectively independent of the instrument's sampling volume in the flow studied herein.

Figure 8 shows the profiles of the normalized axial velocity variance measured at two sampling heights of 9.1 mm and 3.1 mm, and compared with the LDA data of Darisse et al. (2015) and the FHWA data of Panchapakesan & Lumley (1993). The general shape of the profile is comparable with other measurement techniques, but the axial velocity variances are overestimated, especially using the sampling height of 3.1 mm. Overall, it can be seen that the larger sampling volumes result in smaller RMS velocities. Voulgaris & Trowbridge (1997) and McLelland and Nicholas (2000) theoretically showed that the velocity shear in the sampling volume broadens the signal and results in a noise variance which is proportional to the square of the difference in velocity across the transmitted pulse. This is in contrast to the present observations in which increasing the sampling volume size (and shear) resulted in a decrease in the RMS velocities. The reason for a decrease in the RMS velocities is that when the sampling volume size increases, the number of scattered particles in the sampling volume increases and, as a result, the output velocity is averaged over more particles and therefore, the fluctuations are damped. It is hypothesized that when the sampling volume size is less than the integral length scale of the flow, the damping effect becomes negligible.

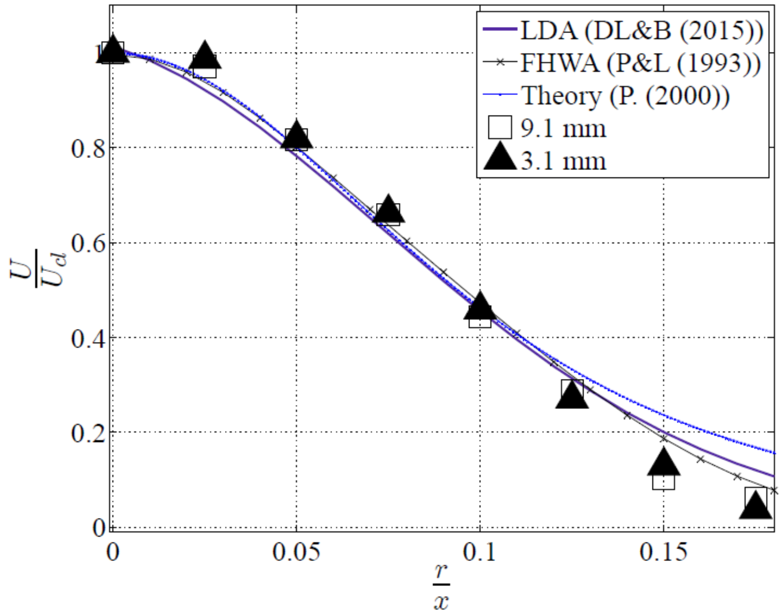

Figure 7: Normalized axial mean velocity measured using different sampling volumes (at x/D = 60) and compared with other studies.

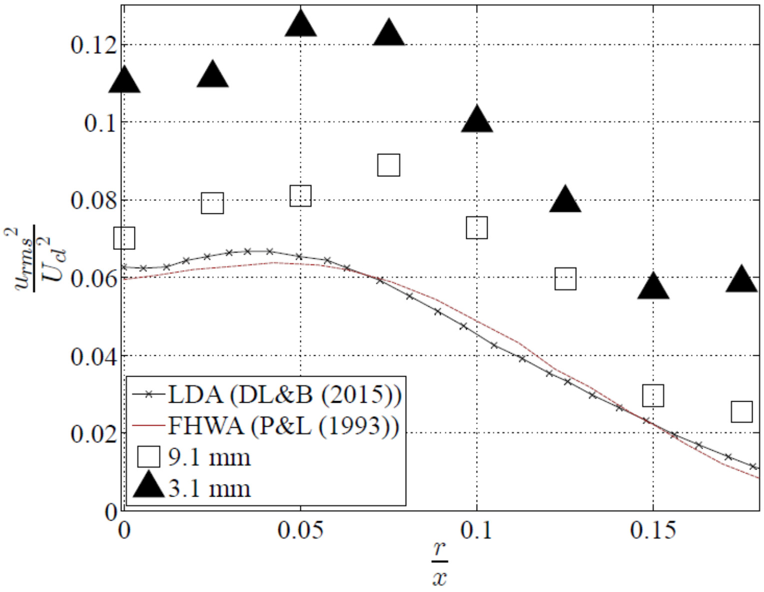

Figure 8: Radial profiles of normalized axial velocity variance measured using different sampling volumes, and compared with other studies.

4 CONCLUSIONS

The effect of the sampling frequency and sampling volume of the ADV on the precision of measurements in a turbulent axisymmetric jet has been investigated. It is shown that the measurements of first-order statistics (the mean velocity, the decay rate, and the spreading rate) are insensitive to the change of sampling frequency, while the increase in the sampling frequency results in increased velocity variances and Reynolds shear stresses. The experimental results point to the conclusion that the damping of turbulence fluctuations due to the averaging of pings, can explain how the sampling frequency affects the turbulence quantities. In this respect, the ratio of sampling interval to the integral time scale was found to be the influential parameter. As this ratio increases, the effect of the sampling frequency becomes considerable. Furthermore, the measurements of mean velocities are not influenced by the size of the sampling volume. On the other hand, the increase in the sampling volume results in decreased velocity variances, due to the fact that the velocity of a larger number of scattered particles are being averaged.

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