A Time Interval Sampling Method for the Removal of Velocity Bias in LDV Measurements in Turbulent Flows

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ABSTRACT

A method is described for the removal of velocity bias from LDV measurements by using an approximately constant time interval sampling approach. The technique was checked by integrating the mean velocity with respect to cross sectional area of the flow field occurring in the recirculation region downstream of an axisymmetric sudden expansion, and comparing this result with flow rates obtained from a bellmouth flow meter. The corrected mean velocity results agreed within 2.5% of the bellmouth results.

NOMENCLATURE

f_s	prescribed sampling frequency
h	step height
$\dot{m}$	measured bellmouth mass flow
N	number of data samples
r	radial coordinate
R	radius of inlet to test section.
Δt_i	doppler burst period of ith data point
T_i	time between counter inhibit release and arrival of ith data point.
u'	axial turbulence velocity
$\bar{U}$	mean local axial velocity
U_i	axial velocity of ith data point
$\bar{U}_o$	biased mean axial centreline velocity
V_i	velocity vector of ith data point
x	distance downstream of step.
ρ	air density

INTRODUCTION

A popular strategy for the solution of fluid mechanics problems involves solution of the Reynolds Equations for various geometries and flow conditions of interest. This strategy requires an empirical model that incorporates present knowledge of various flow classes for relating the Reynolds stresses to mean flow properties. Improvement of these models necessitates time resolved measurements of local fluid velocities.

For many flows the Laser Doppler Velocimeter is the ideal instrument for measurement of flow velocities since it is non intrusive, calibration free and has high spatial and temporal resolution. The technique relies on the detection of the doppler shift of light scattered from small particles within the flow. There are two major interrelated practical problems associated with this technique.

The first is the requirement to seed the measurement region of the flow with sufficient particles to provide statistically significant results in reasonable elapsed time. The particles must be small enough to follow the flow, large enough to scatter sufficient light for photomultiplier detection, yet not so large that they intercept multiple fringes within the measurement volume.

The second problem arises from the fact that counter type signal processors make discrete velocity measurements from individual realizations of seed particles passing through the measurement volume. In a uniformly seeded flow, the number of particles per unit time passing through the measurement volume is proportional to the flow rate through that volume, and simple arithmetic averaging of an ensemble of particle measurements will therefore produce readings biased towards values greater than the true temporal mean. Temporal mean quantities are used in conventional Reynolds stress models.

This problem was first recognized by McLaughlin and Tiederman (1973) and since then has received a great deal of attention, since without the elimination of velocity biasing, the LDV will provide accurate results only in laminar or low intensity turbulent flows.

BACKGROUND

Several correction schemes have been proposed for removal of velocity bias. The majority of these schemes assume a uniform distribution of particles throughout the fluid and weight individual velocity readings by the magnitude of the instantaneous velocity vector V_i (Equation 1).

$$\bar{U} = \sum_{i=1}^{N} \frac{1}{|V_i|} U_i \bigg/ \sum_{i=1}^{N} \frac{1}{|V_i|} \qquad - - - - - (1a)$$

$$u' = \left[\sum_{i=1}^{N} \frac{1}{|V_i|}(U_i - \bar{U})^2 \bigg/ \sum_{i=1}^{N} \frac{1}{|V_i|} \right]^{1/2} - - (1b)$$

Since a three component LDV system is required to determine this vector accurately, other assumptions are usually invoked to enable calculation of a weighting function for one and two component systems. The original McLaughlin and Tiederman (1973) correction assumes one dimensional flow and equates the measured velocity value to the magnitude of the instantaneous velocity vector. Durst (1974) has suggested that the period of the doppler burst is inversely proportional to the magnitude of the velocity vector, and that this value may be used to determine the bias correction factor (Equation 2)

$$\bar{U} = \sum_{i=1}^{N} \Delta t_i U_i \bigg/ \sum_{i=1}^{N} \Delta t_i \qquad - - - - - - - - (2a)$$

$$u' = \left[\sum_{i=1}^{N} \Delta t_i (U_i - \bar{U})^2 \bigg/ \sum_{i=1}^{N} \Delta t_i \right]^{1/2} - - - - - (2b)$$

This approach was used by Buchave (1979) who concluded that residence time weighting provided correct statistical results in uniformly seeded flows. It should be noted however that Buchave in his experiments compared hot wire measurements in a free jet with frequency shifted LDV measurements from both counter and tracker processors and found at least an 8% difference between hot wire and tracker results. He therefore lacked reliable unbiased values for direct comparison with his weighted results. Roesler et al (1980) have reviewed several papers on the above correction schemes and other proposed methods (e.g. weight by time between particles) and concluded that the 'proper' correction method to be used is not clear, since no definitive experiments have conclusively demonstrated the existence of velocity bias and the primary problem is the difficulty of obtaining accurate unbiased measurements in turbulent flows.

In addition to the above difficulties, Durst (1974) has

suggested that additional biases may occur due to variations in particle number concentration which, in a nominally uniform seeded flow, result from turbulent like fluctuations in fluid density, such as might occur in combustion or unsteady flow. Similar problems occur in the mixing region of two flows of different seed concentration.

These biases may be eliminated by a constant time interval sampling process as suggested by Simpson and Chew (1979). This process has been developed and verified by Stevenson et al (1982, 1983) and Craig et al (1980). Their approach was to limit the sampling rate of the LDV processor and to increase the seeding rate until the velocity bias effectively disappeared. At low turbulence levels little change in the mean velocity was observed; at high turbulence levels the mean velocity decreased significantly until effectively constant interval sampling was introduced. Roesler et al (1980) observed that this occurred when the seeding rate to sampling rate was in the ratio of 100:1.

ASSESSMENT OF BIAS

The principal difficulty in assessment of bias in LDV is the lack of a reliable independent velocity measurement technique. The primary instrument for comparison purposes is the hot wire anemometer. However, the flow regimes where velocity bias is most significant (very high turbulence levels) is precisely where the hot wire anemometer is inadequate, because of its inability to detect flow reversals. It is necessary therefore to rely on indirect methods.

The constant time interval sampling method of Stevenson et al (1982, 1983) and Craig et al (1984) enables detection of the velocity bias level in that as the sampling rate/valid data rate ratio is decreased, the measured mean velocity asymptotically decreases from the biased value to the unbiased level. A second procedure, suitable for confined flow, is to compare the mass flow as determined from integration of the mean velocity profile with that determined from a calibrated flow measurement device. Both procedures were used in this study.

This experiment builds on the work of Stevenson et al (1982, 1983) and Craig et al (1984). The experiment is part of a program aimed at developing a technique for two component LDV measurements in confined high speed unsteady combusting flows. As a first step single component measurements have been made in an airflow contained by an axisymmetric sudden expansion.

EXPERIMENTAL FACILITIES

All experiments were conducted in a clear perspex sudden expansion as shown schematically in Figure 1.
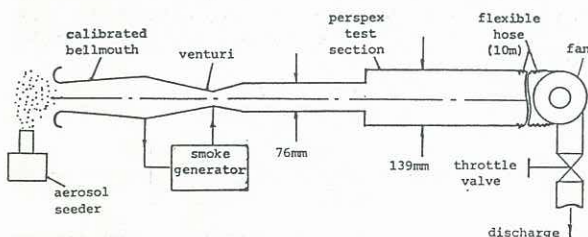

Figure 1. Experimental Rig – Schematic

Air was drawn through the experimental rig by a centrifugal fan. The flow rate was controlled by a valve at the discharge port of the fan. Flow through the rig was measured by a calibrated bellmouth at the entrance. A venturi, located downstream of the bellmouth, was used for pressurizing a smoke generator to introduce seed particles into the flow without air additional to that measured by the bellmouth. The smoke generator flashed small droplets of oil to provide a fine mist of oil particles. The oil rapidly collected on the walls of the perspex test section with consequential degradation of the optical path and the LDV signal to noise ratio. The technique used for the reported experiment was to seed the ambient air surrounding the bellmouth inlet with a mist of an aqueous solution of sugar. The mist was produced by a TSI model 9306 six jet atomiser.

The venturi was followed by a constant area section 920 mm long and 76 mm diameter. Average flow velocity in this section (determined from the bellmouth flow meter) was 29 m/sec, corresponding to a Reynolds number of 1.5×10^5 based on diameter. The test section followed a sudden expansion to 139 mm diameter and was 1100 mm in length. Measurements were taken at various locations downstream of the sudden expansion, both within the recirculation region (x/h = 1.8 & 2.1) and in the reattached flow (x/h = 8.4).
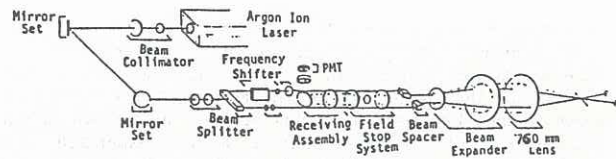
LASER VELOCIMETER

1. Optical System

Figure 2. Optical System – Schematic

The optical system (Figure 2) utilized for these experiments was one component of a standard 2 component TSI four beam, two colour backscatter system optimised for high speed flows. The optics included a 3.75x beam expander, a 13 mm beam separation at entrance to beam expander and a final focusing lens of focal length 760 mm. The Argon Ion laser was operated in the 514.5 nm single line mode at 400 milliwatts power. The corresponding calibration factor for the system was 8.05 m/s per MHz. The measurement volume dimensions, based on $1/e^2$ intensity points, were length 4.2 mm, diameter 133 µm and fringe spacing of 8.05 µm. The measurement control volume was traversed across the flow by means of motion of the final focusing lens. The lens positioning system was accurate to .01 mm. A Bragg cell introduced a 40 MHz shift into one beam and was adjusted so that the fringes moved counter to the average flow direction. The signal from the photomultiplier was downmixed so that the effective frequency shift was in the range 0.5 to 2 MHz, dependent on the local flow conditions.

2. Signal Processing

The signal processing equipment consisted of a TSI model 1990B counter processor, a TSI 1998 Master Interface, an ARL custom made conditional interface (Harch, (1985)) and a Hewlett Packard 9825A Computer.

The photomultiplier signal from the downmixer was fed into the TSI model 1990B counter processor. Each time a velocity data point was validated and latched into the output register, the TSI counter generated the following output:

(a)   16 Bit time output

(b)   8 Bit cycle count output

(c)   1 Bit data ready pulse.

The cycle count plus the time output together determine the doppler frequency, although the latter is sufficient information if the counter is operating in the fixed N cycle mode.

The 1998 Master Interface uses the above information to generate two 16 Bit words for each counter in the system. The interface also generates a third word representing the time between data points (TBD). The words contain the following information:

(a)   Word A   8 Bit cycle count, 2 bit processor address, 1 bit counter mode, 1 bit first transfer after synchronizing pulse

(b)   Word B   16 Bit time output

(c)   Word TBD   16 Bit time between data points.

The ARL custom made conditional interface operates in two modes: ACTIVE and INTERNAL RATE. In the INTERNAL RATE rate mode, a DMA data transfer occurs between the master interface and the computer everytime the counter generates a data ready pulse.

In the ACTIVE mode, the sampling frequency is controlled by either an internally or externally generated square wave. The normal inhibit that is imposed on the TSI 1990 Counter during a data transfer operation is prevented from being cleared until the next rising edge of the sampling square wave, following completion of the data transfer. The maximum data rate from the counter is therefore equal to the prescribed sampling frequency, although the actual rate may be less. The internally generated sampling frequency is periodic and continuously variable in the range .03 Hz to 650 KHz. An externally generated sampling square wave may be used to impose a conditional sampling scheme that is non-periodic or synchronized to an external event.

This form of conditional sampling allows only one data point to be passed to the computer for each sampling pulse, and consequently enables significant reduction in computational overheads when compared with techniques in which all points are recorded together with a synchronizing pulse for post processing, since the conditioned data typically represents less than 1% of all validated data points.

In both the INTERNAL RATE and ACTIVE mode, data is transferred via Direct Memory Access (DMA) to one of two buffers within the 9825A computer. When the first buffer is full, data processing commences while the second buffer is filled with data. Filling and processing of alternate buffers then proceeds until the required number of points (usually 10,000) have been obtained. Computer memory enables storage of 9000 words (3000 unprocessed data points) and this, together with computer speed, are the present limitations on the data acquisition system.

3. Data Analysis

The analysis software calculates the first four moments of the velocity distribution, and these are presented as mean velocity, turbulence, skewness and kurtosis. Turbulence Intensity is also calculated and a histogram of the velocity distribution (100 predetermined bins) may also be plotted. The histogram, together with the calculation of the 3 sigma limits of the velocity distribution, enables setting of software filters to eliminate occasional spurious data points.

The software also enables calculation of the constant sampling rate time error according to equation 3. This term represents the average time interval between release of the counter inhibit and latching of a new valid data point into the output register, expressed as a percentage of the prescribed sampling interval. The term reflects the degree of departure from constant actual sampling rate, and can be used to determine the appropriate ratio of seeding rate to sampling rate for the flow.

$$\text{Sampling Rate Time Error (\%)} = 100\, f_s \sum_{i=1}^{N} T_i / N \;------\; (3)$$

RESULTS AND DISCUSSION

Figure 3 shows profiles of biased mean velocity and turbulence levels across a radius of the test section at the three aforementioned axial locations. Peak turbulence levels referred to centreline velocity (Figure 3(c)) occurred around r/R = 1 at all axial locations tested; corresponding local turbulence levels (Figure 3(b)) were approximately 50%. It was in these regimes of high turbulence that velocity bias was most likely to occur. Integration of the velocity profiles produced mass flows (Figure 4) that were greater by a mean 7% than the measured mass flows, confirming the probability of bias in the LDV readings.

The magnitude of the bias error was estimated at two axial locations by using the constant time interval sampling technique. Figure 5 shows plots of mean velocity versus sampling rate time error for the two locations, at radial positions near r/R = 1. The Figure also indicates the levels of mean velocity recorded at these positions with sampling at the internal data rate (i.e. with the conditional interface inactive), at which condition maximum bias could be expected.

(a) Mean Velocity

(b) Local Turbulence Intensity

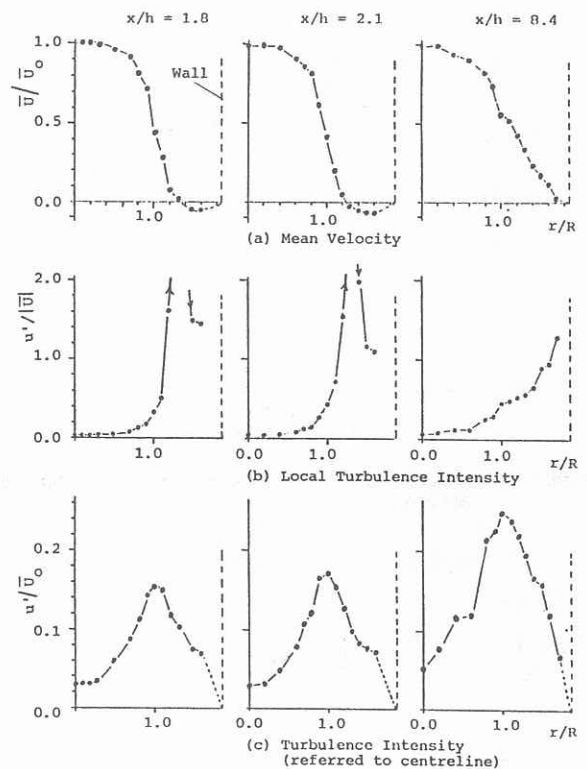(c) Turbulence Intensity (referred to centreline)

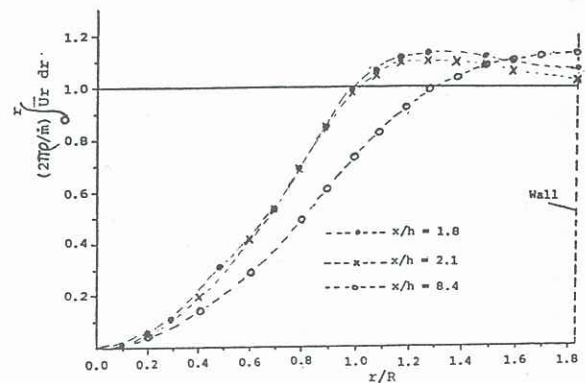Figure 3. Biased Mean Velocity and Turbulence Profiles

Figure 4. Biased Integrated Mass Flux Profiles

On the basis of Figure 5, there was a mean velocity bias error of about 8% associated with sampling at the internal data rate in regions of 50% local turbulence intensity, and a sampling rate time error of around 10% would appear to be the value necessary to reduce the bias to an insignificant level. This latter value represents approximately one order reduction in data rate compared with the two orders suggested by Roesler et al (1980). Craig et al (1984) reported a velocity bias of 25% in a region of 50% turbulence, which was in agreement with the original McLaughlin and Tiederman (1973) analysis, and found that a one order reduction in data rate yielded a sampling rate time error of the order of 1% and reduced the velocity bias to around 0.1%. It is postulated that these contrasting observations highlight the effects of different seeding procedures and the nature of the flow on velocity bias phenomena.

The flow measurements in Figure 3 were repeated using the conditional sampling module and a sampling rate time error of 10%, to eliminate velocity bias. The resultant data are shown in Figure 6. In the region of maximum turbulence intensity (.9 < r/R < 1.1) the mean velocities decreased by up to 8% (consistent with Figure 5), while turbulence levels marginally increased (3%) as expected.
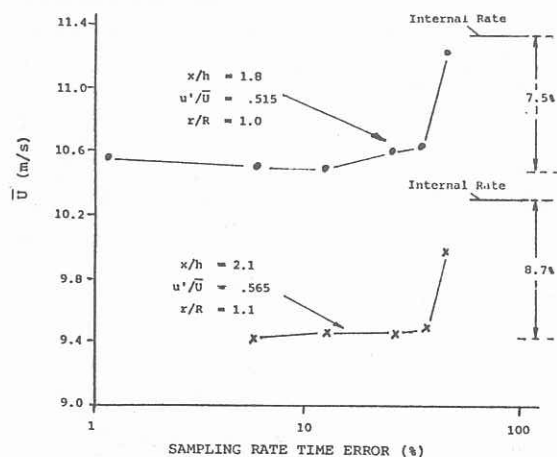
Figure 5. Effects of Sampling Rate Error Constant on Mean Value

(a) Mean Velocity

(b) Local Turbulence Intensity

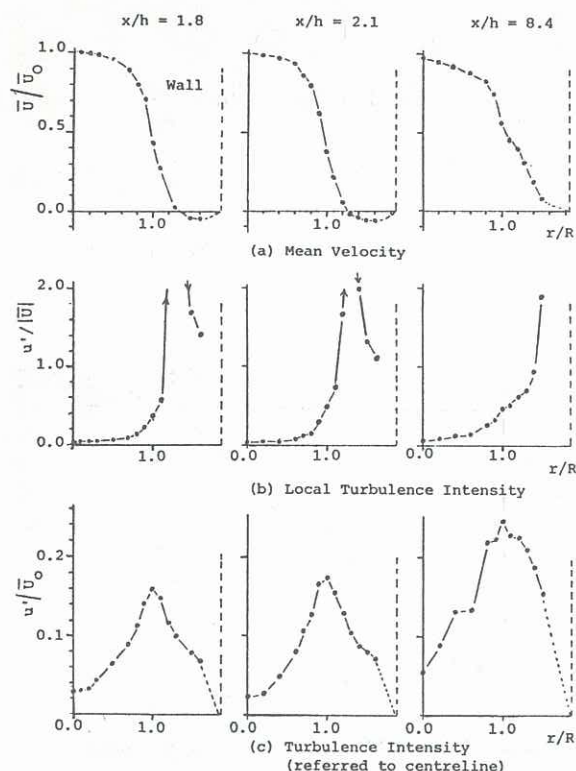(c) Turbulence Intensity
(referred to centreline)

Figure 6. Unbiased Mean Velocity and Turbulence Profiles

Figure 7 shows integrated mass flows calculated from the unbiased mean velocity profiles. Comparison with Figure 4 shows that the bias correction reduced the mean error (relative to the bellmouth) to around 2% which is regarded as being comparable with the margin of overall experimental error. The reduction in integrated mass flow at x/h = 8.4 (9%), where there was no recirculation, was significantly greater than at the flow stations where recirculation occurred (3% mean). This is believed to be due to the negative effect of velocity bias in the reverse flow regions, amplified by the relatively high turbulence levels in those regions.

CONCLUSIONS

The constant time interval sampling procedure has been confirmed as a suitable method for obtaining unbiased mean flow and turbulence data in highly turbulent flows.

Measurement of the sampling rate time error provides an indication of how close the experimental procedure
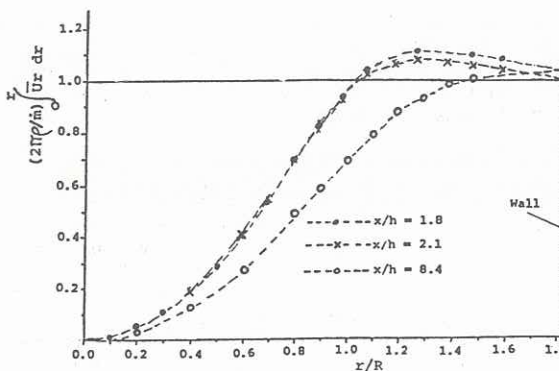

Figure 7. Unbiased Integrated Mass Flux Profiles

approaches constant time interval sampling for various validated data rates and sampling rates. As the sampling rate time error is reduced the measured mean velocity asymptotically approaches the unbiased value and this technique may be used to determine the required sampling rate time error for a given set of flow conditions.

Integration of the unbiased mean velocities in the axisymmetric constant density test flow produced results that agree within 2.5% of the independently measured mass flow measurements.

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