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Direct Measurement of Laser Velocimeter Bias Errors in a Turbulent Flow

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It was suggested in 1973 that a velocity bias might exist in measurements made with individual realization laser velocimetry (LV) systems. However, subsequent attempts by a number of investigators to experimentally verify the theory have produced conflicting results as to the magnitude and even the existence of this bias effect. In this paper an experimental study using a signal processing technique which allowed velocity bias to be measured directly is described. The results clearly demonstrate the effect of signal processing conditions on the magnitude of the velocity bias and suggest means for eliminating it. The related problem of incomplete signal bias was also investigated.

I. Introduction

FOLLOWING the analytical prediction of velocity bias by McLaughlin and Tiederman,[1] a number of investigators conducted experiments specifically to verify the existence of this effect. Other investigators made measurements in turbulent flows where the bias should be present and considered it in their data reduction. Some of these studies are reviewed here to illustrate the various techniques used and the nature of the results. A complete review is not implied.

Durao and Whitelaw[2] proposed that random sampling of the data record from a burst processor (counter) would remove velocity bias "by diminishing the weighting of signals which appear with small time intervals between them." Computer predictions supported this argument, but measurements on the centerline of a free jet at 25% turbulence intensity were inconclusive. Additional measurements at 40 and 100% turbulence were also not definitive.

Quigley and Tiederman[3] made measurements in the viscous sublayer of a water channel. When their velocity profile was corrected using the McLaughlin-Tiederman (M-T) one-dimensional correction, their results agreed quite well with the profile predicted from pressure drop measurements. However, when later measurements were made by Bogard and Tiederman[4] in the same channel neither the corrected nor the uncorrected results agreed with the predicted profile. Bogard and Tiederman did show that particle arrival rate did not affect the measured mean velocity as had been suggested by Barnett and Bentley.[5] They also showed that possible signal detection probability differences between slow and fast particles due to the lower number of photons scattered by fast particles had no effect on the results. This had been suggested as an effect which might compensate for the velocity bias error.

Hoesel and Rodi[6] proposed a probe volume residence time correction for uniformly seeded flows and a particle separation time correction for nonuniformly seeded flows when the average particle separation time is small compared to the time scale of turbulent fluctuations. This was an attempt to generalize the M-T correction to cases where the instantaneous velocity vector can be at large angles to the mean flow direction as in the highly turbulent region near the edge of a free jet. Hoesel and Rodi made measurements across such a jet. They found that the M-T correction agreed with their correction near the axis, but deviated toward the edges as predicted. However, they made no independent measurements so it is impossible to make any judgment as to whether a bias actually existed.

Giel and Barnett[7] made measurements in a jet flow very similar to that of Hoesel and Rodi. A hot wire was used for comparison. They found no evidence of velocity bias, even though an error on the order of 10% was expected near the axis. There was also no evidence of bias in computed turbulence intensities.

Johnson et al.[8] reported measurements in a Mach 2.9 separated boundary layer and in the transonic flow past an airfoil; they also found no evidence of velocity bias. A pitot tube was used for comparison in the separated boundary-layer study and velocities were computed from static pressure data in the airfoil measurements. They claim that their results support the proposal of Barnett and Bentley that no biasing will occur if the particle arrival rate is much less than the turbulence frequencies. Recall that this conflicts with the experimental results of Bogard and Tiederman.

Buchave[9] has reported an extensive analytical and experimental study of biasing. He concludes that a residence time weighting provides the correct statistical results in uniformly seeded flows, since it is equivalent to a time averaging of the data. His experiments included measurements in a free jet using a hot wire and a frequency shifted LV with both tracker and counter-type processors. The assumption was made that the tracker output would best serve as an experimental reference standard for mean velocity measurements. Generally, the residence time weighted mean velocity and the mean based on the tracker did, in fact, agree and differed from the uncorrected (ensemble averaged) velocity in the expected manner. However, the hot-wire measurements were about 8% higher than the tracker data on the jet axis with larger differences off axis.

If the LV tracker gave the "true" mean velocity in Buchave's experiments, then residence time weighting provided the proper bias correction over a wide range of turbulence intensity. The M-T one-dimensional correction, on the other hand, significantly overcorrected the counter data

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once the turbulence intensity exceeded 10-20%. This is to be expected, since the M-T correction is known to be invalid at high turbulence levels.

Although Buchave's results are interesting, the basic assumption that tracker data provide an unbiased standard of reference will invite criticism by some, especially in view of the rather large difference between that data and the hot-wire measurements. A residence time correction is relatively easy to implement and, if more definitive experimental results can be obtained to verify this approach, it would be of significant value to the field.

Erdmann and Tropea[10] have recently carried out a detailed analytical and experimental study of the bias problem. Their analysis took into account the probability distribution of the particle arrival time and assumed a controlled sampling by the signal processor such that velocity samples were only taken at fixed time intervals uncorrelated with the velocity fluctuations. Their analysis indicates that the bias under these conditions should depend on turbulence intensity, particle arrival rate, processor sampling interval, and velocity correlation time. A limited set of measurements in water flow behind a backward facing step confirmed the qualitative trends predicted. Their findings agree with the results reported in our study.

II. Experimental Method

The basic approach used in our study was to obtain data at a variety of particle arrival rates and sampling rates. Particle arrival rate ν_P was controlled by particle seeding density, while the maximum possible rate at which data could be sampled, ν_c, was controlled by the microcomputer which read the output of the signal processor. (Note that the actual sampling rate would be less than ν_c for $\nu_P < \nu_c$.) Depending on the relative value of ν_P and ν_c, data could be obtained randomly in time or at equal time intervals. The average of the latter data should, of course, yield an unbiased mean velocity assuming the velocity fluctuations are uncorrelated with the sampling interval. This experimental technique avoids any comparison with a secondary instrument. Both velocity bias and incomplete signal bias are determined directly from LV counter data.

Measurements were made in a two-dimensional flow over a rearward facing step. The flow upstream of the step was at a low turbulence level (on the order of 1%). Downstream turbulence levels varied depending on the location in the flow. Figure 1 shows the geometry of the test channel and the points at which measurements reported in this paper were made. The upstream section was square with an inside dimension of 101.6 mm. The step height also equaled 101.6 mm. Reattachment occurred approximately 712-mm downstream of the step.

A forward scatter dual beam LV geometry was employed. The LV system was designed so that precise control of the probe volume characteristics was possible.[11] In particular it was possible to insure that the focused beams intersected at their waists to avoid frequency broadening effects and maximize signal quality.[12] A dual Bragg cell system allowed a differential frequency shift between the two beams. Either a 0 or a 10 MHz shift was used for the measurements reported here. A Thermo Systems Model 1980 signal processor was used and processor output was read and stored in a microcomputer. The microcomputer was linked to a large central computer which performed all of the subsequent data analysis.

When the processor has a data point ready, it sends a data-ready pulse to the microcomputer. When the microcomputer receives this pulse, it returns a data-inhibit pulse to the processor which prevents the acquisition of new signals. After waiting a fixed time interval dependent on the desired sample rate, the microcomputer reads the processor output. Once the data point is sampled, the microcomputer removes the data

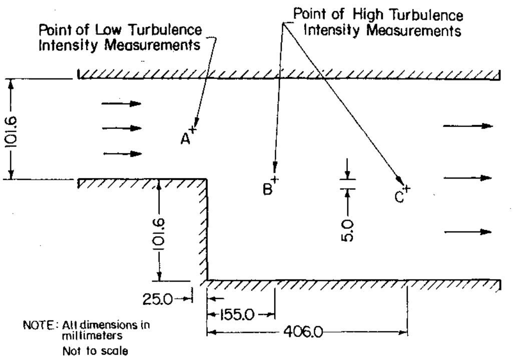

Fig. 1 Two-dimensional step geometry.

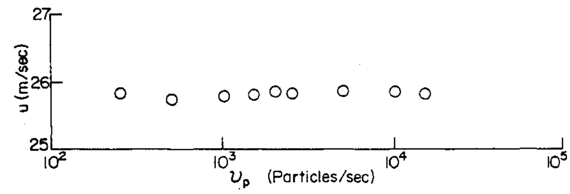

Fig. 2 Mean velocity at point A vs particle arrival rate.

inhibit, waits for another data ready pulse, and the process continues. The computer speed is variable; at the present time its maximum speed is about 4800 points per second. The actual rate at which velocities are sampled and recorded is dependent on the slowest unit in the system.

Velocity bias was investigated at a given point in the flow by collecting a fixed number of data points (on the order of 9000) at each of several particle arrival rates controlled by the particle seeding density. Seeding density was varied by running an atomizer at a constant setting and bypassing a selected portion of the output. This allowed ν_P (as monitored on the signal processor) to be set accurately without disturbing the atomizer. An evaporation-condensation unit was employed following the atomizer to insure a nearly monodisperse aerosol of about 1-μm diam. Dioctyl-phtalate (DOP) was used as the seeding agent. The seeding was introduced at the blower inlet well upstream of the test section to obtain a uniform distribution. With the optics properly adjusted the maximum particle arrival rate attainable was approximately 25,000 points per second. The minimum rate depended on the amount of natural seed in the air and usually was about 50-100 points per second.

III. Experimental Measurements

Figure 2 shows the measured mean axial velocity at several different seeding densities at point A upstream of the step in a low turbulence region. A frequency shift of 10 MHz was used and signal validation was based on 8/16 cycle comparison. The particle arrival rate is the number of validated velocity measurements per second produced by the TSI processor when it is running free (uncontrolled by the microcomputer) and was varied by changing the seeding density as formerly noted. All other parameters remained constant. The microcomputer sampled the processor output at a nominal rate of 2800 samples per second. Therefore, in interpreting the measured results the data at $\nu_P = 250$ points per second was being stored almost as soon as it appeared at the processor output and the average velocity computed from this data is essentially an ensemble average of the random (particle controlled) sampling of the flow velocity. On the other hand, at $\nu_P = 15{,}000$ particles per second, the microcomputer controlled the interval at which velocity samples were acquired resulting in a close approximation to a true time

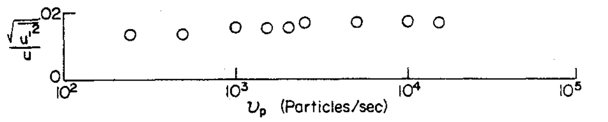

Fig. 3 Turbulence intensity at point A vs particle arrival rate.

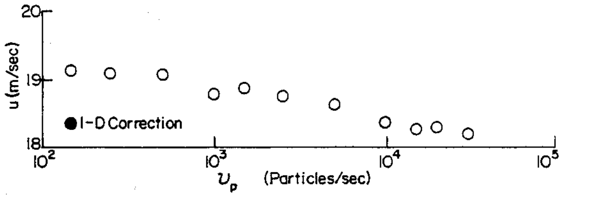

Fig. 4 Mean velocity at point B vs particle arrival rate ($\nu_c = 250$ samples/s).

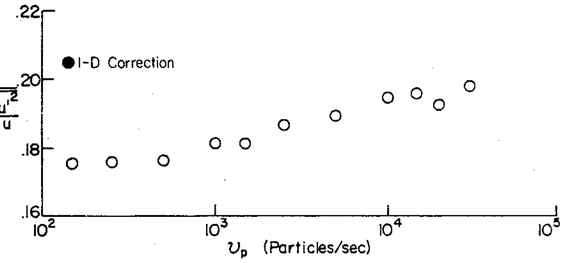

Fig. 5 Turbulence intensity at point B vs particle arrival rate.

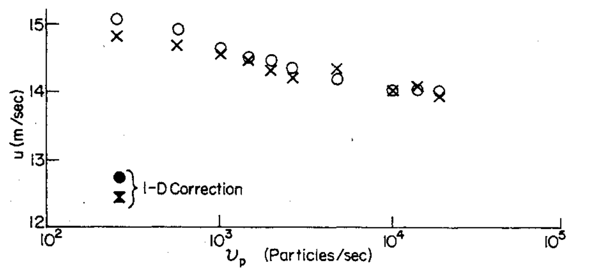

Fig. 6 Mean velocity at point C vs particle arrival rate for two values of ν_c (× = 25 samples/s, ○ = 250 samples/s)

average when the average velocity was computed. Observation of the data-ready pulses on an oscilloscope confirmed that the time between samples was nearly constant in this case. Figure 2 shows that for a low turbulence intensity the average velocities are independent of ν_p. Thus, the ensemble average is equal to the time average, as would be expected. Figure 3 is a plot of the calculated turbulence intensity corresponding to the data in Fig. 2. The histograms are made up of about 9000 measurements each. The few points that were outside a $\pm 3\sigma$ band were discarded. The turbulence level shown is about what would be expected in the flow system, since no effort was made to attain extremely low turbulence levels upstream of the step.

Figure 4 shows mean velocity ν_p at location B in the shear layer downstream of the step for a sampling rate of 250 samples per second. In this case the turbulence intensity was on the order of 20% (see Fig. 5). The ensemble average mean velocity is seen to decrease substantially with ν_p. Figure 6 shows similar data at location C in the flow. Here the turbulence intensity was about 35% (see Fig. 7). Sample rates of both 25 and 250 samples per second were employed. There is little difference in the results for the two sample rates except at the lowest values of ν_p (below 1 kHz) where the 25 sample

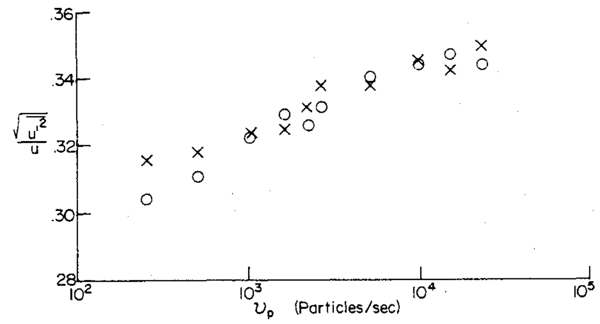

Fig. 7 Turbulence intensity at point C vs particle arrival rate (sampling rates as given in Fig. 6).

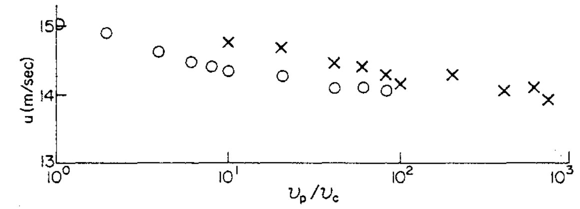

Fig. 8 Replotting of data from Fig. 6 in terms of a nondimensionalized particle arrival rate.

per second data falls slightly below the 250 sample per second data.

Figures 4 and 6 confirm that a velocity bias exists and its magnitude decreases as the ensemble average tends toward a true time average at the higher particle arrival rates. A corrected mean velocity based on the M-T one-dimensional weighting is shown at the lowest value of ν_p in each of the figures. The corrected mean velocity in Fig. 4 is in good agreement with the mean measured at the higher particle arrival rates (above 10 kHz). Recall that the turbulence intensity in this case was about 20%. However, the corrected value in Fig. 6 where the turbulence level was about 35% is well below the mean velocity corresponding to the higher ν_p values. Based on the assumption that the high particle arrival rate measurements are unbiased, these results are as expected and agree with Buchave's findings. (It should be noted that the M-T correction was not applied to any points in a data set corresponding to velocities in the ± 0.1 m/s range, since the correction is invalid for velocities approaching zero.)

Figures 5 and 7 illustrate the effect of bias on the turbulence intensity as calculated using the uncorrected mean velocity. The M-T mean velocity correction brings the low ν_p value into fair agreement with the high ν_p value for the 20% turbulence case as shown in Fig. 5. However, it severely overcorrected the data at the higher turbulence level condition of Fig. 7.

Since the velocity sampling tends toward equal time interval sampling as ν_p/ν_c increases, it was thought that a plot in terms of this nondimensional parameter might prove informative. Figure 8 is such a replotting of the data from Fig. 6. Results at the two different sample rates do not coincide over most of their common nondimensionalized particle arrival rate range. The data do approach the supposedly unbiased velocity when this ratio exceeds 100, but further measurements and analysis are needed to determine the conditions under which this factor would be adequate.

Although velocity bias was expected to be the predominant effect in the measurements just described, the possibility that incomplete signal bias also might be present was checked at the 35% turbulence level. This was done by making measurements both with and without frequency shift and by varying the number of cycles per burst (N) required for signal validation. Table 1 presents the results. For a frequency shift of 10 MHz the value of N had a negligible effect on the

Table 1 Demonstration of incomplete signal bias

Cycles/ burst	Frequency shift, MHz	Average velocity, m/s	Turbulence intensity,[a] %	Skewness
8	10	14.0	34.4	−0.26
16	10	14.1	34.5	−0.21
32	10	14.1	34.5	−0.20
8	0	14.4	30.9	+0.01
16	0	14.9	27.9	+0.13
32	0	15.1	25.1	+0.24

[a] Turbulence intensities here, as elsewhere in this study, were calculated using the local uncorrected measured mean velocity.

average velocity. However, with zero frequency shift, the average velocity increased with N as would be expected if incomplete signal bias was present. (Increasing N reduces the effective polar acceptance angle of the probe volume and introduces a bias toward higher velocities as shown by Whiffen.[13]) A marked influence on the calculated turbulence intensity resulting from the bias is evident in the unshifted data. Table 1 also shows the skewness of the velocity histograms at each condition. The skewness has approximately the same negative value for all of the 10 MHz data, but is positive and increases with N for the unshifted data. Again, this is consistent with the presence of incomplete signal bias. It is possible that the filter used for Doppler pedestal removal could cut off velocity signals near zero in the unshifted measurements. However, the 10 MHz data indicated that very few velocity realizations would have been so affected. In any case, this effect would have been constant with N and does not alter the conclusions. Since all of the data shown in Figs. 2-7 were taken using a 10 MHz shift, the results from Table 1 indicate that incomplete signal bias was not a factor in the velocity bias measurements.

IV. Conclusions

The results of this investigation have shown that the velocity bias error in counter-type LV measurements is dependent directly on the manner in which the temporally discrete velocity data available from the counter processor are sampled. If the sampling rate is much less than the particle arrival rate so that the velocity is sampled at nearly equal time intervals, then an unbiased mean velocity can be obtained. However, a particular value of the ratio of these two rates cannot be used as a criterion for optimum sampling.

The one-dimensional bias correction of McLaughlin and Tiederman was found to be accurate for turbulence intensities below 20% provided the velocity bias was not partially compensated for by the sampling process. At a given sampling rate the bias varied from its maximum value at low values of ν_p to zero at high ν_p. This variation occurred over a very wide particle arrival rate range, which makes it difficult to determine the amount of correction needed if data are only available at one condition. The best approach would probably be to insure random time interval sampling by operating at a seeding density low enough to insure that essentially all validated Doppler signals were measured. Of course, it is important to make sure that only one data point is acquired from each particle.

A residence time weighting of the data was not possible in our study due to processor limitations. The results of Buchave and others suggest that this may be effective even at high turbulence levels. This will be investigated in the near future. Additional details on the present investigation are given in Ref. 14.

It should be noted that the results presented here are only a subset of a much larger set of measurements taken at numerous points in the step flow. In all cases the same behavior was observed and the conclusions reached here, therefore, should apply to all enclosed flows. Mixed flows, such as free jets, present additional difficulties due to the uncertainties which arise in choosing proper seeding conditions.

Acknowledgments

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References

[1] McLaughlin, D. and Tiederman, W., "Biasing Correction for Individual Realization Laser Anemometer Measurements in Turbulent Flows," *Physics of Fluids*, Vol. 16, Dec. 1973, pp. 2082-2088.

[2] Durao, D. and Whitelaw, J.H., "The Influence of Sampling Procedures on Velocity Bias in Turbulent Flows," *Proceedings of the LDA Symposium,* Copenhagen, 1975, pp. 138-149.

[3] Quigley, M. and Tiederman, W., "Experimental Evaluation of Sampling Bias in Individual Realization Laser Anemometry," *AIAA Journal*, Vol. 15, Feb. 1977, pp. 266-268.

[4] Bogard, D. and Tiederman, W., "Experimental Evaluation of Sampling Bias in Naturally Seeded Flows," *Laser Velocimetry and Particle Sizing,* Hemisphere Publishing Corp., Washington, 1979, pp. 100-109.

[5] Barnett, D.O. and Bentley, H.T., "Statistical Bias of Individual Realization Laser Velocimeters," *Proceedings of the Second International Workshop on Laser Velocimetry*, Purdue University, 1974, pp. 428-444.

[6] Hoesel, W. and Rodi, W., "New Biasing Elimination Method for Laser Doppler Velocimeter Counter Processing," *Review of Scientific Instruments*, Vol. 48, July 1977, pp. 910-919.

[7] Giel, T. and Barnett, D., "Analytical and Experimental Study of Statistical Bias in Laser Velocimetry," *Laser Velocimetry and Particle Sizing*, Hemisphere Publishing Corp., Washington, 1979, pp. 86-99.

[8] Johnson, D.A., Bachalo, W.D., and Moddaress, D., "Laser Velocimetry Applied to Transonic and Supersonic Aerodynamics," *AGARD Conference Proceedings No. 193 on Applications of Non-Intrusive Instrumentation in Fluid Flow Research,* 1976, pp. 3-2-3-12.

[9] Buchave, P., "The Measurement of Turbulence with the Burst-Type Laser Doppler Anemometer—Errors and Correction Methods," Report TRL-106, State University of New York at Buffalo, 1979.

[10] Erdmann, J.C. and Tropea, C., "Turbulence-Induced Statistical Bias in Laser Anemometry," *Proceedings of the 7th Biennial Symposium on Turbulence*, University of Missouri-Rolla, Sept. 1981.

[11] Stevenson, W.H. and Thompson, H.D., "Laser Velocimeter Measurements in Turbulent and Mixing Flows," Air Force Aeropropulsion Laboratory, AFAPL-TR-79-2009, 1979.

[12] Durst, F. and Stevenson, W.H., "Influence of Gaussian Beam Properties on Laser Doppler Signals," *Applied Optics,* Vol. 18, Feb. 1979, pp. 516-524.

[13] Whiffen, M.C., "Polar Response of an LV Measurement Volume," *Proceedings of the Minnesota Symposium on Laser Anemometry*, University of Minnesota, 1975, pp. 589-590.

[14] Roesler, T.C., Stevenson, W.H., and Thompson, H.D., "Investigation of Bias Errors in Laser Doppler Velocimeter Measurements," Air Force Wright Aeronautical Laboratories, AFWAL-TR-80-2105, 1980.