References

[1]Crighton, D. G., and Gaster, M., "Stability of Slowly Diverging Jet Flow," *Journal of Fluid Mechanics*, Vol. 77, 1976, pp. 397–413.

[2]Plaschko, P., "Helical Instabilities of Slowly Divergent Jets," *Journal of Fluid Mechanics*, Vol. 92, Pt. 2, 1979, pp. 209–215.

[3]Herbert, T., and Bertolotti, F. P., "Stability Analysis of Nonparallel Boundary Layers," *Bulletin of the American Physical Society*, Vol. 32, 1987, p. 2079.

[4]Herbert, T., "Boundary-Layer Transition—Analysis and Prediction Revisited," AIAA Paper 91-0737, Jan. 1991.

[5]Chang, C. L., Malik, M. R., Erlebacher, G., and Hussaini, M. Y., "Compressible Stability of Growing Boundary Layers Using Parabolized Stability Equations," AIAA Paper 91-1636, June 1991.

[6]Bertolotti, F. P., and Herbert, T., "Analysis of the Linear Stability of Compressible Boundary Layers Using PSE," *Journal of Theoretical Computational Fluid Mechanics*, Vol. 3, 1991, pp. 117–124.

[7]Yen, C., and Messersmith, N., "Application of Parabolized Stability Equations to the Prediction of Jet Instabilities," AIAA Paper 98-0334, Jan. 1998.

[8]Herbert, T., "Parabolized Stability Equations," AGARD-FDP-VKI Special Course on Progress in Transition Modelling, AGARD-R-793, Von Kármán Inst., Rhode-Saint-Genese, Belgium, 1993.

[9]Bertolotti, F. P., Herbert, T., and Spalart, P. R., "Linear and Nonlinear Stability of the Blasius Boundary Layer," *Journal of Fluid Mechanics*, Vol. 22, 1992, pp. 441–474.

[10]Crow, S. C., and Champagne, F. H., "Orderly Structure in Jet Turbulence," *Journal of Fluid Mechanics*, Vol. 48, Pt. 3, 1971, pp. 547–591.

[11]Li, F., and Malik, M. R., "Step-Size Limitation for Marching Solution Using PSE," 45th Annual Meeting of American Physical Society, Div. of Fluid Dynamics, Tallahassee, FL, 1992.

[12]Malik, M. R., and Li, F., "Transition Studies for Swept Wing Flows Using PSE," AIAA Paper 93-0077, Jan. 1993.

[13]Morris, P. J., "The Spatial Viscous Instability of Axisymmetric Jets," *Journal of Fluid Mechanics*, Vol. 77, Pt. 3, 1976, pp. 511–529.

C. G. Speziale
Associate Editor

Laser Doppler Velocimetry Velocity Bias in Turbulent Open Channel Flow

M. Balakrishnan* and C. L. Dancey†
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0238

Introduction

THE lack of a universally accepted method to account for velocity bias in individual realization laser Doppler velocimetry (LDV) at all data densities[1] has led to renewed investigations of the practical performance of various postprocessing correction methods in different turbulent flowfields.[2–5] By and large, separated turbulent flows (forward/backward-facing steps, pipe expansions, or body wakes) have been used as the test flow in such studies. However, one- and two-component LDV is commonly used in the investigation of much simpler wall flows, where the impact (or lack of impact) of velocity bias correction on overall mean flow characteristics (such as the friction velocity or the von Kármán constant) is relevant and not easily ascertained from previous investigations.

In the present work the performance of several velocity bias correction methods is evaluated by applying them to a data set obtained with three-component LDV in a fully developed, smooth-walled, open-channel turbulent water flow. In this Note emphasis is placed on the experimental determination of the mean streamwise velocity profile $\langle u \rangle$ (angle brackets denote ensemble averaging), the kinematic Reynolds shear stress profile $\langle u'v' \rangle$ (primes denote fluctuations about the mean, and v is the component normal to the wall), the friction velocity u_*, von Kármán's constant κ, and the intercept of the wall log law. This classical turbulent flow is well suited for this study of velocity bias because it approximates many turbulent flows in its overall characteristics, with turbulence intensities (as measured by the local streamwise rms and mean velocity) ranging from approximately 40% near the wall to a few percent in the core flow. The popular McLaughlin–Tiederman[2] inverse velocity bias correction methods (one, two, and three dimensional), interarrival time weighting (IA), the empirical Gaussian probability density function (PDF) correction method (GPC) of Nakao et al.,[3] and straight ensemble averaging (no correction; NC) are chosen for comparison.

In the most recently reported bias studies by Gould and Loseke[4] and Herrin and Dutton,[5] two-component LDV was employed in the investigation of the shear layer downstream of a low-speed axisymmetric sudden expansion and downstream of a backward-facing step in high-velocity separated flow, respectively. Gould and Loseke concluded that the most effective scheme for reducing velocity bias in the computed mean velocity was the method proposed by Nakao et al.,[3] termed the velocity PDF shape correction technique. The two-dimensional inverse velocity bias method performed well at low turbulence levels and gave some indications of success at higher turbulence levels for high data rates. The data densities[1] were not reported. Herrin and Dutton carried out a similar but more extensive study and concluded that the time-between-data (sample and hold or interarrival time) schemes were very effective, whereas the two-dimensional inverse velocity weighting method compared less favorably, especially at high turbulence intensities. The data density (based on the integral scale of the turbulence) was estimated to be in the low range. The present study includes both the PDF shape correction and IA time methods in addition to others and utilizes a lower turbulence intensity, unseparated, fully developed turbulent flow for the investigation. In the present study the data density (as defined by Edwards[1]) varied between 0.2 and 0.5 for all reported measurement locations, which is in the intermediate range, 0.05–5.0, according to Edwards.

Results and Comparisons

Details of the flume facility, the three-component LDV system, the flow conditions, and the measured velocity field statistics are given elsewhere.[6] For the present investigation, in an effort to make the comparison between bias correction schemes more straightforward, accuracy and precision error contributions (that would obscure the bias correction effects) were overcome by using the same set of measured Doppler frequencies for all bias correction method calculations. That is, although fringe bias, filter bias, particle tracking errors, etc., may be present, exactly the same set of frequency measurements (2048 measurements per point at 80 different positions above the smooth wall) was used for all correction method calculations. Consequently, the variations that are reported between the different methods are entirely and exclusively due to the correction methods themselves. Because the data density was too low for equal time interval sampling to be effective and because no other independent (and bias-free) set of measurements was available (e.g., hot film velocimetry), the three-dimensional McLaughlin–Tiederman inverse velocity correction scheme was chosen as the reference method. This method, at least, utilizes all three components of the measured velocity vector, whereas the other methods either ignore the spanwise component or employ convenient assumptions to account for it.

To demonstrate the presence of bias in the LDV measurements if no correction is employed, the mean streamwise velocity was computed by straight ensemble averaging. The result is shown in Fig. 1, together with the bias predicted according to the theory of Dimotakis.[7] This prediction, derived under the assumption of low transverse (v and w) velocities and low streamwise, $u'/\langle u \rangle$, intensity, is given by

$$\frac{\langle u \rangle_{\text{bias}} - \langle u \rangle}{\langle u \rangle} = \left[\frac{\sigma_u}{\langle u \rangle} \right]^2 \tag{1}$$

Received May 10, 1997; revision received April 16, 1998; accepted for publication April 30, 1998.

*Research Assistant, Department of Mechanical Engineering.
†Assistant Professor, Department of Mechanical Engineering.

Table 1 Least-squares estimates of u_*, κ, and B and percent deviations

Case	u_*, m/s	κ	B	Deviation of u_* from three-dimensional reference, %	Deviation of κ from three-dimensional reference, %	Deviation of B from three-dimensional reference, %
NC	0.00965	0.423	6.08	−1.2	2.2	12.4
One-dimensional	0.00981	0.416	5.37	0.4	0.5	−0.7
Two-dimensional	0.00978	0.415	5.40	0.1	0.2	−0.2
Three-dimensional	0.00977	0.414	5.41	0.0	0.0	0.0
IA	0.00974	0.395	4.94	−0.3	−4.6	−8.7
GPC	0.00945	0.385	5.01	−3.3	−7.0	−7.4

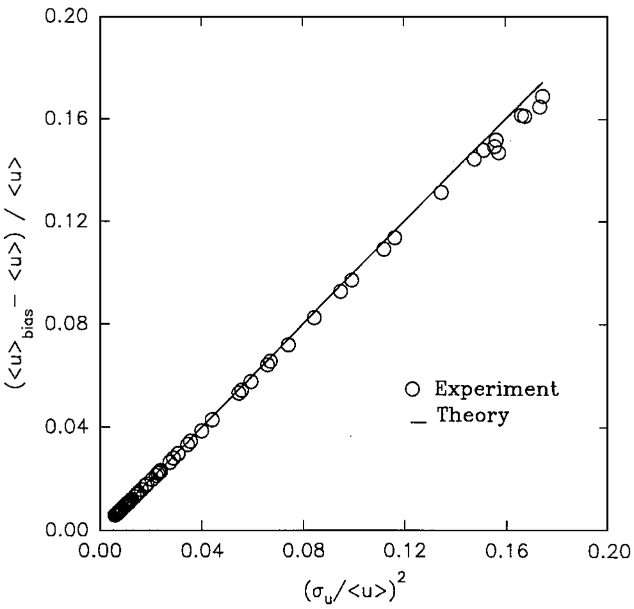

Fig. 1 Fractional mean streamwise velocity bias (arithmetic averaging) vs turbulence intensity.

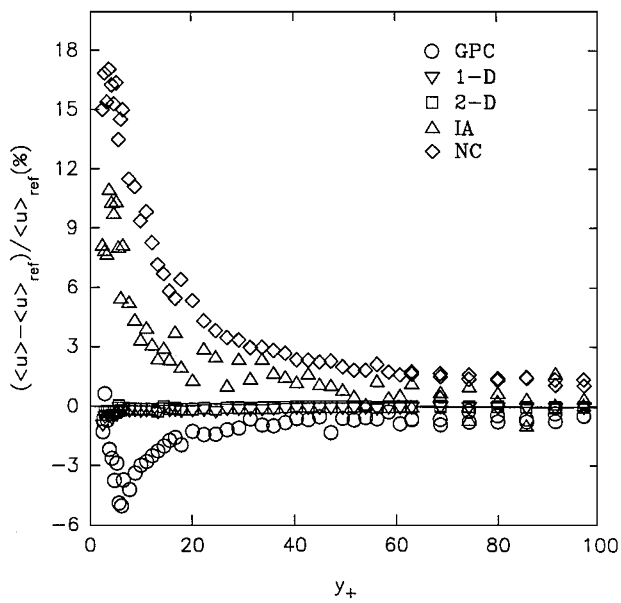

Fig. 2 Mean streamwise velocity bias (%) vs nondimensional distance from the wall (see text for legend definitions).

where $\langle u\rangle_{\text{bias}}$ is the computed mean streamwise velocity using straight ensemble averaging. The symbols $\langle u\rangle$ and σ_u are the true (unknown) mean and rms levels, respectively. In Fig. 1, $\langle u\rangle$ and σ_u were estimated using the three-dimensional inverse velocity weighting method. It is remarkable that the Dimotakis theory fits the experimentally established bias virtually over the entire wall layer, even for turbulence intensity levels exceeding 40% with large spanwise w and normal v velocity fluctuations. These measurements establish the power of this simple yet useful theory and demonstrate bias errors in the mean streamwise velocity as high as 17% for locations near the wall.

Figure 2 presents the percent bias (relative to the reference method) in $\langle u\rangle$ associated with all tested correction methods as a function of y_+. Here, $y_+ = u_* y/\nu$ and ν is the kinematic viscosity of water. The friction velocity u_* is determined from a best fit of the experimental data to the linear shear stress distribution for fully developed two-dimensional uniform turbulent flow in an open channel, i.e.,

$$\frac{\nu(\partial\langle u\rangle/\partial y) - \langle u'v'\rangle}{u_*^2} = 1 - \frac{y}{H} \tag{2}$$

where H is the water depth. The three-dimensional inverse velocity correction was used to determine u_* in Fig. 2.

It is observed in Fig. 2 that the bias (relative to the reference method) is small within and above the buffer region for all methods. This is the case because the total turbulence intensity is lower away from the wall. Near the wall, however, where the turbulence intensity is highest, only the one-dimensional and two-dimensional inverse velocity methods yield mean velocities comparable to the reference, not surprisingly. The results of the IA time method (which performed favorably in Herrin and Dutton's study[5]) differ from the reference by as much as 10%, whereas no attempt at correction produces velocities as much as 17% too high, as mentioned previously. The PDF shape correction method (which performed well in the investigation of Gould and Loseke[4]) yields velocities as much as 5% below the three-dimensional inverse weighting reference method. The estimated statistical uncertainty in $\langle u\rangle$ is approximately 1% (Ref. 6) with the ensemble sample size of 2048.

In Fig. 3 the bias in the kinematic shear stress $\langle u'v'\rangle$ (relative to the reference method values) is plotted as a function of y_+ for each of the correction methods. More scatter is expected because the shear stress is a second moment and the sample size is limited. It is clear that all methods (including simple ensemble averaging) predict stresses within ±10% of the reference method over most of the wall layer. This is within the experimental uncertainty in the measured shear stress.[6] Near the wall the percentage deviation is greater than ±40% for most of the correction schemes, including the one-dimensional and two-dimensional inverse methods. It is emphasized that near the wall the average shear stress $\langle u'v'\rangle$ is itself relatively small (approaching zero at the wall). Under these conditions, the deviation in the stress, as a result of the bias scheme employed, can be a very large fraction of the mean local stress.

Least-squares estimates of u_*, κ, and B, obtained from Eqs. (2) and (3), are summarized in Table 1:

$$u_+ = (1/\kappa)\ln y_+ + B \tag{3}$$

Note that the estimated statistical uncertainties in u_*, κ, and B are ±1, ±2, and ±4.7%, respectively. It is apparent that statistically significant differences are present.

There is little variation between the methods in the determination of the friction velocity. This is likely due to the method used here to obtain u_*, which permits the use of velocity and stress data over the entire flow to be utilized. As the bias errors are small over much of the flow (see Figs. 2 and 3 for large y_+), an excellent estimate is possible, regardless of the correction method employed. If, however, u_* was obtained by estimating the wall shear stress

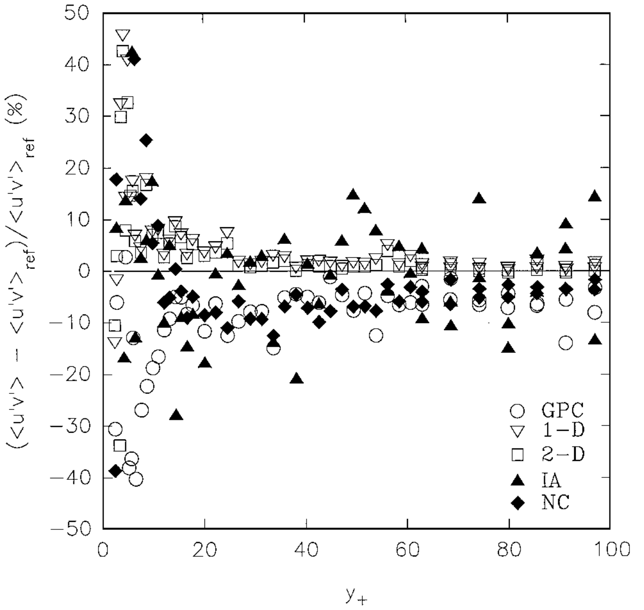

Fig. 3 Kinematic Reynolds shear stress bias (%) vs nondimensional distance from the wall (see text for legend definitions).

[by differentiating $\langle u\rangle(y_+)$ in the viscous sublayer[8]], Fig. 2 suggests that significant variations between the several correction methods would result. The determination of κ also utilizes much of the data set, through a statistical fit to Eq. (3), and again there appears to be little variation between the methods except, surprisingly, the GPC method, which predicts a value significantly lower than any other method. Compared with the commonly accepted value of $\kappa = 0.41$, this method is low by 6%. The intercept B in the logarithmic law is, of course, also obtained from a statistical fit of the data over most of the flow. Nevertheless, significant variability in the predicted value of B is seen between the several methods. Not surprisingly, the three inverse velocity correction methods yield very similar results, whereas straight arithmetic averaging, NC, predicts a value that is higher by 12%. The IA time and GPC methods yield values that are low by 7–9% compared with the inverse methods.

Conclusion

Although a statement of accuracy cannot be made without additional measurements, it is clear that relative deviations of $\pm 10\%$ can easily occur, depending on the bias correction scheme employed, when computing mean flow characteristics in similar wall-bounded flows. For some turbulence statistics, even larger deviations are possible.

Taken together with the other investigations cited in the references, it is concluded from this study that, in the case of low or intermediate data density, the proper choice of the bias correction method is vital if high-accuracy measurements, such as $\pm 2\%$, are required. Considering the literature on the experimental investigation of velocity bias for low or intermediate data densities, the selection of the appropriate method is not straightforward, and perhaps the best method may, unfortunately, be dependent on the flow that is under study.

References

[1]Edwards, R. L., "Report of the Special Panel on Statistical Particle Bias Problems in Laser Anemometry," *Journal of Fluids Engineering*, Vol. 109, June 1987, pp. 89–93.

[2]McLaughlin, D. K., and Tiederman, W. G., "Biasing Correction for Individual Realization of Laser Anemometer Measurements in Turbulent Flows," *Physics of Fluids*, Vol. 16, No. 12, 1973, pp. 2082–2088.

[3]Nakao, S., Terao, Y., and Hirata, K., "New Method for Eliminating the Statistical Bias in Highly Turbulent Flow Measurements," *AIAA Journal*, Vol. 25, No. 3, 1987, pp. 443–447.

[4]Gould, R. D., and Loseke, K. W., "A Comparison of Four Velocity Bias Correction Techniques in Laser Doppler Velocimetry," *Journal of Fluids Engineering*, Vol. 115, Sept. 1993, pp. 508–514.

[5]Herrin, J. L., and Dutton, J. C., "An Investigation of LDV Velocity Bias Correction Techniques for High-Speed Separated Flows," *Experiments in Fluids*, Vol. 14, June 1993, pp. 354–363.

[6]Balakrishnan, M., and Dancey, C. L., "An Investigation of Turbulence in Open Channel Flow via Three-Component LDA," *Fundamentals and Advancements in Hydraulic Measurements and Experimentation, Proceedings of the Symposium*, American Society of Civil Engineers, New York, 1994, pp. 159–175.

[7]Dimotakis, P. E., "Single Scattering Particle Laser Doppler Measurements of Turbulence," AGARD CP-193, 1976.

[8]Durst, F., Kikura, H., Lekakis, I., Jovanovic, J., and Ye, Q., "Wall Shear Stress Determination from Near Wall Mean Velocity Data in Turbulent Pipe and Channel Flows," *Experiments in Fluids*, Vol. 19, July 1995, pp. 417–428.

G. Laufer
Associate Editor

Comparative Analysis of Deployable Truss Structures for Mesh Antenna Reflectors

Jin Mitsugi*
Nippon Telegraph and Telephone Corporation, Yokosuka 239, Japan

I. Introduction

THE rapid growth of the Internet and information systems requires that high-capacity and ubiquitous communication be available for both voice and data transmission. Satellite communication, having the advantages of its inherent wireless access to the network, robustness against terrestrial disasters, and global coverage, is increasingly regarded as an essential element of the communication infrastructure. Accordingly, communication satellites are required to provide a number of spot beams covering their service areas to furnish high-capacity links for small, possibly portable, ground terminals. This task can be done by using a large deployable antenna on the satellite. A reflector antenna with an aperture of over 10 m will be needed to enable a satellite communication service with cellular-phone-size Earth terminals.[1] There are a number of structural concepts for large reflector antennas,[2] and of these, the combination of a deployable truss structure and a mesh reflector surface is considered reliable.[3] Several deployable truss structure concepts have been presented, claiming large reflector antennas as one of their potential applications.

For the secure deployment of a mesh reflector, the deployment force of the truss structure must be larger than the deployment resisting force caused by the mesh surface, including an appropriate margin. As such, the design concept for a deployable truss structure should be evaluated in conjunction with the resisting mesh tension. It is, however, difficult to predict the resisting force of the mesh during deployment because it is a coupled problem that involves the mechanical motion of the truss structure and the elastic deformation of the mesh surface as well as the truss structure.

In this Note, two concepts of deployable truss structures are compared in view of the required deployment force against the mesh surface tension. The comparison was performed using the flexible multibody dynamics computer code that the author has developed.[4] The formulation and the analytical procedure are not presented in this Note to focus on the comparison. This study does not intend to advocate that one deployable truss structure concept is better than the other but instead intends to unveil the essential differences in required deployment forces in accordance with the structural concepts.

Received July 12, 1997; revision received April 1, 1998; accepted for publication May 6, 1998.

*Senior Research Engineer, Wireless Systems Laboratory, Satellite Communication System Department, 1-1 Hikarino-oka. Member AIAA.