Approach for Obtaining Unbiased Laser Doppler Velocimetry Data in Highly Turbulent Flows

R.R. Craig,* A.S. Nejad,* E.Y. Hahn,* and K.G. Schwartzkopf*
Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio

Laser Doppler velocimetry has become the most prevalent of the nonintrusive optical flow measuring techniques. However, the accuracy of the velocity measurements in highly turbulent flowfields suffers from velocity biasing. In this study an extension to Stevenson and Thompson's direct signal processing approach, constant time-interval sampling, has been implemented and verified. An easily measurable time interval was used to provide an indication of when the proper ratio of seeding rate and sampling rate had been achieved to yield constant time-interval sampling. A design for a seeder to provide sufficient TiO_2 seeding is also discussed.

Nomenclature

H = step height
N = requested number of data samples
r = radial measurement coordinate
R = inlet radius
S_r = requested sampling rate
T_i = ideal data collection time, $= N/S_r$
T = actual data collection time
U = measured mean axial velocity
U' = measured mean axial turbulence velocity
U_0 = combustor inlet velocity
V_i = individual velocity realization
X = axial measurement coordinate
α_3 = estimate of the momental skewness
ν_1, ν_2, ν_3 = estimate of the first, second, and third moments, respectively

Introduction

THE majority of the biasing problems associated with laser Doppler velocimetry (LDV) measurements can be eliminated with good optics and frequency shifting of the laser beams. However, the problem of the velocity biasing caused by individual realization of the seeding particles passing through the probe volume remains. This problem was first addressed by McLaughlin and Tiederman[1] in 1973. Since that time, velocity biasing has received a great deal of deserved attention. Without the elimination of velocity biasing, LDV is only useful in laminar or turbulent flows with low turbulence intensity since the velocity bias error is approximately proportional to the square of the turbulence intensity. There are several correction schemes available for removing velocity bias from the data. Usually these techniques use the magnitude of the velocity vector and require a three-component LDV system, although a two-component correction may be adequate in some cases (Ref. 10). Durst[2] suggested that since the length of the Doppler burst is proportional to the magnitude of the velocity vector, it can be used to correct the data. This approach was investigated by Buchhave[3] and appeared to yield the proper correction. However, he did not have an independent unbiased measurement for a direct comparison. This approach has been chosen for implementation in the design of currently available counter processors.

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*Aerospace Engineer.

Due to the inherent need for seeding the flow, other types of biasing may also appear in the data. Durst[4] has suggested the existence of an additional biasing found in uniformly seeded combusting flows. This bias is due to fluctuations in the fluid density, which cases fluctuations in the particle concentration. Magill et al.[5] have recently established the magnitude of this type of biasing.

The use of constant time-interval sampling, as suggested by Simpson and Chew,[6] will not only eliminate velocity biasing, it will also take care of the density biasing and the very difficult requirement of equal seeding density in two mixing flows. This approach has been investigated by Roesler et al.[7] and Stevenson et al.[8,9] Their approach has its own built-in verification of the magnitude of the velocity bias. At low turbulence levels, no effect of seeding rate on measured velocity was seen. In regions of the flow with relatively high turbulence levels, the magnitude of the measured velocity decreased with increasing seeding rate. For obtaining unbiased velocity, they suggest that one has to increase the seeding rate while keeping the sampling rate constant until no further reduction in the measured velocity is observed. Although their approach yields a true time-averaged value, it does not lend itself easily to establishing when the proper ratio of sampling rate to seeding rate for constant time-interval sampling has been achieved for each data point.

Reference 10 takes another approach at correcting biased data by using a McLaughlin-Tiederman two dimensional correction. Comparing this corrected data with continuous wave data seems to validate this approach. The main disadvantage of their approach is that it requires a two-component LDV system and would not be valid in a reacting flow with violent density fluctuations. The present investigation was designed to establish the validity of constant time-interval sampling for obtaining unbiased velocity data in complex flowfields and to identify a criterion to indicate when the proper ratio of seeding and sampling rate has been achieved to yield constant time-interval sampling.

Experimental Facilities

Axisymmetric Dump Combustor Model

All experiments were conducted in a clear plastic cold-flow model of a ramjet dump combustor, schematically shown in Fig. 1. The combustor inlet was formed by a converging section with a constant radius of curvature of 25.4 mm, leading to a constant-area section 50.8 mm in length and 50.8 mm in diameter. The combustor region consisted of a sudden expansion to a diameter of 96 mm and length of 800 mm.

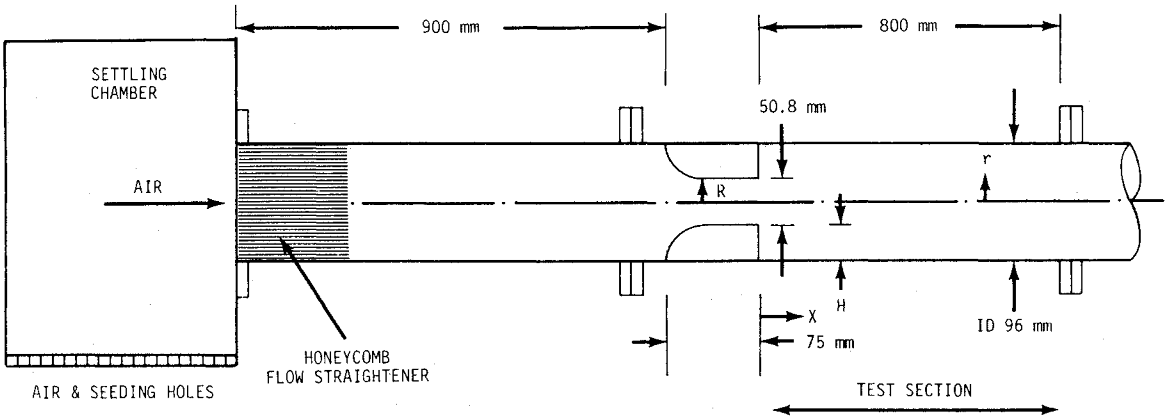

Fig. 1 Schematic diagram of the dump combustor model.

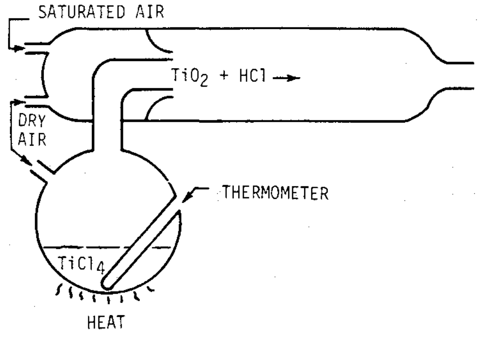

Fig. 2 Schematic diagram of the chemical seeder.

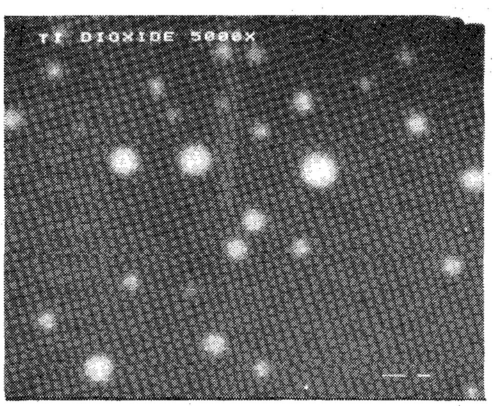

Fig. 3 Photograph of the seeding particles (5000×).

Airflow was pulled through the model from ambient conditions by a centrifugal blower. Flow velocity U_0 at the entrance of the combustor was held constant at 27 m/s, corresponding to a Reynolds number of 86,000 based on the combustor inlet diameter. In order to approach a uniformly seeded flow, seeding particles were introduced into a reservoir 900 mm upstream of the inlet convergence. Measurements were taken at six stations downstream of the dump plane ($X/H=0.56$, 2.25, 5.6, 7.8, 13.5, 16.9).

Laser Anemometer Optical System

The optical system, which was operated in the backscatter mode, consisted of a standard TSI beam splitter, a frequency shifter (Bragg cell) operating at 40 MHz, and a 3.75× beam expander with a 35-mm beam entrance spacing. The focusing lens was 152 mm in diameter with a focal length of 482 mm. The 514.5-nm line of an argon ion laser, operating at 50–150 milliwatts, was used for all measurements. The Bragg cell was adjusted so that the moving fringes were running in the same direction as the main airflow in order to reduce the maximum signal frequency that the counter processor would have to handle. The computed probe volume dimensions at $1/e^2$ intensity points were 84-μm diam, 610-μm length, and 1.9-μm fringe spacing. More realistic values of the probe volume dimensions are probably related to the $1/e$ intensity points, which yield a diameter of 59 μm and a length of 424 μm. The entire optical system was mounted on a three-dimensional traversing table controlled by stepping motors. The table could be positioned with an accuracy of 0.03 mm.

Signal Processing and Data Analysis

A custom-made interface with two modes of operation was designed to allow parallel communication between the TSI 1990-B counterprocessor and a Mod Comp II computer system. The counter processor required 16 fringe crossings to validate the data. In the unfiltered data acquisition mode, the interface would transfer all the samples from the LDV processor to the computer memory. The filtered mode, or constant time-interval sampling, was implemented by using a 1-μs-resolution decrementing interval timer. The desired sampling rate was set by specifying a value for the decrementing interval timer. The computer then continued to accept all the samples from the counter processor but discarded them instead of storing the velocity realizations in its memory. When the interval timer had counted down to zero, it signaled the computer to store the next valid data sample. With the additional overhead of interrogating the timer, this sequence could take place at a minimum rate of 40 and a maximum rate of 25,000 times/s. A maximum of 10,000 samples could be stored in the computer memory. A separate system clock with a resolution of 5 ms was read prior to storing the first data sample and again after the last one was stored in the memory. This data collection time period T was then used to assess whether or not the seeding and the sampling rates were in proper ratio to yield constant time-interval data sampling (discussed in the following section). Normally 5000 samples were stored for each velocity measurement. The moment calculations were done in double precision using the following standard formulas:

$$\nu_1 = \sum_{i=1}^{N} V_i/N \tag{1}$$

$$\nu_2 = \sum_{i=1}^{N} V_i^2/N \tag{2}$$

$$\nu_3 = \sum_{i=1}^{N} V_i^3/N \tag{3}$$

The mean velocity U is (ν_1); the root-mean-square turbulence velocity u' is

$$u' = \sqrt{(\nu_2 - \nu_1^2)} \tag{4}$$

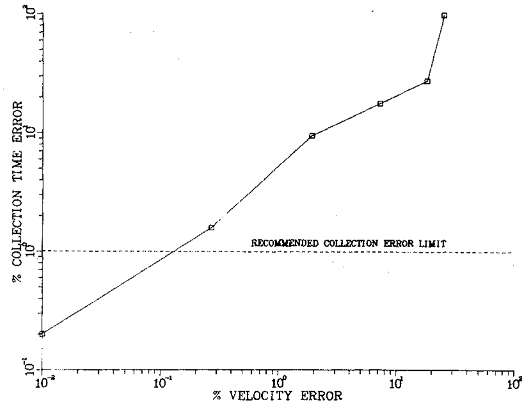

Fig. 4 Velocity error vs collection time error.

and twice the momental skewness (α_3) is

$$\alpha_3 = \frac{\nu_3 - 3\nu_2\nu_1 + 2\nu_1^3}{(\nu_2 - \nu_1{}^2)^{3/2}} \tag{5}$$

The velocity probability distribution function (pdf) was plotted, and a judgment was made as to where to set the limits for valid data. Although it is common practice to reject data outside 3σ limits from the mean, our histograms were noise-free enough that very often data within 4δ or 5δ of the mean were retained. The moments were then recalculated and the velocity pdf's replotted with 100-velocity bins covering the selected velocity range.

Seeding Generator

The most severe requirement of the constant time-interval data sampling approach is to maintain high seeding rates over long periods of time. In noncombusting flows, these requirements can be met with an evaporation-condenser type of seeder using dioctyl phthalate. Charring microballoons have also been used with some degree of success to seed the combusting flows. However, seeding very hot combusting flows requires refractory-type particles with high melting points. It was concluded that particle generation through chemical reaction with subsequent nucleation was the only technique capable of satisfying the high seeding rate requirement set by constant time-interval sampling. TiO_2 is a popular refractory material, as well as a widely used paint pigment. The studies of Cozzi and Cadorin[11] used the reaction of titanium tetrachloride ($TiCl_4$) with a CO-air flame to produce TiO_2 particles. Their studies predicted particle sizes of 0.4 μm and smaller. Initial tests with a pool of $TiCl_4$ reacting with the moisture in the room air produced a very fine smoke and a clean LDV signal with good visibility. This was a good indication that the particles were generally smaller than the fringe spacing of the measuring volume. To better control the seeding production, the reactor shown in Fig. 2 was constructed. Titanium tetrachloride was kept in a separate vessel. Dry air was used to carry $TiCl_4$ vapor into the reaction chamber. Introduction of a mixture of dry and moist air into the reaction chamber was used to control the particle production rate. Hydrochloric acid is a by-product of the reaction but has not been a problem in the laboratory setup. Neutralization of the acid is also quite easy with a vapor of ammonia or baking soda in water.

A sample of generated particles was collected and allowed to settle in a collection chamber. Electron microscope photographs of the collected particles at 1000× and 5000× magnification show the particle size to be fairly spherical and generally in the 0.2–1.0 μm range, with a small fraction in the 2–3 μm range, as shown in Fig. 3.

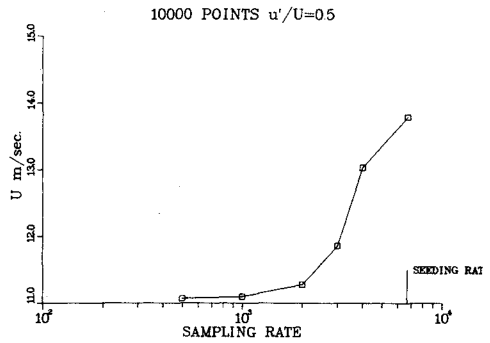

Fig. 5 Effect of sampling rate on mean velocity measurement.

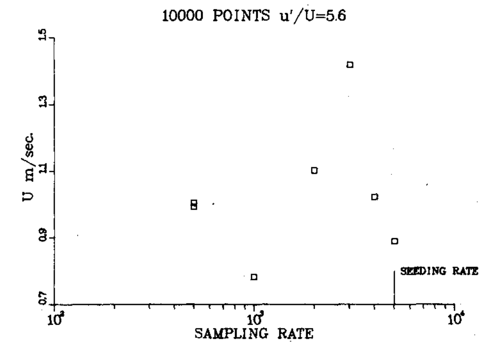

Fig. 6 Effect of sampling rate on mean velocity measurement.

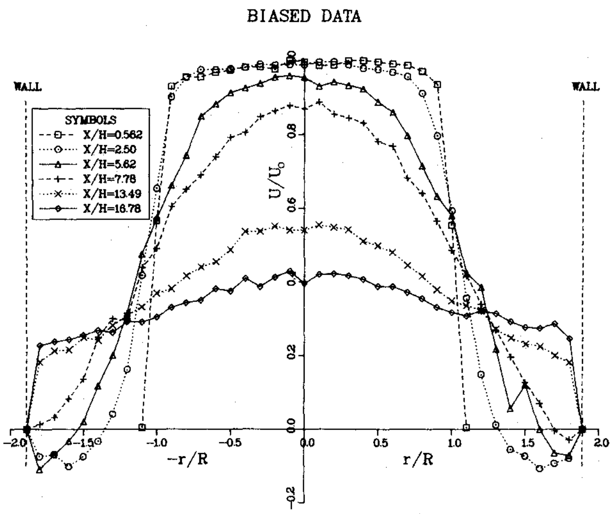

Fig. 7 Measured biased mean velocity profiles.

Results and Discussion

A simple time measurement scheme can easily verify whether the data have been collected at constant time intervals. This approach is intuitively obvious when one considers the fact that ideally the total time T_i for acquiring the requested number of samples N should be simply the time period between samples (the value assigned to the decrementing timer) multiplied by the number of the requested samples. Since it is impossible to always have a particle in the probe volume when the computer expects to store a sample, the actual collection time period T will always be greater than the ideal collection time T_i. For a fixed seeding rate, this time difference ($\Delta T = T - T_i$) increases with increasing sampling rate. The experiment showed that measured mean velocity increases from the true average as (ΔT) increases. Figure 4 shows the effect of time error on measured velocity error. A maximum col-

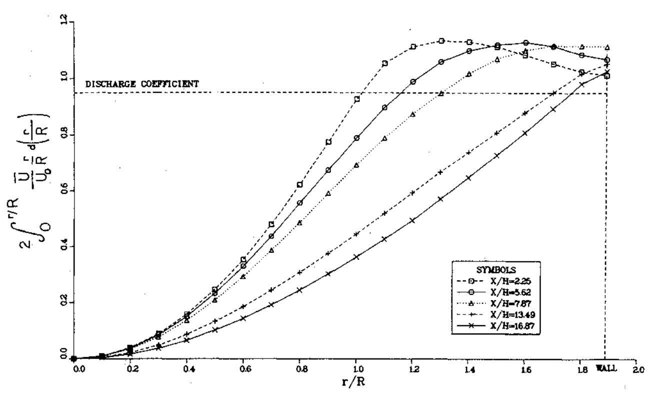

Fig. 8 Integrated mass flux profiles (biased).

lection time error of 1% was chosen as the criterion for deciding when constant time-interval sampling was achieved.

With the present computer and LDV system, it was found more convenient to fix the data rate at some relatively high value, say, 10,000/s, and then vary the computer sampling rate. The effect of sampling rate on the mean velocity derived from 10,000 individual realizations is shown in Fig. 5. These data were obtained in a region of the flow where the local turbulence intensity was 50% and indicate that a seeding-to-sampling rate of about 10:1 is needed to unbias the data. The biased velocity (14 m/s) is about 25% greater than the unbiased value (11.2 m/s), which is in general agreement with McLaughlin and Tiederman's original analysis that the bias error varies as the square of the local turbulence intensity. The data indicate that at turbulence intensities greater than 50%, the biased velocities are generally lower than the values predicted from the square relationship. In regions of flow with low mean velocities and very high turbulence, i.e., in recirculation regions, it is difficult to obtain sufficient data to establish a trend for mean velocity as a function of the sampling rate (Fig. 6), which indicates that the 10:1 rule may not be stringent enough for recirculating flows. This is probably due to the fact that at these levels of turbulence intensity, 10,000 individual realizations will yield only a 17% accuracy on mean velocity with a 3σ confidence level.

The main difficulty in verifying the magnitude of the velocity biasing error in LDV has been the lack of a reliable independent assessment of the error. The primary comparison has always been the hot-wire anemometer. However, the flow regimes where the velocity biasing error becomes significant are where the local turbulence intensity u'/U is roughly 25% or greater. In these regimes the hot wire is also in error because, at times, the local instantaneous velocity fluctuation will be negative and the hot wire cannot distinguish between velocity directions. For a nonreacting axisymmetric confined flow, measurement of the mass flow is the best independent technique for assessing the magnitude of the velocity bias. The measured velocity profiles at each station can be integrated across the model diameter and compared with the measured mass flow. In the present study measurements cannot be made closer than 2 mm to the wall, and the integrations assume a quadratic profile from the last point to the wall. Mass flow measurements were made with a Cox 2.5-in. turbine flowmeter, which had an accuracy of 0.75%. A pitot measurement upstream of the combustor inlet orifice and a static pressure at the orifice were used to establish the ideal mass flow through the orifice. The turbine flowmeter measurements established a discharge coefficient of 0.95 for the inlet orifice. Biased and unbiased velocity profiles were measured at six axial locations downstream of the dump plane. In general, 5000 data samples were taken at each point except for a couple of isolated instances. In the recirculation zone downstream of the dump plane, next to the wall, it was difficult to achieve data rates higher than 1000–2000/s. This dictated sampling rates as low as 40/s to meet our constant time-interval sampling criterion. In these cases, only 1000 samples were collected.

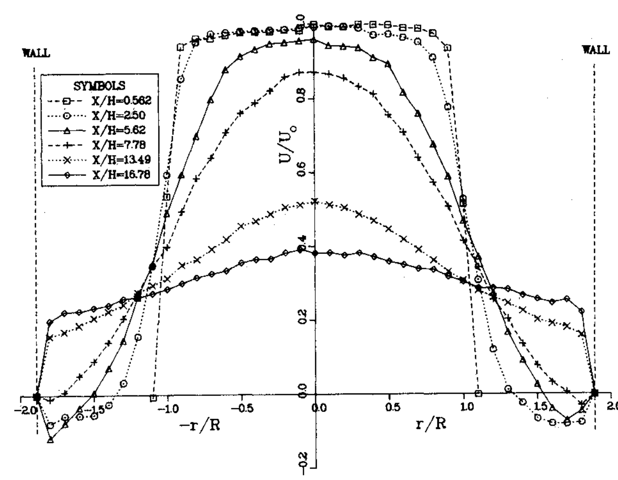

Fig. 9 Measured unbiased mean velocity profiles.

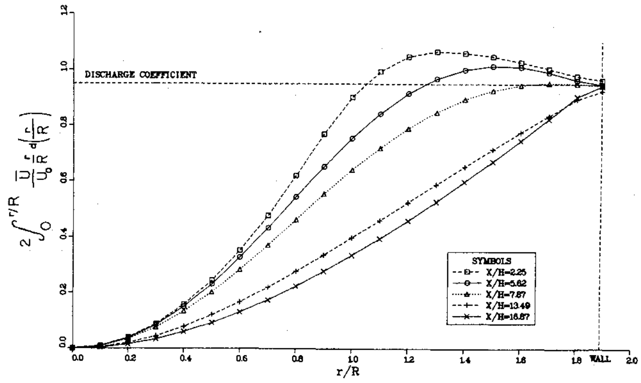

Fig. 10 Integrated mass flux profiles (unbiased).

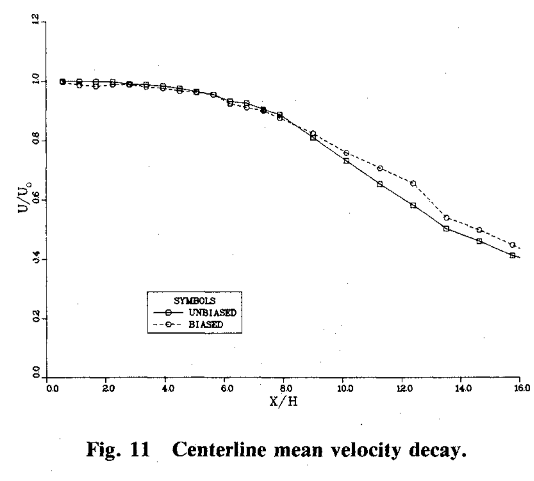

Fig. 11 Centerline mean velocity decay.

Figure 7 shows the biased velocity profiles at each of the six stations. The mass flow profiles calculated from these data are shown in Fig. 8. The profiles overestimate the mass flow through the model with the best-case error of +7% and the worst-case error of +17% greater than the true mass flow rate. Figure 9 is the plot of the unbiased velocity profiles; their shape is much smoother than the corresponding biased velocity profiles. The mass flow obtained from integration of the unbiased data falls within 2% of the true mass flow rate, as shown in Fig. 10.

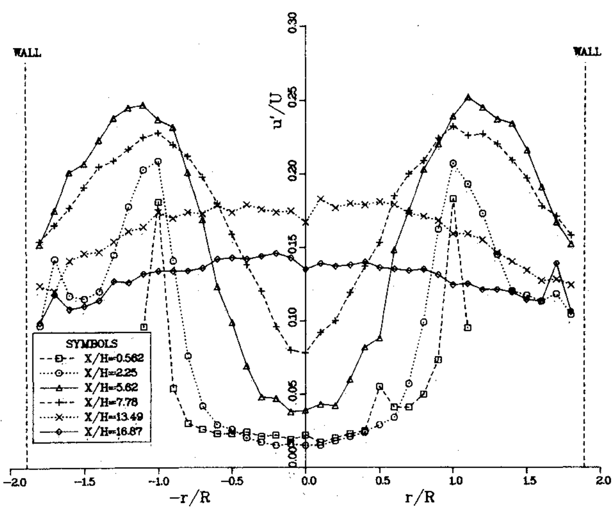

Fig. 12 Unbiased turbulence profiles.

The centerline mean velocity decay is shown in Fig. 11. At the upstream locations where the local turbulence intensity is relatively low, there is not a significant difference between the biased and the unbiased values of the measured velocities. At locations greater than six diameters downstream of the dump plane, where local turbulence levels are high, the biased and unbiased values of the measured velocities are significantly different.

All the turbulence velocities were normalized with respect to the combustor inlet velocity U_0. The biased and unbiased turbulence velocities were very similar in shape and magnitude. Only the unbiased normalized turbulence velocities are shown (Fig. 12). Generally, the unbiased turbulence velocities were slightly higher than the biased values. As an example, at a point in the flowfield where the local turbulence intensity u'/U was 50%, the unbiased turbulence velocity was roughly 4% higher than the biased value.

Summary and Conclusions

A simple approach has been developed to determine when constant time-interval sampling of LDV data has been achieved. The total time to acquire the data should be the time interval between samples multiplied by the number of samples. Measuring the actual time to acquire the data then becomes a good measure of how well constant time-interval sampling was achieved. Unlike Ref. 7, where only a few locations in the flow are used to establish required seeding-to-sampling rates for unbiasing the data, this approach allows every data point to be verified for constant time-interval sampling.

With the constant time-interval sampling approach, adequate seeding of the flow is of paramount importance. It has been shown that TiO_2 seed of proper size and seeding density can be produced via the reaction of $TiCl_4$ with moisture in the seeding generator flow. Neutralization of the HCl vapors has not been found to be a problem.

Integration of unbiased velocity profiles measured at all axial locations yielded mass flow within 2% of a turbine flowmeter measurement. Therefore, this is a good test case for the current predictive codes that make various assumptions for turbulence models in the solution of the Navier-Stokes equations.

Acknowledgments

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