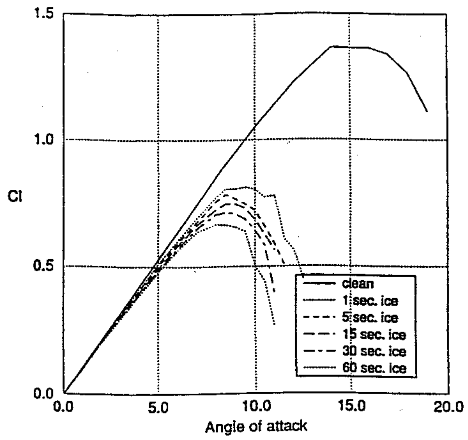

Fig. 3 Ice shapes for 15, 30, and 60 s on the leading edge of the NACA 0012 airfoil.

Recent studies[6] with the calculation method of Ref. 1 also indicate excellent agreement between calculations and measurements on clean airfoils where the Reynolds number is low. It will be interesting to extend this study to an iced airfoil operating at low Reynolds numbers. For example, typical Reynolds numbers for the blades of a rotorcraft near the hub may be around 2×10^5. For the NACA 0012 airfoil, the stall angle without ice accretion is 11 deg at this Reynolds number (Fig. 1). The question would be, will a small leading-edge ice reduce the stall angle as drastically as it does in the higher Reynolds number case, and what will that stall angle be?

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Investigations of Angle Bias Errors in Laser Velocimetry Measurements

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Nomenclature

I = streamwise turbulence intensity, $(u')_{\text{rms}}/\bar{U}$
N = number of fringes required to validate a measurement
N_T = total number of physical fringes in LV probe volume
T = threshold level
$\bar{U}$ = mean streamwise velocity
u' = fluctuating component of streamwise velocity
V_f = fringe velocity, down mixed Bragg frequency $*$ fringe spacing
V_p = particle velocity
γ = particle trajectory angle, 0 deg being perpendicular to the fringe planes, opposing the Bragg cell frequency shift direction
σ = standard deviation

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Introduction

IN 1987, a panel of recognized experts in the field of laser velocimetry was assembled and tasked with addressing problems of statistical bias errors in laser velocimetry (LV).[1] One source of statistical bias addressed by the panel was fringe bias or, more appropriately, angle bias. Angle bias had been studied theoretically, and limited experimental data supporting the theory had been published. Although the panel members had confidence that the theoretical predictions were accurate, additional detailed experiments were recommended to confirm the quantitative accuracy of the theory.[1] Following this recommendation, angle bias experiments have been conducted at West Virginia University and will be discussed in this paper.

Background

Angle bias results from the decrease in probability of measuring the velocity of a seed particle as the trajectory angle of the particle becomes increasingly more parallel to the fringe planes in the LV measurement volume (i.e., as $\gamma \to \pm 90$ deg). If angle bias is present within a system, the flow turbulence statistics will not be measured accurately since LV system response as a function of particle trajectory angle is nonisotropic. The importance of understanding and minimizing the potential of angle bias prior to taking measurements is that 1) it is a systematic error source whose effects can be minimized by user intervention and 2) to date, there are no postprocessing techniques to correct for it. Consider a single component LV system measuring a steady, turbulent flow. For any particle passing through the probe volume, the exact particle trajectory angle is unknown, making an angle bias correction method impossible to apply. The same argument applies for two or three component systems operating in a noncoincident measurement mode. For a three-component LV system acquiring coincident measurements, the particle trajectory angle can be determined providing a linear trajectory through the probe volume is assumed. However, to apply an angle bias correction scheme, the LV system response must be accurately known for all flow angles encountered by each component. This behavior is, of course, instrument and flow specific, and difficult to assess.

Prior to the present study, efforts to describe the angular response characteristic for a single component, counter-type processor system were undertaken by Whiffen et al.[2] with the hopes that their findings may be applied to a three-component system. Whiffen et al. derived a simple expression for the probability of particle detection (PPD) as a function of the particle trajectory angle γ:

$$\text{PPD}(\gamma) = \sqrt{1 - \left(\frac{N/N_T}{\cos(\gamma) + V_f/V_p}\right)^2} \tag{1}$$

The derivation of Eq. (1) is based on geometrical considerations of a two-dimensional probe volume model. Whiffen et al. justify the simplification of two dimensionality by stating that the useful portion of the probe volume is nearly cylindrical permitting PPD calculations to be performed assuming a constant probe volume cross-sectional area. However, since the actual probe volume is three dimensional, the validity of this assumption is not without question. Additionally, Eq. (1) predicts the PPD for particles traveling at a given trajectory angle γ. For turbulent flows, particles will pass through the probe volume over a range of trajectory angles, changing the average probability of particle detection. It was desired to obtain computational and experimental data including the effects of turbulence and probe volume three dimensionality to determine the quantitative accuracy of the theory expressed by Eq. (1).

Computational Model

Initial efforts for the angle bias investigation were focused on the development of a computational model representative of a single component LV system. The current model is a simplified version of other models[3] known of by the authors and was developed as such to accentuate the underlying physics of the simulated processes. The LV probe volume has been modeled as a three-dimensional ellipsoid, whose diameter, length, and fringe number are governed by the traditional probe volume equations.[4] Monte Carlo simulation techniques have been used to simulate a three-dimensional turbulent flow, with spatially uniformly distributed particle passages through the probe volume. The simulated particles are assumed to follow a linear trajectory through the probe volume. Particle size is not considered since no form of particle scattering theory has been incorporated into the simulation. To account for the measurement probability density function within the probe volume, a Gaussian light intensity distribution ($\pm 3\sigma$) has been assumed. The simulated processor is a counter type, requiring 10 fringe crossings (1 reset, 1 arm, 8 counts) with measurement probabilities (signal amplitudes) higher than a user-input threshold level to validate a measurement. Further details of the model may be found in Ref. 5.

Angle bias has been computationally investigated by looping the program through a range of mean flow angles. At each mean flow angle, velocities and trajectories were generated for an ensemble of 4096 simulated particles that passed through the mathematical probe volume. The percentage of particles satisfying the 10 fringe crossing measurement criteria was computed, and this ratio was taken as the PPD at the given mean flow angle. The optical parameters, Bragg shift, mean particle velocity, turbulence intensity, and measurement probability (signal amplitude) threshold level were adjusted depending on the case to be studied.

Experiments

Angle bias experiments were conducted at West Virginia University using two separate flow facilities. The first facility, here called the uniform flow facility, made use of a small calibration wind tunnel. Turbulence screens and/or a circular cylinder were placed upstream of the test section to control the turbulence intensity, and 0.8-μm-diam polystyrene latex (PSL) particles were used to seed the flow. A single component LV system using rotatable optics was assembled, without the incorporation of a Bragg cell. To change the mean flow angle with respect to the fringe planes, the optics were rotated from 0 through 350 deg in 10-deg increments. Following each angular increment, an LV ensemble measurement was taken, and the average validated data rate was computed from the particle interarrival times. Each measured data rate was then normalized by the average data rate observed when the optics were at 0 deg to obtain the PPD.

It was desired to install a Bragg cell into the rotatable optics to acquire data for different values of V_f/V_p. However, acquiring reliable PPD data by rotating the optics with the Bragg cell installed proved nearly impossible because of differences in signal quality associated with the rotation. Although the signal quality should have remained consistent throughout the rotation, a slight attenuation of the frequency shifted beam was repeatedly noticed, affecting the measured data rate. Since data rates (not velocities) were the measured quantity of interest for this experiment, it was necessary to avoid this effect. Therefore, a second flow facility, here called the rotatable flow facility, was constructed so that measurements of the PPD as a function of flow angle could be taken while the LV system remained stationary. This flow facility is shown schematically in Fig. 1. The tube length to diameter ratio was 120, ensuring fully developed turbulent flow at the tube exit. The flow turbulence intensity at the LV probe volume was changed by moving the flow tube radially, and the flow was again seeded with 0.8-μm PSL particles. The circular mounting plate was perforated with mounting holes every 10 deg, so that PPD measurements could again be made in 10-deg increments. As before, the average validated data rate was measured for each mean flow angle, then normalized by the average validated data rate when the mean flow was perpendicular to the fringe planes to obtain the PPD profile.

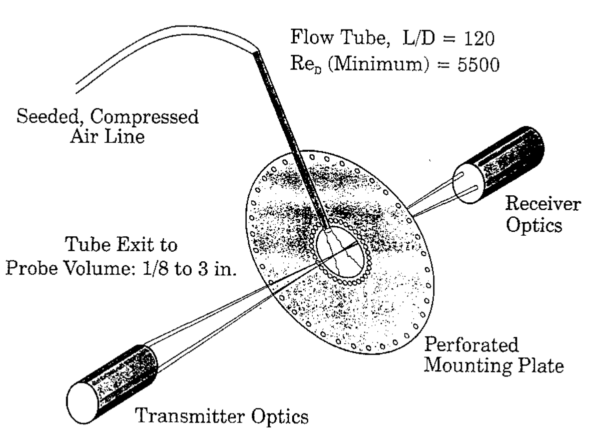

Fig. 1 Rotatable flow experimental setup.

Results

Figures 2a and 2b show typical results obtained using the uniform flow facility with no Bragg cell. All computational results presented have been computed using conditions of a uniform, turbulent mean flow and a three-dimensional probe volume model with thresholding effects. Additional results for varying frequency shift and turbulence levels may be found in Refs. 5 and 6. The experimental and computational results match well, and show that Eq. (1) overestimates the PPD (with the exception of $\gamma \rightarrow \pm 90$ deg), thus underestimating

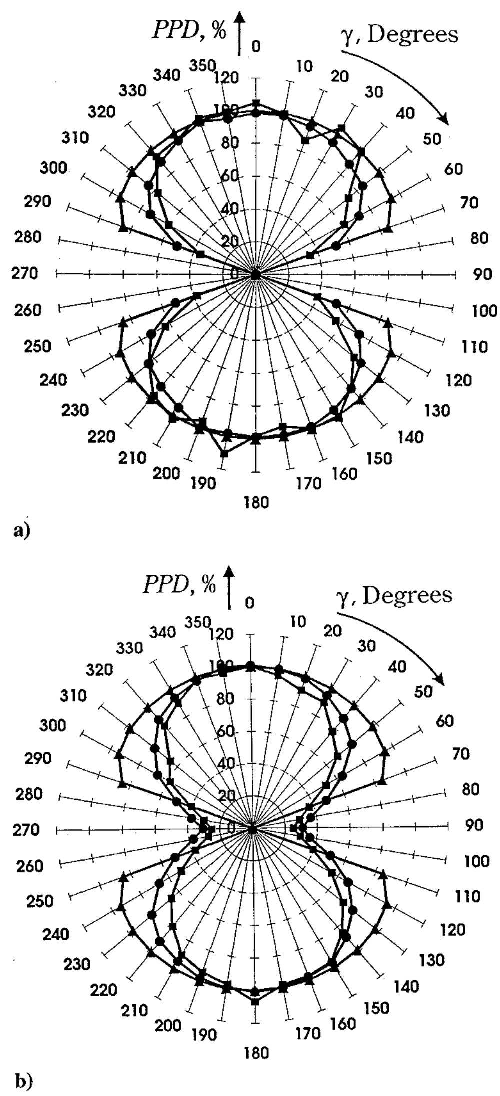

Fig. 2 Comparison between present PPD simulations and experimental measurements and Eq. (1): a) $V_f/V_p = 0, I = 0.9\%$ and b) $V_f/V_p = 0, I = 32.0\%$; -■-, experimental; -●-, computational; and -▲-, Eq. (1).

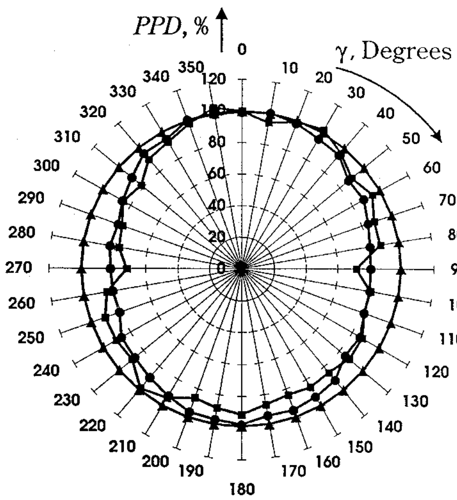

Fig. 3 Comparison between present PPD simulations and experimental measurements and Eq. (1), V_f/V_p = 2.1, I = 18.1%; -■-, experimental; —●—, computational; and -▲-, Eq. (1).

the potential error magnitudes associated with angle bias. The effect of turbulence is also shown in comparing Figs. 2a and 2b. As would be expected, the increased turbulence tends to increase the PPD when the mean flow angle is close to parallel to the fringe planes. However, the PPD is slightly reduced when the mean flow angle is close to perpendicular to the fringe planes.

Of particular interest are the results shown in Fig. 3, which were obtained using $V_f/V_p \cong 2$. As a rule of thumb, LV users typically use this ratio to ensure uniform instrument response for all flow angles, based on predictions of the Whiffen et al. theory. The data presented in Fig. 3 show that uniform instrument response is not achieved at $V_f/V_p = 2$. For optical and flow parameters that are representative of those present in this experimental setup, the simulation shows that, for practical limits of V_f/V_p, perfectly uniform response will not be achieved. For example, using these parameter values and $V_f/V_p = 4$, the simulation predicts a minimum PPD of 87% at a mean flow angle of 90 deg. Although this PPD is relatively high, it still does not ensure isotropic instrument response.

Conclusions

A combined experimental/computational study investigating angle bias errors in laser velocimetry measurements has been performed. Experimental and computational results matched well, and indicate that the previously published theory overestimates the probability of particle detection (PPD), thus underestimating the potential error magnitudes associated with angle bias. The PPD overestimation in the theory arises primarily because the theory was developed using a two-dimensional, geometric probe volume cross section. The probability of particle detection is dependent on a large number of parameters and is too complex to quantitatively model in two geometrical dimensions. Even so, the theory remains useful in its simplicity in qualitatively predicting PPD profiles.

The results have also shown that the probability of particle detection is nonisotropic for fringe velocity/particle velocity ratios of approximately 2. Most LV researchers use this criteria to ensure uniform polar response of the instrument. Simulations have shown that, for practical configurations of the experimental setups used in this study, perfectly isotropic response will not be achieved. Rather, the instrument response will remain slightly dependent on the mean flow angle.

For single-component LV systems, or systems not acquiring three-component coincident measurements, angle bias cannot be corrected for. For three-component systems acquiring coincident measurements, it is not likely that a postprocessing correction scheme can be applied to compensate for angle bias. More importantly, the user should recognize what flow angles can be measured isotropically under the conditions present and realize the accuracy of the results obtained are limited by this instrument characteristic.

Acknowledgments

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Shape Control of Plates Using Piezoceramic Elements

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Introduction

THE use of piezoceramic elements to control the vibrations of a beam has been extensively studied; see, for example, Baz and Poh.[1] However, their use to control the shape and vibrations of a thin plate has received less attention. We show here that the deflections of the centerline of a simply supported plate and the tip deflection of a cantilever plate, both deformed quasistatically, can be controlled by applying suitable voltages to the PZTs. The voltage to be applied to the actuators as a function of the surface area covered by them in the former case and as a function of their distance from the free end for the latter case is depicted graphically.

Formulation of the Problem

We consider a fiber-reinforced laminated composite plate with piezoelectric ceramic (PZT) elements bonded symmetrically to its top and bottom surfaces (Fig. 1), assume that the plate is symmetric about the midplane, and use the first-order shear deformation theory to study its infinitesimal elastic deformations. The adhesive between the PZT and the plate is assumed to be of negligible thickness, and displacements and surface tractions across the interfaces between the PZTs and the plate are taken to be continuous. The constitutive

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