Three Component Velocity Measurements Using Fabry-Perot Interferometer

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ABSTRACT

A method for measuring the three components of mean flow velocity using a backscatter optical system based on a confocal Fabry-Perot interferometer is described. An analysis of the expected uncertainties in the velocity component measurements is presented along with experimental data taken in a free jet at two flow velocities (100 and 300 m/s).

INTRODUCTION

The measurement of the three components of velocity is needed in many fluid mechanics experiments. Because of its non-intrusive nature, laser anemometry is frequently selected for these measurements. The preferable laser anemometer approach is to measure the three orthogonal velocity components directly (as preferable laser anemometer approach is to measure the three orthogonal velocity components directly (as described by Meyers and Wilkinson, 1982, for example). This generally requires optical access from two orthogonal directions if the usual dual-beam fringe or two-spot techniques are employed. With optical access limited to a single viewing port, other approaches must be considered.

With a single optical viewing port, one approach is to measure non-orthogonal velocity components using backscatter dual-beam fringe optics, such as described by Neti and Clark (1979) and by Johansson (1976). This method offers the advantage of all real-fringe systems - the capability to effectively use scattered light collected over large apertures. Unfortunately, the error of the velocity component along the optical axis derived in this manner becomes large when only components close to the optical axis are measured (Orloff and Snyder, 1982).

Another approach for measuring three velocity components used by Orloff and Logan (1973) is to combine a reference-beam heterodyne technique to obtain the on-axis component with fringe optics to obtain the components normal to the optical axis. One difficulty, however, in using the reference-beam method in high speed flows is that the Doppler frequency shift for backscatter is about 4 MHz/m/s for visible laser light. This results in a dynamic frequency range that can easily exceed the frequency response of most commonly used photomultiplier tubes. Another fundamental limitation of the reference-beam technique is expressed by the Antenna Theorem (Siegman, 1966), which states that the maximum effective aperture area is limited to about 2π/ρ where ρ is the solid angle subtended by the probe volume at the receiver aperture.

An alternative approach for measuring the component along the optical axis is to directly measure the Doppler shift using an interferometer. In previous work (Seasholtz and Goldman, 1982) we demonstrated the feasibility of using a confocal Fabry-Perot interferometer to measure the line-of-sight velocity component in a flow that is predominantly transverse to the line-of-sight.

The direct measurement of the Doppler shift with a Fabry-Perot interferometer offers advantages in high speed flow experiments compared with the more common dual-beam fringe and reference-beam laser anemometers. One advantage is an essentially unlimited velocity range. Dual-beam fringe and reference-beam techniques are limited by the frequency response of the photodetectors and signal processing equipment to a few hundred Megahertz. Another advantage of interferometric measurements is that the amount of usable scattered light is not limited by the Antenna Theorem, but by the light-gathering power (etendue) of the interferometer. This generally allows more of the scattered light to be used.

Other workers have used the Fabry-Perot interferometer for single component measurements in wind tunnels (Jackson and Paul, 1970, 1971; Egging and Jackson, 1972; Jackson and Egging, 1976), in rocket exhausts (James, Babcock, and Seifert, 1968; Morse et al., 1969), and in an MHD generator (Self, 1974).

This paper describes a more general technique suitable for measuring the three components of the mean flow velocity using a confocal Fabry-Perot interferometer (CFP). A backscatter optical configuration is described that can be operated in two modes. The first mode uses a single beam offset from the optical axis with the scattered light collected along the optical axis. The second mode is a dual-beam configuration using optics similar to those in a dual-beam fringe system.

In the dual-beam mode, the CFP can measure two orthogonal velocity components with a single orientation of the input beams. The components measured are the component along the optical axis and one component normal to the optical axis. Rotation of the plane of the two input beams allows the third velocity component to be measured.

An analysis of the expected uncertainties in the velocity measurements is presented along with experimental results for a small free jet operated at two velocities (100 m/s and 300 m/s).

In this paper, the following terminology will be used: a conventional dual-beam fringe-type laser anemometer using a counter-type signal processor will be referred to as a "fringe" anemometer; a reference-beam heterodyne anemometer will be referred to as a "reference-beam" anemometer; and an anemometer based on the direct measurement of Doppler shift using a confocal Fabry-Perot interferometer will be referred to as a "Fabry-Perot", or "CFP", anemometer.

APPARATUS

Optical System

The layout of the optical system is shown in Figure 1. An argon-ion laser was equipped with an etalon and produced 0.2 W single-frequency output at 514.5 nm. After the beam passed through the coll-
where $A$ is the aperture area and $\Omega$ is the solid angle of the field of view subtended at the aperture.

The measured finesse was $F = 60$. The transmittance function of the CFP for an aperture small compared to $D_s$ is

$$T(f,d) = T_0/(1 + (2F/n)^2sin^2(4\pi fd/c))$$

where $T_0$ is the maximum transmittance (about 0.1) and $c$ is the velocity of light.

The measure of an instrument's light-gathering power is the etendue $U$ defined as

$$U = A \Omega$$

where $A$ is the aperture area and $\Omega$ is the solid angle of the field of view subtended at the aperture.

For a CFP both $A$ and $\Omega$ have an upper limit that cannot be exceeded without degrading the effective finesse. These limits, here designated $A_s$ and $\Omega_s$, are

$$A_s = \pi D_s^2/4 = 1.15 \times 10^{-6} m^2$$

$$\Omega_s = \pi D_s^2/4 = 1.84 \times 10^{-3} sr$$

The maximum light-gathering power (etendue) of the CFP is thus

$$U = A \Omega = \pi D_s^2/4 = 2.12 \times 10^{-9} sr\cdot m^2$$

For the optical parameters used in this work, the probe volume image area was $2.9 \times 10^{-8} m^2$, and the solid angle of the scattered light entering the CFP was $1.9 \times 10^{-4}$ sr. Thus both the image area and solid angle are less than the maximum allowable values. The etendue of this system was $1.5 \times 10^{-11}$ sr\cdot m$^2$, which is much smaller than the maximum given by Equation 6. This indicates that much more of the scattered light could have been used, which would have significantly increased the signal-to-noise ratio. Note that this configuration, which only used a fraction of the maximum light-gathering power of the CFP, still uses much more of the scattered light than would be possible with a reference-beam system. (The maximum light-gathering power of a reference-beam system, as given by the Antenna Theorem, is $\pi^2/2 = 2.7 \times 10^{-3}$ sr\cdot m$^2$.)

In the dual-beam configuration, the system may be operated as a fringe-type anemometer. As shown in Figure 1, the removable mirror may be used to direct the scattered light to lens $L_4$, which focuses the light onto $100 \mu m$ diameter pinhole aperture mounted on a PMT. A commercial counter-processor interfaced to the computer is used to measure the velocity component normal to the optical axis.

The system also included an acousto-optic modulator (Bragg cell) to generate a reference signal offset from the laser frequency. This reference beam was directed to a surface on the optical axis so some of the scattered light would reach the photodetector.

Electronics and Data Acquisition

A linear ramp generator that produced a sawtooth waveform with adjustable period, amplitude, and offset was used to scan the CFP over the desired frequency range.

The CFP spectral measurements were made by scanning over a frequency range less than the free spectral range to reduce the data acquisition time. Some unshifted light and some light shifted by a Bragg cell were used to calibrate the output spectrum. The photomultiplier signal was processed with photon counting electronics that accumulated the number of photon counts for a preset time interval equal to $1/256$ of the ramp period. These counts were sent to a small laboratory computer, which stored them in the form of a 256 bin histogram.

A digital storage oscilloscope synchronized with the ramp generator was used to continuously monitor the analog output of the photon counter. This gave the operator a real-time picture of the spectrum being accumulated in the computer.

MEASUREMENT THEORY

Scattering Theory

Consider a plane wave with wave vector $k_0$ incident on a particle moving with velocity $\mathbf{V}$ as shown in Figure 2. Light scattered with wave vector $k_s$ will be Doppler shifted by an amount

$$f_s = f_0 - (1/2\pi)(k_s - k_0)\cdot \mathbf{V}$$

where $f_0$ and $f_s$ are the frequencies (Hz) of the incident and scattered waves respectively. If we assume that $|k_0| = |k_s| = k = 2\pi/\lambda$ (a good
approximation for particle velocities much less than
the velocity of light), then the vector $(k_s - k_{oi})$
lies on the bisector of $k_s$ and $-k_{oi}$.
If the scattering wave vector $k_s$ lies along
the $-z$ axis and the incident wave propagation direc-
tion is described by the angles $\alpha_i$ and $\beta$ shown
in Figure 2, the Doppler shift given by Equation 7 may
be written
\[ f_i = \frac{V}{2\pi \lambda} \left[ \sin \alpha_i \sin \beta \cos (\phi - \alpha_i) - \cos \phi \sin \alpha_i \right] \] (8)

In general, three independent measurements (at 3
values of $\alpha_i$) will allow the determination of the
two components of the velocity.

Instead of using only three measurements to
determine the vector velocity, it is often preferable
to use the method of least squares (Wolberg, 1967)
with more than three measurements to calculate the
velocity components along with estimates of their
uncertainties.

Prediction of Measurement Uncertainties
The use of prediction analysis allows the exper-
imenter to obtain estimates of the expected uncer-
tainties in a least squares analysis of the data
before the experiment is conducted. Here, we apply
this technique to find the expected uncertainty in the
measurement of velocity using the Fabry-Perot
interferometer.
The expected uncertainty in a parameter $a_k$ is
given by the square root of the diagonal components
of the inverse C matrix (Wolberg, 1967, pp. 75-82)
\[ \sigma_k = \sqrt{(C^{-1})_{kk}} \] (9)
where the C matrix has components
\[ C_{ij} = \sum_l \frac{a_{ij}}{L_l} \frac{a_{lj}}{a_{ik}} \] (10)
In Equation 10, the $f_i$ are given by Equation 8;
the $a_k$ are the parameters $V$, $\alpha$, and $\beta$; and the $L_l$
are weighting factors given by
\[ L_i = \sigma_f^2 + \left( \frac{a_{ij}}{a_{ik}} \right)^2 \] (11)
where $\sigma_a$ are the uncertainties in the measure-
ment of the independent variable $a_i$, and $\sigma_f$ are
the uncertainties in the measurements of the
dependent variable $f_i$.

To obtain analytical expressions for the C matrix
components, we assume $n$ equally spaced values of
$\alpha_i$ over the range $0$ to $2\pi$. The summation in
Equation 10 is converted to an integral and the C matrix
components are found to be
\[ C_{11} = \int \frac{1}{2\pi \lambda \sigma_f^2} \left[ \frac{(1/2)\sin^2 \phi \cos \phi \sin \alpha_i \phi + \cos \phi \sin \alpha_i \phi \cos \phi \sin \alpha_i \phi}{\sin \phi \cos \phi \sin \alpha_i \phi} \right] \] (12)
\[ C_{12} = C_{21} = \int \frac{1}{2\pi \lambda \sigma_f^2} \left[ \frac{(1/2)\sin^2 \phi \cos \phi \sin \alpha_i \phi + \cos \phi \sin \alpha_i \phi \cos \phi \sin \alpha_i \phi}{\sin \phi \cos \phi \sin \alpha_i \phi} \right] \] (13)

Note that $\sigma_f^2$ is the variance in the measurement of the
frequency $f$. Here we assumed that $\sigma_f^2 = 0$
is the same for all measurements and that there is no
uncertainty in the independent variable $a_i$ (i.e.,
$\sigma_a^2 = 0$).

Evaluation of Equation 9 using the C matrix
elements given in Equations 12 gives the uncertain-
ties in the velocity parameters $(V, \alpha, \beta)$
\[ \sigma_V = \int \frac{1}{2\pi \lambda \sigma_f^2} \left[ \frac{(1/2)\sin^2 \phi \cos \phi \sin \alpha_i \phi + \cos \phi \sin \alpha_i \phi \cos \phi \sin \alpha_i \phi}{\sin \phi \cos \phi \sin \alpha_i \phi} \right] \] (14)
\[ \sigma_\alpha = \int \frac{1}{2\pi \lambda \sigma_f^2} \left[ \frac{(1/2)\sin^2 \phi \cos \phi \sin \alpha_i \phi + \cos \phi \sin \alpha_i \phi \cos \phi \sin \alpha_i \phi}{\sin \phi \cos \phi \sin \alpha_i \phi} \right] \] (15)

To illustrate the application of this prediction
analysis, we consider the following example:
(1) velocity magnitude $V = 300$ m/s
(2) no uncertainty in angle $\alpha_i$, i.e.,
$\sigma_\alpha = 0$
(3) uncertainty in measurement of Doppler
shift, $\sigma_f = 3$ MHz
(4) 8 measurements made at equal spacing
over $360^\circ$
(5) laser wavelength $\lambda = 0.5 \mu m$
(6) angle between incident beam and optical
axis $\theta = 10^\circ$

From equations 14 and 15 the uncertainties in the
measurement are
\[ \sigma_V = 0.1 \text{ m/s} \]
\[ \sigma_\alpha = 0.8^\circ \]
\[ \sigma_\phi = 0.5 \text{ m/s} \]
mine the vector velocity. For this hybrid mode, the optical axis is measured with less accuracy than the component along the optical axis. That is, the uncertainty in the magnitude of the velocity is a strong function of the beam angle and that is much greater for the flow normal to the optical axis. This is a result of the measured Doppler shift frequencies being a measure of velocity components close to the optical axis. Recall that this is the opposite situation one encounters with fringe type anemometers where the component along the optical axis is measured with less accuracy than the components normal to the optical axis (Nei and Clark, 1979).

**Dual-Beam Configuration**

With the dual-beam configuration two orthogonal velocity components may be measured from a single spectrum. If the scattered light wave vector \( \mathbf{k}_s \) is along the optical axis and the two incident beams are symmetrically located about the optical axis (Fig. 3), the average and difference of the Doppler shift frequencies of the two scattered beams are proportional to the velocity components along and perpendicular to the optical axis. That is,

\[
\begin{align*}
\omega_1 &= \omega_2 - \omega_0 = (1/2\lambda)(\mathbf{k}_{01} - \mathbf{k}_{02}) \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{s} \\
\omega_H &= [(\omega_2 - \omega_0) + (\omega_1 - \omega_0)]/2 = \mathbf{v} \cdot \mathbf{s}_H
\end{align*}
\]

where,

\[
\begin{align*}
\mathbf{s} &= \lambda/(2 \sin \alpha) \quad \text{(16)} \\
\mathbf{s}_H &= \lambda/(1 + \cos \alpha) \quad \text{(17)}
\end{align*}
\]

Note that \( \mathbf{s} \) is the usual fringe spacing of the fringe anemometer. With this dual-beam configuration, two spectra taken at two orientations of the real-fringe pattern (as measured by the angle \( \alpha_1 \)) are needed to determine the vector velocity.

**Hybrid Mode**

The dual-beam configuration may also be used in a hybrid mode where the transverse velocity components are measured using conventional fringe signal processing techniques, and the on-axis component is measured with the CFP. For this hybrid mode, the removable mirror shown in Figure 1 would be replaced by a beam splitter. The hybrid mode is preferable if the velocities are low enough so that the frequencies are within the bandwidth of the photodetector and signal processor.

This mode may also be used with a fluorescent dye as the seed material (Stevenson, dos Santos, and Mettler, 1975). The fluorescence would be used to measure the transverse component and the part of the light at the incident wavelength would be used for the CFP measurement of the line-of-sight component. The advantage of using the laser-induced fluorescence is that measurements may be made near surfaces.

**Spectral Broadening**

In addition to the inherent instrumental bandwidth of the CFP, there are three additional factors that cause broadening of the spectral line of the light scattered by particles moving through the probe volume. One factor is fluctuations (jitter) in the laser frequency. In a controlled laboratory environment this is about 10 MHz for time periods on the order of seconds, but will be larger for high acoustic noise or high vibration environments. This jitter in the laser frequency, of course, likewise affects the reference and non-Doppler shifted frequencies.

A second reason for spectral broadening is the range of scattering angles caused by the turbulence intensity provided that the other broadening effects are smaller.

**Experimental Results**

Two sets of measurements were made in a small free jet. One set was made with a velocity magnitude of about 100 m/s using the single beam configuration. The second set of measurements was made at sonic flow conditions. The free jet had a 8.9 mm exit diameter and was operated from the laboratory compressed air supply. The exit was at ambient pressure. All measurements were made 4 mm from the exit plane on the centerline of the jet. The flow angle of the jet relative to the optical axis was set at approximately 70°, which corresponded to a component along the optical axis of 34 percent of the velocity magnitude. This assured that the Doppler shifted spectral peak did not overlap the unshifted peak. The velocity magnitude was determined by measuring the total temperature and total pressure and assuming isentropic flow through the nozzle. A mineral oil aerosol was injected upstream of the nozzle to provide seed particles.

The CFP spectral measurements were made by scanning over a frequency range less than the free spectral range to reduce the data acquisition time. The scan time was 4 seconds. The known Bragg cell frequency was used to calibrate the CFP spectrum. The Doppler shift frequencies are then determined using nonlinear least square parameter estimation techniques (Wolberg, 1967, Chap. 3) that provide both estimates of the Doppler shift and the error in the

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**Figure 3.** Dual-beam configuration (a) wave vector diagram showing incident beams \( \mathbf{k}_{01} \) and \( \mathbf{k}_{02} \), scattered beam \( \mathbf{k}_s \), velocity \( \mathbf{v} \), and spectral components, \( \omega_1 \) is proportional to transverse velocity component and \( \omega_H \) is proportional to component along the optical axis.
were then used to determine the mean velocity magnitudes. The frequencies of the peaks were assumed. The frequencies of the peaks were modeled as Gaussian functions plus a constant, and Poisson statistics were assumed. The spectral peaks were modeled as the model function. The apparent systematic error in the CFP measurements is believed to be caused by errors in the measurement of the calibration factor of the spectra. The velocity magnitude and direction determined from the least squares fit shown in Figure 4b is 30.2° and 92.6°. The statistical error bounds correspond to one standard deviation.

Low Velocity Measurements

The single beam technique was used to measure spectra at 27 values of the angle $\alpha_i$. A typical spectrum with the least squares fit is shown in Figure 4a for $\alpha_i = 30^\circ$. The left peak is caused by light scattered from the seed particles in the jet. Seven spectra were taken and used to calculate the least squares parameter estimation with Equation 8 as the model function.

Figure 4.- Low velocity free jet Fabry-Perot data (a) single beam spectrum at $\alpha_i = 30^\circ$ with least squares fit shown as dotted line (b) Doppler frequency shift data and least squares fit; the * indicates the datum taken from the spectrum shown in part (a).

The statistics, an indication of systematic errors. This apparent systematic error in the CFP measurements is believed to be caused by errors in the measurement of the calibration factor of the spectra.

Sonic Velocity Measurements

For these measurements, the jet was operated at sonic flow. Because the nozzle mounting hardware was changed between tests, the orientation of the jet was not identical to the orientation in the low velocity measurements. The CFP measurements were made using the dual-beam optical configuration. A typical spectrum is shown in Figure 5a for the incident beam angles of 30° and 210°. The calibration constant was determined for each spectrum using the unshifted peak (the left peak) and the fourth order (155.4 MHz) Bragg diffracted peak, (the next to left peak). The right two peaks are due to Doppler shifted light scattered from the seed particles in the jet. Seven spectra were taken and used to calculate the least squares fit shown in Figure 5b. (Each spectrum contributed two Doppler shift frequencies, corresponding to the light scattered from the two incident beams.)

The velocity magnitude and direction determined from the least squares fit were $V = 320 \pm 3$ m/s, $\theta = 69.2^\circ \pm 0.2^\circ$, and $\phi = 90.1^\circ \pm 1.4^\circ$. The velocity calculated from the total temperature was 313 m/s. As with the low velocity measurements, the velocity magnitude calculated from the pressure and temperature measurements was outside the statistical error bounds of the CFP measurements.

Discussion of Results

For both measurements described above, the CFP measurements of the velocity magnitude did not agree with the value determined from the total temperature and pressure measurements. (The velocity calculated using the isentropic flow relations for the velocity as a function of total temperature and pressure is believed accurate to at least one percent.) The CFP errors were more than could be accounted for by statistical errors, an indication of systematic errors. This apparent systematic error in the CFP measurements is believed to be caused by errors in the measurement of the calibration factor of the spectra.
It was observed that the measured calibration factor tended to change with time. Since the Bragg cell frequency was constant, this change was probably caused by either a drift in the ramp voltage that was used to scan the CFP, or by a change in the relation between the piezo-electric element displacement and the applied voltage.

In the first set of data (the low velocity measurements), the calibration factor was measured separately from the velocity data. Two measurements of the calibration factor were used. Over the course of the measurements, the calibration factor changed by about 8 percent. This change could account for the apparent systematic error of 6 percent.

In the second set of data (the sonic velocity measurements), the calibration factor was determined from each spectrum, thus eliminating the drift problems encountered in the low velocity measurements. However, the frequency spacing of the spectral peaks used for the calibration was only about one-third of the Doppler shift frequencies. This means that an one percent error in the calibration would result in a three percent error in the Doppler frequency measurement. This could easily account for the two percent error in the velocity magnitude measurement.

To reduce errors in the calibration factor measurement, the Bragg cell frequency should be selected so that the spacing of the spectral calibration peaks is at least as large as the Doppler shift frequencies. Also, the calibration should be determined for each spectrum (as was done for the sonic velocity measurements).

CONCLUDING REMARKS

In this paper it was shown that a Fabry-Perot interferometer can be used to measure the three components of velocity using a backscatter optical configuration. Because the velocity component measured with a Fabry-Perot lies approximately along the line-of-sight, this component can be more easily measured than with a fringe system. However, the transverse components are measured with less accuracy. In this sense the interferometric systems (along with reference-beam heterodyne systems) are complementary to the fringe systems. To obtain accurate three-component measurements with either system requires a fairly large viewing cone (about f/3 or larger). With limited optical access, one is led to consider hybrid techniques that combine the fringe method with either reference-beam or interferometric methods. Interferometric methods are more suitable with high velocity flows because of lack of any limitations on the measurable Doppler frequency shift.

One final consideration that should be mentioned is that interferometric laser anemometry techniques, such as described in this paper, require that the laser frequency have only a small amount of jitter. This is usually not a problem in laboratory environments, but in test facilities that generate high levels of mechanical vibration and/or acoustic noise levels the laser may exhibit an unacceptable amount of frequency jitter. In previous work conducted in a turbine stator cascade facility (Seasholtz and Goldman, 1982), it was necessary to locate the laser and optics in an acoustic enclosure. This problem of frequency stability is generally not a problem with fringe-type anemometers.

REFERENCES


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