Low–Coherence Self–Referencing Velocimetry

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Low–coherence self–referencing velocimetry optically measures the relative velocity between a point in a particle–laden fluid and a (potentially moving) reference surface. Low–coherence light scattered off the particles and off the reference surface is coupled into an interferometer with variable optical delay in one arm and an acousto-optical modulator in the second arm. The measurement location is set relative to the reference surface. Its location can be scanned along a line by adjusting the optical delay in the interferometer. The spatial resolution is typically tens of micrometers. Only one low–coherence light beam is required for each component of the velocity vector. Proof–of–principle measurements in a boundary layer and in Taylor–Couette flow have been performed. © 2006 Optical Society of America

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Velocimetry techniques for boundary layer measurements face two challenges: spatial resolution and non–intrusiveness. In most technical applications, the thickness of the boundary layers is on the order of 1 mm such that sub–millimeter resolution is required for meaningful measurements. The requirements are even more strict when the viscous sub–layer and the log–layer have to be resolved.1

Traditionally, hot–wire anemometry (CTA) has been the method of choice for such measurements.2–4 The diameter of the wires is on the order of micrometers. They are typically 1 . . . 2 mm long, but the spatial resolution in the wall–parallel direction is usually less important. The probe has to be moved to obtain the velocity profile across the boundary layer. This renders CTA problematic for measurements over moving objects (consider in particular wall–normal displacements). Recently, micro–PIV has been used for high–resolution boundary layer measurements. PIV either requires optical access from at least two directions (one for the illuminating laser sheet, the second for the camera) or a depth–resolving focusing optic.5,6 Depending on the geometry and the object’s movement, this might not be feasible. Laser–Doppler velocimetry (LDV) lacks the required spatial resolution, which is determined by the diameter of the intersecting laser beams and the crossing angle. LDV measures the velocity component perpendicular to the long axis of the intersection ellipsoid. The spatial resolution is poorest in the direction where it is most critical. A novel technique using a tilted fringe system allows spatial resolutions of a few micrometers.7,8 The technique proposed here is most similar to distributed laser–Doppler velocimetry (DLDV), i.e., reference beam LDV using low–coherence light.9 One major difference is that the designated reference beam is replaced either by weak reflections off the optical surfaces of the launching optics or by reflections off a surface behind the fluid. The second major improvement is that a fixed frequency shift is introduced, thus eliminating the sign ambiguity in the flow direction.

In a PIV image, the flow is visible together with the object. It is thus possible to deduce the measurement location (relative to the object) from the data without independent knowledge of the object’s trajectory. CTA, LDV and DLDV on the other hand, all have in common that they are not self–referencing. Hence, the relative location of the object with respect to the measurement volume has to be known. If the motion is irregular or if the shape of the object changes over time, this might pose a problem in itself. The new technique is self–referencing with respect to the distance of the measurement location to the reference surface (e.g. an object) and has a spatial resolution, which mainly depends on the coherence length of the light source (typically 30 µm).

Fig. 1 shows the setup of the optical components in the interferometer unit of the system. A superluminescent diode (SLD) emits low–coherence light into a single–mode fiber. An isolator protects the light source from back–reflections and guides the light to a polariza-

![Fig. 1. Schematic setup of the optical components in the interferometer unit including the light source.](image-url)
tion insensitive optical circulator. The circulator patches the light into a single-mode fiber leading to the sensor head. There, a lens couples the light out of the fiber and onto the object surface (Fig. 2). The same interferometer setup and a slightly modified sensor head (with a single beam) have been used for turbine tip-clearance measurements.

A fraction of the incident light is reflected back from the surface of the test object onto the lens and back into the fiber. The circulator directs it into the interferometer. A small fraction of the light is also reflected off the particles passing the laser beam. Following the nomenclature in Fig. 2 for a two-component setup, denote light reflected off the test object as rays 1a and 1b and the light scattered off the seeding particles as rays 2a and 2b. All light back-reflected (rays 1, 2) is fed into both interferometer arms by the beam splitter. In the reference arm, an acousto-optical modulator shifts the frequency of the light upwards by \( f_{AOM} = 55 \text{ MHz} \). The delay arm contains a motorized variable delay line (VDL). The light from the two interferometer arms is recombined by another beam splitter/combiner and a broadband photoreceiver serves as detector.

At first, only consider one incident beam (rays a). The path length of ray 1a is longer than that of ray 2a. Denote the path length between the surface and the particle as \( d \) and the path lengths of the interferometer arms as \( l_\alpha \) and \( l_d \), respectively. If the VDL is set such that \( l_\alpha + 2d = l_d \) ("positive delay"), for example, then that part of ray 1a which passed through the reference arm interferes with those parts of ray 2a which passed through the delay arm. In a quiescent fluid, \( f_{AOM} \) would be seen as beat signal at the detector. The same phenomenon occurs if the VDL is set to \( l_\alpha - 2d = -l_d \) ("negative delay"). Then that part of ray 1a going through the delay arm interferes with the part of ray 2a which goes through the reference arm.

With relative movement between the particle and the surface there is a frequency difference between rays 1a and 2a due to different Doppler shifts of the two reflections. In case of interference this results in a frequency shift of the beat signal relative to \( f_{AOM} \). The direction of the shift depends on the setup of the interferometer, positive or negative delay, and on the sign of the velocity difference. In the absence of interference, no beat signal is present. This means that only those particles produce relevant signals, which are within a thin layer from the surface. The thickness of the layer is approximately equal to half the coherence length of the light source, i.e., typically 30 micrometers for a high power SLD.

The distance between the measurement volume and the wall can be adjusted through the VDL – independent of the vertical position of the sensor head. Irrespective of any movement of the surface, measurements are always performed at a set distance from the wall. One could say that the measurement location is in wall-fixed coordinates instead of lab-fixed coordinates as for other techniques. As shown in Fig. 2, the measurement volumes of the two beams do not coincide exactly. But the spacing of the beams and their diameter is small. And since the resolution in wall-parallel direction is usually not crucial, this should not pose a problem in practice. In the foregoing example, a solid surface behind the fluid served as reference surface. Alternatively, weak reflections off the optical surfaces of the laser optics can be utilized for this purpose. In this case, the flow velocity and the location of measurement volume are relative to those of the sensor head.

Consider the velocity vector \( \mathbf{u} = (u, v) \). \( u \) and \( v \) are the in-plane and out-of-plane velocity difference between the particles and the reference surface, respectively. Further assume for simplicity (without loss of generality) that the bisector of the laser beams is perpendicular to the wall. Interference between rays 1a and 2a produces a peak in the power spectrum at \( f_a = f_{AOM} + 2(sin(\alpha)/\lambda)u + 2(cos(\alpha)/\lambda)v \) (\( \lambda \) is the wavelength). The second beam produces a signal with frequency \( f_b = f_{AOM} + 2(sin(-\alpha)/\lambda)u + 2(cos(-\alpha)/\lambda)v \). Let the spacing of the two peaks be \( \Delta F = |f_a - f_b| \) and the average Doppler shift be \( \bar{F} = \frac{1}{2}(f_a + f_b) - f_{AOM} \). The velocity vector is then obtained from

\[
\begin{align*}
    u &= \frac{\lambda \Delta F}{4 \sin(\alpha)} \\
    v &= \frac{\lambda \bar{F}}{2 \cos(\alpha)}
\end{align*}
\]  

Since \( \alpha \) is small, the sensitivity to wall-normal velocities is much larger than to in-plane velocities (the ratio of the sensitivities is \( 1/\tan \alpha \)). The scheme can easily be extended to three-beam (i.e., three-component) and non-symmetric setups.

Measurements between two coaxial rotating cylinders (i.e., Taylor–Couette flow) were performed to demonstrate the self-referencing capabilities. A metal cylinder (outer diameter 83.2 mm) was placed coaxially in the center of a vertical Plexiglas cylinder (inner diameter 89.3 mm, 5 mm wall thickness). The length of both
cylinders is approx. 30 cm. The resulting gap of 3.05 mm, was filled with olive oil and aluminum powder (∼ 50 μm particle diameter) as seeding. The inner cylinder rotated with frequencies of up to 6 Hz. The sensor head was located ∼ 60 mm (corresponding to a collection angle of 5°) radially outside of the outer cylinder and slightly tilted against the flow direction. Due to the beam deflections at the curved Plexiglas surface, the angle of incidence relative to the inner cylinder is not known a priori. It was later determined based on the measured frequency shifts near the wall and the known rotation rate. To improve the reflection levels from the reference surface, the inner cylinder was covered by a retro-reflecting foil (0.2 mm thickness). The reference surface does coincide neither with the cylinder wall nor the surface of the foil. It lies within the foil, whose optical delay was measured to be 0.18 mm. Note that measurements very close to the reference surface are not possible. There, all reflections interfere with themselves in the interferometer, masking the weaker interference between different rays. This offset is thus not entirely unwelcome. It allows measurements closer to the physical wall than would be possible otherwise.

Fig. 3 shows the frequency shift of the beat signal versus the optical delay of the VDL (divided by two) at different rotation speeds of the cylinder. The data series are labeled by the surface speed of the rotating cylinder. The data at all rotation speeds shows a linear behavior in accordance with theory. The largest velocities are measured for large optical delays (i.e., near the stationary outer cylinder). This means that indeed relative velocities are measured. Because the reference surface lies within the foil, velocity data does not start at zero optical delay. The optical delay has not been converted to physical distance, because the index of refractions is not precisely known. But the horizontal scale is consistent with tabulated values of α = 15°.

The uncertainty is comparable to the size of the data points, measuring approx. 2% of the surface velocity and is nearly constant across the gap for a given rotation speed. The uncertainty depends mainly on the particle passage time (duration of the Doppler burst), sampling rate, and spectral resolution of the FFT. At low flow velocities, the spectral resolution gives a lower bound (such as here), while the short particle passage time would be the limiting factor at high flow speeds. The data was obtained at a sampling rate of 50 MHz. Spectra with a resolution of 2 kHz were calculated over 25k samples (5k samples at the highest rotation rate resulting in a resolution of 10 kHz). A trade-off exists between temporal and spatial resolutions, because the number of particles passing the sample volume per unit time is proportional to its thickness (given by the coherence length).

The maximum measurement range was approx. 4 mm (without moving the sensor head). Using a more powerful light source, measurements without a retro-reflecting foil and measurements in air were demonstrated. With a further increase in optical power of broadband light sources we see the low coherence self-referencing velocimetry concept as a powerful tool for boundary layer investigations.

References


Fig. 3. Measured velocity profiles in laminar Taylor–Couette flow at various rotation speeds.