Image-based diagnostics for flow field characterization

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Abstract

The rapid evolution of digital imagery and the fast growth of computational power over the last ten years have contributed significantly in the development and maturity of image-based diagnostic techniques for flow field characterization. Of the several techniques that have evolved, particle image velocimetry (PIV) and laser induced fluorescence (LIF) for velocity and concentration/temperature determination, respectively, have reached a good level of maturity and thus currently enjoy an increasingly level of popularity and acceptance by experimental fluid dynamicists. The current paper focuses on PIV and LIF, presenting their methodology and implementation for fluid flow characterization.

1 Introduction

Since the early sixties, the investigation of three-dimensional coherent structures in turbulence has been of significant interest to researchers. Time series analysis and theories based on the statistical interpretation of flow have influenced the development of instrumentation dealing with such flows, and led to the evolution of hot-wire anemometry and laser Doppler anemometry as standard tools in turbulence research. The latter came along with the introduction of the laser, and offered researchers a robust way for making non-intrusive measurements of the flow velocity at a point in space. Furthermore, while flow visualization existed prior to this time, the introduction of the laser transformed visualization to speckle photography, opening a new era of laser-based whole field metrology (Fomin [1]). It was not until the advent of digital imagery and powerful personal computing, however, that the benefits of laser-based visualization really transformed from being qualitative to quantitative.

These two technological advances, digital imagery and computational prowess, have been key for the rapid development of image-based metrology,
which in the past decade has enabled researchers to expand their view of
turbulent flow phenomena from single-point time series events to multi-point
spatially and temporarily evolving events. Currently, image-based flow
diagnostics enjoy rapid growth and maturity, as researchers seeing the benefits of
non-intrusive multi-point quantification are eager to deploy such techniques in
their respective applications. The present paper reviews the two currently popular
techniques, presenting their methodology, implementation and practicality as
tools for obtaining valuable insight to fluid processes.

2 Particle image velocimetry (PIV)

PIV has its roots on early quantification techniques that relied on the tracking of
individual particles or patterns to infer the velocity of the flow. However, unlike
these particle tracking techniques, it differs since it relies on groups of particles
whose most probable displacement over time is mathematically determined using
robust statistics. Thus, PIV offers a higher temporal and spatial resolution of the
instantaneous flow field. The early application of PIV relied on photographic film
technology, but advances in image-capture using digital technology in the late
1980’s and early 1990’s have dramatically improved the technique’s robustness
([2]-[4]). During the last decade numerous publications on various aspects of PIV
have been reported, and a recent book by Raffel et al. [5] captures this rapid
development.

The power of PIV lies in its ability to provide two- or three-component
velocity information at many points in the flow simultaneously. Thus, it can
provide a list of direct or derived quantities useful for flow characterization,
especially turbulence. Such information includes, mean and fluctuating
component velocities, normal and Reynolds stresses, high order moments
(skewness & flatness), spatial correlations of in-plane velocity components,
integral scales within the plane, vorticity, strain rate, momentum and energy flux
estimation, flow rate, and spatial structure information. Furthermore, the recent
integration of high framing rate digital cameras and high pulsing rate Nd:Yag
lasers (in the kHz range) gives the added capability of determining robustly time-
dependent statistics, such as, multi-point spectra and time correlations.

2.1 PIV methodology

The basic relation of displacement divided by time to yield velocity is the
fundamental principle of the PIV technique, as illustrated in Figure 1. Although
PIV is a non-intrusive measurement technique, it requires tracer particles to be
suspended in the flow under investigation. These tracer particles can be either
naturally occurring or artificially added to the flow. Hence, PIV directly estimates
the displacement information of these tracer particles, \( \Delta \tilde{X}(\tilde{X};t',t^*) \), having
velocity \( \tilde{u}(\tilde{X},t) \) with \( \tilde{X} \) denoting the position vector and \( t \) denoting time. If these
particles are small and follow the flow, the displacement information of these
small “seeding” particles are said to infer the flow velocity, \( \tilde{v}_i(t) \).

The PIV apparatus consists of an illumination source, an image capture
device, synchronization and data acquisition hardware, and software for user control and data analysis. This technology behind the PIV technique is illustrated in Figure 2. Illumination of the tracer particles is done using a thin light sheet, which is pulsed to freeze the particle motion. The Mie scattering from the imaged tracer particles is recorded at two instances in time using a digital camera. The two sequential digital images are then sub-sampled at particular areas via a prescribed interrogation window, and a spatial cross-correlation is performed using fast Fourier transform (FFT) analysis, as described by Willert and Gharib [3], resulting in a surface function, as shown. If the two images are recorded on a single camera frame, then an auto-correlation is performed.

\[
D(\vec{X};t',t^*) \approx \int \int [\vec{X}(t),t] dt
\]

Figure 1: Illustration of the basic relationship governing PIV (after Adrian [7])

The separation time between the light pulses is selected so as to have particles displace several pixels within the interrogation area (IA), and have most particles remain common to both images. A high cross-correlation value is determined where many particle images match up with their corresponding spatially shifted partners, and this is considered to represent the best match of particle images between the sequential recordings. A good rule of thumb is to insure that within time \( \Delta t \) the in-plane components of velocity, \( v_x \) and \( v_y \), carry the particles no more than a third of the IA dimensions, and the out-of-plane component of velocity, \( v_z \), carries the particles no more than a third of the light sheet thickness. Furthermore, as shown by Keane and Adrian [6] at least five particles (with eight being optimal) should remain common to achieve 100% valid detection probability.

While a single, dominant peak is typically observed when cross-correlating two separate images, two peaks, aside from the center peak, are observed when auto-correlating a single composite image containing particle information at the two instants of time. The latter signal suffers from the inability of knowing which was the initial position of the particles, and thus only provides magnitude information. Directional information is a required input from the user. It is therefore preferred to capture the particle locations at two separate camera frames, and thus perform a cross-correlation on the pair of images, eliminating directional ambiguity while at the same time improving the signal-to-noise ratio.

The displacement vector of the cross-correlation peak from the center (origin) of the two-dimensional interrogation window denotes the average distance traveled by the particles within the interrogation area. Accurate estimation of the displacement vector to sub-pixel resolution is performed by locally fitting the two-dimensional array of correlation values in the vicinity of
the peak. The absolute displacement vector is then calculated from a calibration of the magnification factor between the pixel domain of the digital recording device and the physical field of view. Finally, division of the displacement vector, determined for each interrogation area along the entire pixel domain, by the time separation between the two sequential laser pulses yields the velocity vector field in the physical area under investigation.

![Diagram of PIV measurement principle](image)

Figure 2: The PIV measurement principle.

To improve on the signal-to-noise ratio and spatial resolution while reducing errors in displacement estimation, a multi-pass second-order accurate adaptive correlation technique is often used whereby the second interrogation area is dynamically displaced to capture the particle movement, while at the same time being reduced in size (Wereley and Meinhart [8]). In this way, the effective probe volume of PIV is reduced and stretched to follow along particle path lines, while at the same time yielding good spatial resolution along flow gradients. To enhance this adaptation one step further, the IAs are allowed to deform independently of one another in a non-rectangular way, and thus better accommodate the flow gradients and anticipated particle motion.

This type of processing is valuable when dealing with boundary layers or shear layers, which are characterized by large velocity gradients. Furthermore, adaptive correlation techniques prevent random and systematic errors from increasing, due to the FFT computation of finite digital images, as particle displacements within the IA increase. Although correlation values are found for integral pixel values with an uncertainty of ±0.5 pixels, a peak estimation accuracy of between 0.1 pixels and 0.01 pixels can be obtained by using various peak fitting (centroid, Gaussian or parabolic) or subpixel refinement techniques. However, in order for such techniques to work properly, it is necessary for particle images to occupy multiple (2 to 4) pixels. For sparsely seeded flows, a hybrid PIV – particle tracking approach yields good results at the cost of some robustness (Cowen and Monosmith [9]).
2.2 Implementation of PIV

The layout of a typical PIV system is shown in Figure 3. Synchronization is a critical part of the system, since laser pulses and camera acquisition need to come together within nanoseconds, especially for high relative (with regards to the image plane) velocity events. In addition, the system needs to control camera shutters to limit background light exposure (such as in combustion), as well as, to be responsive to external trigger events for phase-locked acquisition. Ambient conditions may vary during testing, and thus, acquisition of external transducers simultaneous with PIV data is also important. The end result of acquisition following a simple field-of-view calibration is a planar field of velocity vectors, which may be further reduced to other quantities characterizing the underlying fluid mechanics, as described earlier.

Figure 3: (a) Typical configuration of a commercial PIV system; (b) PIV data analysis software.

2.2.1 Stereoscopic PIV

With a single camera, oriented orthogonal to the laser sheet, the PIV technique yields two-component velocity information in the plane defined by the light sheet. By adding a second camera and through a skewed viewing arrangement (as shown in Figure 3a), the capability of PIV is expanded to yield all three components of velocity in the thinly illuminated volume. This expansion is called Stereoscopic-PIV, and it is based on the same principle as the human stereo eyesight. The two eyes see slightly different images of the objects around us, and upon comparing the differences in the images the brain interprets the 3D perception. Each camera thus records a different perceived particle translation between the two instants of time, and the 3D displacements are constructed by combining the 2D vector results from each camera by means of a calibration procedure that uses a special multi-level target to incorporate the plane-normal motion effect of the particles ([10], [11]).

2.2.2 PIV for micro-flows

Recent interest in microfluidics has prompted the adaptation of PIV to measure under the microscope, thus achieving spatial resolutions on the order of several microns (Santiago et al. [12]). However, while a thin light sheet can be used to illuminate the flow in conventional or macroscale PIV and thus define the
measurement plane, this is not possible at the microscale. Instead, the entire measurement volume is illuminated and the numerical aperture of the microscope objective (lens) defines the measurement plane and its depth (typically 2 μm – 15 μm), as shown in the insert at the top-right of Figure 4. Using this scenario, however, produces many reflections, and to eliminate this problem, tracing particles (0.2 μm – 1 μm) that fluoresce when illuminated by the laser are used in conjunction with an Epi-fluorescent cube that houses band-pass and high-pass filters to only allow the particle fluorescence to reach the CCD camera (seen in Figure 4). Significant laser power is not required to illuminate the small volume, but pulses need to be short to avoid particle streaking at high relative velocities.

The flow at these small scales is typically laminar due to the low Reynolds number, and thus steady or periodic. This laminar nature of flow can be taken advantage of in order to improve the PIV signal by performing correlation averaging of several image pairs prior to calculating the velocity field (Meinhart et al. [13]). It then follows that any broadening of the correlation function is due to, aside from random noise, the Brownian motion of the tracer particles. This Brownian motion is a function of fluid temperature, and will increase the measurable peak width as the temperature increases, thus adding the capability of measuring flow temperature to the PIV technique ([14]). Lastly, while it is physically impossible to image the same field of view using a second objective and perform stereoscopic PIV measurements the conventional way, by keeping with the assumption of laminar, steady flow, three-components of velocity can be evaluated by translating the field of view and reconstructing the 3D velocity field within the overlapped region using stereoscopic viewing principles ([15]).

![Figure 4: Optical configuration for doing PIV in micro-flows.](image)

3 Laser induced fluorescence (LIF)

LIF is an optical, whole-field quantitative method used to measure scalar properties (e.g. concentration and temperature) in liquid or gaseous flows. The measurement is carried out by recording the fluorescence emitted by a substance (either artificially or naturally present in the flow), which is induced by laser light.
3.1 LIF methodology

The emitted fluorescence, $F$, is related to the environmental parameters like the concentration, $C_n$ (or molar fraction $\chi_i$ of the tracer ‘i’ considered with gases), the temperature, $T$, and physical parameters like the local energy level, $E$, the pressure, $P$, and the fluid composition, i.e. a binary or a multiple component fluid, $\chi_i$. This relationship is expressed in eqn (1):

$$ F = \alpha \cdot \left( \chi_i \frac{E \cdot P}{T} \right) \cdot \sigma(\lambda, T) \cdot \phi(\lambda, T, P, \sum_i \chi_i) $$  \hspace{1cm} (1)

The variables $\sigma$ and $\phi$ are the absorption and quantum efficiencies of the tracer considered, respectively. The quantum efficiency varies with the physical environment (temperature and pressure) and with the composition of the fluid ($\chi_i$ for gases and ions for liquids). This requires delicate measurements, but at the same time, the technique is complete in terms of the information that can be acquired or determined. In conclusion, definition of the properties of the tracer used is fundamental since differential diffusion between species may occur ([16, 17]). Often, parameters are dissociated to avoid additional image processing and equipment costs, either by controlling the flow conditions (when possible) or by judiciously selecting markers that are not very sensitive to other physical parameters. This, of course, is not an experimental requirement, as in principle every parameter can be measured by adding equipment (another camera) to the set-up and adapting the image processing procedure.

3.2 Determination of concentration and temperature

3.2.1 Liquid applications

Preliminary examinations of the physico-chemical properties of organic dye candidates provide sufficient information to select the adequate tracer, for which the parameters $C$ and $T$ are separated (e.g. a dye which fluorescence is not sensitive to temperature). Since pressure variations are not an issue with liquid applications, straightforward access to the concentration is available. The relationship between $C$ and $F$ & $E$, assuming operation in the linear regime, is then given by $C = (F - a)/(bE)$, where $a$ and $b$ are calibration coefficients.

When temperature is measured, the flow is seeded at constant optimal concentration $C_o$ and $T$ is then given by $(T - T_0) = (F - F_0)/(bE)$ by applying a first order decomposition around $T_0$ over a temperature range of 100-150K. The linear approximation of $(1/T)$ has the advantage of rendering the signal processing easier and faster. As phase change typically occurs over this range (e.g. desorption of dissolved gases and ebullition), experience shows that this approximation yields very good results. When required, concentration and temperature can be measured simultaneously, either by applying a dual-LIF methodology (i.e. with two tracers [18]) or a multiple-band LIF methodology (i.e. with one single tracer and recording fluorescence light on several spectral emission bands [19]). These techniques, though powerful, also possess significant
limitations with direct implications on the accuracy of the scalar values
determined. This topic is not discussed in the present paper.

Not many years ago, precision and accuracy of the planar-LIF technique
were greatly limited by the CCD camera itself, which had reduced light
sensitivity and only 8-bit intensity resolution. These mostly affected the precision
of the overall measurement, given the quality of the instantaneous accuracy on
the concentration or temperature information. With current CCD cameras more
than 10 times more sensitive and with intensity resolutions of 12, 14 and 16 bits,
the digital information is now stored with extreme precision translating to larger
dynamic ranges for scalar measurements. Hence, the limitation on precision and
accuracy is now on the shot-to-shot stability of the laser.

In practice, the precision of concentration measurements (in \(\mu g/\text{GreyLevel}\))
is controlled by local energy, \((1/E)\), and the quantum efficiency of the dye used,
as seen in eqn (1). Temperature resolution (in \(K/\text{GreyLevel}\)) on the other hand is
defined by \((1/C_\varepsilon E)\) as the temperature sensitivity of the dye is fixed (often around
2%-5% per K). In both cases, laser shot-to-shot stability and camera response
(spectral range, sensor quantum efficiency, pixel resolution, exposure time, and
intensity resolution) affect measurement accuracy, and need to be addressed if
good quantitative LIF is to be realized.

3.2.2 Gaseous applications

Gaseous LIF applications may be found in many engineering disciplines covering
heat and mass transfer processes (engineering/fluid mechanics aspects), air
quality aspects (with NO\(_2\), CO\(_2\) etc.) to pre-/and post-combustion processes. All
these applications involve stable and/or reactive species and therefore allow in-
situ calibrations. The case of combustion LIF is not discussed here as it involves
further complex image analysis due to the formation of unstable species rendering
common calibration procedures not plausible.

Gaseous species emit fluorescence in the UV-blue region of the light
spectrum. Camera limitations are thus similar to that found with red emitters for
liquid LIF. Furthermore, quantum efficiency of the tracers is significantly lower
(typically <5%) thus making image intensifier units almost always a requirement
to amplify the weak fluorescence signal.

Compressibility, which is commonly encountered with gases, can be
addressed in various ways. One can compensate the LIF signal by either
measuring the total pressure (e.g. in closed systems like in spark-ignition engines)
or by recording the fluorescence of a marker sensitive to pressure. The latter
method implies the use of a second camera to record the pressure-related LIF
signal.

3.2.3 Implementation of LIF

The equipment necessary to perform planar-LIF measurements is similar to that
of PIV (shown in Figure 3). However, careful considerations are necessary during
the selection of camera, laser and related optics, depending on the application, as
well as, on the practicality and user friendliness of the overall system
configuration. The latter two are important from a time savings perspective
during system optimization and data processing.
The optimization cycle for LIF is illustrated in Figure 5. It consists of getting the maximum resolution on $C$ (or/and $T$) and thereby requires that the intensifier unit (if present), camera and optic lens are adjusted properly. Also, numerical image pre-processing helps significantly transform LIF data from good to excellent. Further optimization comes from the simultaneous measure of additional parameters, like the energy delivered by the laser pulse ($E$) and the total pressure ($P$) for compressible flows. The accuracy of instant LIF images varies with the equipment and the operator’s experience in setting up the entire system, but a value of 90% to 98% is typical. The integration of additional parameters in the LIF measurement in order to achieve high accuracy increases the complexity of the overall system and thus puts high demand on software/hardware control, calibration and image processing tools.

Once optimized, the system can give impressive LIF results, as shown in Figure 6. The figure shows an instantaneous planar-LIF measurement of the mixing occurring in a round turbulent free jet. The potential core region (100% concentration) is easily identified, and as seen, it is quickly broken up by the vortical structures in the expanding shear layer. These structures bring ambient fluid into the jet core and are responsible for the rapid mixing that characterizes turbulent jets. Thus, the planar-LIF technique not only offers whole-field quantitative data, but also provides a global qualitative picture of the mixing process investigated.
The recent interest in “Lab-on-a-Chip” systems has prompted researches to apply LIF under the microscope. The hardware is similar to that of PIV for microflows. Since the entire volume is illuminated, the LIF signal is an integral over the measurement depth. Although this limits the spatial accuracy, it offers a unique tool for measuring heat & mass transfer phenomena in micro-flows.

3.2.4 Combined PIV and planar-LIF
With a second camera recording PIV data synchronously with planar-LIF images, whole-field correlations between velocity and scalar properties may be determined. This possibility is illustrated in Figure 7 where velocity and Reynolds flux results for a hot plume rising in a stratified fluid are presented. Taking advantage of the strength of distributed computing, the average of 5,000 pairs of velocity/temperature maps recorded in this case was quickly determined.

Figure 7: Average velocity field (arrows) and Reynolds flux calculated with 5,000 velocity/temperature maps.

4 Conclusions
Image-based diagnostic techniques are riding a wave of technological prowess that is constantly increasing their robustness and their practicality as tools for experimental fluid dynamic research. PIV and LIF have progressed significantly in the last few years given new capabilities in camera and laser technologies, as well as, increased accessibility to fast and distributed computing. Deployed simultaneously, the two techniques give researchers valuable insights to the dynamics of flow, as well as, serving to increase the number of quantities that are either directly or indirectly determined from measurements and can be used to validate computational methods for complex problem simulation.

References


