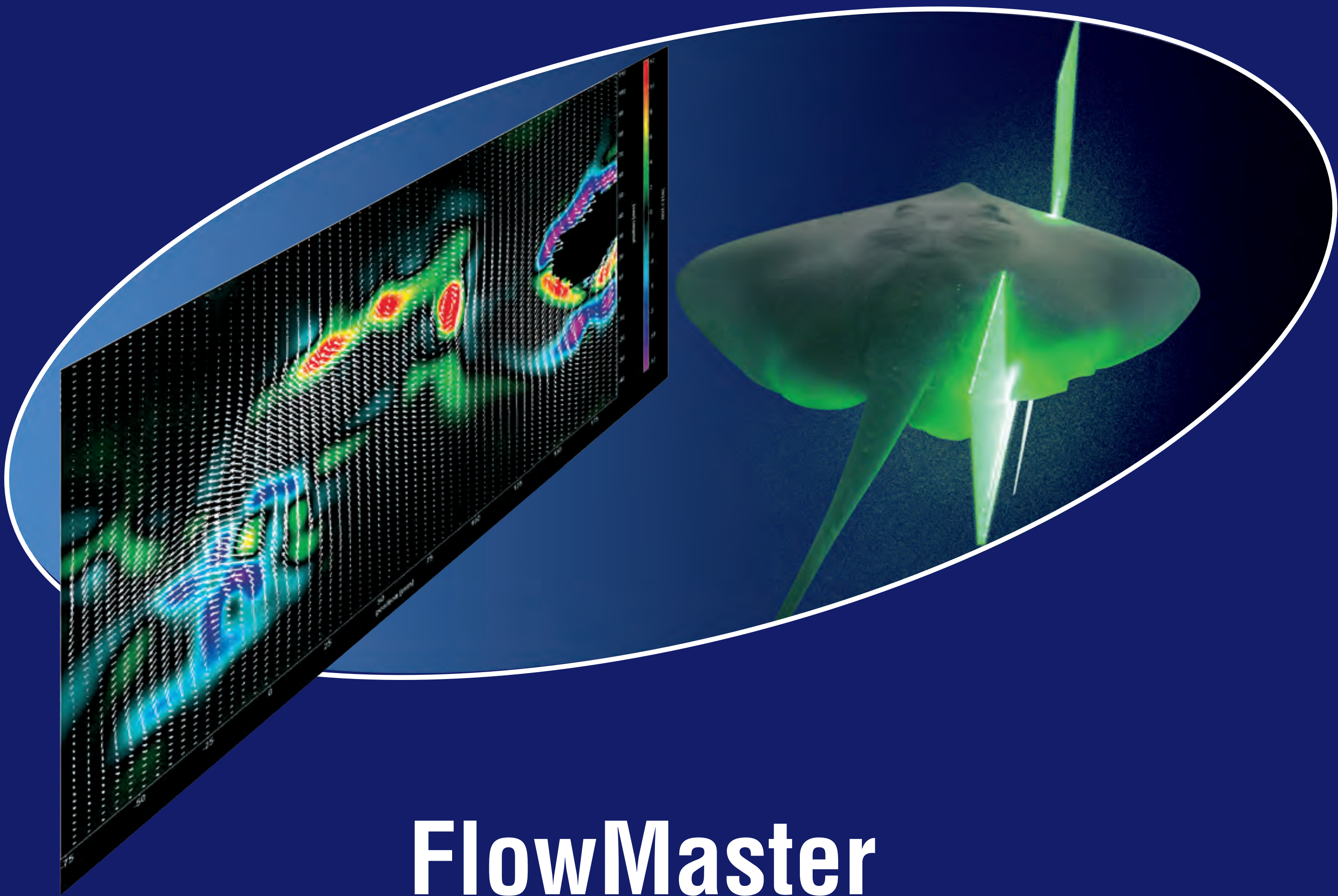


FlowMaster

Time-Resolved
Particle Image Velocimetry Systems

LaVision
FOCUS ON IMAGING

FlowMaster

Time-resolved PIV Systems combine Spatial Information with Temporal Evolution

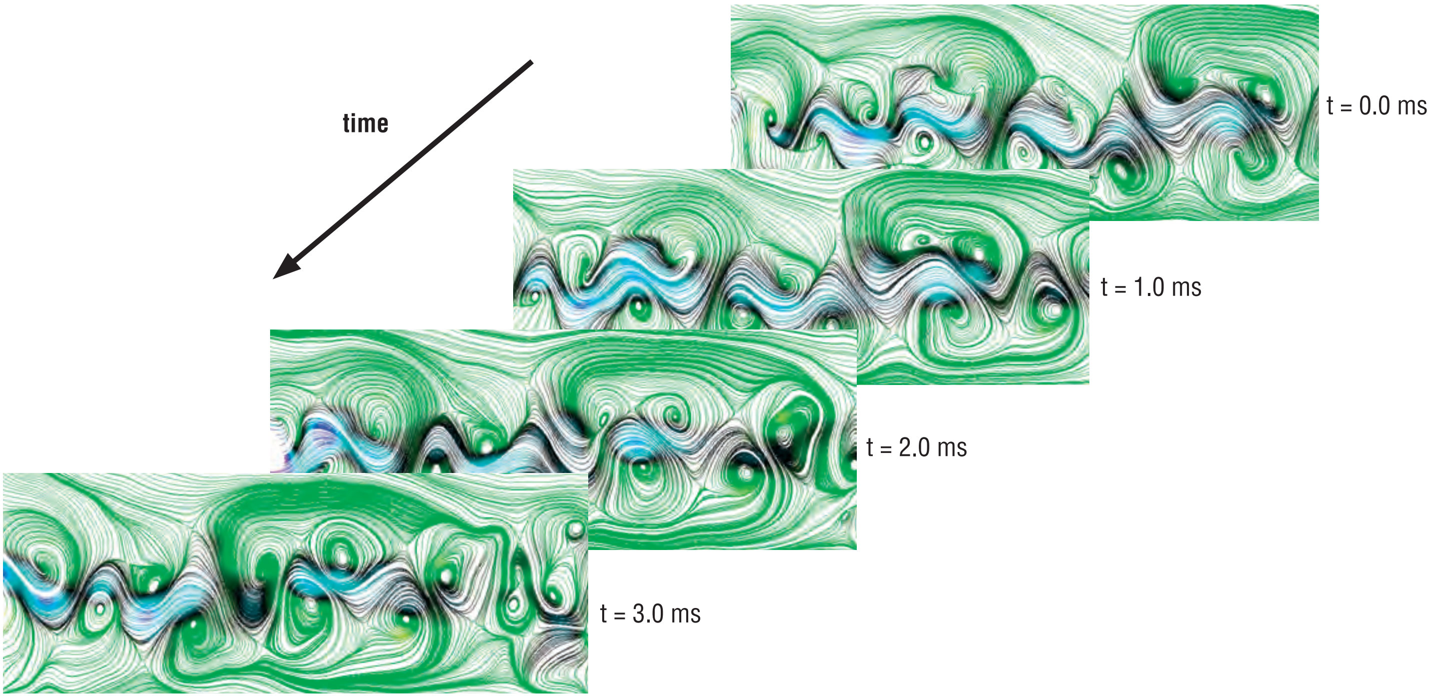
FlowMaster Time-Resolved PIV systems open up new possibilities for quantitative flow mapping at frequencies up to tens of kHz. Time-resolved PIV combines the instantaneous velocity mapping of conventional PIV with high frame rate CMOS cameras and high repetition rate pulsed and cw lasers. Velocity mapping at high frequencies allows characterization of flow features that are short lived and unrepeatable, allowing the measurement of flow features in time as well as space. Most flows of scientific and engineering interest are characterized as turbulent and unsteady. Investigators can make use of time-resolved PIV as a powerful tool with extended experimental measurement capabilities to allow for the investigation of the detailed interaction of flow structures in space and time.

Additionally, time-resolved PIV provides the means to collect large amounts of data quickly for statistical analysis when the measurement window is brief or when equivalent conditions cannot be sustained for prolonged periods.

What is TR-PIV?

PIV has historically been a measurement technique that provided high spatial resolution data where individual vector maps are typically statistically independent from the previous vector map (i.e. de-correlated in time). When time-correlated information was necessary, point measurement techniques (HWA, LDV) were utilized. In special cases these point measurement techniques can also be used to provide spatial information by virtue of Taylor's hypothesis.

Now with the advent of high frame rate cameras and high repetition rate pulsed light sources, it is possible to collect instantaneous vector maps with high spatial resolution that are correlated in time.



Karman vortex street behind a cylinder. Re_D= 12,000.
Image courtesy of German Aerospace Center (DLR), Goettingen, Germany

TR-PIV Operating Modes

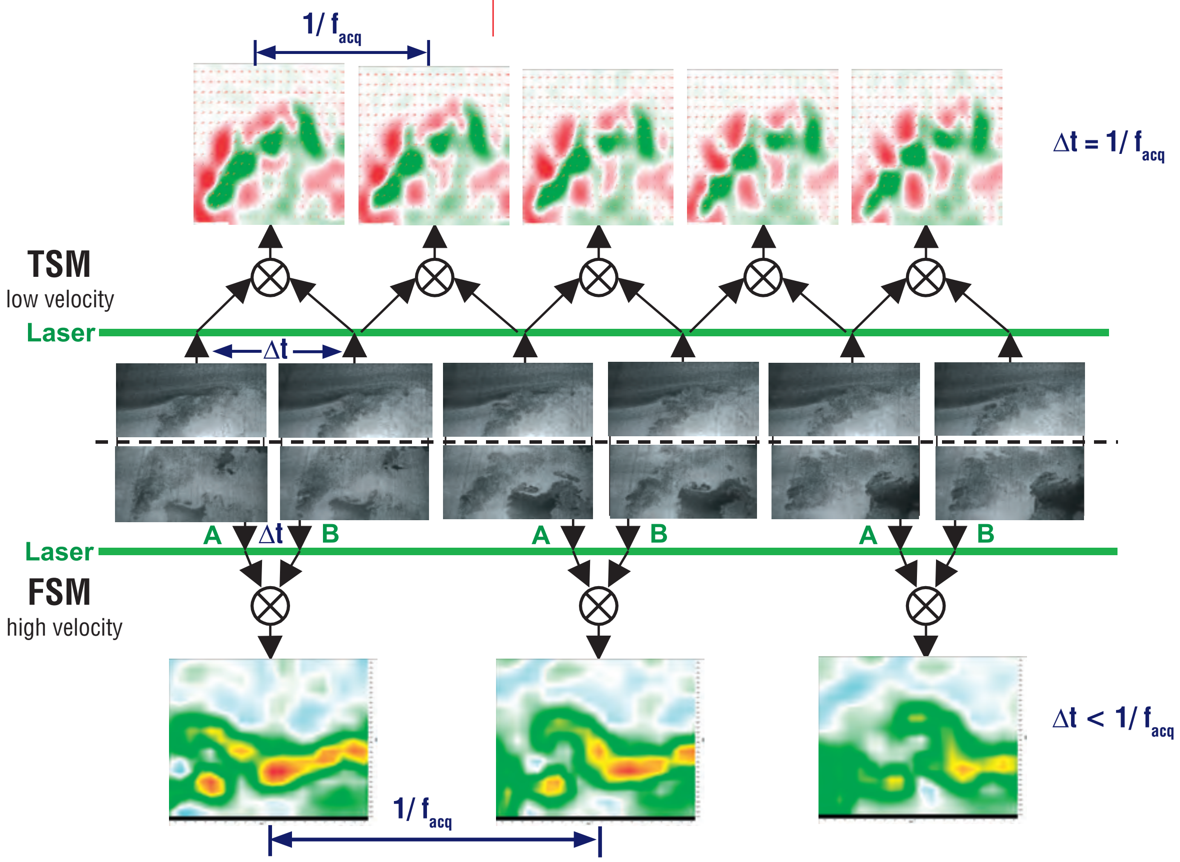
In TR-PIV two operating modes are possible. Each have distinct advantages and the mode selected depends on the experimental conditions as well as the specific motivation (i.e. usage) for the data.

Time Series Mode (**TSM**): In this mode, a single laser pulse is fired in each camera frame. From each pair of neighbour images a vector field is computed so that the camera frame rate is equal to the vector field acquisition frequency f_{acq}.

The acquisition rate f_{acq} should be selected such that the resulting time between laser pulses $\Delta t = 1/f_{acq}$ is adequate for the flow velocities within the field of view. When properly established, this mode provides highly time-resolved vector fields. These data can yield time-related information such as power spectra, Lagrangian tracking and space-time correlations.

Application Examples

- investigation of fluid dynamics, time-space correlation
- experiments with fluid structure interaction, large scale separation, turbulence analysis



Frame Straddling Mode (**FSM**): In this mode, pairs of images are collected with laser pulse A fired towards the end of the first frame and laser pulse B fired at the beginning of the second frame. This mode gives the user flexibility in choosing a Δt without it being coupled to the camera frame rate. FSM mode is selected when the velocity is too high to be captured by a Δt of $1/f_{acq}$. Velocity fields are less correlated in time than with TSM.

For very high velocities, time correlation between adjacent vector fields disappears completely and, in such cases, the system is simply being used to capture large amounts of data in a short time. An example of this would be in a blow down wind tunnel where the period of time that the facility can be used is very short.

Application Examples

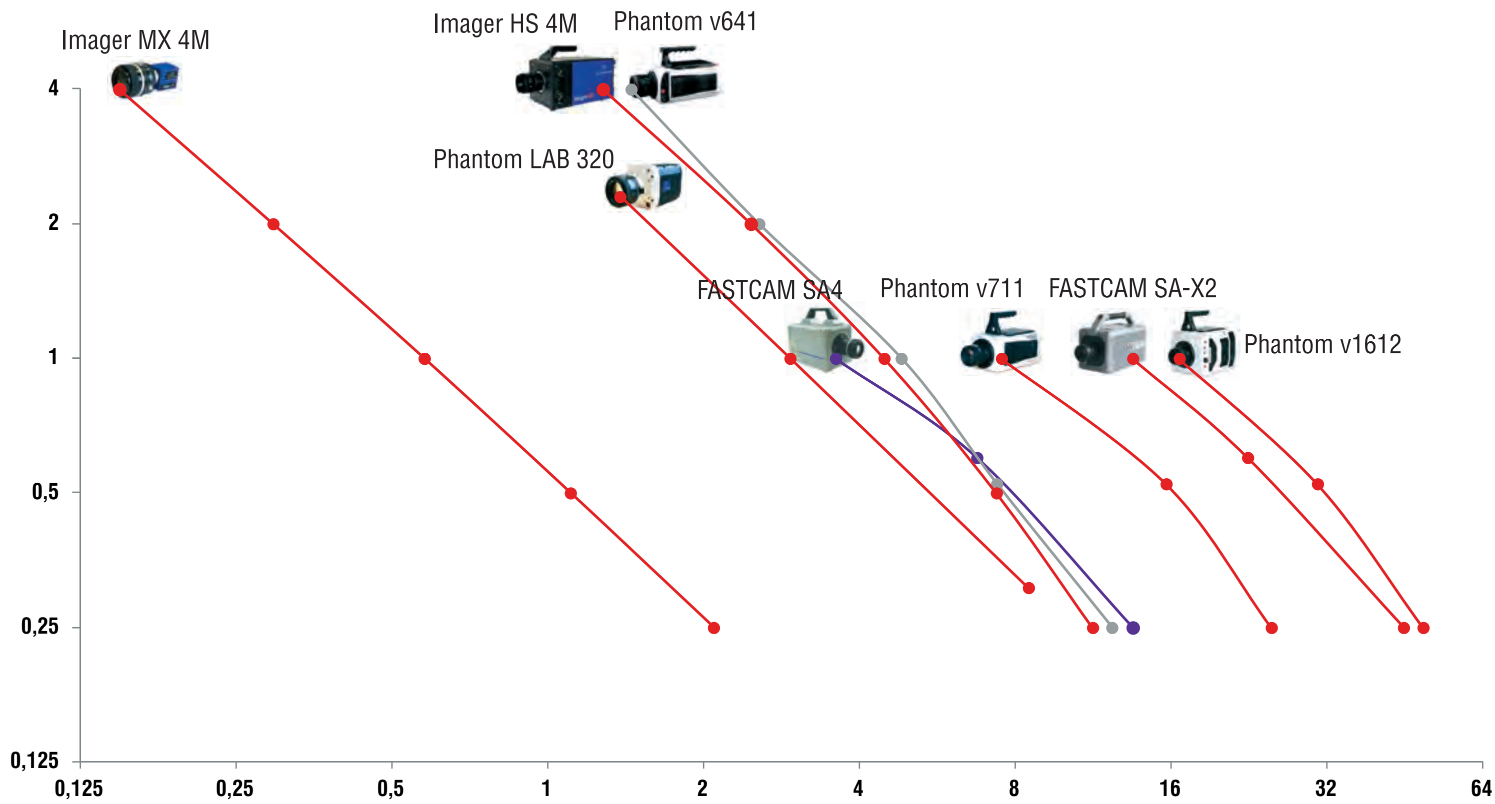
- experiments with high velocities
- experiments with short operating windows, e.g. blow-down wind tunnels

Technology Overview

The key technologies that enable TR-PIV include high frame rate complementary-metal-oxide-semiconductor (CMOS) cameras and diode pumped solid state pulsed lasers. These technologies combined with an accurate and sophisticated triggering system such as the LaVision **Programmable Timing Unit (PTU) X High-Speed** allows images to be acquired in either time series or frame straddling modes for ultimate flexibility to characterize velocity fields across a broad range of velocities and time scales.

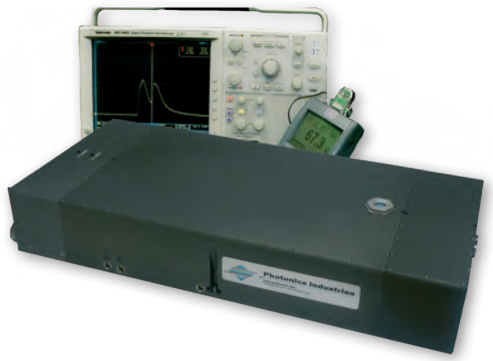
Cameras

CMOS technology has evolved rapidly in recent years to provide both high pixel count and high frame rates with sensitivity and low background noise - features that were previously only associated with Charge Coupled Device (CCD) sensors. There are a substantial number of CMOS camera developers and LaVision evaluates new models as they come to market and continues to offer support for those cameras that represent the current state of the art and the best combination of frame rate, resolution and sensitivity.



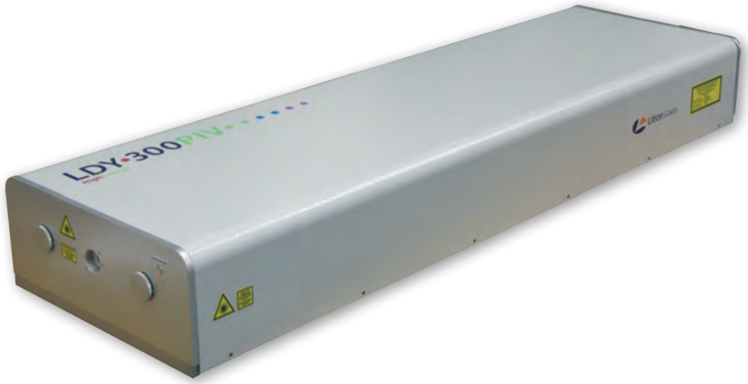
CMOS cameras are typically characterized by their maximum recording rates (kHz) and their maximum resolution (MPx). However, when higher recording rates are desired, their area of interest (AOI) can be reduced in the interest of increasing the recording rates. The above figure shows the extents of these capabilities for a few popular TR-PIV cameras. LaVision currently supports 33 different models fully integrated in DaVis. The Δt for the frame-straddling mode can be as small as 0.4-4 µs depending on the camera model.

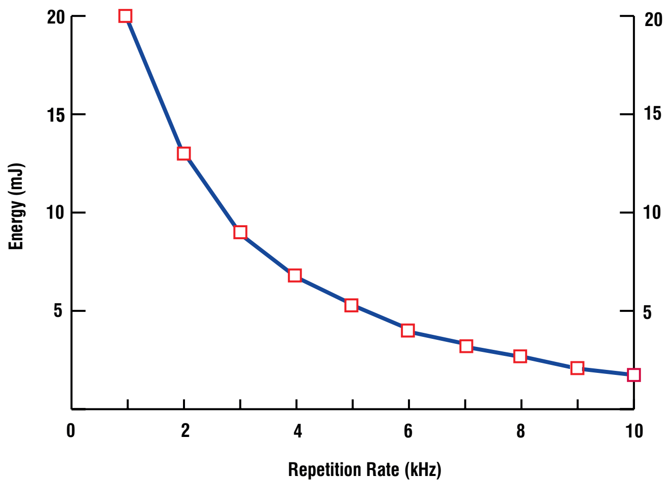
Pulsed Lasers



Pulsed lasers

The default light source for PIV is a double cavity, Q-switched pulsed laser (YAG or YLF).
In this case a substantial amount of light energy (1 mJ - 50 mJ) is delivered in a very short amount of time (7-200 ns for Nd:YAG and Nd:YLF DPSS lasers).





Energy versus repetition rate for Litron LDY-300

Shuttered Continuous Wave (CW) lasers

Certain PIV applications can benefit from the use of continuous wave (cw) lasers. These lasers provide a compact and cost-effective light source that can be paired with CMOS cameras. The laser light can be freely turned on and off on very small time scales.

Both types of lasers are under complete control of LaVision‘s **PTU X High-Speed** offering advanced trigger options for challenging applications. LaVision supports numerous state-of-the-art lasers completely integrated in **DaVis**.

TR-PIV Tools and Processing Possibilities

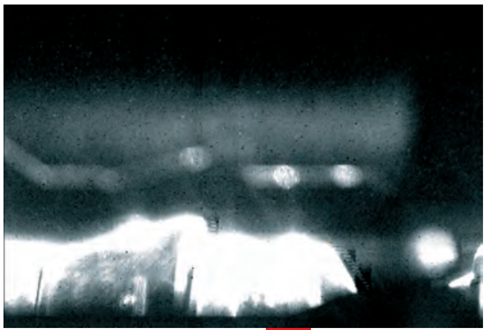
Time-Based Image Processing Tools

A time-resolved sequence of images can allow for the removal of background luminosity in images that are not associated with the particles, including:

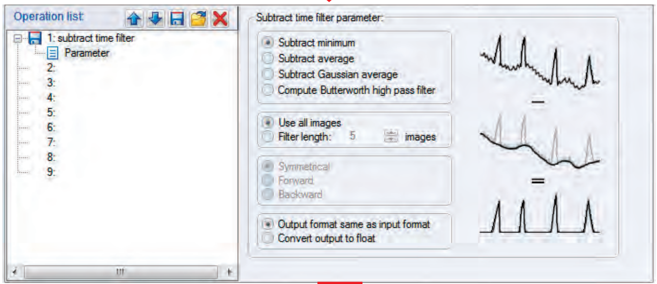
- background light and reflections
- secondary scattering of light from particles
- bright glare from the laser sheet impinging on flow boundaries

Removal of these features improves the accuracy and reliability of the correlation processing and can be achieved by subtraction of a statistically calculated stable control image. This can be fixed for a whole sequence or as a sliding value for sequences that have a varying background.

Additionally, tools for characterization and removal of residual fixed pattern noise in CMOS camera images are provided to improve beyond the intensity correction that many CMOS cameras provide. Local and global normalization routines further refine image sequences to maximize the contrast of images and reduce bias effects due to unavoidable seeding non uniformities.

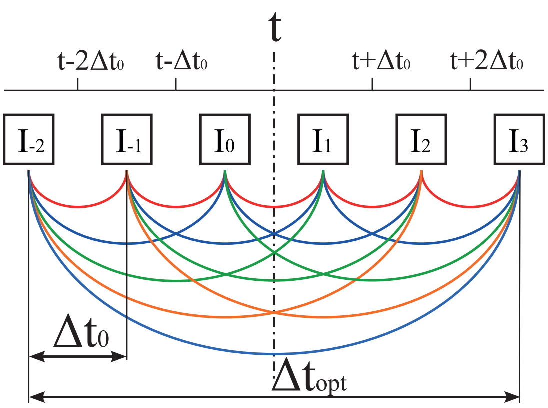


Original data



DaVis Time Series Filter

Processed image, courtesy: F. Scarano, A. Sciacchitano, TU-Delft, ARIANE V main engine, in: Robust elimination of light reflections in PIV, PIV'11, Japan



n	$t-2\Delta t_0$	$t-\Delta t_0$	t_0	$t+\Delta t_0$	$t+2\Delta t_0$
1	$R_{-2,-1}$	$R_{-1,0}$	$R_{0,1}$	$R_{1,2}$	$R_{2,3}$
2	$R_{-2,0}$	$R_{-1,1}$	$R_{0,2}$	$R_{1,3}$	
3		$R_{-2,1}$	$R_{-1,2}$	$R_{0,3}$	
4		$R_{-2,2}$	$R_{-1,3}$		
5			$R_{-2,3}$		

Reference:
Sciacchitano, A., Scarano, F. and Wieneke, B., Multi-frame pyramid correlation for time-resolved PIV, Exp. in Fluids, 53 (2012): 1087-1105.

TR-PIV Vector Calculation Tools

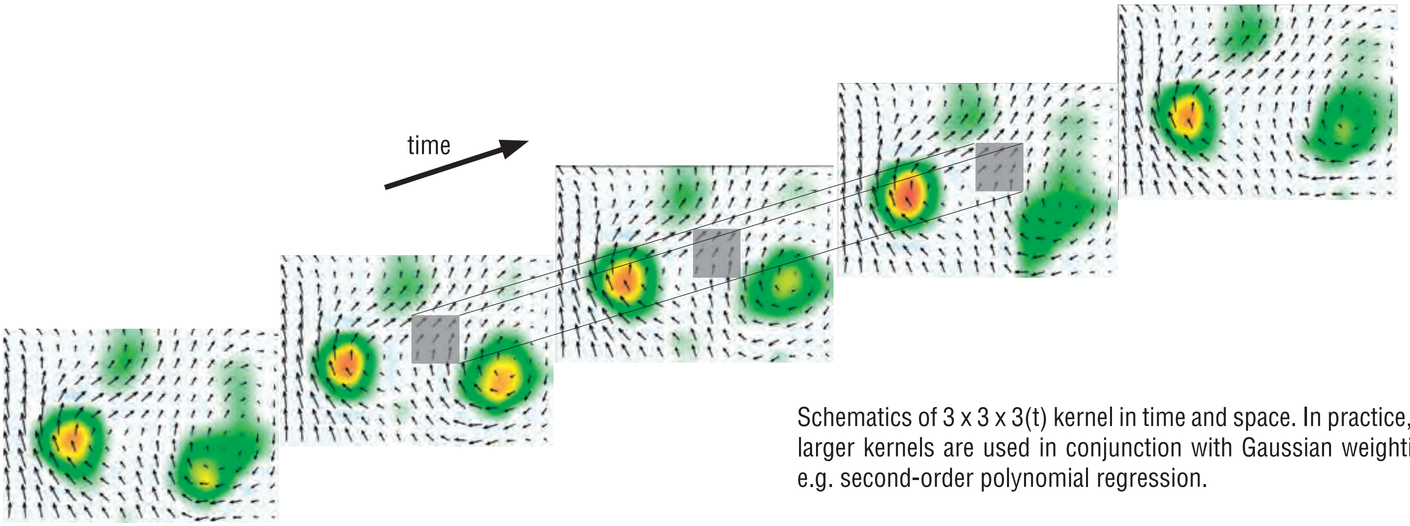
Basic processing is the same as for standard double-frame PIV correlating two subsequent images. Advanced vector calculation tools utilize continuity and similarity over time in correlation functions. Examples include:

Sliding Sum-of-Correlation - consolidates correlation peak height while averaging over random background correlation noise. Using sum-of-correlation on as few as two correlations can substantially improve peak to background noise ratios and displacement accuracies.

Pyramid Sum-of-Correlation - provides the possibility of accessing progressively longer effective Δt values between images so that the dynamic range of velocity values can be magnified. This technique better resolves velocity fields that include large variations in velocity in space and time.

TR-PIV Vector Post Processing

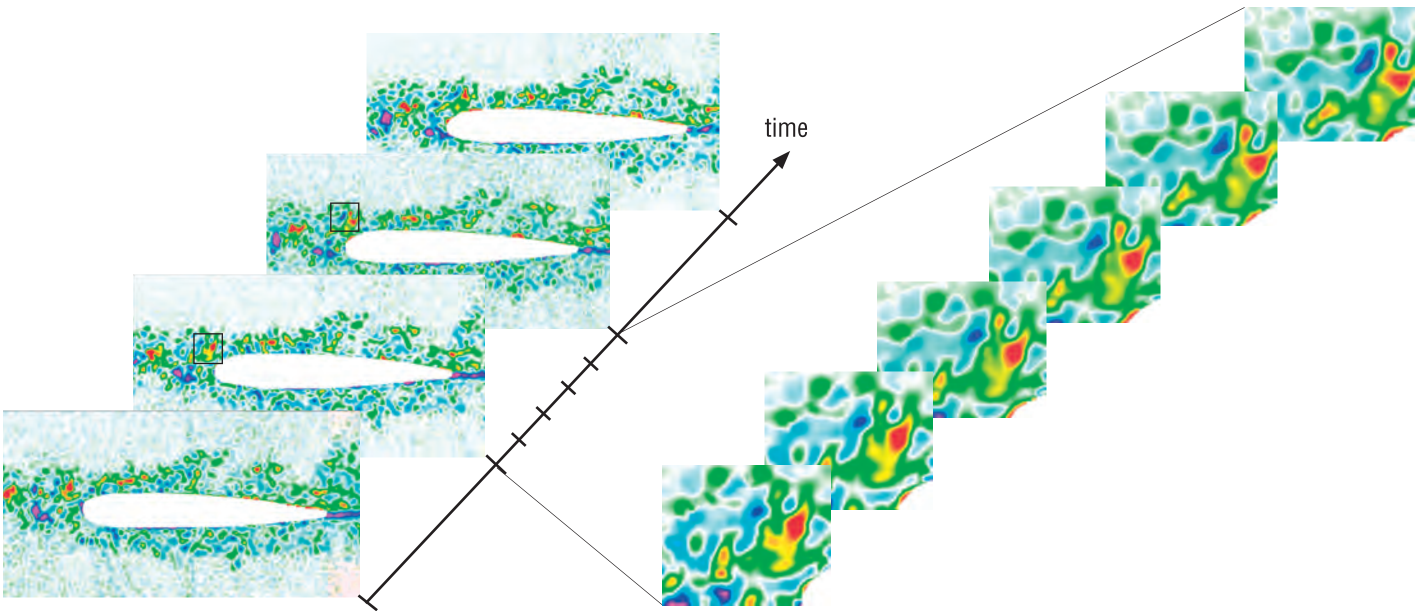
Time-resolved vector post-processing includes a variety of tools that employ time correlation and spatial continuity to more reliably identify outliers while preserving true flow features. Similar to standard vector post processing, the validation process also includes the possibility of re-evaluating the correlation peak information to recover the true displacement correlation peak. A variety of de-noising filters operating in space and time domain are available to preserve high frequency variations in the measured flow field while removing image-to-image noise in the displacement field due to various sources of errors.



Schematics of 3 x 3 x 3(t) kernel in time and space. In practice, often larger kernels are used in conjunction with Gaussian weighting or e.g. second-order polynomial regression.

TR-PIV Vector Field Enhancement

Vector Field Enhancement includes functions that operate on post-processed vector map sequences to enhance that data prior to condensing fluid dynamic quantities or visualizing for the purpose of gaining global insight into the flow phenomena. This includes time-varying POD-modes as well as time-super-sampling that can generate intermediate vector maps. This can be useful for tracking coherent structures or simply provides a smoother and more progressive visualization of the evolving flow field.



Original image, color = vorticity

Enhanced temporal resolution with time-super-sampling (n=5)

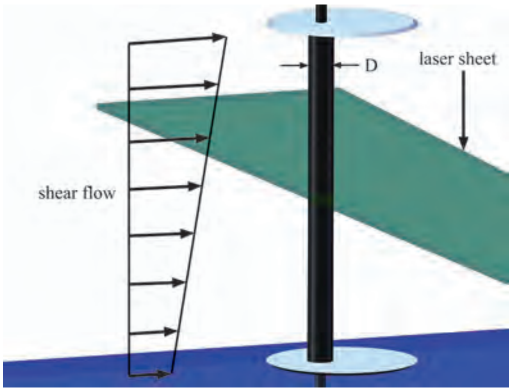
Reference:

Scarano, F., and Moore, P., An advection-based model to increase the temporal resolution of PIV time series, Exp. in Fluids, 52 (2012): 919-933.

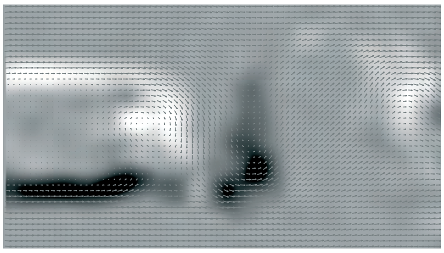
Coherent Structures

Reconstruction of dominant coherent structures in the turbulent wake of a circular cylinder

Time-resolved PIV measurements on five independent planes are phase averaged using Proper Orthogonal Decomposition (POD) of each set of PIV data obtained.
Simultaneously acquired Laser Doppler Velocimetry (LDV) measurements at a fixed location provide the average oblique angle of the vortex shedding phenomenon.



Two-dimensional PIV setup:
low speed water flow (U ≈ 85 mm/s)
imposed velocity gradient
uniform cylinder model (D = 25.4 mm)



Sample instantaneous velocity and vorticity field.

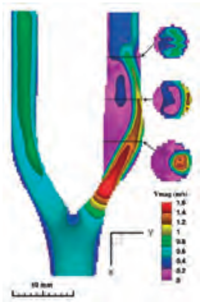
3D Reconstruction: the vorticity field is reconstructed in three-dimensions using a time-resolved phase averaging approach with POD and LDV phase reference signals.

Courtesy of C. Morton, S. Yarusevych,
University of Waterloo, Canada

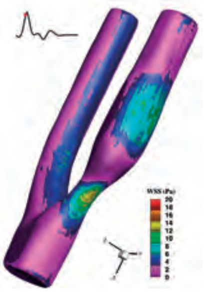
Time Unsteady Flows

Flow visualization in a carotid artery bifurcation model using stereoscopic PIV incorporating a 50% diameter reduction

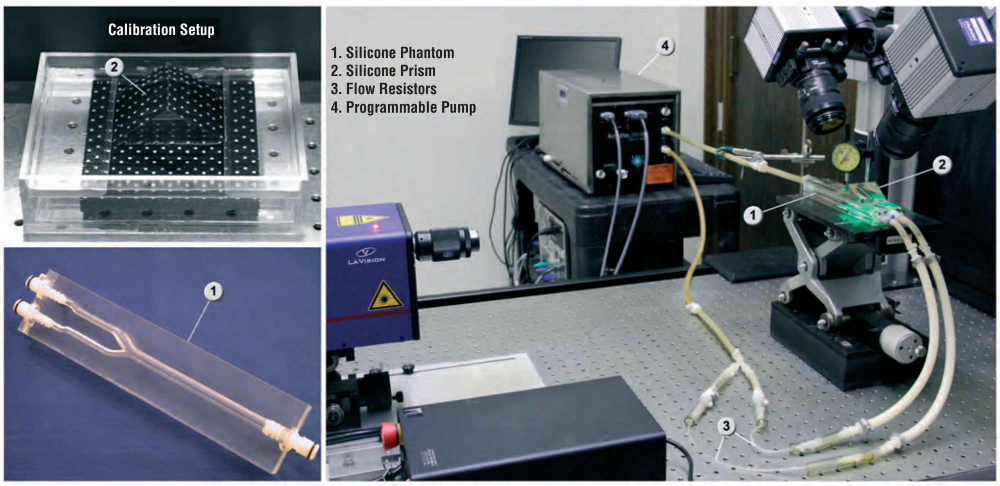
TR-PIV is an ideal technique for characterizing the complex blood flow patterns in models of both healthy and diseased vessels. Time-resolved vector maps provide insight into the complex interaction between flow conditions, changes in blood biology and vessel geometry as well as plaque buildup and stability. Results obtained provide clues to unlocking the puzzle of how damaged blood cells progress into thrombogenic conditions, rupture of plaque, and vessel damage.



central-plane map of velocity magnitude



3-D wall shear stress from the systolic phase of the cardiac cycle.



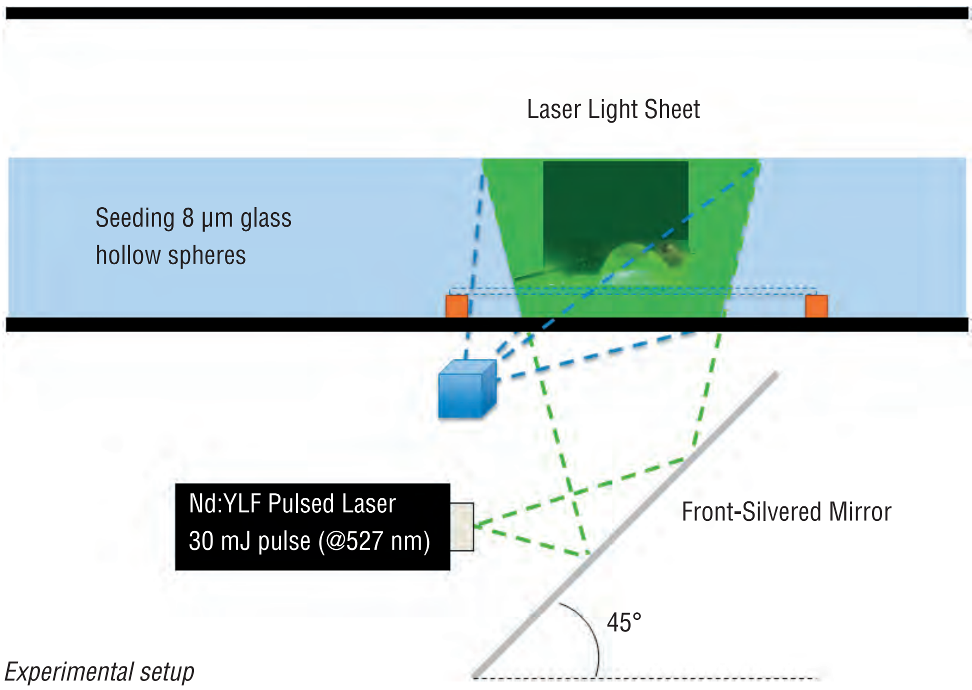
Courtesy of T. Poepping and S. Kafayati,
University of Western Ontario, Canada

Highly Non-repeatable Flows

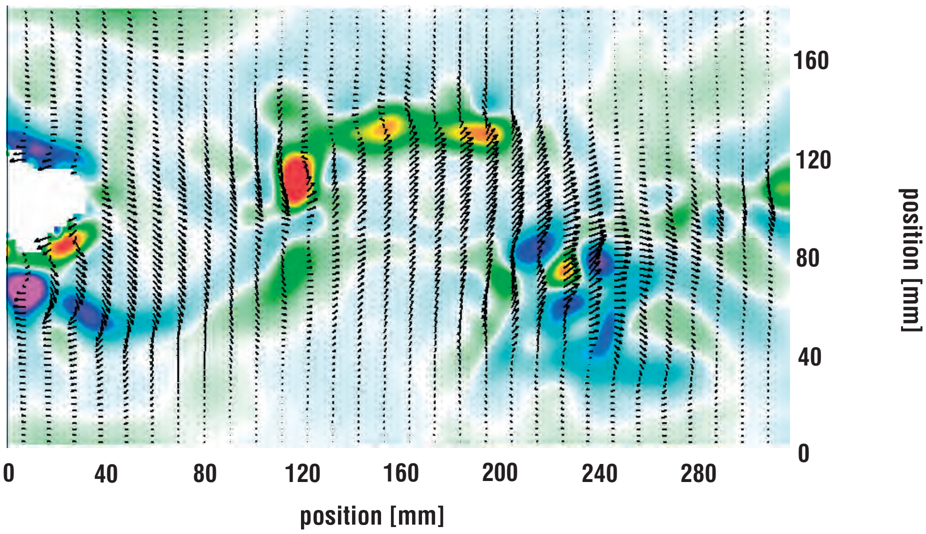
TR-PIV on a stingray

The wake structures caused by the swimming motions of the Atlantic stingray (Dasyatis sabina) is investigated using TR-PIV. The very nature of collecting data on live animals creates a situation where no two experimental runs are identical, eliminating the possibility for phase-averaging. Each run shows the stingray passing through the light sheet at a different horizontal position and a different distance from the bottom of the tank. These data show that the various swimming modes are related to distinct flow patterns that are linked to the propulsive efficiency of the fin motion. The fluid motions and vorticity in the wake of the Atlantic stingray show distinct differences in pattern that are associated with the thrust production based on each swimming mode, buoyancy control and proximity to the bottom.

Photo courtesy of Douglas Neal, LaVision Inc.



Experimental setup



Time-resolved data on a stingray showing shed pairs of vorticity

Courtesy of Frank Fish,
West Chester University, USA

Turbulence

High spatio-temporal resolution TR-PIV below wavy surfaces

Experiment

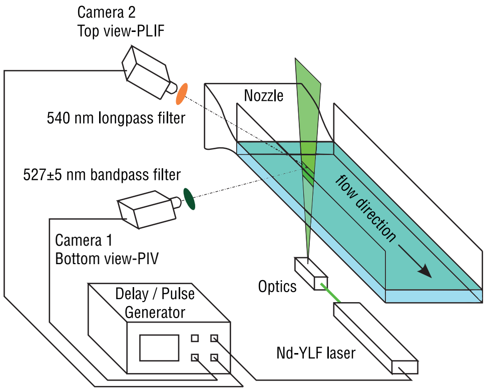
- study boundary layer instability at free-surface of a high-speed water jet
- instability generates mm-waves with strong vortices below
- study interaction of vorticity with free-surface

Diagnostics

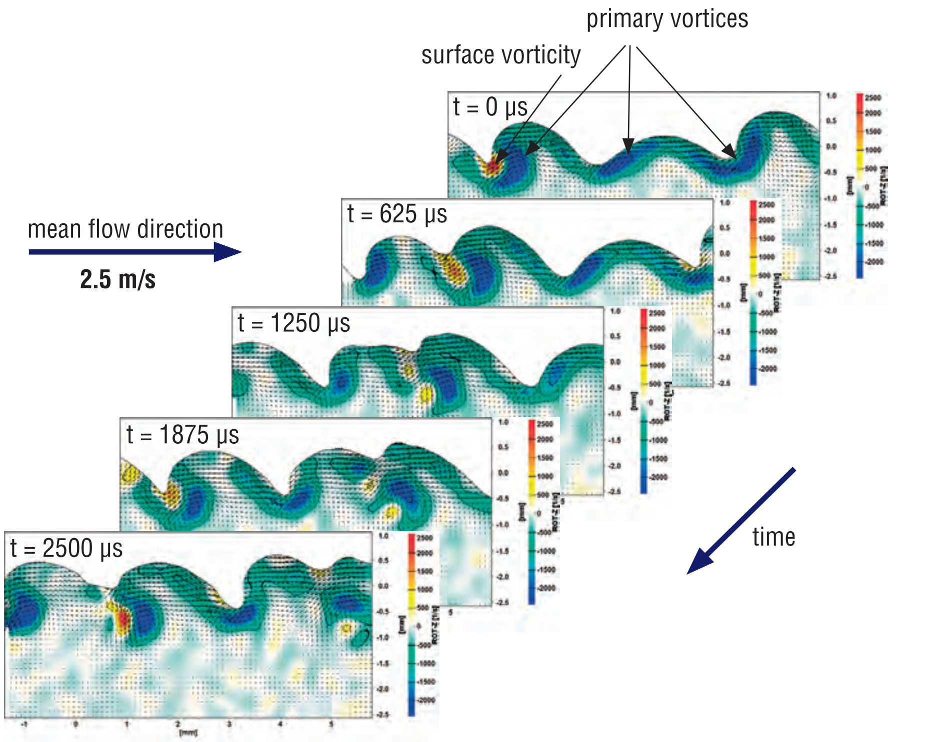
Velocity field	TR-PIV
Surface profilometry	TR-PLIF
Resolution	spatial < 100 µm
	temporal = 62.5 µs

Physical Insight

- primary vortices are responsible for steep surface deformation
- vorticity is generated by the free-surface in sharp troughs
- vortex pairs are formed leading to closing of the waves



Experimental setup



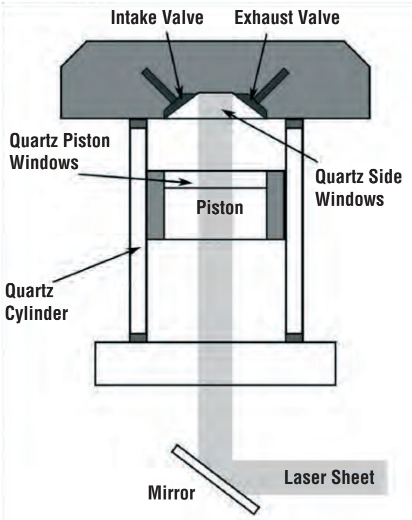
Sequence (1 every 10 frames) of fluctuating velocity vector field with vorticity as contour map

Courtesy of M.A. Andre and P.M. Bardet,
The George Washington University, USA

References:

- M.A. Andre and P. M. Bardet to appear in Experiments in Fluids 2013, Velocity field and surface profile resolution below steep and short surface waves
- M.A. Andre and P. M. Bardet, Experimental investigation of boundary-layer instabilities on the free surface of a non turbulent jet, Proceedings of the Open Forum on Multiphase Flows, FEDSM2012-72328

IC Engine Flows

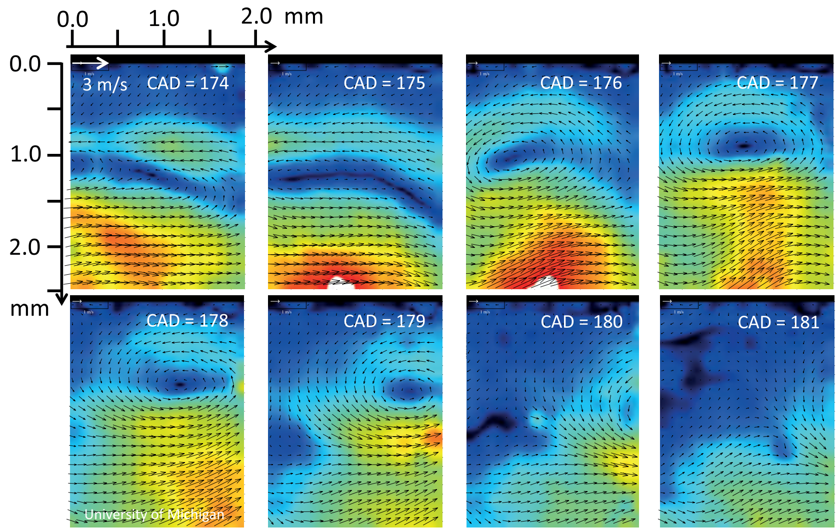


Experimental setup

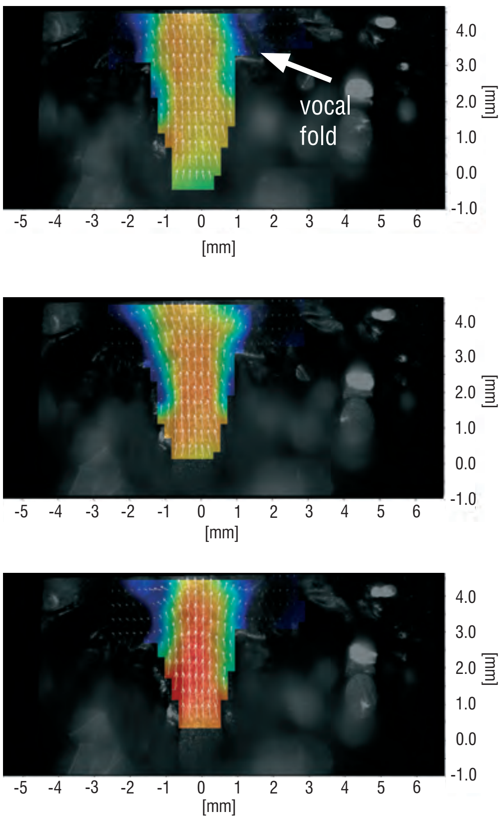
Courtesy of V. Sick et al.,
University of Michigan, USA

Internal combustion engine study on boundary layers

Boundary layer flows in internal combustion engines are very poorly understood because of a lack of detailed high-resolution experimental data. The image sequence shows eight vector fields (only every second vector is shown for clarity) with the velocity magnitude as the colored image background that were measured with a high-speed micro-PIV setup at the University of Michigan.

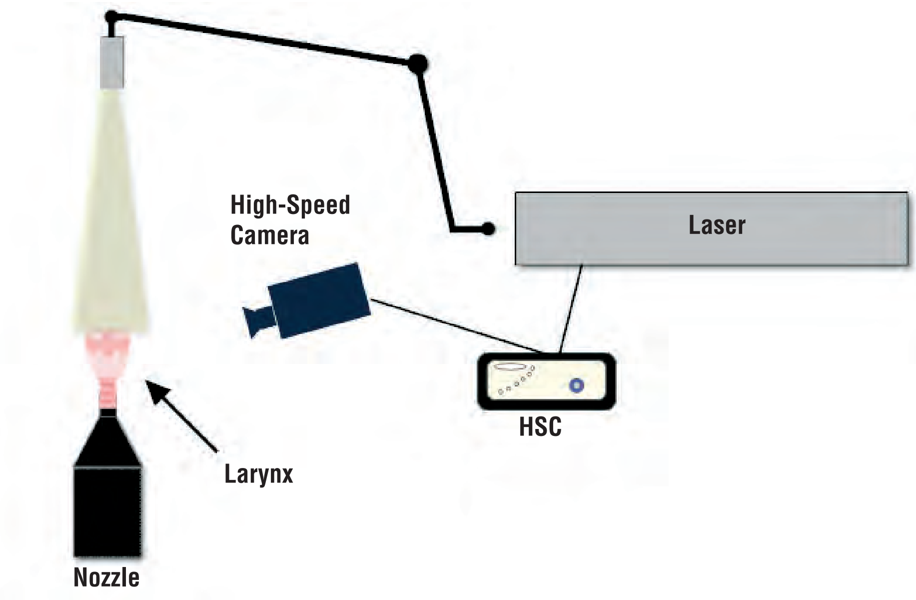


Aero-Acoustics



Study of flow-structure interaction occuring in vocal folds

The human voice is generated by the oscillatory motion of the vocal folds. The vocal folds are located within the larynx and typically vibrate at 100 - 300 Hz. Using time-resolved PIV, it is possible to resolve the flow dynamics between the folds during vibration. The data is correlated with acoustic measurements and is used to study the flow-structure interaction that occurs in the vocal folds.



Experimental setup

Courtesy of L. Oren et al.,
University of Cincinnati, USA

FlowMaster Time-Resolved PIV

System Features

Cameras

- wide range of cameras
- variable AOI and reciprocal frame rate increase
- sub-µs PIV Δt
- single camera, Stereo- and multi-camera Tomo-PIV supported
- time series mode (TSM) and frame straddling mode (FSM)

Lasers

- flashlamp, diode pumped solid state YLF, YAG and cw DPSS lasers

PTU X High-Speed

- multiple inputs and outputs
- externally triggerable operation
- variable parameters such as PIV Δt within burst

Processing Tools

- time based image pre-processing
- local and global particle image normalization
- vector calculation for FSM, TSM with standard and pyramidal processing
- temporal and spatial vector post-processing operations
- confidence and uncertainty evaluation
- de-noising filters
- time-space correlation algorithms
- POD and power spectra calculation

Complementary Time Resolved Techniques

- Time-resolved Tomographic PIV
- PLIF Concentration/Temperature in liquids and gases
- Tunable PLIF for identification of specific species
- Raman
- Schlieren and Background Oriented Schlieren
- Spray Imaging
- Laser Sheet Imaging including SLIPI
- Bright Field Imaging
- Lagrangian 2D- and 3D-Particle Tracking Velocimetry

Support

- LaVision always strives to provide the best possible support to all its customers

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