2D Least Squares Matching

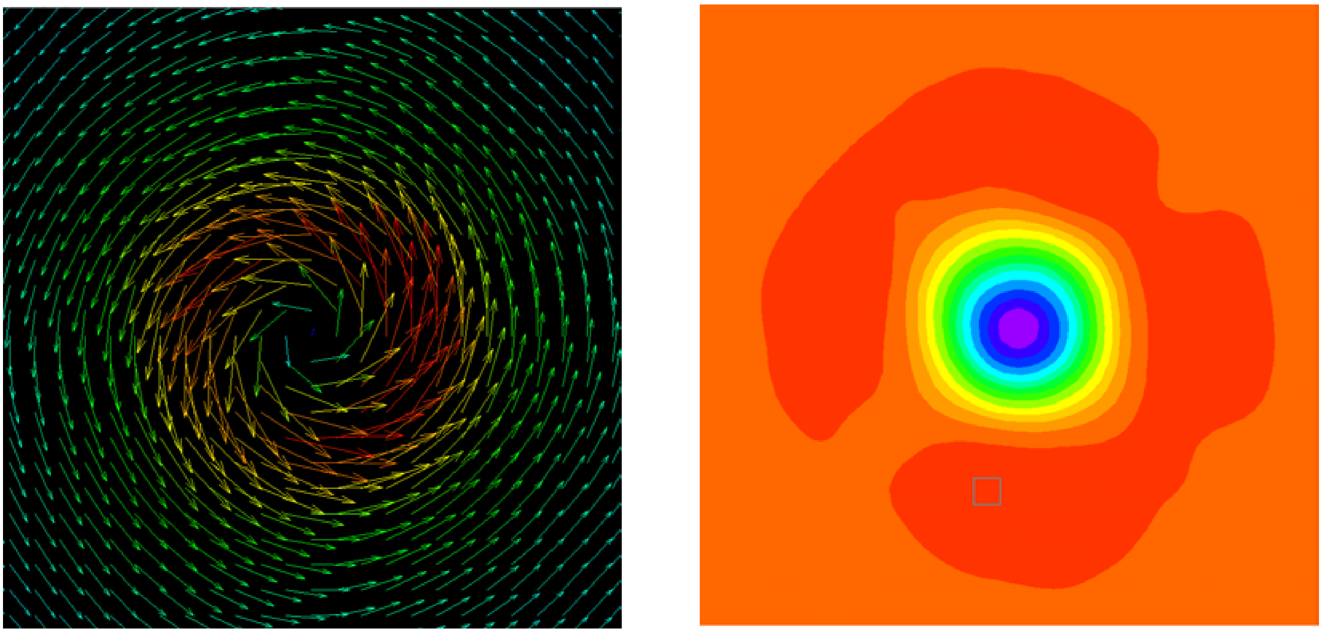
Velocity and velocity gradients simultaneously

Applications

- Particle Image Velocimetry
- Stereoscopic PIV
- Flow with high velocity gradients
- Turbulent flow analysis
- Analysis of vortical structures

Features

- Precise velocity calculation
- Direct velocity gradient calculation
- Physical flow modelling
- Accurate vortex identification



Left: Velocity field inside of a vortex calculated with 2D LSM. Right: Lambda2 vorticity criterion computed with the estimated flow gradients.

Introduction

For more than 25 years, the cross-correlation operator has been used to calculate the velocity field from pairs of particle images. During these years much effort has been made to improve the quality of the results. Multi-grid methods were implemented to increase the spatial resolution. Multi-step schemes with successively decreasing interrogation area size were deployed to handle larger velocity ranges and to increase the dynamic range of Particle Image velocimetry.

Deforming windows techniques were introduced to better accommodate for velocity gradients. High-accuracy methods were proposed to alleviate the effect known as peak locking. But the fundamental concept of cross-correlation as displacement estimator was never really challenged until today.

For the first time ever, Least Squares Matching (LSM) brings flow physics to the processing of particle images. Unlike cross-correlation, LSM uses a model to describe the movement of fluid elements. This model contains six parameters describing translation, scale, rotation and shear of the interrogation areas. The six affine transformation parameters are obtained in an iterative manner and converge to the correct solution within a few iterations. The benefit is that not only the velocity is calculated, but in addition the velocity gradients are directly computed without introducing noise, which is an unfortunate by-product of using traditional difference schemes.

Least Squares Matching

The fundamental theorem of Helmholtz states that every infinitesimal motion of a fluid element can be decomposed in translation, rotation and deformation. In the last decades several investigations have been performed to experimentally describe these fluid motions. In classical PIV based on correlation techniques, 2D cross-correlation is most frequently applied to extract the zero order translational velocity components, neglecting the higher order terms of rotation and deformation. The assumption is that the flow field is smooth and not significantly influenced by rotational or shear displacements, thus yielding the zero-order translational displacement field with an additional measurement uncertainty due to neglecting the higher-order terms.

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The measurement uncertainty can be reduced by window deformation techniques, which require manipulation of the raw particle images. The higher-order motion terms are then indirectly estimated on discrete grids by finite difference schemes. The assumption is that the higher order fluid motion of an element is only affected by the translational velocity components of the neighboring elements.

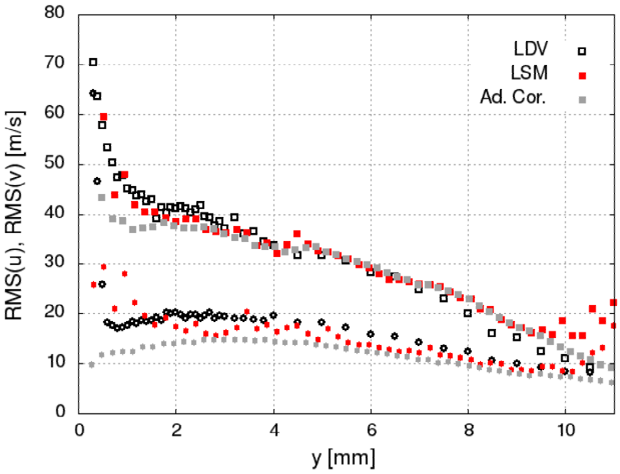
In contrast to correlation based techniques, LSM shifts, rotates and stretches a fluid element. For this purpose, the LSM algorithm iteratively compares gray value information of an interrogation area in the first time step with the gray value information in the second time step. This is an iterative least squares procedure applying a proper transformation on the interrogation areas. In 2D this results in six transformation parameters, and the resulting dis-placement gradient tensor includes parameters like rotation, shear and strain of the interrogation area resulting from the particle displacement within the area.

Application Examples

Turbulence analysis

A Mach number 2.3 turbulent compressible boundary layer is a complex flow for PIV measurements. The main difficulty comes from the seeding: very small particles (typically 1 µm) are needed to ensure their ability in following the flow motions, so that deducing a velocity field from particle images is a challenge in itself.

Until now, Adaptive Correlation algorithms were the only alternative capable of obtaining reliable information on such difficult flows. The figure below shows turbulent velocity profiles measured by PIV and LDA on the same flow. It is shown **with comparable interrogation window size** (*i.e.* 64x32 pixels in this case) the velocity fluctuations obtained via 2D LSM are much closer to the LDA ones than those extracted by Adaptive Correlation. This is more and more visible as



Comparison of turbulent velocity profiles form LDA and PIV. PIV interrogation window 64x32 pixels. (Courtesy of the Supersonic Group of the IUSTI, Marseille).

we get closer to the wall because of the intensity of the velocity gradients: from the wall to 1 mm, the mean velocity goes from null to 350 m/s.

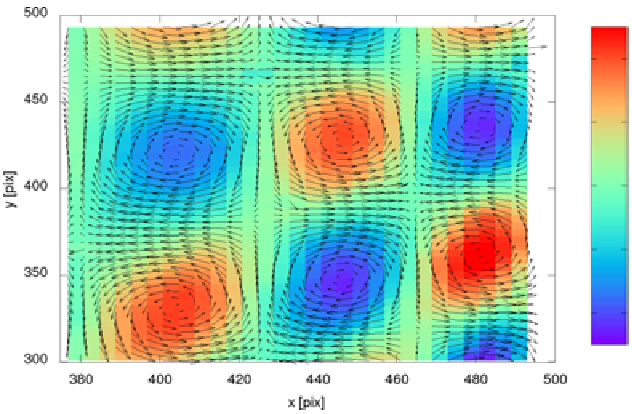
In other words, evaluating rotation and shear in addition the translation, the 2D LSM algorithm gives more reliable results than the Adaptive Correlation in regions of strong velocity gradients.

Identification of Vortices: information about gradients

As mentioned previously, the 2D LSM technique computes directly the flow derivatives and from this information one can compute any kind of vorticity criterion. On the contrary, using Adaptive Correlation technique, the derivatives have to be computed using finite difference schemes which amplifies the noise contained in the data.

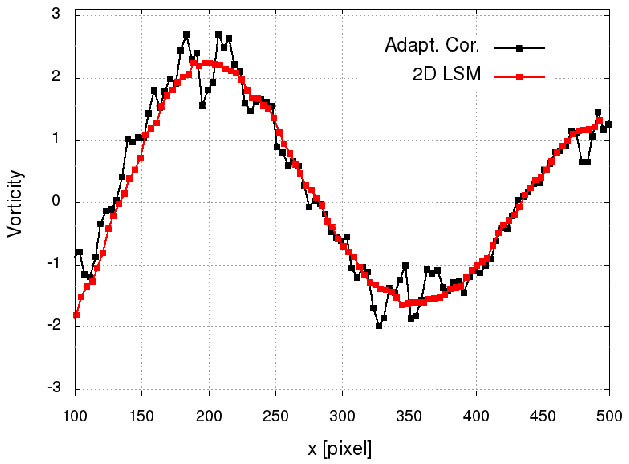
The vorticity (*i.e.*: the curl of the flow), as well as the velocity field, have been computed using synthetic particle images extracted from the initially provided data of the PIV Challenge 2003. The results are plotted on figure below. The accuracy of the 2D LSM in locating the centres of the vortices is obvious on these results.

As it can be seen on this figure, the vortex strength and wave length evolves continuously in the x-direction, and the 2D LSM is perfectly adapted in this kind of situation.



Vector field and Isocontours of vorticity, PIV Challenge 2003.

The next figure shows vorticity profiles obtained using Adaptive Correlation and 2D LSM with comparable parameters. Note that neither of the two results have been post-processed, but it is obvious that the Adaptive Correlation profile is more noisy, which results from the fact that the velocity field has been differentiated afterwards. Hopefully the amplitude of the 2 results is the same, but in some cases this additional noise can lead to errors the location of the center of the vortices.



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Ordering Information

Item	Description
9080S0581	2D PIV Add-on for Dynamic-Studio 2D PIV vector field calculation with the unique and innovative Least Squares Matching method (LSM) for highest velocity accuracy and direct calculation of the velocity gradients, cross correlation, adaptive multi-grid cross correlation and average correlation for PIV. Supports deforming windows and high accuracy calculation. Advanced Graphics functionality included. CUDA based GPU cards are supported.

Related Products

Item	Description
9080S0431	FlexGrid and FlexPIV Add-on for DynamicStudio
9080S0461	Optical Flow and Motion Tracking Add-on for DS
9080S0451	Stereoscopic PIV add-on for DynamicStudio
9080S0291	Volumetric Particle Tracking Add-on for DynamicStudio
9080S0831	DynamicStudio Volumetric Velocimetry Add-on
9080S0571	DynamicStudio Base Package