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## Time-resolved image analysis for turbulent flows

C.J. Kähler<sup>1\*</sup>, C. Cierpka<sup>1</sup>, S. Scharnowski<sup>1</sup>, M. Manhart<sup>2</sup>, A. Sciacchitano<sup>3</sup>, K. Lynch<sup>3</sup>, F. Scarano<sup>3</sup>, B. Wieneke<sup>4</sup>, C. Willert<sup>5</sup>, Y. J. Jeon<sup>6</sup>, L. Chatellier<sup>6</sup>, B. Augereau<sup>6</sup>, B. Tremblais<sup>6</sup>, L. David<sup>6</sup>

<sup>1</sup> Bundeswehr University Munich, Institute for Fluidmechanics and Aerodynamics

\*Christian.Kähler@unibw.de

<sup>2</sup> Technical University Munich, Institute of Hydrodynamics

<sup>3</sup> Technical University Delft, Faculty of Aerospace Engineering

<sup>4</sup> LA Vision GmbH

<sup>5</sup> German Aerospace Center (DLR), Institute of Propulsion Technology

<sup>6</sup> CNRS- Université de Poitiers – ENSMA, Institut Pprime

### ABSTRACT

Classical Particle Image Velocimetry (PIV) uses two representations of the particle image distribution to determine the displacement of the particle image pattern by spatial cross-correlation. The accuracy and the robustness are however limited by the fact that only two representations at  $t$  and  $t + \Delta t$  are present. Thus, only a first order approximation of the velocity can be estimated. To enhance the precision in estimating the flow velocity, multi-pulse or multi-frame techniques were already investigated in the early days of PIV as summarized by Adrian (1991) and Hain and Kähler (2007). Today with the increasing power of high repetition rate lasers and enhanced sensitivity of the digital cameras it is possible to have a time-resolved sampling of even aerodynamically relevant flows, where the particles are much smaller than in water flows. The easiest sampling scheme is the equidistant temporal sampling of the particle distribution such that a robust displacement estimation between successive frames (1+2, 2+3, 3+4, ...) is possible. This so called TR-PIV does not only provide the possibility to follow the evolution of flow structures, but offers the ability to strengthen the data processing by using information from more than two frames (e.g. Hain and Kähler, 2007). Within the AFDAR-project (Advanced Flow Diagnostics for Aeronautical Research funded by the European Union) different approaches to evaluate time-resolved image series were developed by the different groups. The current contribution focuses on the comparison of the algorithms that were developed within the AFDAR project by the partners of the consortium. To verify and validate the performance of the different algorithms a short image sequence of an experiment on the flow over periodic hills (ERCOFTAC test case 81) was provided to all partners and evaluated with the current version of the algorithms.

The pyramid correlation (Sciacchitano et al., 2012) uses correlation functions built with different time separation. In contrast to previous approaches that used a sliding averaging of correlation planes with the same time separation (Scarano and Moore, 2011), or the combination of single correlation planes from different time separations (Hain and Kähler, 2007), the innovative element is the correlation space matching by homothety. This enables the linear combination of the correlation signal obtained at different temporal separation.

Lately, Lynch and Scarano (2013) presented an approach to replace and deform the correlation windows according to the estimate of the trajectory of a fluid parcel. The fundamental aspect of the fluid trajectory correlation, the use of a discretized model for estimating the trajectory of a fluid parcel across the sequence, allows the nonlinear motion to be tracked and reduces bias errors due to streamline curvature.

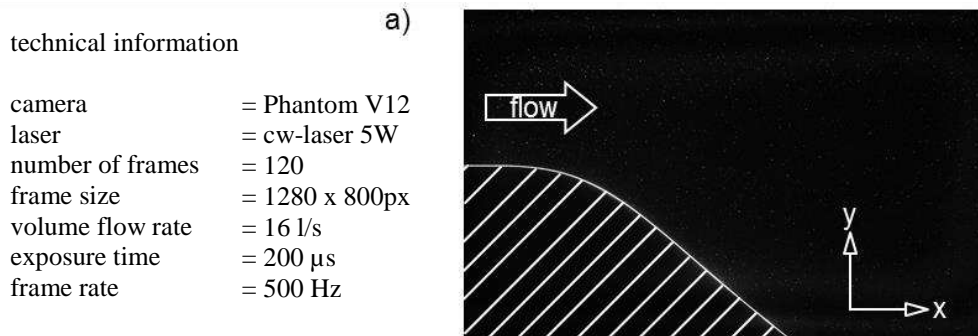
Other approaches developed by DLR cologne include the Gaussian weighted averaging of the intermediate data sets obtained by the correlation analysis. The correlation is performed as a first step on image pairs or image triplets (triple correlation algorithm). The philosophy of the algorithms is to be both computationally efficient and as well as easy to implement.

Correlation methods are largely considered as the more accurate methods for the evaluation of velocity fields in experimental fluids dynamic. Concurrently, various attempts have been made to use optical flow (OF) methods by the Université de Poitiers. Widely used in other scientific domains, OF methods generally suffer in the scope of fluids dynamic of important drawbacks. Among them, the large displacement is one problem and the extreme sensitivity to various noise factors another one. To mainly avoid these drawbacks, the discrete complete bases transform optical flow method was proposed. This method uses a multi-scale and multi-resolution transformation of the original data.

Particle tracking schemes have some advantages in terms of resolution (Kähler et al., 2012) but require usually high signal-to-noise ratios and low seeding concentrations. Taking the information of four consecutive frames (four-frame particle tracking) allows for a fit of the particles trajectory. The vector position and length can be estimated by this trajectory, which was shown to reduce both bias errors in the case of trajectory curvature and random errors in general (Cierpka et al., 2013).

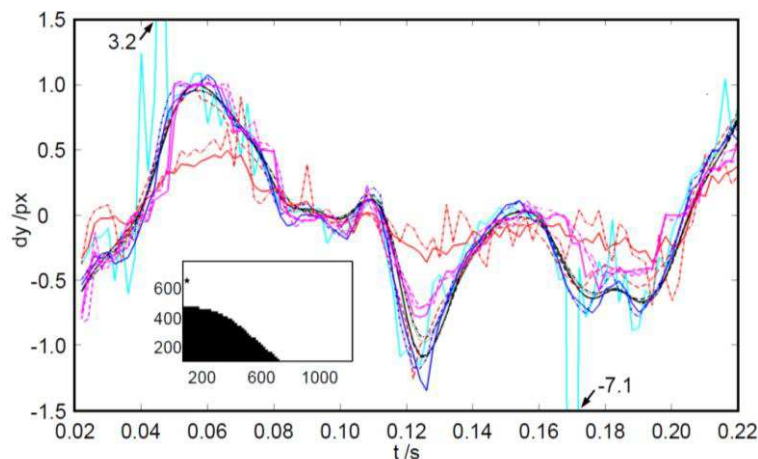
For the comparison of all evaluation approaches a common data set was provided. This data set contained 120 single frame particle images from the measurements of a downstream region (cmp. Fig.1) of the periodic hills experiment at

the Technical University Munich (Rapp and Manhart, 2011). The data set is very challenging, since the particle images are small in general and the flow is strongly three-dimensional in that region and the out-of-plane velocity causes a loss of particle image pairs. A common grid size for the comparison was provided and special emphasis was on the temporal evolution of the velocity. Finally, the mean values, the fluctuating components and the amount of peak-locking were evaluated and compared.



**Figure 1:** Introduction to the data set, a) scheme of the measurement area

The differences for the developed algorithms can already be seen in the time averaged velocity and fluctuation fields. However, of special interest in the current investigation is the temporal evolution of the flow. In Fig. 2 the displacement in y-direction at a position above the hill top is shown for all algorithms for the whole time period provided. As can be seen the results of some algorithms show much higher fluctuations than others. The differences at some time instances are 1 pixel and above, which have to be considered as significant. A detailed analysis of the results and the underlying algorithms shows the reasons for these large differences and provide guidelines for the application of either concept for a specific experiment.



**Figure 2:** Particle displacement in y-direction over time at  $x=96$  px and  $y=608$  px.

The presentation aims to first briefly describe the different image evaluation methods and their implementation and experimental requirements. The comparison with standard two-frame methods (for PIV and PTV) shows, that is in any case beneficial to take additional information from other time steps into account. Nevertheless, this first comparison of the algorithms on the basis of this common test case in the current state of development uncovers differences of the individual algorithms that arise due to the different approaches applied.

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