Uncertainty quantification for particle image velocimetry: prospections in postprocessing

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Resumo: Apresentamos uma breve revisão sobre as principais fontes de incerteza na velocimetria por imagem de partículas, destacando algumas das metodologias disponíveis para sua quantificação. Adicionalmente, chamamos a atenção para o potencial de algumas técnicas matemáticas, oriundas da mecânica geométrica e teoria do controle, que podem ser de interesse para a comunidade de Quantificação de Incertezas (UQ) para fluidos.

Palavras-chave: velocimetria por imagem de partículas, quantificação de incertezas, estatística em variedades, mecânica geométrica.

Abstract: We present a short review on main sources of uncertainty in particle image velocimetry and available methodologies for its quantification. In addition we call attention to the potential of some mathematical techniques, coming from the area of geometric mechanics and control, that could interest the fluids UQ community.

Keywords: particle image velocimetry, uncertainty quantification, statistics on manifolds, geometric mechanics and control.

"We must measure what is measurable and make measurable what cannot be measured" (Galileo)

1. INTRODUCTION: 1984-1985

One could date the birth of particle image velocimetry (PIV) around 1984-1985, when several groups, notably in Germany (Oldenburg and Gottingen) began to photograph the scattering of light off particles seeded in the fluid, illuminated by a laser sheet.

From a pair of pictures taken on a short time interval, the velocity components of particle motion in the plane of the sheet were obtained.

Ronald Adrian, one of the most influential PIV researchers, actually mentions earlier work in 1917-1918 [1]. His bibliography up to 2009 is available in the web site of the meeting held in Gottingen to commemorate the 25th year of PIV, http://25-years-piv.dlr.de.

1.1 Thirty years after.

PIV is presently a mature experimental technique. It is a widely used tool for the study of gas and liquid flows due to its noninvasive, global nature. Applications of PIV range from high Reynolds number flows in aerodynamics to low and mid Reynolds in biofluidynamics; from multiphase to non-Newtonian; from turbomachinery and aeronautics flows to medical microfluidics.

For recent trends and literature in we refer to the review by Westerweel et al, [2]. Symposia on PIV are held regularly, for instance the conference series which is now in its 11th edition http://www.piv2015.org (September, 2015, two months after this assessment was submitted). A whole section will be devoted to PIV accuracy and uncertainty quantification.

The purpose of this assessment is modest: we review some of the work on UQ since 2011 done by the PIV community. In the last section we outline, rather prospectively, a few mathematical techniques that could be potentially useful to address some of the uncertainty sources in PIV postprocessing.

1.2. Sources of uncertainty.

From the metrological perspective, PIV is still in its infancy. Uncertainty sources galore: in *processing*, they come from illumination, camera positioning and data recording. Seeding requires a mix of "art and science" and it is impossible to make it reproducible.

Moreover, *postprocessing* has an "original sin": the estimated velocity at a image pixel comes from statistical correlations of a group of nearby particles motion. In addition, most commercial softwares extrapolate measurements to non-seeded areas in ways not detailed in the manuals.

Seeds, being material particles, do not move precisely along the flow. There is a transversal component, due to several physical effects [3]. This is a serious issue specially for particle tracking velocimetry.

2. REVIEW OF UQ EFFORTS IN PARTICLE IMAGE VELOCIMETRY

2.1. The 2011 meeting in Las Vegas

Probably the first concerted attempt to discuss UQ in PIV was the meeting held in May 11-13, 2011, Las Vegas, organized by Barton Smith (Utah State) and Pavlos Vlachos (Virginia Tech). The web site [4] contains slides/notes of fifteen presentations on uncertainty quantification for PIV and a short course by Coleman and Steele about their UQ book [5].

We now summarize some of the aspects discussed in that meeting, aimed to "establish the foundations for developing a comprehensive PIV uncertainty estimation methodology".

The determination of the measurements accuracy with PIV was the main discussion topic in this meeting. The uncertainty sources analysis have been approached in numerous speeches. The Ronald J. Adrian presentation described an attempt to develop a systematic framework for the development and application of the analysis schemes for detections of the uncertainty sources on experiments with PIV [1]. The following presentations have described studies with different methods to detect the uncertainty sources. As such, experiments with complementary measurements, the use of CFD solutions for verification and evaluation of the auto-correlation used in postprocessing. Hence, this event shows the need of more investigations in this research field.

2.2. Measurement Science and Technology

MST recent issue 25:8 ([6], 2014) contains a whole section devoted to current developments in particle image velocimetry. Besides the focus on characterizing uncertainties sources, hardware and system reliability were also discussed.

More questions were posed than answers: in fact, new challenges for UQ are coming from recent experimental techniques, such as tomographic PIV. For instance, an artifact that haunts experimentalists are so called "ghost particles". Curiously, these are easier to detect and eliminate in time resolved image sequences.

As for hardware, the uncertainties of CCD and CMOS sensors (charge-coupled devices and complementary metal-oxide semiconductors) were addressed in the article by Abdelsalam et al, specially how individual pixels behave.

From the quantitative perspective, an exciting development in this MST issue and other recent sources is the possibility to estimate dynamic quantities (accelerations, pressures) from the velocity measurement. These questions may give rise to interesting mathematical developments.

2.3. Towards an automatized UQ for PIV

As far as we know, only one research group, that leaded by Barton L. Smith in Utah has already proposed a thorough methodology for UQ in PIV [7,8]. Their work could serve as a departure point for further advances, leading to metrologically standardized procedures as advocated in GUM.

The Timmins master's thesis describes a method to estimate the PIV uncertainty [7]. Initially, the relationshop between error sourcer and their velocity mesurements is investigated. Once choice the error source an "uncertainty surface" is provided for the PIV algorithm used. After PIV processing, it's possible to mesure the value of each of these parameters and estimate the uncertainty of each vector. This methodology was described to be general and adapted to any PIV analysis.

3. MATHEMATICAL TOOLS

3.1. Probabilistic Methods

We mentioned that seeding is not reproducible, but this does not prevent metrologists to think of a fluid flow measurement as a realization from a probabilistic ensemble of admissible initial conditions. In that sense, the practical need of doing repeated PIV recordings becomes an experimental feature.

We refer to [9,10] for data assimilation in fluids. Spectral methods are currently the state of the art.

We finish this brief report presenting two prospective mathematical techniques coming from geometric mechanics and control.

3.*2. Observers.*

Observer theory gives life to Galileo's motto that opens our assessment. It is well now in geometric control [11]. It allows estimating parameters and dynamic variables not directly measurable in an experiment.

The observer ODE or PDE adds artificial terms to the model equation so that it converges exponentially fast to a desired trajectory. Observed measurements y(t) are fed into the observer equation. The desired quantities appear in the output x(t), which is "best" fit in a Bayesian philosophy.

In metrology the observer method it is not widely disseminated. We believe it will be, since GUM is moving towards the Bayesian statistics. The only reference we found is Rohm [12], where he describes it as a "model-based measurement".

Observer theory has been already used for fluids [13,14]. Its use in PIV was advocated by Rouchon [15,16].

3.*3. "Jetlets".*

In a nutshell, a k-jetlet is a local kth degree polynomial that approximates the flow near a particle.

Exact solutions of regularized Euler equations can be constructed from a finite set of particles, which follow the corresponding flow field. This flow is automatically volume preserving and can explicitly be numerically simulated [17,18].

For metrology, jetlets could become a novel way to reconstruct the velocity field from a finite set of measurements of seed positions and velocities.

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