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Particle Image Velocimetry near Interfaces: A Moving Future

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Particle Image Velocimetry (PIV) has become a standardized measurement technique in the field of experimental research both in academic and industrial environments with applications covering the breadth of fluid dynamics. The metrology's success must be ascribed to its non-intrusive nature together with its intrinsic simplicity and ability to retrieve vast amounts of instantaneous spatial velocity information (order of giga- to terabytes) relative to the short operation time (order of seconds). While the majority of PIV image processing related studies have been aimed so far at improving the accuracy of the fluid velocities extraction, PIV image analysis involving arbitrarily moving bodies has received limited to no attention. Notwithstanding, it is expected that great advances can be made in the field of fluid-structure interactions by improving the technique's measurement capabilities as a direct result of enhanced image analyses.

Interfaces are encountered in many engineering applications. Flow over moving or stationary rigid surfaces (boundary layers, turbomachinery, aerofoils), deformable surfaces (pulmonary and arterial flows, morphing wings, flexing membranes), interfacial/multi-phase flows (bubbles, waves, free surface turbulence) are all examples of fluid-structure-related problems where the primary concerns are either the transport of momentum across or near the surface, the interactive coupling between fluid motion and surface deformation, or both. Although Computational Fluid Dynamics (CFD) has made considerable progress over the last decades, the inherent modelling of the fluid-structure interactions remains at the forefront of CFD development necessitating high resolution and reliable experimental verification.

From both an experimental and image analysis point of view, it is considered a worldwide challenge to obtain reliable, accurate PIV velocity measurements with sufficient resolution near dynamic surfaces. This fundamental limitation of PIV has driven typical experiments to be restricted to fields of view, free of interfaces or other boundaries. The inhibition to characterize the coupling between boundary motion and fluid forces consequently hampers a proper understanding of the underlying physics. This presents a very stringent limitation in the study of aero- or hydro-elastic effects. Being scientifically important, future PIV development should therefore drive towards ameliorating the measurement capability close to dynamic interfaces in spite of the accompanying difficulties.

Particle Image Velocimetry allows the measurement of flow velocity of air or water by injecting microseed particles. Being illuminated, these tracer particles reflect the light which is recorded by a specialised camera. A spatial section of the investigated flow is illuminated at two sequential time instances. High-energy light sources, typically lasers, are capable of light pulse durations in the order of nano-seconds and ensure sharp tracer images. Comparison of the two image recordings then enables the calculation of the displacement of the particles' images and thus the 2D (or 3D depending on the camera arrangement) velocity components of the flow in which they are transported. Nowadays, the acronym PIV embodies a collection of imaging methodologies but all are based on the original operational principle.

The PIV image processing problem essentially involves detection and tracking of particle image patterns between consecutive recordings and is typically initiated by a segmentation of the images into rectangular sections so called as correlation or interrogation windows. Each window must contain a sufficient amount of particle images to constitute a recognizable and traceable pattern yielding a reliable velocity measurement [1]. This criterion enforces a stringent condition on the allowable interrogation window size and ultimately the achievable spatial resolution for a given experimental setup. Corresponding windows in the two snapshots are compared by means of a statistical operator, typically cross-correlation, yielding a map in which the highest peak indicates the most probable tracer displacement. Knowing the time separation between snapshots and the optical magnification, the retrieved displacement field is scaled to return an estimate of the spatial flow velocity distribution.

Velocity fields are extracted by means of evaluating the digital recordings. In consequence, the measurement quality is dependent on recording conditions. Especially near optical interfaces, strong undesirable reflections may occur which have a negative effect on measurement accuracy and robustness. For such reflections to occur in an image, two conditions must be satisfied: a) a gradient in refractive index must be present between the different media; b) the camera positioning is such that reflected and/or refracted light rays impinge on the image sensor. By orienting the camera to coincide with the Brewster angle, surface reflections in multi-phase flows dealing with e.g. free-surface waves can be completely eliminated or minimized [2]. In gas-liquid mixtures however, as a result of the time-dependent spatial locations and varying surface curvatures of the gas bubbles, alteration of the viewing angle is not an option. For such flows, it is a common practice to use fluorescent tracers and dedicated optical filters such that the camera only records the light scattered by the fluorescent particles and (bubble) shadows [3]. In more traditional PIV testing on opaque objects, surface imperfections (material roughness) cause omnidirectional light scattering. A reduction can be achieved by proper camera orientation, yet full elimination of recorded reflections is only possible with mirror surfaces exhibiting specular reflection. Moreover, the viewing angle cannot be guaranteed optimal in case of dynamic surfaces. If rigid body motions are considered, additional surface treatments such as polishing or adding a fluorescent coating may potentially reduce reflections further [4,5].

While the importance of good experimental practice should not be depreciated, reflections can be minimized by manipulation of the experimental setup or conducive image pre-processing [6]

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and limitations imposed by the image interrogation process itself become more stringent. Much research has been devoted the last decades to improving the inherent image processing with the main focus on accuracy and spatial resolution (e.g. [7]). Limitations of the PIV technique have been well documented through many gatherings among the community of PIV users e.g. [8] and general consensus has been reached in defining what constitutes PIV image processing good-practice. Nevertheless, interfaces tend to remain problematic.

Interrogation windows are typically located on the nodes of a regular Cartesian grid and are likely to overlap object boundaries, if present. This automatically reduces the number of particle images captured within the interrogation windows, limiting robustness of velocity measurements near an interface. To counteract this effect, enlarging the correlation windows then again leads to a reduction in spatial resolution. Secondly, object-flow interfaces constitute recognizable structures and will therefore hamper a reliable velocity measurement; the object interface will distort the correlation map to the extent of retrieving completely erroneous velocity vectors. Thirdly, viscosity will lead to a no-slip condition near the interface introducing strong wall-normal velocity gradients. The resolution of typical interrogation windows near the interface is consequently limited due to a bias in displacement towards lower values. For these reasons, interrogation windows should ideally exclude interfaces and be reduced in size to maximize resolution.

While advanced algorithms have been developed to tackle the problematic image analysis near stationary objects [9], the handling of boundaries moving between snapshots proves to be even more intricate. With interfaces moving between image recordings, the correspondence between correlation windows in consecutive snapshots is no longer preserved; correlation windows encapsulating interface sections in the first snapshot do not necessarily do so in the second and vice-versa. The most straightforward solution to negate the influence of moving boundaries is to minimize the recorded motion of the geometry by reducing the time separation between recorded snapshots. However, PIV image interrogation techniques typically yield an error in the order of 0.01 pixels [10]. Accordingly, for a given field of view, reducing the time separation will only result in increasing relative error and uncertainty in obtained flow velocities. Moreover, limiting the maximum particle image displacement reduces the measurable dynamic velocity range. The only option left is thus to resort to dedicated image processing routines and it is exactly here that a high impact can be expected.

PIV image processing algorithms capable of yielding well resolved velocity data in the immediate vicinity of moving geometries are bound to boost current CFD and experimental research. The more in-depth experimental data obtained will simultaneously enhance understanding of the underlying physics governing the fluid-structure interaction and aid further development of numerical techniques/models on the basis of improved validation. In turn, these advances will permit preliminary concept studies of increasingly complex ideas incorporating dynamic surfaces of which morphing blade technology in wind turbine design is but one example. This technology already extends in the next generation of airplane wing design where aerofoil camber is adapted in-flight to optimize performances [11]. The ability to measure near moving objects will increase the progress of analysis of the complex and unsteady flow field inherent to biologically inspired propulsion devices and advanced clinical technologies e.g. cardiovascular flows, pulmonary drug delivery, etc.

With this in mind, the author looks forward to an exciting future of high quality publications in the Journal of Aeronautics & Aerospace Engineering, discussing new discoveries instigated by the enhanced measurement potential of PIV. The Open Access policy of this journal together with the special features offered by OMICS Publishing Group will ensure a quick dissemination of the established research among peers, which can only be conjectured to inspire even more fascinating novel research applications previously thought undoable.

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