Novel ex-situ calibration procedure for Tomographic PIV in a confined environment: application to a single-cylinder optical engine

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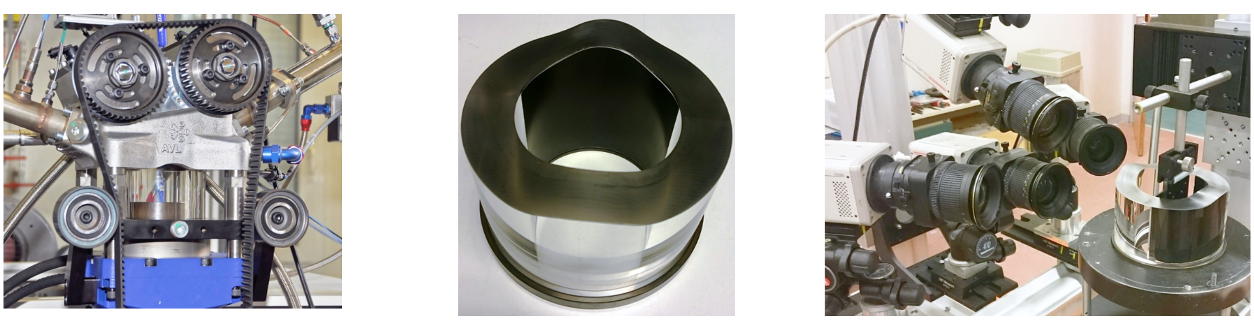
ABSTRACT

For over a decade, Tomographic PIV has been rapidly developing and is now applied in a wide range of domains in fluid mechanics [1]. This progress has been very rapid, especially thanks to the knowledge acquired during the last twenty years in the development of the PIV technique. This 3D optical measurement technique appears to be of high interest in fluid mechanics due to its ability to investigate complex 3D flow structures. However, in many situations relevant to fluid mechanics, its application is complex and inaccurate or even unthought-of without new developments. Among the most critical experiments, we can mention confined configurations where the maximum magnitude of the view angles of the cameras is limited and not optimal for Tomo-PIV reconstruction as well as experiments with local optical index variations induced by flat or curved glass windows [2] and/or by the flow itself [3][4] (combustion, thermal flow). In the present work, the applicability and improvement of the Tomographic PIV technique to investigate in-cylinder flow in a single-cylinder optical engine is addressed. The process can then be applied to other comparable configurations with glass windows. The engine test bench consists in a mono-cylinder GDI engine (AVL) with a displacement volume of 450 cm^3 (Figure 1-a), a compression ratio of 8.5 and a maximum rpm of 3000 rpm in firing conditions. The engine is equipped with a single transparent quartz liner that has an 82 mm bore and an 86 mm stroke (Figure 1-b). In such a configuration, for the Tomo-PIV technique, the two major difficulties are the optical arrangement which has to deal with strong geometrical constraints inducing limited angles of view (columns, timing belt…) and the imaging system viewing through-out a thick curved window producing image distortions and optical aberrations (Figure 1-b). In addition to the previous remarks, the difficulty concerns the calibration step of the investigation volume. Indeed, in-situ calibration is much more complex with the quartz liner than in an opened space, especially to obtain an accurate positioning of the calibration grid in different planes. The camera model has also to take into account the strong image distortions as a function of the 3D coordinate system X/Y/Z.

For the image acquisition part, we developed an original optical arrangement (Figure 1-c) based on four 12 bits Hamamatsu cameras (C9300 - 4M pixels) equipped with PC-E Micro NIKKOR (45mm f/2.8D) lenses with perspective control including both tilt and shift corrections. With this configuration in place, the X/Y dimension of the investigation domain images the whole cross-section of in-cylinder volume with four independent angles of views ranging between 20° and 30°. The experiment was optimised using shift and translation settings to maximise the angles and the field of view without introducing optical blocking from external parts of the engine. Compared to previous optical arrangement proposed in the literature [2], our approach improves the volumetric reconstruction from four fully independent angles of view.

For the calibration, our objective in this work is to transpose a multiplanes 3D calibration done without the quartz liner onto the configuration with the liner presence, using like in classic PIV, only a single fixed view of the calibration target recorded with the glass liner and located at the centre of the investigation volume. Comparison of the middle plane images with and without quartz liner allows us to evaluate the optical distortion introduced by the cylinder and compensate them in the ex-situ calibration model.



(a) (b) (c)

Figure 1 – Experimental set-up: a) single-cylinder optical engine b) Quartz liner c) Tomo-PIV optical arrangement

In order to validate our approach, two complete calibrations were performed with and without quartz liner (Figure 1-c) for a 12 mm volume thickness (25 planes equally spaced of 0.5 mm). The reconstruction of the plane distant 5 mm to the mid-cylinder plane is presented in Figure 2-A. We can clearly see that in the X/Y iso-surface plot, all grid points are in focus and well contrasted and therefore, validating our optical arrangement and reconstruction procedure, even if the grid point signals stretching along the Z component (plane X/Z) shows clearly the effect of the low angles of view. The same reconstruction is performed based on raw images recorded in the presence of the cylinder (Figure 2-B). The grid points contrast is notably lower than in the case A). The effect of the optical deformation is observed in the X/Z slice where the focal point is oscillating along the real grid positioning. This effect can be corrected using a higher order camera model [2]. In Figure 2-C, we propose another corrective approach based on the evaluation of the optical deformation obtained from only the central grid image of the investigation volume. In this approach, all in-cylinder raw images were corrected with a 5^{th} order 2D polynomial function before the calibration and reconstruction procedures. Figure 2-C shows that our approach compensates optical deformations (grid points well-focused and no-oscillating in X/Z plan) with a high computational efficiency using simple camera models (Soloff) and a single step image deformation that is easy to process in a parallel computing. The main drawback of this approach is the necessity of an in-situ recording of the calibration target at different depth positions. The proposed methodology consists on associating an *ex-situ* calibration (without cylinder – Case A) to an image deformation model deduced from the comparison of one single plane of the calibration target (Z=0mm in our case) recorded with and without cylinder. Next, all in-cylinder images are corrected from that deformation model. The reconstruction of grid image at Z=5mm recorded with cylinder from that approach is shown in Figure 2-D. The image target is well-contrasted but less than in case A) which indicates a satisfying reconstruction. The loss of contrast in plane Z=5mm is due to a small shift in depth of the signal focusing (See X/Z plan: 0.1 mm) but that defect, less pronounced for the planes closer to the volume centre, will be fully compensated from the final self-calibration step to be performed with low density particle images recorded with cylinder. It can be noted that our approach has the advantage of excluding in-situ calibration, while compensating in the same way all the effect of the optical deformations observed in a full conventional in-situ calibration (Figure 2-B).

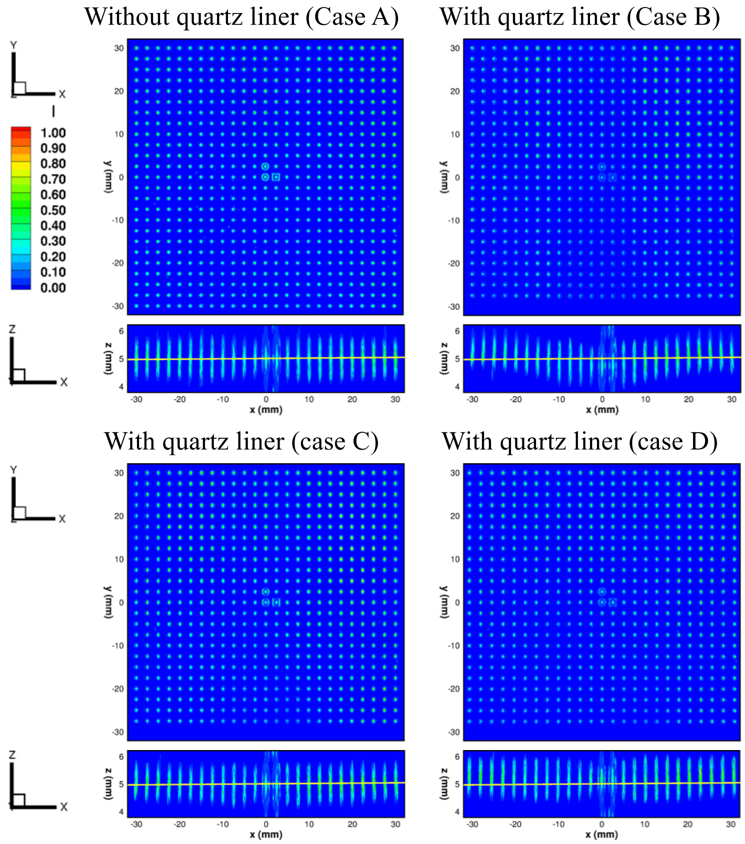


Figure 2 – Reconstruction of the calibration target at 5 mm (Soloff camera model and MinLOS-BIMART using VIVE3D software [5]) A) Without cylinder; B) Full in-cylinder calibration and raw images; C) Full in-cylinder corrected calibration images; D) Calibration without cylinder and corrected images.

In this work, an original optical arrangement for Tomographic PIV technique adapted to a confined environment with limited optical access like a single-cylinder optical engine is proposed. Our recording system is associated with a volumetric *ex-situ* calibration procedure performed without quartz liner and based on a simple evaluation of optical deformations from a single calibration target recorded with and without quartz liner. Our approach is successfully compared to the usual *in-situ* calibration procedure which is much more complex to perform in a confined volume in presence of glass windows.

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