

Three-Dimensional Three-Component Air Flow Visualization in a Steady-State Engine Flow Bench Using a Plenoptic Camera

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ABSTRACT

Plenoptic particle tracking velocimetry (PTV) shows great potential for three-dimensional, three-component (3D3C) flow measurement with a simple single-camera setup. It is therefore especially promising for applications in systems with limited optical access, such as internal combustion engines. The 3D visualization of a plenoptic imaging system is achieved by inserting a micro-lens array directly anterior to the camera sensor. The depth is calculated from reconstruction of the resulting multi-angle view sub-images. With the present study, we demonstrate the application of a plenoptic system for 3D3C PTV measurement of engine-like air flow in a steady-state engine flow bench. This system consists of a plenoptic camera and a dual-cavity pulsed laser. The accuracy of the plenoptic PTV system was assessed using a dot target moved by a known displacement between two PTV frames. In this manner, the PTV accuracy at different seeding densities, particle displacements for lateral and depth directions, and different depth planes was evaluated. Then, 3D3C PTV was conducted on a steady-state engine flow bench at two different flow conditions; one with strong tumble, the other with a combination of tumble and swirl. Silicone oil droplets were seeded into the air flows and were illuminated by the volume-expanded laser beam. Mie scattering from the droplets was recorded by the plenoptic camera running in double-frame mode. A sequence of double-frame images was required to produce an averaged 3D velocity field. The 3D3C velocity fields for both flow conditions are clearly captured, demonstrating the plenoptic 3D PTV technique as a feasible tool to investigate the complex 3D engine flow.

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INTRODUCTION

In-cylinder air flow is an important mechanism that controls the fuel-air mixing, heat-transfer and combustion process in internal combustion engines [1, 2]. The in-cylinder air flow structure, especially the flow during the intake stroke, is mainly determined by the geometry of the engine cylinder head and the intake system, i.e. intake ports, intake valves, etc. Nowadays, engine designers are still focusing on optimizing the intake air design to create organized flows, which can produce an efficient air induction and enhancing the air-fuel mixing and turbulence for flame growth and complete combustion. For example, locating the intake valves' offset from the axis of the cylinder generates organized tumble flow, which is defined as the coherent flow structure rotating orthogonally to the engine cylinder axis. The tumble structure usually lasts until late in the compression stroke, and then breaks up into small-scale turbulence as the piston moves upward [3]. This way, the turbulence intensity is amplified during ignition and combustion process, resulting in faster flame speeds.

The steady-state flow testing of engine cylinder heads is a widely employed procedure to assist the design of intake ports, cylinder head geometry, etc. Steady state flow bench testing is commonly used to measure the swirl ratio, tumble ratio, and global discharge coefficients [4]. An optically accessible steady state flow bench [5] was developed, and particle image velocimetry (PIV) allowed

non-intrusive in-cylinder flow visualization to provide the spatial flow structure information. Hartmann et al. [6] conducted high spatial and temporal resolution PIV measurement in the vicinity of the valve on an steady-state flow bench, and compared results with numerical simulations. They showed that the flow through the intake valve is unsteady with implications on the air jet entering the combustion chamber. Imberdis et al. [7] investigated the temporal development of the in-cylinder flow in a production cylinder-head in a steady-state configuration using stereoscopic PIV, which provides two-dimensional, three-component (2D3C) velocity measurements of the flow. However, they concluded that the 2D3C flow fields are not enough to validate simulations, because the 2D measurement cannot resolve the velocity gradients along the third dimension.

Engine in-cylinder flow is a complex 3D phenomenon with strong cycle-to-cycle variations [3, 8, 9, 10, 11]. Even 2D2C and 2D3C PIV are now standard techniques that can provide accurate flow visualization, but extending to 3D3C flow measurement remains as a challenge. Different 3D techniques are being developed for engine flow applications. Konrath et al. [12] attempted to resolve the 3D flow in an optical engine by holographic PIV (HPIV), but the system was very sensitive to beam alignment errors and hence the measurement was limited to a plane. 3D scanning PIV [13] offers velocity fields in multiple parallel planes using a rapid scanning light-sheet, which samples the flow in the depth direction. However,

scanning PIV is not rapid enough to capture the highly transient dynamic in-cylinder flow. Peterson et al. [14] demonstrated a 3D single-camera tomographic particle tracking velocimetry concept and showed applications in an engine within a smaller measurement volume. Baum et al. [15] conducted 3D velocity measurements in a motored optical engine using a four-camera tomographic PIV system. Typically, 3D measurement techniques have been impeded by the impracticality of arranging multiple cameras within a limited space around an optical engine, or by the complexity and expense of the multi-camera imaging systems. An easy-to-use single-camera 3D3C velocity measurement technique is therefore of great interest to research and practical engine development.

In this context, 3D3C velocity measurements with a single plenoptic camera are finding their way into engine research. The concept of plenoptic cameras was proposed a century ago by Lippmann [16]. The basic idea is to insert a micro-lens array (MLA) between the camera sensor and main lens. The main lens creates an intermediate image in front of the MLA, then each micro-lens acts as a 'camera' to image a subset of the intermediate image from a unique perspective onto the sensor. This approach allows depth reconstruction to obtain a 3D image of the photographed scene. The depth is estimated based on the disparities at the micro-lens images, which is like stereo approaches, but from several angles. Only recently, the increased computing power and advances in camera and MLA production have made the application of plenoptic cameras simpler. Ng et al. [17] demonstrated the 3D capability of a hand-held plenoptic camera by a modification of an existing digital camera. Commercial systems are now available as well [18, 19, 20, 21]. Greene and Sick [22] employed a plenoptic camera to volumetrically resolve the chemiluminescence of simple flames and laser-induced fluorescence from a gas jet. However, current reconstruction algorithms assume that light can only originate from opaque surfaces and thus reconstructed 3D images of translucent objects, such as flames, can include artifacts. Nien et al. [23] investigated a model-based 3D reconstruction algorithm with the purpose of solving this problem. In addition, it was demonstrated that the plenoptic imaging technique is a viable and unique tool to investigate the complex 3D fuel-spray structure in an optical spark-ignition direct-injection (SIDI) engine [24, 25]. For those conditions, the density of fuel droplets is high enough to allow reconstruction using the assumption of opaque surfaces.

A plenoptic camera also has potential use in measuring the flow in 3D3C manner with a simple compact setup [26]. Kyle et al. [27] introduced the concept of plenoptic 3D PIV based on volume illumination and plenoptic imaging. In their study, the developed 3D rendering and PIV algorithm were tested using simulated uniform and vortex flows. Fahringer et al. [28] described the unique implementation of the multiplicative algebraic reconstruction technique (MART) in the context of plenoptic particle image data for 3D3C PIV measurements. In that study, plenoptic PIV was conducted in the wake of a low Reynolds number circular cylinder flow in a wind tunnel and compared with conventional 2D2C PIV. They showed that single-camera plenoptic PIV is a viable 3D3C

velocimetry technique. Recently, with the aim of reducing the computational cost, they developed another 3D reconstruction algorithm based on computational re-focusing with a filter to remove out-of-focus particles [29]. Their preliminary results demonstrated the filtered refocusing algorithm performs as well as MART in terms of recognizing the particle position, but produced more elongated particles. Shi et al. [30] performed a comprehensive parametric simulation study on the key camera design features that affect the performance of a plenoptic camera for 3D3C velocity measurement. They found that hexagonal micro-lenses perform better than square micro-lenses in terms of resolution and 3D reconstruction quality. The other key parameter is pixel to micro-lens ratio (PMR), which affects lateral and depth resolution, and high PMR does not necessarily result in better 3D reconstruction quality.

Plenoptic 1.0 cameras were employed in these pioneering PIV studies. In plenoptic 1.0 cameras, the MLA is placed one focal length away from the camera sensor. The major drawback is that spatial resolution is sacrificed for angular resolution. The spatial resolution of the light field measurement is characterized by the micro-lens pitch, while the angular resolution is determined by the number of pixels located behind each micro-lens. In [27, 28, 31], the lateral resolution is 290×194 pixels even with a 16-megapixel camera. Since the lateral resolution is determined by the micro-lens pitch, even with the highest resolution PIV camera sensor (8880×5304 pixel, KAI-47051 CCD sensor) that is currently available, the lateral resolution is only approximately 523×312 . For many applications, this is a substantial restriction.

The need to improve the spatial resolution led to the development of plenoptic 2.0 cameras, i.e. so-called 'focused' plenoptic cameras [32]. This camera is realized by placing the MLA further than one focal length away from the camera sensor to relay-image an intermediate image created by the front lens. In this fashion, a plenoptic 2.0 camera captures dense spatial information; however, it does so at the cost of angular information. The spatial resolution of the plenoptic 2.0 camera is significantly higher than the number of micro-lenses used. Approximately 1-megapixel effective resolution was realized with a 16-megapixel camera sensor. The introduction of the multi-focus plenoptic cameras (MFPC), in which the MLA consists of micro-lenses with three different focal lengths [18] has been shown to increase the depth-of-field compared with single focus plenoptic cameras, and the effective lateral resolution can reach approximately a quarter of the camera sensor resolution.

In the current study, a multi-focus plenoptic 2.0 camera, with effective spatial resolution of 7 megapixels, is used to measure the 3D3C velocity of in-cylinder flow in an optical steady-state engine flow bench. A four-valve single-cylinder SIDI engine head is utilized in the steady-state flow bench. Opening both intake valves, or only opening one intake valve, created two different intake flow structures; one with strong tumble, the other with a combination of tumble and swirl. These two flow structures were measured by the plenoptic 3D PTV to demonstrate the feasibility of this technique for automotive steady-flow bench applications.

PLENOPTIC 3D PARTICLE TRACKING VELOCIMETRY

Figure 1 depicts the fundamental principle of plenoptic 3D particle tracking velocimetry (PTV) using a plenoptic 2.0 camera. The main lens creates a real image of the particle in front of the MLA. Several micro-lenses re-image the same particle image, each at slightly different perspective, which then allows for depth determination. Figure 1a shows a sub-region of the raw plenoptic image, where the same object particle is imaged by 14 neighboring micro-lenses. The circles in Fig. 1a illustrate the micro-lenses with three different focal lengths, which are represented by red, green and blue circles. As seen in Fig. 1a, the same single particle appears at different locations in the micro-images since each micro-lens has a different perspective of the same particle. Then, a correlation algorithm is used to identify the particle position in each micro-image. Additionally, with the known geometry and orientation of the micro-lenses the depth position of this particle can be computed. The high redundancy of the 14 micro-images offers the possibility of achieving robust 3D computation despite the limited angular coverage, determined by the f-number of the front lens.

After determining the 3D position of the particles, a particle tracking algorithm can be used to identify the matching particle images between two PTV frames. The current PTV algorithm (RxLive 3.1, Raytrix GmbH) employs a minimal movement constraint to find the matching particle in two PTV frames. Then, the 3D positions of the matching particle in two frames are utilized to calculate the 3D3C displacement. To ensure the performance of the tracking algorithm, a short time interval between two frames to ensure small displacements and low seeding density are required. Finally, the local 3D3C velocity vector is obtained based on the 3D3C displacement and the time interval between the two frames.

The plenoptic 3D PTV system consists of a double-exposure plenoptic camera and a dual-cavity PIV laser (Litron Nano T120-15, 120 mJ/pulse). A 29-megapixel color plenoptic camera (R29, Raytrix GmbH) was utilized in this study. However, due to the 3D reconstruction procedure, the effective resolution is reduced to about 7 megapixels. The micro-images created by the neighboring micro-lenses should just touch but not overlap to make best use of the camera sensor. To this end, the f-number, $f_{\#}$, of the main lens should be matched with the micro-lens, which is fixed when the MLA is designed. In this study, $f_{\#} = 8$ must be used for the main lens.

Several calibration steps are necessary each time either the focus or aperture setting is changed. As the first step, the MLA geometry calibration must be performed. This creates a calibration grid with the micro-lens images using a homogeneous illumination. Then, a spatial calibration determines the 3D physical dimensions by recording a sequence of target images at different orientations. The calibration target is positioned at an oblique angle to the camera axis with the aim of covering the entire desired depth-of-field. After these two steps, the camera is fully calibrated for a given focal length and aperture setting.

To evaluate the accuracy of the 3D reconstruction of the plenoptic camera, a simple setup was developed as shown in Figure 2. A dot array target of known dimensions was placed at an angle of approximately 60° with respect to the table surface. This geometric arrangement creates a dot array that covers a depth range of about 25 mm within the camera's field-of-view. As the target is black dots on white background, the inverse of the intensity signal is utilized, and each dot stands for a representative particle in the PTV measurement. The plenoptic image is processed using RxFlow 3.1 to determine the particle coordinates in 3D as shown in Figure 3. To assess the ability to determine the depth position, the y and z coordinates for these dots are plotted in Figure 4. A linear fit was performed and the uncertainty of the slope and intercept of the linear fit was estimated using the least square fit, showing that the angle between target and table surface is $57.7^\circ \pm 0.1^\circ$, which is about 3% different than the geometrically determined angle. Note that the camera was aligned parallel to the optical table as best as possible but an accurate measure of whether the sensor array is perfectly vertical to the table surface is not possible. The observed discrepancy in the angle can easily be caused by any imperfection in placing the target or camera and is not solely (or at all!) caused by inaccuracies of the 3D positioning algorithm.

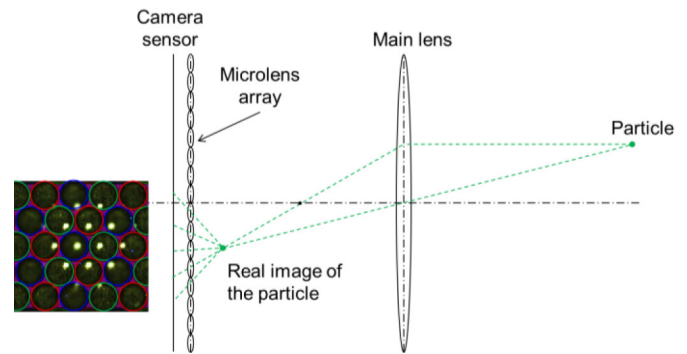


Figure 1. Principle of plenoptic 3D PTV.

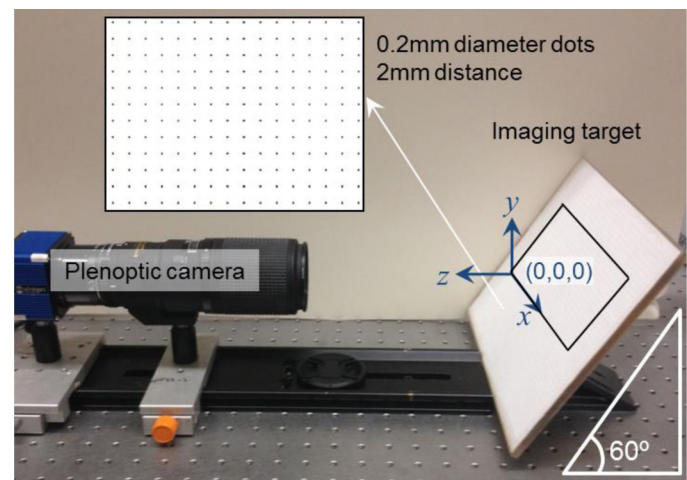


Figure 2. A demonstration case.

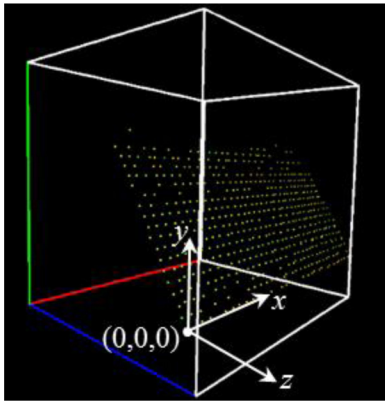


Figure 3. 3D particle distribution recognized by the plenoptic camera.

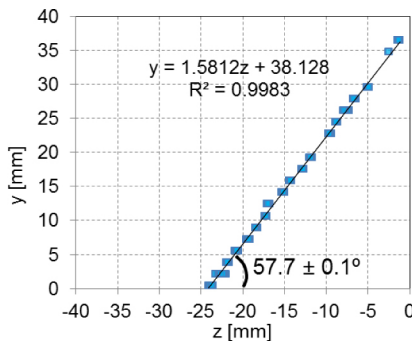


Figure 4. The angle of the dots target obtained from the reconstructed 3D particle positions.

ASSESSING PLENOPTIC PTV

After ensuring the 3D position of particles can be accurately determined, the next step is to assess the accuracy of the PTV algorithm in RxFlow 3.1. The accuracy of the plenoptic 3D PTV was assessed experimentally as shown in Figure 5. A printed target with randomly distributed white dots with diameters of 0.5 ± 0.1 mm on black background was used to simulate the particles. The camera was installed on a translation stage (Newport model 401), which allows moving the camera in both lateral (x) and depth (z) directions accurately to simulate particle movement between two images. The micrometer equipped on the translation stage offers $10 \mu\text{m}$ resolution and $1 \mu\text{m}$ the sensitivity. Both PTV frames were taken with homogeneous LED light illumination, and thus a long exposure time (1 second) is used to ensure good signal-to-noise ratio. The double-frame images are the ideal image to test the 3D PTV algorithm. However, note that the particle images are larger in diameter than those obtained from Mie scattering for seed oil droplets in the flow bench. RxFlow 3.1 was used to process the particle images obtained at two translation stage positions, then the 3D3C PTV result was compared with the true displacement. In this manner, the accuracy of the plenoptic 3D PTV system was evaluated at different depth planes, different x and z displacements, and simulated seeding densities.

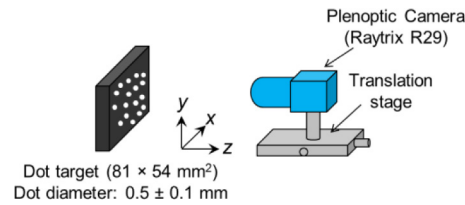


Figure 5. Setup to assess the accuracy of plenoptic PTV.

Plenoptic PTV at Different Depth Planes

In current plenoptic camera settings, the depth-of-field is between 492 mm and 441 mm away from the camera sensor chip. This depth range is obtained by software RxOptics (Raytrix GmbH), and verified by placing a target with the arrangement to cover the whole depth range. Geometrically, the angle from which the micro-lenses image particles is different for particles with different distances from the camera. Particles in near field are imaged from a bigger angle than these in far field, and this larger angle is beneficial for the 3D reconstruction. Hence, the accuracy of plenoptic PTV at different depth planes is different. To assess this accuracy, the camera was placed at five different distances to the target: 492, 483, 474, 465, 456, 447 mm. Then, the camera was moved 0.2 mm at both x and z direction to create the displacement at each distance.

Figure 6 compares the 3D PTV results and the true displacements. The average and standard deviation were obtained from all dots' displacements in one PTV image-pair. On the secondary y -axis in Figure 6b, the percentage of vectors recognized from one image-pair are also included. There are 282 dots in total in the field-of-view of the camera. Ideally, 282 vectors should be obtained. But even for the best case (474 mm plane), only 85 vectors (30.1%) are obtained. This result is due to the following facts. First, to simulate a real PTV test, the dots in the target are not homogeneously distributed. Then the dots' 3D positions in dense regions are difficult to evaluate, because they will be imaged by the same set of micro-lenses and confused with each other. Second, some dots are located in an area such that they appear at the boundary area of the micro image and are rejected by the software. Third, the 3D tracking algorithm employed a minimal movement constraint for particle matching, and thus not all dot-pairs can be matched. Even though the averaged 3D PTV results agree well with the true displacement, the standard deviation for lateral direction (Figure 6a) is much smaller than for the depth direction (Figure 6b). The lower accuracy in determining the depth position (z direction) of a dot compared to that for lateral position (x direction) is responsible for this difference.

Figure 7 depicts the particle micro-images from a single dot at three different depth planes. The large circles (green, red, blue) represent the micro-lenses; each color highlights lenses of a particular focal length. The dots highlighted by small green circles are used for 3D reconstruction; red ones are located too closely to the boundary of micro-images and are rejected for 3D reconstruction.

Several conclusions can be drawn from Figure 6 and Figure 7. First, the 3D PTV results agree well with the true displacement in the middle region within the depth-of-field, about 20 mm from 465 mm to 483 mm. In addition, more vectors can be computed in this region