Three Dimensional Plenoptic PIV Measurements of a Turbulent Boundary Layer Overlying Rough and Permeable Surfaces

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ABSTRACT

A plenoptic camera was used to make three dimensional, three component (3D-3C) measurements on a variety of flow geometries to investigate the effect of roughness and permeability on an overlying turbulent boundary layer. Specifically, this study uses data collected in two experiments: an initial experiment measuring the flow over a single hemispherical roughness element and a secondary experiment measuring the flow over a smooth wall, an impermeable rough wall, and a permeable rough wall. 3D measurements of the single hemispherical roughness element show flow features such as spiraling legs of the shear layer, a recirculation region, and shed arch vortices. The proper orthogonal decomposition (POD) was used to assist in identifying these features, which was applied to the instantaneous velocity and vorticity data. The modes from the vorticity data serve to better identify the direct effect of the hemispherical roughness element on the flow, as opposed to structures already present in the overlying turbulent boundary layer. A distinction between these two structures proved difficult to find with only POD modes from velocity data. This first experiment has shown that plenoptic PIV is a viable technique to making statistically significant volumetric velocity measurements. Preliminary results from the second experiment are shown, limited to instantaneous volumes for each of the flow geometries. These volumes indicate that the same statistical analysis performed on the first experiment promises noteworthy results.

1. Introduction

A multitude of environmental and industrial flow scenarios are characterized by a turbulent boundary layer overlying a permeable surface, termed permeable-wall turbulence. In natural flow systems, permeable-wall turbulence is found in a wide range of scales, spanning from small-scale arterial transport through fibrous plaques during the development of cardiovascular diseases (Khakpour and Vafai 2008) to larger-scale geophysical flow systems such as river beds or forests (Blois, Sambrook Smith, et al. 2012). In engineering and industrial application, porous media are utilized for their large specific surface area, commonly to enhance heat and mass...
transfer. The widespread use includes packed beds for nuclear reactors (Hassan and Dominguez-Ontiveros 2008), fuel cells (Wang, Wang, and Chen 2001), and the geological storage of CO₂ (Golding et al. 2011). Driven by the prevalence of porous beds, many studies have focused on determining theoretical and numerical models of permeable-wall turbulence, however the physics of this phenomena is poorly understood. One of the largest obstacles in developing a better understanding of these flows is the highly 3D nature of the flow, which have largely been studied in 2D. Aided by recent advances in measurement technology, this study has made 3D-3C measurements of permeable-wall turbulence, utilizing a novel coupling of plenoptic PIV and a refractive index matched (RIM) flow facility. The study was divided into two phases, the first focusing on the successful application of plenoptic PIV with the RIM flow facility and the fundamental physics of a singular hemispherical roughness element. The second phase of the study has now measured the flow over an impermeable smooth wall, a impermeable rough wall, and a permeable rough wall. This paper presents results from the first part of this study and preliminary results from the second part of this study.

2. Plenoptic PIV
   a. Background
Driven by the need of 3D measurement systems, researchers have been relentlessly developing volumetric PIV methods including, tomographic PIV, plenoptic PIV, and holographic PIV. Plenoptic PIV is a single camera technique that uses a modified traditional PIV camera, which can capture the light field of a scene. As described by Levoy, a light field constitutes both the spatial and angular information about the light rays in a scene (Levoy 2006). A plenoptic camera was first suggested as a tool to capture the light field by Adelson and Wang (Adelson and Wang 1992) and later realized in a compact form factor by Ng et al. (Ng et al. 2005), who describes the plenoptic camera’s most well-known ability to change the perspective and focal plane of a plenoptic image computationally. The Advanced Flow Diagnostics Laboratory (AFDL) of Auburn University, has been manufacturing and utilizing plenoptic cameras since 2011 (Lynch 2011). For the first phase, the prototype 16 MP plenoptic camera was used. The second phase used the more recently developed 29 MP plenoptic camera.
To create a plenoptic camera, an array of microlenses is placed in between the main lens and image sensor of a traditional PIV camera. The microlens array that was added to the Imperx Bobcat ICL-B6620 (29MP) is shown in the photograph in Fig. 1(a). The array consists of 471×362 microlenses with a pitch of 77 μm and a focal length of 308 μm. For comparison, the prototype camera used a microlens array of 289×193 microlenses with a pitch of 125 μm and a focal length of 500 μm. In Fig. 1(b) the 29MP plenoptic camera is shown next to the small-scale RIM facility.

When capturing a light field, the main lens focuses the light of the scene onto the microlens array, which in turn focuses the light rays onto difference pixels behind each microlens, depending on the incident angle of the light ray. This process illustrates the main trade off with plenoptic imaging: a loss of spatial resolution for angular resolution.

b. Plenoptic PIV

When implemented for PIV, the plenoptic camera is utilized nearly identically to a conventional PIV camera. The only difference lies in how the laser illumination is spread, as volumetric illumination is needed for plenoptic PIV and traditional PIV uses only a sheet. A sample of a plenoptic image from the smooth wall study is shown in Fig. 2. It should be noted that some banding is caused by the aliasing of compressing a 29MP image into a text document. The inset shows a highly magnified region where the sub-aperture images are shown. Each microlens images its unique view of the main aperture onto the image sensor forms each sub-aperture image. The aperture of the main lens has been selected such that each sub-aperture image
touches but does not overlap with the neighboring sub-aperture images, to maximize the information captured about each light field.

![Fig. 2 A raw plenoptic image from the smooth wall experiment, inset shows zoomed in region around a particle and shows sub-aperture images](image)

Before traditional cross-correlation, each plenoptic image needs was reconstructed into a 3D volume. This step was implemented using two different techniques for each of the two phases. For the first phase, the multiplicative arithmetic reconstruction technique (MART) was used. This technique is similar to the reconstruction technique used by tomographic PIV. However, this technique is computationally expensive, driving the researchers at the AFDL to develop a faster algorithm, termed filtered refocusing. A volume is reconstructed using filter refocusing by filtering out-of-focus particles based on relative voxel intensity at many refocused slices through the measurement volume. A comparison and further description of both of these techniques is found in recent publications by the AFDL. (Fahringer, Lynch, and Thurow 2015). After each
A plenoptic image was reconstructed into a volume, an in-house three-dimensional cross-correlation algorithm produced the displacement vectors.

A 3D calibration was performed using a first order model based on the thin lens equation and estimation of the magnification from imaging of a ruled target. This calibration does not account for higher order effects such as pincushion or barrel distortion associated with real, complex lenses. Such a calibration procedure is currently under development by the AFDL. As such, the reconstructed volume is slightly warped compared to the real volume such that the data presented here is considered quasi-quantitative. The visualizations are expected to accurately identify regions of vorticity and the approximate magnitude of the velocity and velocity gradients; however, a direct comparison with other quantitative measurements will require a higher order volume calibration. Using the same 3D calibration method as this study, Fahringer, Lunch, and Thurow (Fahringer, Lynch, and Thurow 2015) report the potential of MART to resolve particle locations to better than 1 voxel in the lateral direction and better than 3 voxels in the depth direction. Errors in particle displacement from a 16×16×16 voxel cross-correlation were estimated to be 0.2 voxels and 1.0 voxels for the lateral and depth directions, respectively. Thus, the absolute accuracy of the plenoptic PIV measurements made here are limited in comparison to conventional PIV, but are considered sufficient for the visualization and identification of large-scale structures based on the 3D velocity and vorticity fields.

3. The Small Scale RIM

The non-intrusive optical approach to experimental investigations of fluid systems has seen widespread use in a variety of scientific disciplines. However, there exist a number of technologically relevant flows that are ill-suited for these optical techniques, limited by the presence of a solid phase with a complex geometry (e.g. flow in porous media, IC engines, geophysical flows, etc.). To mitigate the effect of the solid geometries, a small-scale RIM flow facility was developed at the University of Illinois, Urbana-Champaign (Blois, Christensen, et al. 2012), in which the phase 1 experiments were conducted. A nearly identical small-scale RIM flow facility has been constructed at the University of Notre Dame, where a larger flow facility is being constructed. The phase 2 experiments were conducted at the University of Notre Dame, in the small-scale facility picture in Fig. 3.
The RIM facility is a recirculating tunnel designed to use an aqueous solution of 62.5% sodium iodide (NaI), which has been tailored to have a nearly identical index of refraction to the acrylic models, which can also be seen in the photograph of Fig. 3. The selection of NaI for the working fluid was also based on its similar viscosity to water, allowing for easy comparison to Reynolds numbers in traditional water tunnels.

The tunnel test section is a constant $0.1125 \, \text{m} \times 0.1125 \, \text{m}$, with a movable floor to add a porous layer. This design consideration aims to keep the flow rates relatively the same by not greatly changing the open area of the test section. Additionally, the top cover is removable to allowing the placement of models into the tunnel, although the tunnel is filled such that the test section still has a free surface. The necessity of the top cover is due to the discoloration of the NaI solution when exposed to oxygen, which is avoided by slightly pressurizing the tunnel with N$_2$. A further concern is the variation of the index of refraction of the NaI solution with temperature. Thus, a heat exchanger regulates the temperature of the working fluid within a $\pm 0.05^\circ \text{C}$ window which corresponds to a 0.001% change of index of refraction. This precise matching of index of refraction allows the laser illumination and the particle reflections to travel through the solid.
geometries. Additionally, this allows the field of view to contain the solid geometry, which is particularly useful when measuring the flow in the pore space of the permeable bed.

4. Experimental Arrangement
As previously described, the arrangement for plenoptic PIV closely resembles an experimental arrangement for conventional PIV. The schematic in Fig. 4(a) shows the experimental arrangement for the rough permeable wall in which the free flow was measured. The false bottom of the RIM facility, seen in the photograph in Fig. 3, has been removed and filled with the permeable bed. The illumination was provided by a Quantel EverGreen 200 mJ dual pulsed Nd:YAG laser. The beam has been directed to the top of the tunnel where it is formed into a volume by two cylindrical lenses. The laser volume is reflected into the test section through the top of the tunnel, where it is clipped by a mask along the optical axis of the camera. The hard edge in the depth direction ensures particle images are reconstructed to a definitive volume. The experimental arrangement was similar for each experiment, although both the single hemisphere and the rough impermeable wall were mounted on the back wall of the test section. The detailed schematics of each measurement volume are shown in Fig. 4(b). Also, the illumination for single hemisphere, measured during phase 1, entered from the bottom of the test section. This is because the earlier facility did not have the cavity in the test section for the permeable bed to lie, the bottom of which has a number of screws that obstruct illumination paths.
Fig. 4 (a) Experimental arrangement schematic; (b) Diagrams of the measurement volume for each data set. The smooth wall (top left) was measured over a flat plate the covers the tunnel reservoir. The single hemisphere (top middle) was measured on the side wall of the tunnel. The impermeable rough wall (top right) was measured on the back wall. The permeable rough wall was created in the tunnel reviver and measured in three different regions: the free flow (bottom left), the interface (bottom middle) and the pore space (bottom right).

The impermeable study used three different free stream velocities for each of the different geometries. With the goal of matching the Re (based on momentum thickness) between all of the flow geometries to about 2000. The free stream velocities were 1.024, 0.396, and 0.393 ms$^{-1}$ for the smooth, single roughness, and rough wall, respectively. The permeable rough wall study was divided into three different experiments, labeled by the region of measurement: the free flow, the interface, and the pore space. The free stream velocity was the same as the impermeable rough wall velocity, 0.393 ms$^{-1}$.

In phase 1, 1000 image pairs were recorded. The allowed for a statistical analysis of the flow, primarily through the proper orthogonal decomposition (POD). The reader is referred to *The Springer Handbook of Experimental Fluid Dynamics* (Nobach et al. 2007) for a complete description.
of the decomposition. In phase 2, the number of image pairs was increased to 2500, after encouragement by a 2D PIV study by the authors at the University of Notre Dame, with conditional averaging in mind.

5. Results
   a. Phase 1

A brief summary of the results from phase 1 are presented here, as the detailed report of this experiment is in preparation for the AIAA journal (Johnson et al, in preparation). In Fig. 5(a), the mean flow is shown, depicting a turbulent boundary layer and a recirculation region in the near-wake of the hemispherical element. The stratification of the mean flow clearly indicates the ability of the plenoptic camera to resolve different displacements at different depths, as the optical axis of the camera was along the y axis of the figure. An instantaneous volume is shown in Fig. 5(b), depicting a shed arch vortex. The vortex is slightly slanted and off center, highlighting the asymmetric behavior of the flow. The vortex is identified by an isosurface of vorticity magnitude, which is colored by y vorticity to accentuate the counter rotating legs. The tightly packed streamtraces flow around the legs of the arch vortex and back upstream through the center of the arch vortex.

![Fig. 5](image)

**Fig. 5** (a) Time-averaged mean flow, shown with streamtraces and a contour slice of normalized downstream velocity; (b) An instantaneous volume depicting a shed arch vortex, visualized with streamtraces of downstream normalized velocity and an isosurface of vorticity magnitude, colored by y vorticity to highlight the counter-rotating legs of the structure

The proper orthogonal decomposition was applied to both the velocity and vorticity vectors of
the dataset, resulting in 984 modes (16 instantaneous volumes were discarded because of poor correlation). The POD was performed on vorticity to better separate the effects of the hemispherical roughness element was having on the flow, from the physics of the overlying turbulent boundary layer. The first four vorticity POD modes are shown in Fig. 6. The first mode depicts an extruded arch shape similar to the time-averaged vorticity. This mode is completely concentrated in the near-wake region. The arch shape only extends from 1.4 x/k to 2 x/k, as from 0.6 x/k to 1.4 x/k the shape is connected along the bottom, resembling a donut. The opposing y vorticity fluctuations show two counter-rotating legs in this arched structure. The surface is nearly symmetric along 0 z/k, except for a bulge in the surface at 0 x/k on the –z side and a less defined end of the arched surface on the –z side at 2 x/k. A similar asymmetry is seen on the –z side in the second mode. This mode is largely concentrated in the near-wake region, except for two small isosurfaces in the upper boundary layer. The second mode shows a more defined arch shape compared to the first mode, although it is offset in the +z direction, such that the +y vorticity leg is centered behind the hemisphere. The isosurface shows another leg branching off in the –z direction that is at the upstream end of the volume, representing the flow directly over the hemisphere. Although this mode shows three small isosurfaces in the upper boundary layer, it is largely dominated by near-wake structures. This mode suggests a coupling between the vorticity of the flow directly over the hemisphere to the superposition of the arch vortex. The arched vortex in the third mode is larger than the previous and has a smoother, more regular arch shape. Additionally, the arch vortex is symmetric and centered about 0 z/k. As in the second mode, a similar curved isosurface exists over the –z side of the hemisphere in the third mode. This suggests that the superposition of the arch vortex is not dictated by an increase of vorticity of the flow directly over the hemisphere. The relatively small difference in percent of total enstrophy between the two modes also suggests that the modes are closely related. This superposition of the arch-shaped vortex has been seen in the instantaneous pairs, although the arch vortex is rarely as well-defined as in these modes. Unlike the first three modes, the fourth mode is composed of isosurfaces in the upper boundary layer, which are each dominated by x vorticity (shown on the colorbar). The small structure in the near-wake is largely constituted of z vorticity, possibly representing the top of an arch vortex. This mode represents the motivation of calculating the POD of the vorticity components, as it is possible these structures originate from the incoming turbulent boundary layer and are not directly seeded into the flow by the hemispherical roughness element, whereas the earlier modes are clearly generated by the hemisphere.
Fig. 6 The first four vorticity POD modes shown with vorticity magnitude $\|\omega\|$ isosurfaces at 1.1 which are colored by y vorticity or x vorticity, depending on which is more dominant.
b. Phase 2
The results presented in this section are preliminary, as only a handful of volume pairs have been processed. Thus one instantaneous volume is presented for each of the flow geometries. Before the large data sets are completely processed, the reconstruction parameters and cross-correlation settings will be further optimized. This optimization step will also include the use of a 3D calibration. However, these preliminary results show some expected features of each flow, suggesting that a significant statistical analysis can be conducted with the recorded data.

The impermeable smooth wall is shown in Fig. 7, visualized with streamtraces and a contour slice. The streamtraces are calculated using a two-step Runge-Kutta method with a step size of 0.25 times the vector spacing and were randomly seeded throughout the volume. Both the streamtraces and the contour slice are colored by normalized streamwise velocity. The instantaneous volume shows characteristics of a thin turbulent boundary layer reaching the free stream velocity of about 1 ms$^{-1}$.

Fig. 7 Instantaneous volume of smooth, impermeable wall geometry, visualized with streamtraces and a contour slice of normalized streamwise velocity

Results from the impermeable rough wall are shown in Fig. 8. The volume is visualized again with randomly seeded streamtraces and a contour slice, however, the slice show the normalized wall normal velocity. The streamtraces show a boundary layer-like profile that becomes disrupted below about 0.5 y/k. The contour slice shows a large contiguous region of upward
movement at the upstream end of the volume, as the flow approaches the leading edge of the centered hemispherical element. The leeward side of the centered hemispherical element shows a less contiguous mix of upward and downward motion.

Fig. 8 Instantaneous volume of the rough, impermeable wall, visualized with streamtraces colored by streamwise velocity (upper colorbar) and a contour slice of normalized wall normal velocity (lower colorbar)

The permeable rough wall is shown in the next three figures, beginning with the free flow region shown in Fig. 9. This region is similar to the region of the impermeable rough wall and shows similar trends. Analysis of more instantaneous volumes, specifically a statistical analysis should help identify both injection (flow from pore space to free flow) and suction (flow from free flow into pore space) events. This instantaneous volume does not exclusively show an injection or suction event, although the bottom of the contour slice shows a general downward motion of the flow that may be a precursor or after effect of an event.

In Fig. 10, the interface region is shown. This region is difficult to visualize and this figure represents a first attempt of visualizing the flow between the solid geometry. To provide better visibility, the solid model has been rendered with 90 percent translucency. Unfortunately, the translucency makes it difficult to identify where the streamtraces are traveling between the
individual elements. In this instantaneous volume, the streamtraces are regularly placed. Twenty isosurfaces are placed across the z direction at .2 intervals between 0.4 and 2 y/k. This procedure was implemented at -1 and 1 x/k to better visualize the flow around the centered spherical element. The contour slice is colored with normalized wall normal velocity and includes velocity vectors. From the combination of the slice and streamtraces it is seen that in this instantaneous volume there is a suction event on the upstream side of the centered spherical element, which is characterized by reverse flow. On the leeward side of the centered spherical element a small injection event is taking place, also characterized by reverse flow.

The final region, the pore space, is even more difficult to visualize. As a result, the same instantaneous volume is shown using two views: a side view Fig. 11(a) and a front view Fig. 11(b). A normal contour slice in each is colored by the normalized wall normal velocity. Together the figures depict opposing vertical motion in each of the pore spaces, suggesting that there may be some small recirculation regions formed in the pore spaces.

**Fig. 9** Instantaneous volume of the rough, permeable wall in the free flow region above the roughness, visualized with streamtraces colored by streamwise velocity (upper colorbar) and a contour slice of normalized wall normal velocity (lower colorbar)
Fig. 10 Instantaneous volume of the rough, permeable wall in the interface region between the free flow and the roughness, visualized with streamtraces colored by streamwise velocity (upper colorbar) and a contour slice of normalized wall normal velocity (lower colorbar), the roughness elements have been rendered with transparency to help see through the geometry

Fig. 11 Instantaneous volume of the rough, permeable wall in the pore space region, visualized with a contour slice of normalized wall normal velocity (shared colorbar), shown as the side view (a) and a front view where the flow is out of the page
6. Conclusion

Overall, this study has shown that plenoptic PIV is capable of making statistically significant volumetric measurements to study permeable wall turbulence. This has been confirmed by the results of the phase 1 experiment, which have prompted the experiments of more complex geometries in phase 2. The first phase signifies the first ever pairing of a plenoptic camera and RIM facility, as well as the first extensive application of plenoptic PIV. A statistical analysis was performed on the 986 volumes to provide insight to the physics of the instantaneous flow. A wide variety of flow phenomena were observed, including spiraling legs of the shear layer, heavily perturbed overlying boundary layers, various sizes of recirculation regions and both full and partial arch vortices. Only the arch vortex has been shown in this report for brevity. The arch vortex presented, well resembles the most energetic POD vorticity modes presented in this paper.

The second phase, is concerned with apply the techniques developed during the first phase, to higher resolution measurements of more complex geometries. The selected geometries serve as a comparison to isolate the effect of a permeable wall on an overlying turbulent boundary layer. The models include, an impermeable smooth wall, an impermeable rough wall, and a permeable rough wall. A single instantaneous volume has been presented for each of these geometries, including three volumes for the permeable rough wall, positioned at different physical locations. Although the analysis of this data set is still in its infancy, these preliminary results indicate that the phase 2 data is well suited for the same statistical analysis applied to the phase 1 data.

The current direction is to better refine the reconstructions on a small number of volumes for each data set of phase 2, including a 3D calibration. Concurrent work is focused on executing the reconstruction on a high performance computing cluster to speed up reconstruction times for the large data set. Additionally, it will take some time to determine a proper presentation technique of such unique measurements.
References


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