3D Velocity Measurements of a Hemispherical Roughness Element with Plenoptic PIV

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ABSTRACT

Plenoptic PIV was used to image the near-wake of a single hemispherical roughness element at a Reynolds number (based on roughness height) of $4.57 \times 10^3$ and boundary layer to roughness height-ratio of 4.67. The flow was created in a refractive index matched flow facility to allow the measurement volume to include a region of the hemispherical element. The instantaneous 3D velocity fields show a backflow region and a shear layer, which have asymmetric characteristics. Additionally, the flow is found to contain recirculation regions and shed arch vortices, seen in the instantaneous results. POD was applied to both the 3D velocity and 3D vorticity fields producing vorticity modes showing features associated with the wake and velocity modes showing features associated with the overall flow. The most energetic POD modes confirm the fluctuations in the shear layer and backflow region, as well as suggest the existence of shed arch shaped vortices.

I. INTRODUCTION

Three dimensional fluid flow over surface protrusions has long been an interest of fluid dynamicists. In general, many experiments in the field pertain to rectangular features, often resembling buildings. The wakes of highly curved bodies, such as hemispheres, have only been studied by a relatively small number of researchers. However, curved bodies are commonly used in engineering applications, such as surface protrusions on aircraft in aerospace engineering. This study is motivated by roughness effects on the impinging boundary layer, utilizing a hemispherical roughness element to perturb a turbulent boundary layer. The hemisphere model is a simple representative geometry for real surfaces found in these flows, such as a river rock.

Some of the earliest work on hemispherical roughness elements dates back to studies by Kovasznay in 1960 [1] and Klebanoff et al. in 1961 [2] which were both focused on investigating the boundary layer instability in 3D using both hot wire anemometry and visualization techniques recorded with film cameras. While largely concerned with transition on a smooth plate, both studies also noted that flow over a hemispherical roughness element exhibited similar structures and behaviors as seen in smooth plate testing. The most striking similarity being that both geometries generated hairpin vortices, first described by Theodore Theodorson in 1954 [3].

Later studies, such as Acarlar and Smith [4], focused entirely on the studying the flow over a hemispherical roughness element. Specifically, Acarlar and Smith studied an impinging laminar boundary layer over a hemispherical element. This slow moving flow creates large hairpin vortices that are stretched in the downstream direction, which were visualized using hydrogen bubble and dye injection techniques, coupled with hot film anemometry. Acarlar and Smith used a number of different sizes of hemispheres and varying flow speeds and downstream conditions to create varying relationships between the Reynolds number (based on hemisphere radius) and the height of the impinging laminar boundary layer. As a result, Acarlar and Smith well catalogued and described the flow structures over a hemispherical protuberance, including the propagation of a hairpin vortex. Hairpin vortices were shed from the hemisphere at a measurable frequency and overlapped each other’s counter-rotating legs. In addition to hairpin vortices, Acarlar and Smith also visualized a standing vortex that
wrapped around the front of the hemisphere and trailed off into the near-wake. However, important descriptions of the flow, such as the Reynolds number based on boundary layer height or the ratio of boundary layer height to roughness height, were not well defined.

Another study devoted to impinging flow on a hemisphere is the work of Savory and Toy, which investigated the near-wake of a hemisphere immersed in a turbulent boundary layer. [5] Velocity data was gathered in a dense sampling of the wake with a pulsed wire anemometer, using a blow down wind tunnel. Visualization of the near-wake was also performed in a recirculating water tunnel using the thymol blue technique. Of the three flow conditions of the study, the case with the largest boundary layer corresponded to a similar range of Reynolds numbers to the data presented in this paper. Although, the ratio of boundary layer height to roughness height is twenty percent larger than that of this paper. At these conditions, Savory and Toy describe a horseshoe vortex forming immediately upstream of the hemisphere that wraps around the element and interacts with propagating flow structures in the far-wake. A similar flow feature was seen by Acarlar and Smith. In the near-wake, Savory and Toy describe a shear layer between the separated boundary layer and the recirculation region immediately downstream of the hemisphere. This shear layer has been shown to interact with vortex loops, which are suggested to generate slightly above the upstream stagnation point of the hemispherical element. Half of the vortex loop is seen to propagate over the top of the hemisphere and through the shear layer, forming a structure resembling an arch. The arch structure does not have the drawn out structure in the downstream direction that is associated with hairpin vortices. These structures can be seen in the results of this paper as well.

There have been a handful of other studies performed on hemispherical roughness elements, although the previously presented work has been the most similar. Studies involving a turbulent boundary layer impinging on the element are common, although many do not provide visualization or insight to the coherent structures of the flow [6], [7]. In one study, Manhart does provide insight to the flow structures in a numerical simulation of the flow using Large Eddy Simulation (LES), but due to the significant scale and resolution differences, do not provide a useful comparison to this paper [8]. In addition, there has been some computational work regarding the strictly laminar flow past a hemisphere, but is primarily focused on comparison of mean lift forces with a sphere [9]. Additionally, many researchers are concerned with hemispherical elements that protrude above the boundary layer, commonly involving turrets [10], [11]. These studies are useful to review, but lack strong similarities with the experiment presented.

In order to make three-dimensional, three-component measurements on this flow, a plenoptic camera was used together with a refractive index matching (RIM) flow facility. This unique collaboration of two novel experimental devices allowed for measurement of the turbulent wake of a hemispherical roughness element and the identification of key flow structures previously described by visualization techniques. A plenoptic camera captures the entire light field of a scene, recording both the angular and spatial information of light entering its aperture. Coupled with particle image velocimetry (PIV), a plenoptic camera can record the 3D motion of a flow with a single camera. The RIM facility is a free-surface recirculatory tunnel, with a working fluid of a sodium iodide solution that has an index of refraction identical to the acrylic hemisphere model used for experimentation. This allows the laser used for illumination in PIV to pass directly through the hemisphere-fluid interface with minimal scattering. The pairing of these two technologies has allowed for the measurement of 3D velocity fields that include the hemisphere and the near-wake.

II. PLENOPTIC PIV

The plenoptic camera is useful a tool for flow diagnostics since it enables the rapid acquisition of light field data. As described by Levoy, a light field constitutes both the spatial and angular information about the light rays in a scene [12]. A plenoptic camera was first suggested as a tool to capture the light field by Adelson and Wang [13], and later realized by Ng et al. [14], [15]. Ng describes the plenoptic camera’s most well-known ability to refocus and shift perspective of a scene computationally after the image has been captured. The Advanced Flow Diagnostics Laboratory (AFDL) of Auburn University has constructed several plenoptic cameras for a wide variety of applications, including plenoptic PIV.

A plenoptic camera can be constructed by modifying a conventional camera, by adding an array of microlens, seen in Figure 1(a), in between the image sensor and the main lens. The microlens is precisely positioned using a custom-made mount, shown in Figure 1(b), above the image sensor, shown in Figure 1(c). This microlens array changes how the light is focused on the image sensor. In a conventional camera, the main lens focuses light rays directly onto the image sensor. Now, with the microlens in place, a plenoptic camera uses the main lens to focus light rays onto the microlens array. This, in turn, distributes the light rays onto the pixels of the image sensor. Each lens in the microlens array will focus the light rays onto different pixels, depending on the angle of the ray that struck the microlens. In this way, a plenoptic camera encodes the angular information in addition to the spatial information for each light ray entering the camera. The plenoptic camera used in this study uses a 16 megapixel (MP) Imperx Bobcat ICL-B4820 conventional camera with square pixels 7.4 microns in size. The microlens array was manufactured by Adaptive Optics Associates, Inc. to have a focal length of 500 microns and a microlens pitch of 125 microns. A grid of 289 × 193 microlenses image light onto the image sensor.
Figure 1: (a) shows a rectangular microlens array; (b) a custom designed microlens array mount to accurately position the microlens above the image sensor; (c) Imperex Bobcat ICL-B4820 image sensor

The plenoptic camera functions similarly to standard PIV cameras, recording image pairs of an illuminated volume. The images are a two dimensional (2D) representation of the illuminated 3D volume. Thus, when compared to traditional PIV, there is an additional step of reconstructing the 2D plenoptic images into 3D volumes. Tomographic reconstructions are created using an implementation of the multiplicative algebraic reconstruction technique (MART), similar to the algorithm used for tomographic PIV. The process is detailed by Fahringer, Lynch, and Thurow [16]. This reconstruction technique iteratively solves a system of linear equations that model the imaging system, shown in Equation (1). This equation can be thought of as the projection of the volume intensity distribution, $E(x,y,z)$, onto a 2D image, $I(x,y)$. However, the reverse of this operation is required to obtain a volume $E(x,y,z)$ from the image $I(x,y)$. Thus, $E(x,y,z)$ is initially defined as a volume discretized into cubic voxels (volume equivalent of a pixel), each with an intensity of 1. Each voxel, $j$, can then be projected onto a pixel located at $(x_i, y_i)$, mathematically expressed by

$$\sum_{j \in N_i} w_{ij} E(x_j, y_j, z_j) = I(x_i, y_i)$$  \hspace{1cm} (1)

where $N_i$ is the number of voxels in the line-of-sight of the $i$th pixel and $w_{ij}$ is the weighting function, which describes what portion of light emitted from a voxel strikes each pixel. The weighting function of a plenoptic camera is different from cameras used in tomographic PIV because the entire volume is not in focus during plenoptic PIV. Thus, a novel approach to create the weighting function was developed by Fahringer, Lynch, and Thurow [16], that used a similar method to the refocusing procedure described by Ng [14].

Equation (1) is rewritten as the standard MART process described by the following iterative relation defining the $k+1$ iteration

$$E(x_i, y_i, z_i)^{k+1} = E(x_i, y_i, z_i)^k \frac{I(x_i, y_i)}{\sum_{j \in N_i} w_{ij} E(x_j, y_j, z_j)^k}$$  \hspace{1cm} (2)

where $\mu$ is the relaxation parameter which can range between 0 and 1. The results from each iteration are then reviewed until procedure has sufficiently defined a particle volume that corresponds to the plenoptic image. Fahringer, Lynch, and Thurow present results from this process for both simulated and experimental data [16]. Once the plenoptic data has been reconstructed into a 3D intensity distribution, cross-correlation techniques are applied in an identical fashion to tomographic PIV.

III. THE SMALL SCALE RIM FACILITY

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 presences of a solid phase with a complex geometry (e.g. flow in porous media, IC engines, geophysical flows, etc.). Refractive index matching (RIM) techniques present a solution to allow optical measurements on flow systems of this nature. Blois et al. describe that by tailoring the refractive index (RI) of the working fluid in a flow facility to match the RI of the solid geometries to be studied, the refracting light at the solid-fluid interface can be diminished
This is the fundamental concept of the Small Scale RIM flow facility (referred to as RIM facility) constructed at the University of Illinois, Urbana-Champaign. Details on the challenges and design parameters can be found in Blois et al. [17].

The RIM facility (pictured in Figure 2) is a recirculating tunnel designed to use an aqueous solution of 62.5% sodium iodide (NaI) that has a refractive index identical to the acrylic models, about 1.49 [17]. The NaI solution has the advantage of having a similar viscosity to water, allowing a wide spectrum of complex flows to be simulated at comparable velocities to a standard water tunnel.

The tunnel test section is entirely constructed with clear acrylic, 19.10 mm thick, and is 2.50 m long. The cross-section is a constant 0.1125 m × 0.1125 m with a removable cover that allows for a free surface to be generated and full access to the to the interior of the test section for installation of models. The NaI solution is driven by twin pumps, capable of producing a combined discharge in the range of 0.016 – 1 m³s⁻¹. When using NaI as the working fluid, additional considerations need to be addressed in the design and operation of this RIM facility. The tunnel is slightly pressurized (+5 psi) with nitrogen gas (N₂) in order to reduce the discoloration of the NaI solution that occurs when I₃⁻ ions form by simultaneous exposure to oxygen and visible light. The NaI solution must remain at a relatively constant temperature and is held within a 0.05°C window which corresponds to a 0.001% change in fluid refractive index. The nearly exact index matching of the fluid in the model allows for the plenoptic camera to image a volume that includes the model, which is crucial to the study of the near-wake structures of a hemispherical roughness element.

IV. EXPERIMENTAL ARRANGEMENT

A plenoptic PIV experiment is presented, investigating the near-wake region of a single hemispherical roughness element. The element was fixed to the side tunnel wall of the RIM facility, with the plenoptic camera positioned outside of the opposite wall. The laser volume entered perpendicularly to the bottom of the tunnel. A schematic describing the configuration of the experimental apparatus is presented in Figure 3(a).

The Small Scale RIM Facility was set to a frequency of 10 Hz, which corresponds to a free stream velocity \( U_\infty = 0.3957 \text{ m/s} \). At the location of the measurements, the boundary layer has previously been measured to have a height of \( \delta_{99U_\infty} = 59.29 \text{ mm} \), corresponding to \( Re_\delta = 2.13 \times 10^4 \). In the near-wake case, a single hemispherical roughness element of height \( k = 12.7 \text{ mm} \) alters the flow, corresponding to \( Re_k = 4.57 \times 10^3 \) and \( \frac{k}{\delta} = 4.67 \). The facility was seeded with
silver-coated, hollow glass spheres with a mean diameter of 15 \( \mu m \) and a specific gravity of 1.7, commonly selected for use in water tunnels because of the relatively low specific gravity and high reflectivity.

Illumination was provided by a Quantel (formerly Big Sky) EverGreen 200 mJ double pulse Nd:YAG laser system. The laser beam was spread into a volume using two cylindrical lenses and entered the tunnel from the \( z \)-direction. A balsa mask clipped the laser in the \( y \)-direction to 30 mm. A mirror was placed on top of the RIM to increase particle illumination. The laser was spread in the \( x \)-direction to be slightly wider than the field of view of the camera, which was 31.47 mm in the \( x \)-direction and 47.04 mm in the \( z \)-direction. The volume was offset 3 mm in the \( y \)-direction from the wall opposite the plenoptic camera, shown in Figure 3(a). The dimensions of the volume measured can be seen in Figure 3(b). In order to provide the correct amount of particle motion, the time between laser pulses was set to \( \Delta t = 6 \text{ ms} \).

V. PROCESSING SUMMARY

The data gathered was processed in three main steps: tomographic reconstruction using MART, 3D cross correlation, and proper orthogonal decomposition. The process begins with the 2D plenoptic image pairs, which are reconstructed into volumes using the iterative process MART. Using a cross correlation algorithm, velocity vector fields are calculated from the volume pairs. The POD is applied to the instantaneous velocity fields, yielding the modes of the data set. These modes represent the velocity fluctuations. In order to better understand and identify the structures of the near-wake, the vorticity is also calculated from the instantaneous velocity fields, and the POD is applied to the three component vorticity fields. The resulting modes portrayed vorticity fluctuations in structures that largely occurred in the near-wake. The overall process is summarized in the flowchart in Figure 4.

Figure 3: (a) Schematic depicting the experimental arrangement; (b) schematic detailing the measurement volumes of the near-wake of the hemisphere; (c) photo of the plenoptic camera and the roughness element inside the empty RIM facility

The 16 MP plenoptic camera was fitted with a 50 mm prime lens and 43 mm of extension tubes is pictured in Figure 3(c). The magnification of the optical configuration was \( \approx 0.765 \) at the focal plane, in the center of the volume. The f-number of the prime lens was set to \( f/# = 2.85 \), so that the images formed by the microlens were touching, but not overlapping. Using these imaging parameters, 1000 image pairs were captured for the near-wake case.
The tomographic reconstruction using MART, previously described, was the most computationally expensive of the processes, utilizing a 12-core machine for 28 days. To obtain the particle volumes, 7 iterations were used and the relaxation parameter was set to $\mu = 0.3$. The plenoptic images were reconstructed into a $205 \times 205 \times 300$ voxel grid, based on the volume dimensions shown in Figure 3(b). The resulting volumes were slightly larger than the measured volume to allow particles to be placed more accurately on the edges of the measured volume, having dimensions of $34 \text{ mm} \times 34 \text{ mm} \times 50 \text{ mm}$.

The instantaneous vector fields were calculated using a 3D cross-correlation algorithm which consisted of 4 passes utilizing cubic windows of 64, 48, 32, and 16 voxel sides for each pass, respectively. Each correlation window overlapped the previous, such that the percent overlap for each pass was 25, 33, 25, and 50 percent, respectively. The cubic $8 \times 8 \times 8$ voxel correlation window corresponded to a physical volume of $4.8 \text{ mm} \times 4.8 \text{ mm} \times 4.8 \text{ mm}$. Vector fields of $24 \times 24 \times 36$ vectors were produced by the final pass, which is a sparser lateral sampling than conventional PIV. This illustrates the main trade-off in plenoptic PIV: a sacrifice of lateral resolution for depth resolution.

The proper orthogonal decomposition is a robust, linear procedure that has proved useful in analyzing large data sets from assorted fields. The POD extracts synthetic information from a data set that is representative of the complete set of data. To accomplish this, POD approximates the data set as a sum of the products of time coefficients and an optimal basis function. Mathematically,

$$ u(x, t) \approx \sum_{k=1}^{K} a^{(k)}(t) \phi^{(k)}(x) $$

where $u(x, t)$ represents a set of $K$ observations, or snapshots, obtained at discrete times throughout the domain of interest. In the case of PIV data, each snapshot is an instantaneous velocity or vorticity measurement and $x$ is a function of all 3 velocity or vorticity components. The collection of each $\phi^{(k)}(x)$ represents a basis function, denoted as $\Phi$. The basis is chosen such that it is naturally intrinsic for approximating $u(x, t)$. It is found that $\Phi$ is obtained by solving the eigenvalue problem

$$ \mathcal{R} \Phi = \lambda \Phi $$

where $\mathcal{R}$ is a Fredholm integral operator, related to the covariance of the data set. It follows that $\lambda$ are the eigenvalues of the problem and $\Phi$ are the eigenvectors. The eigenvectors, or modes, can be ordered by decreasing eigenvalue to represent the most probable realizations of the data set and define an optimal basis for approximating the original data set. The eigenvalues represent the modal energy of the modes and, because the POD is used on mean subtracted data, also represents the energy of fluctuations in velocity or vorticity. The POD can be applied in two different methods, classical or snapshot, depending on the type of data to be decomposed. For PIV data, the snapshot method is used, which averages the data through time and correlates the data spatially. The modes, also called the coherent structures of the flow, can provide insight to the structures and phenomena of a flow. An interested reader is referred to *The Springer Handbook of Fluid Mechanics* for a derivation of the basis function and further explanation of the POD [18].
VI. RESULTS AND DISCUSSION

After the images were processed, fourteen pairs were discarded because of poor correlation results, reducing the data set to 986 velocity fields. The time-average of these fields is presented below in Figure 5(a) and (b). As presented, the flow is traveling in the x/k-direction, impinging on the roughness element which is mounted in the y/k plane. The streamtraces for this figure, and the following figures, are calculated using a two-step Runge-Kutta method with a step size of 0.25 times the vector spacing. The streamtraces in (a) are colored with the normalized downstream velocity, U*, which is the instantaneous velocity divided by the free stream velocity. The axes of the figures are normalized by the roughness height, k. Streamtraces were only calculated for the wake region from about -1.1 z/k to +1.1 z/k in order to make the wake structure more visible. The mean flow field shows a region of backflow directly behind the hemisphere, which is in agreement with the previous work. The separated boundary layer nearly reattaches in the mean flow, at about x/k of 2. As y/k is increased, the normalized velocity increases and approaches 1. Figure 5(b) shows a center slice of the normalized downstream velocity, highlighting the backflow region, seen in the darker blue. The lighter blue marks the shear layer between the backflow and the turbulent boundary layer, seen in the stratified colors above y/k of 1.

The shear layer is further defined by the time-averaged vorticity field, shown in Figure 6. Two isosurfaces are used to show how the largest regions of vorticity form around the region of backflow. In this figure, the volume has been repositioned to better show the wake structures, such that the flow is traveling nearly perpendicularly out of the page. The first isosurface, in green, shows vorticity magnitude, which encapsulates the second isosurface, in blue, of zero velocity. The location of the vorticity magnitude isosurface is consistent with the observations from Figure 5, both portraying a symmetric flow.

Figure 6: Time-averaged vorticity magnitude shown with an isosurface at $\|\vec{\omega}\|=0.4$ and highlighted with a slice to show the interior structure, a second isosurface of $U^*=0$ shows the region of backflow.

Figure 5: (a) Streamtraces of mean velocity field of the near-wake region, colored by normalized downstream velocity; (b) A center slice showing velocity vectors, colored by normalized downstream velocity.
The instantaneous velocity and vorticity results show a variety of phenomena, depicting the unsteady nature of the flow. However, the two instantaneous velocity fields, shown in Figure 7 and in Figure 8, represent a majority of the realizations. The streamtraces in Figure 7(a) show a backflow region that stretches from the surface of the hemisphere to the downstream end of the measurement volume at $x/k$ of 2. The backflow region extends to $y/k$ of 0.6, well below the crest of the hemispherical element. As a whole, the region is slightly off center with respect to the hemisphere, shifted in the positive $z/k$ direction by about 0.1. Two small swirling legs can be at the edge of the backflow region at ($x/k$, $y/k$, $z/k$) location of (0.9, 0.2, 1.4) and (1.5, 0.2, 1.5), shown in the inset. In the separated boundary layer the streamlines are relatively uniform, although as $y/k$ approaches 2, the $-z/k$ side of the boundary layer is seen to decline in the $y/k$ direction. An isosurface of vorticity magnitude is shown in (b) and (c), describing the shear layer. From (b) it is seen the layer has a much stronger vorticity on the $+z/k$ side of the wake and is relatively centered in the $z/k$ direction. The isometric view shows the complex structure of the surface, which has a number of legs protruding down on the $+z/k$ side of the structure. The two largest legs align well with the swirling legs described in the streamtraces. As the structure extends in the downstream direction, it narrows in both the $y/k$ and $z/k$ directions as the separated boundary layer moves towards the wall to reattach.

Figure 7: Image pair 10 shown using (a) streamtraces colored by normalized downstream velocity with an inset showing two vortical legs; (b) an isosurface of vorticity magnitude of 0.9 shown from the rear; (c) an isometric view of the same isosurface

The near-wake in Figure 8(a) is seemingly calmer than the near-wake in Figure 7(a). From the velocity streamtraces shown in Figure 8(a), it is immediately seen that the many of the streams travel in a relatively straight path downstream with a seemingly constant velocity. The streamtraces in the backflow region have a unique structure with many of them terminating at the bottom of the measurement volume. This is due to a combination of the measurement volume being displaced from the wall by 3 mm and the lower accuracy of PIV algorithms at the edge of volumes. Regardless, the streams define a region of backflow that extends outside the measurement volume in the $x/k$ direction. The region as whole has little recognizable structure, except for a small swirling element at $x/k$ of 1.2. As with the example in Figure 7, the backflow region is slightly off center, although centered at $z/k$ of -0.1 in this realization. The vorticity magnitude isosurfaces in (b) and (c) further describe the differences between the realizations in Figure 7 and Figure 8. In (b) it is clear that overall structure is not centered with respect to the hemisphere. The isosurface is centered at about $z/k$ of -0.2, similar to the backflow region. The overall volume enclosed by the isosurfaces is noticeably less than the realization in Figure 7 and has less of a curved shape. The
isometric view in (c) reveals that the isosurfaces are far less continuous than the realization in Figure 7 and lacks any vertical structure in the downstream end of the volume. The structure is relatively flat however, maintaining a height of $y/k$ of 0.8 for its extents, whereas the surface in Figure 7(c) approaches the wall as it extends downstream.

Variations similar to these two image pairs exist frequently in the data samples, categorized by a large region of backflow that extends towards the downstream end of the measurement volume. These realizations also contain an elongated shear layer which resembles the shear layer in the mean vorticity field. The isosurfaces of the vorticity magnitude are not always continuous in the downstream direction, as seen in Figure 8, but overall show some downstream continuity. The center of the backflow region and the vorticity magnitude have been seen to fluctuate by as much at ±0.25 in the $z/k$-direction. In addition, the top of the surface rarely extends above $y/k$ of 1 or below $y/k$ of 0.7 throughout the data set. A majority of the data is seen to behave following these descriptions, although there exist some notable exceptions.

Figure 8: Image pair 52 shown using (a) streamtraces colored by normalized downstream velocity; (b) an isosurface of vorticity magnitude of 0.9 shown from the rear; (c) an isometric view of the same isosurface
An interesting phenomena seen in less than five percent of the data set by manual inspection is a well-defined instantaneous large-scale recirculation region. This feature is present in the two realizations compared in Figure 9. The velocity streamtraces of the first realization, shown in (a), detailing a small recirculation region that extends from the surface of the hemisphere to \( x/k \) of 1.4, clinging near to the hemisphere. This region is shown larger in the inset. The isosurface of vorticity magnitude in (b) is virtually exclusively in this region. The surface does not resemble the isosurfaces in the previous examples, as it does not extend to the downstream edges of the volume. In addition, there exists only one weak vertical component to the isosurfaces, outside of the recirculation zone. Figure 9(c) shows the velocity streamtraces for the second realization that contains a large recirculation zone. This expansive region spans from the surface of the hemisphere to the downstream end of the measurement volume. Furthermore, the recirculation zone has a nearly flat peak that is at a constant \( y/k \) of 0.9 for its entire span suggesting that the separated boundary layer will remain separated for a prolonged distance. It is seen the recirculation is centered at a \((x/k, y/k, z/k)\) location of \( (1.6, 0.8, 0) \), which is where the inset is centered. The vorticity magnitude isosurface in (d) is much more expansive than in (b). Again, the vorticity isosurface aligns well with the recirculation area, extending to the downstream end of the measurement volume. The structure of the surface resembles the vorticity isosurface from (c), having some vertical legs, although, the isosurface from (d) is more contiguous. In contrast to the isosurface in (b) the surface in (d) almost occupies the entire near-wake. Of the identifiable recirculation zones, these realizations represent the smaller and larger of the zones, with a handful of realizations in the data sized in between.

![Figure 9: A comparison of recirculation zone size, (a) shows streamtraces of a small recirculation zone in image pair 106, shown larger in the inset; (b) isosurface of vorticity magnitude of 0.9 for image pair 106; (c) shows streamtraces of a large recirculation zone in image pair 253, shown larger in the inset; (d) isosurface of vorticity magnitude of 0.9 for image pair 253](image-url)
The two realizations shown in Figure 10 both contain another interesting flow structure, a shed arch vortex. By manual inspection, about ten percent of the realizations has a complete or partial arch vortex. This structure is defined by high levels of vorticity, forming an arch structure with counter-rotating legs, which is not connected to the hemispherical roughness element. The realization shown in Figure 10(a), contains a complete arch and the realization shown in (c), contains a partial arch. In (a), the streamtraces show that that backflow region extends to the downstream end of the measurement volume and likely beyond. The streamtraces flowing over the hemispherical element show that the shear layer and the separated boundary layer initially follow the contour of the hemisphere, seen in the downward motion at $x/k$ of 0.8 – 1 and $z/k$ of 0. Then, at $x/k$ of 1.5, the boundary layer turns back up in the $y/k$-direction, traveling over the peak of the arch vortex. A vorticity magnitude isosurface is shown in (b), colored by $Y$ vorticity, and further defines the arch vortex. The structure of the isosurface is clearly an arch, which fits perfectly into the arch-shaped streamtraces in (a). Despite appearing fairly symmetric, the arch vortex is slightly off center, at $z/k$ of -0.1. In addition, the legs of the arch vortex are not of equal strength. The $+z/k$ leg is has a higher vorticity value and encloses more volume than the $-z/k$ leg. The velocity streamtraces of the second realization, shown in Figure 10(c), again show a large backflow region extending to the downstream end of the volume. This realization has a visible recirculation region at (2, 0.8, 0.3), which is actually the peak of the arch structure. The vorticity magnitude isosurfaces in (d), depict a partial arch vortex, which missing a $-z/k$ leg. The streamtraces show that the region where the $-z/k$ leg is expected, $z/k$ of -0.3, is dominated by backflow. The partial arch vortex is centered relative to the hemisphere and occurs at nearly the same $x/k$ location as the complete arch vortex in (b), at $x/k$ of 1.8. In both realizations it is seen that the region of backflow passes directly through the arch vortex. The arch vortices found by manual inspection consist of both complete and partial arches located at about the same $x/k$ location and centered anywhere from $z/k$ of -0.25 to +0.25. In a previous study, Savory and Toy visualized a similar arch vortex being shed from the hemisphere at a measurable frequency [5]. As the PIV data in this experiment is not time resolved, it is likely that the sampling frequency only coincided with the shedding frequency a small number of times. Savory and Toy did not reference any partial arch structures, although they are a significant portion of the arch vortices in this data set.

Figure 10: A comparison of arch vortices, (a) shows velocity streamtraces of image pair 649; (b) shows isosurfaces of vorticity magnitude at 1.5 and colored with $Y$-vorticity image pair 649 (c) shows streamtraces of image pair 575; (d) shows isosurfaces of vorticity magnitude at 1.5 and colored with $Y$-vorticity of image pair 575
The POD analysis of this experiment used both the instantaneous velocity data and the instantaneous vorticity data. The cumulative normalized energy for each the velocity and vorticity modes can be seen in Figure 11. It was found that the first 100 modes contain about 70 percent of the energy for the velocity case whereas the first 100 vorticity modes contain less than 50 percent of the total enstrophy. Of these modes, eight of both the velocity and vorticity realizations are shown.

**Figure 11: Cumulative modal energy for velocity and vorticity data for all 984 modes**

The velocity POD modes are shown in Figure 12 using two separate isosurfaces for positive and negative fluctuations in normalized downstream velocity. The first mode, shown in (a), has two large regions of positive fluctuations. One region is in the near-wake spanning from \( x/k \) of 1.5 to the downstream end of the measurement volume. In the previously presented realizations, this area is commonly associated with a region of backflow, but this mode implies that is not exclusively the case. The second positive surface encompasses the higher levels of the boundary layer at the upstream end of the volume, suggesting that this level of the boundary layer often enters the measurement volume with an increased velocity. An area of negative velocity fluctuation is seen intersecting the hemisphere. The second mode, (b), shows two main regions, a positive and a negative. The negative surface is in the near-wake and also spans the entire \( z/k \)-direction of the measurement volume. This surface can be seen as the counterpart to the positive fluctuations seen in the first mode, implying that the backflow region is commonly stronger than the average. The positive isosurface shows an accelerated flow around the hemispherical roughness element. Figure 12(c) shows the third mode, which is dominated by a large isosurface of a negative fluctuation in the shear layer and backflow region. The fourth mode, (d), shows a positive fluctuation in the shear layer on the \( -z/k \) side of the hemispherical element and another region of negative fluctuations in the near-wake. The fifth and sixth modes, (e) and (f), show similar structures depicting positive fluctuations in the \( +z/k \) side of the wake and boundary layer. Both modes also have a smaller region of negative fluctuations on the \( -z/k \) side of the wake. Regarding the \( -z/k \) side of the wake, the fifth and sixth modes imply the opposite. The higher modes show similar fluctuation surfaces to the first six modes. Modes preceding the fifteenth, shown in (g), mode tend to have larger isosurfaces that the first six modes, occurring seemingly in pairs, with modes resembling the opposite of each other. A few of these modes show distinct asymmetries in the wake. The modes following the fifteenth trend to smaller isosurfaces, dotted throughout the near-wake region and often have alternating patterns of positive and negative fluctuation in the wake, as seen in the hundredth mode, seen in (h).

The POD was applied to the vorticity data of the realizations to aid in categorizing the structures that occur in the data set. The first six vorticity modes can be seen in Figure 13, which uses isosurfaces of vorticity magnitude, colored by \( Y \) vorticity, to visualize the modes. The first mode, (a), has an extruded donut-like shape beginning slightly below the crest of the hemisphere. Isosurfaces in (b) show a three pronged structure in the near-wake. The prongs of this structure resemble extruded legs of an arch-shaped surface having alternating \( Y \) vorticity signs. The structures in the boundary layer are largely made of \( X \) vorticity fluctuations. An extruded arch shape is shown in the third mode, (c). The structure is centered in the \( z/k \)-direction with respect to the hemispherical element. A secondary structure extends out of the first surface and the surface of the hemisphere, having a similar rounded shape. Isosurfaces in the fourth mode, (d), appear largely in the boundary layer. Of these three surfaces, the larger centered surface has a positive \( X \) vorticity fluctuation and the two smaller isosurfaces are of negative \( X \) vorticity fluctuations. In the near-wake, a curved surface ranges from 1.5 to 2 in the \( x/k \) direction. Two arch-shaped structures appear in the fifth mode, (e), however, they are in different planes. The surface in the near-wake resembles the third mode and the \( Y \) vorticity fluctuations of each leg match between each structure. In the \( z/k \)-plane, an arched surface exists.
near the top of the measurement volume, consisting largely of $X$ vorticity fluctuations. The upstream facing legs of the structure nearly align with the structures seen in the fourth mode and have consistent $X$ vorticity fluctuations. The sixth mode, $(f)$, shows similar structures to a few of the previous modes. The large curved surface near top of the volume resembles the mirror image of the arched structure previously described in the fifth mode, although it is missing an upstream leg. In the near-wake, the arched structure aligns well with the surface in the fifth mode, although the legs have opposite $Y$ vorticity fluctuations. Similar fluctuations at this location are seen in the second mode and fourth mode, whereas the third mode has a similar structure but opposite fluctuations. Also seen in the sixth mode is a similar curved surface to the third mode, protruding out of the hemispherical roughness element, however, with the opposite fluctuations. Similar structures to the first sixth modes appear throughout the first twenty modes. The higher modes contain significantly smaller surfaces generally dotted through the near wake, shown in the fiftieth and hundredth modes, $(g)$ and $(h)$, which show isosurfaces at a reduced value so the vorticity structures can be visualized. Further analysis of the POD modes is required to properly relate the instantaneous flow structures to the various modes.
Figure 12: Isosurfaces of normalized downstream velocity are shown at a value -0.25 and +0.25 for the velocity 1st-6th POD modes, (a)-(f) respectively, while (g) and (h) show the 15th and 100th modes, respectively.
Figure 13: Isosurfaces of vorticity magnitude $\|\vec{\omega}\|$ are shown at a value 0.6 for the 1st-6th modes, (a)-(f) respectively, colored with $Y$ vorticity; (g) and (h) show the 50th and 100th modes, respectively with isosurfaces at 0.4.
VII. CONCLUSION

Through the union of a plenoptic camera and a RIM facility, unique 3D flow measurements have been made in the near-wake region of a hemisphrical roughness element. The plenoptic camera, built from a modified 16 MP standard PIV camera, captured 984 image pairs of the flow created by the index matching tunnel. By using this flow facility, the measurement volume included the downstream half of the hemisphrical roughness element, allowing particle data to be collected around the surface of the hemisphrical element. The plenoptic particle images were reconstructed into 3D particle volumes using seven iterations of MART, which were in turn cross-correlated to produce the velocity data shown.

In the average velocity field, a symmetric shear layer is defined, with the boundary layer nearly reattaching at the downstream end of the measurement volume. From the instantaneous data, small variations of this structure is seen throughout many of the realizations, with examples of the asymmetrical structure of the shear layer and back flow region. Furthermore, a number of realizations exhibit intense recirculation regions, both small and large, which drastically change the reattachment point of the separated boundary layer. Additionally, a few realizations contain a shed arch vortex similar to the shed vortex described by Savory and Toy [5]. The arch vortex in this data set also had an asymmetrical nature, and often occurred as an incomplete arch vortex, lacking a vertical leg. The POD analysis of both the 3D velocity and vorticity distributions presented further descriptions of the behavior of the flow field. In the vorticity POD modes, interesting arched surfaces are found in the boundary layer near the top of the volume, in addition to the arched surfaces in the near-wake.

The procedure developed for capturing, processing, and analyzing the 3D plenoptic data will be applied to future plenoptic PIV experiments in the Small Scale RIM facility. Future experiments will utilize a 29 MP plenoptic camera, which will allow for a larger field of view, to capture the entire near-wake and a section of far-wake. In addition, more complex geometries will be tested, including arrays of hemisphrical elements and multi-level arrays of hemisphrical and spherical, both regularly and irregularly packed. This study has laid the foundation for these future experiments to expand upon.

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