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RPPR Final Report
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Major Goals: The chief goal of this project is the acquisition and implementation of new experimental infrastructure necessary for testing novel and fundamental theory/numerics that, ultimately, may lead to revolutionary practical methods for the prediction and control of unsteady and turbulent flow. Recent work suggests a class of exact Navier-Stokes solutions termed "Exact Coherent Structures" (ECS) may provide new and powerful ways to describe turbulence; as one example, PI Schatz and Co-PI Grigoriev demonstrated experimentally the dynamical role of ECS for 2D turbulence. Co-PI Grigoriev is presently leading an ARO-supported effort (Contract W911NF-15-1-0471) to lay the theoretical/numerical foundation needed for quantitative experimental tests of ECS in 3D turbulence in an experimentally-accessible paradigm problem: the moderately-turbulent flow between rotating cylinders (Taylor-Couette flow). PI Schatz's laboratory possesses extensive equipment and expertise for Taylor-Couette experiments that can be used to validate theoretical/numerical results of Co-PI Grigoriev's work. The additional key infrastructure obtained with help from this grant includes:

*A Nd:YLF laser (Photonics DM30 527DH) whose substantial, sustained energy output (70 mJ at a continuous 1 kHz repetition rate) that enables the rapid illumination of large volumes necessary to quantify Taylor-Couette flow dynamics via time-resolved 3D-3C velocimetry.

*A novel image processing package, the LaVision FlowMaster 4D-PTV/Shake-the Box package (henceforth referred to as the "STB package"), that provides orders-of-magnitude speedup (compared to more standard tomographic PIV approaches) in processing the enormous quantities of particle image data obtained from Taylor-Couette turbulence experiments. (NB: Non-DURIP funds were used to purchase the STB package; however, the DURIP funds used to purchase the laser also facilitated the STB package purchase by providing the bargaining power to obtain both items from a single vendor (LaVision) at a price that was substantially less than the total price

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of each item purchased separately.)

These upgrades now position PI Schatz's lab to conduct experiments that will provide the world's best and strongest tests of ECS-based descriptions of 3D turbulent flow dynamics.

More details can be found in the attached PDF document.

Accomplishments: The new laser provides a vast increase in brightness (70 mJ per pulse vs 5 mJ with the old laser), enabling changes to the optical train that are significantly advantageous for 3D-3C velocimetry. Specifically, the brighter laser induced brighter fluorescence that, in turn, enabled a substantial reduction in optics f number (from $f/8$ to $f/32$).

One major consequence of the brighter laser/increased fluorescence/altered optics is a big increase in the particle contrast (Fig. 1); large numbers of pixels register intensities near zero indicating high particle contrast and, therefore, lead to much improved velocity measurements.

A second major consequence of the brighter laser/increased fluorescence/altered optics is a large increase in the flow domain where 3D-3C velocimetry can be performed. The large f number optics leads to a large increase in depth of field (from 8mm to more than 30 mm). Without this increase in depth of field, the full radial flow domain of the computations currently being performed by Co-PI Grigoriev could not be probed in the current Taylor-Couette apparatus in PI Schatz's lab. Additionally, the new laser is sufficiently bright to illuminate a substantially larger azimuthal range in the experiments: 3D-3C velocity measurements can be obtained over nearly one-fifth of the azimuthal domain of the experiment. (With the old laser, the azimuthal range was restricted to less than one-tenth of the full domain.)

Additionally, the new LaVision FlowMaster 4D-PTV/Shake-the-Box package (STB package) provides orders-of-magnitude speedup in 3D-3C velocimetry analysis needed to handle the enormous quantities of data from the upgraded velocimetry hardware. In the standard tomographic PIV approach, time-consuming 3D particle reconstruction must be performed before 3D correlations to obtain velocity vectors can be done. The STB package is a PTV (particle tracking velocimetry) technique that eliminates the need for particle reconstruction, and, thereby, enables much faster processing. For our Taylor-Couette experiments, a dataset consisting of 5,500 images from four cameras (at 1024 X 1024 pixel resolution), tomographic PIV processing distributed across twenty-four quad-core computers takes 18 hours to complete. By contrast, the STB package running on a single computer can process the same data in approximately 6 hours, including the use of an interpolation scheme to obtain velocity fields from the particle tracks. We anticipate that parallelization of the STB package in the near future will lead to correspondingly large gains in the rapid processing of Taylor-Couette data.

Finally, the upgraded infrastructure now puts within reach some very novel flow measurements for Taylor-Couette flow. PI Schatz and Co-PI Grigoriev have proposed designing and building a new Taylor-Couette apparatus that permits optical access from both the side (through a transparent outer cylinder) and above through a transparent upper endcap. In conjunction with the new laser and STB package, time-resolved 3D-3C velocimetry could be performed over a selected azimuthal sector, and, simultaneously, 2D-3C velocimetry performed in a plane intersecting with the entire azimuthal domain of the flow. Somewhat speculatively, it may even be possible for the new laser to be sufficiently bright to illuminate the entire flow domain in the new apparatus; thus, with a sufficiently large number of cameras strategically placed, it might be possible to collect time-resolved 3D-3C turbulent velocity data for the whole flow. Regardless, both the new laser and the STB package will play a central role in enabling quantitative characterization of turbulent Taylor-Couette flow (including detailed signatures of possible ECS) that can be directly compared to the predictions of theory and numerics.

More details (including illustrative figures) are included in the attached PDF document.

Training Opportunities: The infrastructure upgrades provided opportunities for graduate student Chris Crowley to develop unique skills (both hardware and software) for 3D-3C tomographic PIV and STB PTV.

Results Dissemination: A contributed talk on measurements in turbulent Taylor-Couette flow (using the infrastructure upgrades funded by this project) will be delivered by graduate student Chris Crowley at 2017 APS/DFD Meeting to be held in Denver, Colorado.

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as of 09-Aug-2017

Honors and Awards: Nothing to Report

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PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Christopher Crowley

Person Months Worked: 12.00

Funding Support:

Project Contribution:

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International Travel:

National Academy Member: N

Other Collaborators:

1 Introduction

This grant enabled acquisition of new experimental infrastructure necessary for testing novel and fundamental theory/numerics that, ultimately, may lead to revolutionary practical methods for the prediction and control of unsteady and turbulent flows. Recent work suggests a class of exact Navier-Stokes solutions termed “Exact Coherent Structures” (ECS) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] may provide new and powerful ways to describe turbulence; as one example, PI Schatz and Co-PI Grigoriev demonstrated experimentally the dynamical role of ECS for 2D turbulence [13]. Co-PI Grigoriev is presently leading an ARO-supported effort (Contract W911NF-15-1-0471) to lay the theoretical/numerical foundation needed for quantitative experimental tests of ECS in 3D turbulence in an experimentally-accessible paradigm problem: the moderately-turbulent flow between rotating cylinders (Taylor-Couette flow). PI Schatz’s laboratory possesses extensive equipment and expertise for Taylor-Couette experiments that can be used to validate theoretical/numerical results of Co-PI Grigoriev’s work. The additional key infrastructure obtained with help from this grant includes:

- A Nd:YLF laser (Photonics DM30 527DH) whose substantial, sustained energy output (70 mJ at a continuous 1 kHz repetition rate) that enables the rapid illumination of large flow volumes necessary to quantify Taylor-Couette flow dynamics via time-resolved 3D-3C velocimetry.
- A novel image processing package, the LaVision FlowMaster 4D-PTV/Shake-the Box (henceforth referred to as the “STB package”), that provides orders-of-magnitude speedup (compared to more standard tomographic PIV approaches) in processing the enormous quantities of particle image data obtained from Taylor-Couette turbulence experiments. (Note: Non-DURIP funds were used to purchase the STB package; however, the DURIP funds used to purchase the laser also facilitate the STB package purchase by providing the bargaining power to obtain both items from a single vendor (LaVision) at a price that was substantially less than the total price of each item purchased separately.)

These upgrades now position PI Schatz’s lab to conduct experiments that will provide the world’s best and strongest tests of ECS-based descriptions of turbulent flow dynamics.

The remainder of the report is organized as follows. In Section 2, we provide, by way of background, a short description of Taylor-Couette experimental infrastructure in PI Schatz’s lab, prior to the improvements made possible by the DURIP grant. In Section 3, we discuss substantial improvements that the new infrastructure provides to current experiments. In Section 4, we briefly describe exciting possibilities for future experiments that are now within reach using the new infrastructure.

2 Background: Prior Infrastructure

A high-precision Taylor-Couette apparatus mounted on an optical table with vibration isolation capabilities is already in operation in PI Schatz’s lab. The apparatus can be kept under tight temperature control by liquid cooling (within ± 50 milliKelvin) and the rotation rates of both inner and outer cylinders are computer-controlled to better than 1 part in 10^4 ; as a result the Reynolds numbers of the flows can be specified to better than 0.1%. Most importantly for the study of weakly turbulent flow, the Taylor-Couette apparatus has been customized and equipped to make possible the

measurement of time series of three velocity components in a 3D fluid volume (3D-3C) that are time-resolved even in moderately turbulent regimes [14]. Four high-speed Phantom V210 cameras, each with a 105 mm f/2.8 macro lens mounted on a custom-built Scheimpflug adapters, are each focused on the measurement volume in the Taylor-Couette apparatus. The optical system is calibrated by use of a custom-made target that is machined into the side of one of the Taylor-Couette axial boundaries. Index-matching of both the cooling fluid and the working fluid with the outer glass cylinder is essential for eliminating optical distortion due to diffraction at curved surfaces; in particular, the working fluid is a customized aqueous solution of ammonium thiocyanate which permits simultaneous index matching and density matching with particles for velocimetry while still achieving a kinematic viscosity that sufficiently low to permit exploration of turbulent regimes. The velocimetry particles are custom-made to a selected density and dyed with a high concentration of Rhodamine 6G; the particles fluoresce at $\approx 552\text{nm}$ when illuminated with 527-nm laser light. To reduce the effects of laser light that scatters (in an undesired way) from the solid boundaries, optical filters on the lens of each camera permits light to be collected only from the fluorescing particles. Acquisition of particle image time series is synchronized and controlled by a LaVision High Speed Controller; the data is subsequently analyzed using a dedicated cluster of 46 quad-core 2.0 Ghz desktop computers.

3 Impact of New Infrastructure on Current Experiments

The new laser provides a vast increase in brightness (70 mJ per pulse vs 5 mJ with the old laser), enabling changes to the optical train that are significantly advantageous for 3D-3C velocimetry. In the Taylor-Couette geometry, walls are always in close proximity to the flows of interest; thus, interrogation of fluorescing particles requires the use of camera filters to pass the fluorescent light and attenuate the laser light (see Sec. 2). For low energy laser light, the corresponding fluorescence is weak, thereby forcing the use of low f number optics with wide passband filters to enable the cameras to sense the fluorescent light. The order-of-magnitude increase in pulse energy with the new laser leads to a similar increase in fluorescence (i.e., dye bleaching effects appear to be negligible for the operating conditions of the Taylor-Couette experiments). In turn, the increased fluorescence enable a substantial reduction in optics f number (from f/8 to f/32).

One major consequence of the brighter laser/increased fluorescence/altered optics is a big increase in the particle contrast (Fig. 1). With the old laser, very few camera pixels registered

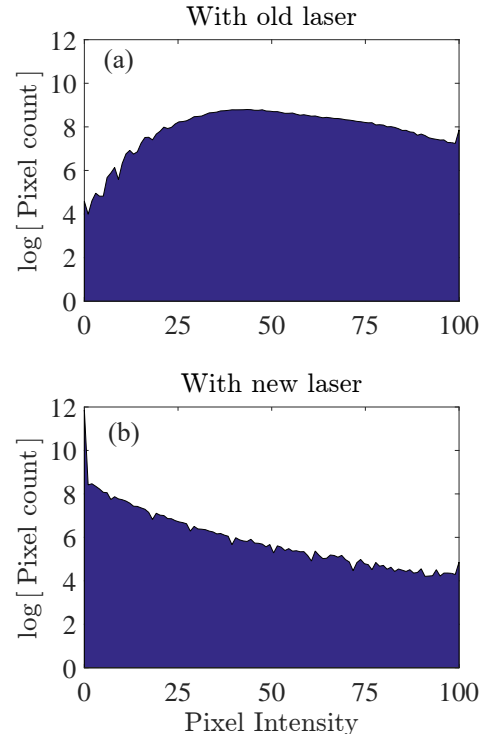


Figure 1: Images of particles suspended in the flow exhibit stronger optical contrast (and, therefore, leads to better velocimetry measurements) when the particle are illuminated with the new laser purchased with DURIP funds. Histograms of pixel number as a function of pixel intensity (arb. units) are shown for particles illuminated with the old laser (a) and new laser (b). The large peak near zero intensity shown in (b) indicates that pixels where no particles are imaged register a much small intensity than pixels where particles are imaged. The tenfold decrease in laser power for the old laser causes camera noise effects to be much more apparent, as indicated in (a) by a far smaller number of particle-free pixels that register intensities near zero.

intensities near zero (Fig. 1(a)), indicating poor contrast between regions of an image containing particles and regions showing only the background (no particles). For the old laser, the camera background noise was large (relative to the weak particle fluorescence) due to a combination of camera sensor noise and unwanted laser light (leaking through the filters with wide passband). This poor particle contrast leads to velocity measurement with high noise, due to excessive numbers of fake (ghost) particles in tomographic reconstruction and to a low density of properly reconstructed particles. By comparison, with the new laser, large numbers of pixels register intensities near zero (Fig. 1(b)), indicating high particle contrast and, therefore, much improved velocity measurements.

A second major consequence of the brighter laser/increased fluorescence/altered optics is a large increase in the flow domain where 3D-3C velocimetry can be performed (Fig. 2). The large f number optics (made possible by the brighter laser) leads to a large increase in depth of field (from 8mm to more than 30 mm). Without this increase in depth of field, the full radial flow domain of the computations currently being performed by Co-PI Grigoriev could not be probed in the current Taylor-Couette apparatus in PI Schatz’s lab. Additionally, the new laser is sufficiently bright to illuminate a substantially larger azimuthal range in the experiments. Figure 2 shown that 3D-3C velocity measurements can be obtained over nearly one-fifth of the azimuthal domain of the experiment. (With the old laser, the azimuthal range was restricted to less than one-tenth of the full domain.)

The new LaVision FlowMaster 4D-PTV/Shake-the Box package (STB package) provides orders-of-magnitude speedup in 3D-3C velocimetry analysis needed to handle the enormous quantities of data from the upgraded velocimetry hardware. In the standard tomographic PIV approach, time-consuming 3D particle reconstruction must be performed before 3D correlations to obtain velocity vectors can be done. The STB package is a PTV (particle tracking velocimetry) technique that eliminates the need for particle reconstruction, and, thereby, enables much faster processing. For our Taylor-Couette experiments, a dataset consisting of 5,500 images from four cameras (at 1024 X 1024 pixel resolution), tomographic PIV processing distributed across twenty-four quad-core computers takes 18 hours to complete. By contrast, the STB package *running on a single computer* can process the same data in approximately 6 hours (including the use of an interpolation scheme to obtain velocity fields from the particle tracks.) We anticipate that parallization of the STB package in the near future will lead to correspondingly large gains in the rapid processing of Taylor-Couette data.

The upgraded infrastructure now provides very clean, low noise, highly-resolved 3D-3C velocimetry measurements of turbulence in the current Taylor-Couette flow apparatus; see Figure 3 for one

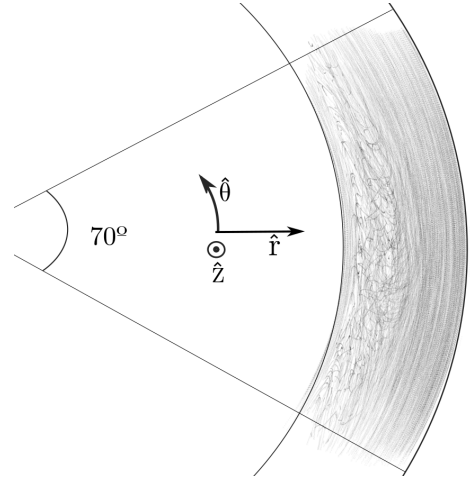


Figure 2: The new lasers make possible 3D-3C velocimetry measurements in Taylor-Couette flow over large radial (\hat{r}) azimuthal ($\hat{\theta}$) domains. The image shows 3D-3C PTV measurements of turbulent Taylor-Couette flow for the parameter values of Co-PI Grigoriev’s on-going theoretical/numerical studies of ECS.

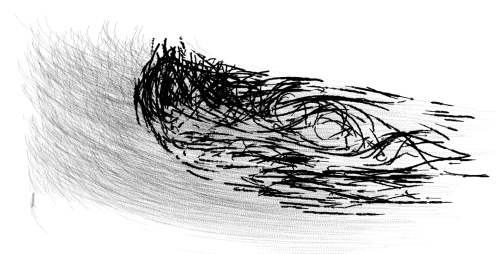


Figure 3: 3D-3C PTV measurements of bursting turbulence in Taylor-Couette flow.

nice example.

4 Impact of New Infrastructure on Future Experiments

The optical access of the current Taylor-Couette apparatus in PI Schatz’s lab is limited. To overcome this limit, we have proposed an upgrade by designing and building a new Taylor-Couette apparatus that permits optical access from both the side (through a transparent outer cylinder) and above through a transparent upper endcap. Figure 4 illustrates one possible measurement configuration in which time-resolved 3D-3C velocimetry is performed over a selected azimuthal sector, and, simultaneously, 2D-3C velocimetry is performed in a plane intersecting with the entire azimuthal domain of the flow. Our recent experience with the new laser suggests that it may be bright enough to illuminate the entire flow domain in the new apparatus; thus, with a sufficiently large number of cameras strategically placed, it might be possible to collect time-resolved 3D-3C turbulent velocity data for the whole flow. In either event, both the new laser and the STB package will play a central role in enabling quantitative characterization of turbulent Taylor-Couette flow (including detailed signatures of possible ECS) that can be directly compared to the predictions of theory and numerics.

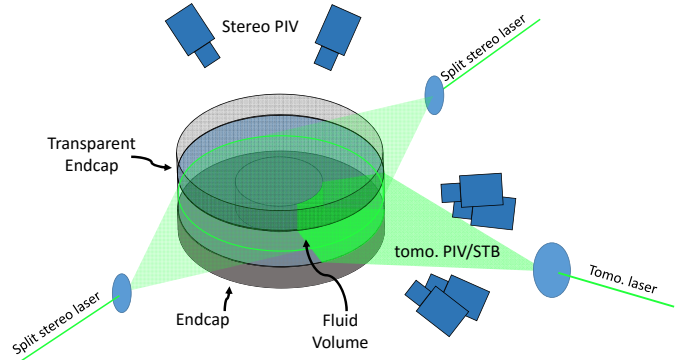


Figure 4: Schematic illustrating simultaneous stereo-PIV and tomographic PIV that the new laser makes possible in a yet-to-be-constructed Taylor-Couette flow apparatus. The new apparatus would feature a transparent upper endcap. With the new laser and new apparatus, time-resolved 3D-3C velocimetry of the full turbulent flow domain may also be possible.

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