Rotating Tank Flow Visualization

Fall 2022 ME Executive Summary

Design Team

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Sponsor

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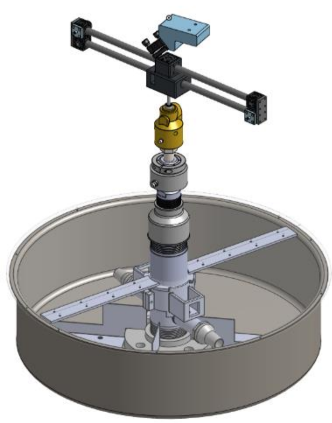
The separation of crude oil is an inefficient and often wasteful process, producing approximately 18 billion barrels of waste in the US annually. Of this waste, 3-6% is reject crude oil that was unable to be extracted, translating to 75 to 150 million dollars of wasted oil per day. The team's client, CentriCrude Services Inc, wants to improve the efficiency of this process by developing a more effective centrifuge to separate the oil, water, and sediment from crude oil. This project is a continuation of a Phase 1 Capstone project that aimed to create a prototype centrifuge rig intended to inform the design of a large-scale oil separating centrifuge. For this Phase 2 portion of the project, the team's client wants to evaluate the performance of the prototype by visualizing and quantifying the fluid flow in the tank using particle imaging velocimetry (PIV). In PIV, small reflective beads are injected into the fluid and are illuminated by a sheet of laser light. A camera can record the motion of the beads in the light, and the video can be analyzed to quantify the velocity of the fluid flow in the illuminated cross-section. For the centrifuge prototype, this is a complicated task. A stationary laser beam must be deflected using optical components such that the beam ultimately rotates with the tank and forms a sheet that is stationary in the rotating frame of reference. The team developed two subsystems to achieve this goal: an upper rotary system which takes the stationary laser beam and reflects it into the rotating reference frame of the tank, and a lower system which fans the laser beam into a sheet. The team applied thorough mechanical and optical analysis to ensure stability of the optical path and sufficient spreading of the laser sheet. At the time of this writing, the team has begun assembly of the subsystems onto the centrifuge and hopes to have each system aligned and functional as a proof-of-concept for Capstone Day. The project is expected to be continued by Dr. Allshouse and his graduate students.



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For citations and references, please see our Final Report

Need

The team’s client, CentriCrude Services Inc, needs to visualize fluid flow in a centrifuge developed by a prior Capstone team. This is important to the client because it will allow CentriCrude to validate the design of the centrifuge and ensure that the flow is behaving in a manner conducive to extracting oil from refinery runoff. In the future, these types of wastewater separation centrifuges will play a significant role in cleaning up the oil industry. They will reduce the impact on the nearby environment while also maximizing the fuel that can be processed from the world’s finite reserve supply.

Background and Significant Prior Work

This Capstone project is a Phase 2 development of a centrifugal prototype made by a previous Capstone team. The rig is depicted in Figure 1 and is a scale model of the client’s intended larger centrifuge. The rotating drum is filled with water and rotates at 200 rpm. In the client’s application of the centrifuge, crude oil will be injected near the centerline of the rotational axis, and the oil will experience artificial gravity due to centrifugal forces. This increased body force allows the oil to be separated from water far more effectively than just settling from gravity.

The team’s client is interested in measuring the fluid flow out of the feedpipe to evaluate how effectively the incoming flow is merging with water already in the tank. The Phase 1 prototype was designed with a clear observation window, but with insufficient instrumentation to perform the required measurements. In industrial and experimental applications, a technique called particle image velocimetry (PIV) is commonly used to capture precise flow measurements. A PIV schematic from Ayegba and Edomwonyi-Otu is depicted in Figure 2 and consists of an optical system and data processing. For the optical system, a laser is fanned into a sheet and illuminates a cross-section of interest in the fluid flow. Small glass beads are injected into the flow and are visible when in contact with the laser sheet. The flow is then imaged with a high-speed camera, and the data can then be processed to track the location of the beads as they move through the flow. This gives information about the velocity of the fluid at all locations, giving critical information about the flow, turbulence, and shear.

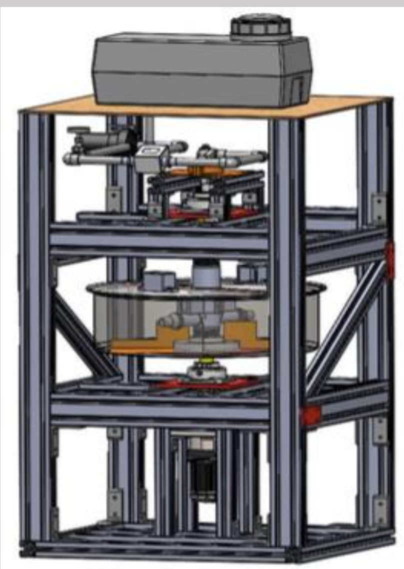

Figure 1. Model of the Phase 1 centrifuge. The upper section contains plumbing which pumps water into the rotating drum in the middle section. This drum is mounted to a motor located in the bottom section of the rig.

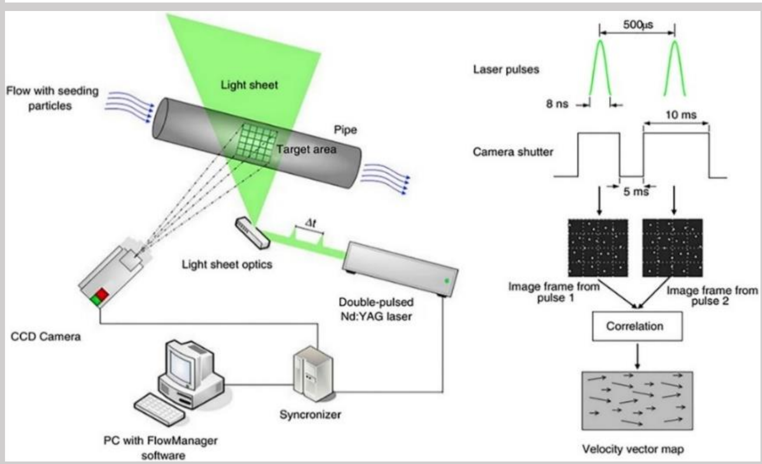

Figure 2. Schematic of a PIV system. A scientific camera observes flow through an illuminated cross-section, and post-processing tracks the locations of the illuminated beads to measure the flow velocity.

The scope of this Capstone project is to design and install the optical system required to perform PIV within the Phase 1 centrifuge tank.

Design Solution

The goal of this project is to create an optical system that converts a stationary laser into two laser beams that synchronously rotate with the centrifuge tank using a series of optical components. The laser beam is then fanned out into a rotating laser sheet using a series of lenses to illuminate the desired plane of the tank. The prototype optical system is separated into an upper subsystem and a lower subsystem. The upper subsystem receives the laser beam directly along the central axis, splits it into two beams, transfers it into the rotational plane of reference, and then reflects both beams downwards into the centrifuge tank. The lower subsystem receives this beam, expands it into a laser sheet using cylindrical lenses and projects it at the area of interest.

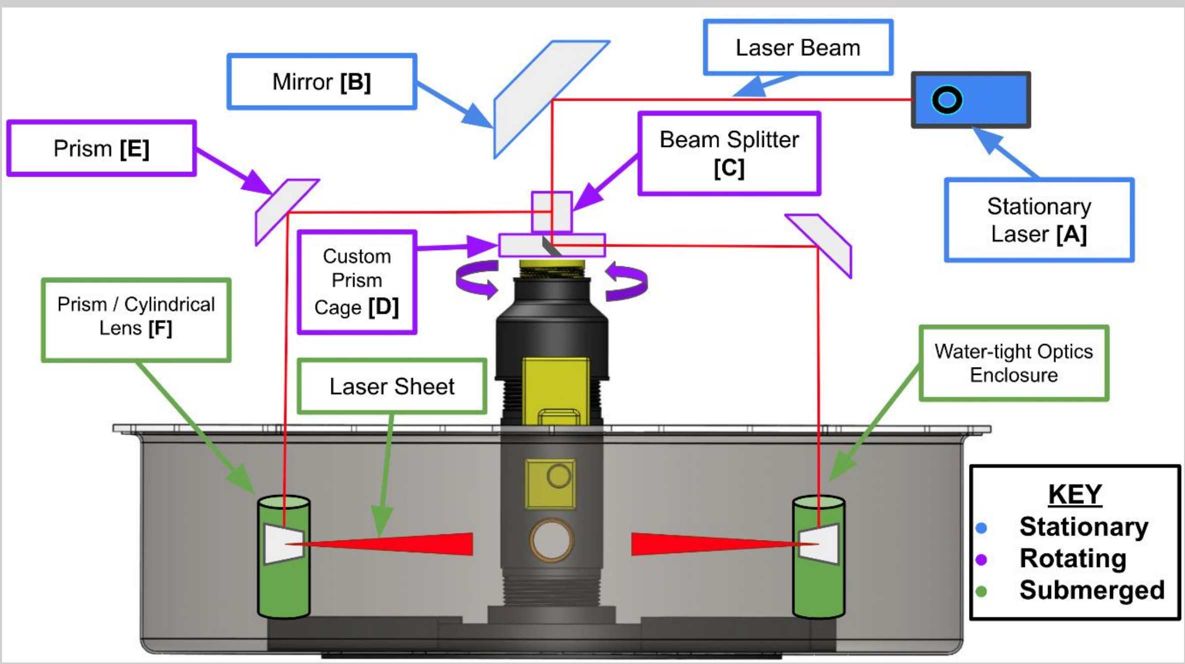

Figure 3. Side view of design solution with lettered components to outline the laser path. The blue parts represent stationary components, the purple parts represent rotating upper assembly components, and the green parts represent rotating lower assembly components.

The path for the laser as it is converted to two rotating beams and subsequently into a laser sheet can be seen in Figure 3 above. The laser beam enters the assembly horizontally from point A, where it is then directed vertically downward at point B by a mirror held at a 45-degree angle directly above the central axis of the tank. The beam then travels downwards and passes through a beam splitter at point C that directs half the beam horizontally outwards from the central axis through an arm system. The second half of the vertical beam then passes through a 90-degree prism at point D, where it is then redirected horizontally outwards from the central axis in the opposite direction through a second arm system. Both of the now horizontal beams travel until they reach 90-degree prisms at point E and are directed downward into the tank. The beams are then received at point F where they are folded and converted to two separate sheets that encompass the desired area of visualization that will be maintained throughout tank rotation.

The upper subsystem is comprised of four arms that are connected to the inside of the feedpipe assembly and therefore rotate with the tank. This system is attached to a rotary union adapter through a connecting rod that passes through a rotary union and has a free end above the top of the assembly. This connecting rod is centered about the axis of rotation and attaches to a series of cubic enclosures that house a beam-splitter and 90-degree prism respectively. One arm attaches to each enclosure that allows each beam to pass through horizontally once the singular beam is split into two beams. The two beams have a vertical offset due to the beam being split at a 90-degree angle and the second beam being redirected horizontally with the 90-degree prism. Two cubic enclosures are attached to the opposite ends of the rods that also house 90-degree prisms that direct the beam vertically downward into the tank. Two additional arms are also present to maintain the symmetry of the system and further ensure stability. This subassembly can be seen with the laser path outlined in red in the lefthand image in Figure 4.

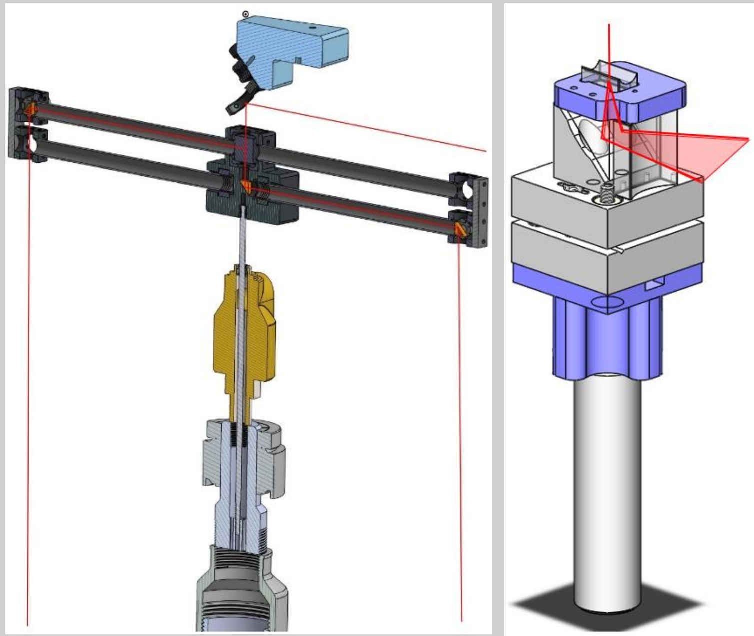

Figure 4. Solid models for the upper subsystem components (section view) and lower subsystem components respectively with the laser path outlined in red.

The lower subsystem is comprised of an optical system that is mounted to the bottom of the tank, as well as an external casing that seals the system from the contents of the tank. The optical components in the lower subsystem are aligned vertically with the prisms mounted on the ends of the arms in the upper subsystem. These components receive the laser beam, create the laser sheet, and fold it into its correct orientation. A custom tip-tilt platform holds the optical components, allowing them to be adjusted using a ball bearing and two screws. A cylindrical lens will receive the beam and fan it into a sheet, which will then be folded using a 90-degree prism. This prism will be able to be adjusted so that the sheet is level with the bottom of the tank. The external casing consists of a polycarbonate casing that is bonded to an aluminum mount that is bolted and sealed to the bottom of the tank. This piece will then be able to be removed so that the optics can be adjusted. This subassembly can be seen in the righthand image in Figure 4.

Design Process

As previously mentioned, this capstone project was a Phase 2 project building a subsystem for a previously assembled prototype. The design process for this project was atypical given that we did not have access to the prototype rig until late in the semester. As such, the team worked to finalize the theoretical design early in the semester, relying on a significant amount of CAD solutions and computational analysis such as Finite Element and Ray Tracing.

Those analysis methods had two main impacts on the final product. Finite Element was used to test the arm thickness needed to support the upper subsystem of the optical system. It was revealed that the 4 skinny Thorlabs arms typically used in Opto-Mechanical Solutions were insufficient for this application. As such, a single, larger arm was designed to the proper specifications. Ray Tracing was used to guide the development of the lower subsystem. In particular, it was used to test the fan angle and tolerances of the laser beam. This guided the design as it showed how cylindrical lenses would be more effective than the sensitive Powell lenses. It also showed how only one cylindrical lens is needed to cover the area of interest with the laser sheet.

At the early stages of the design process, a variety of other designs were proposed featuring various suggestions for additional controls and modified mirror setups. However, using the rotational reference plane of the axle and only redirecting lasers at 90 degrees was determined to be the most foolproof approach. While there were additional concerns about overall system vibration and misalignment, the majority of these could not be modeled with the amount of information available on the rig. As such, minor design modifications were saved for the end of the semester and all alignment tests were done once the entire system was assembled.

Results

The team has successfully verified the individual components of an optical system design to meet the minimum viable product criterion. The laser beam was able to be successfully converted from a stationary source to co-rotate with the centrifuge tank. Furthermore, the laser beam was fanned out into a laser sheet using a set of cylindrical lenses, providing a proof of concept for the client's PIV system.

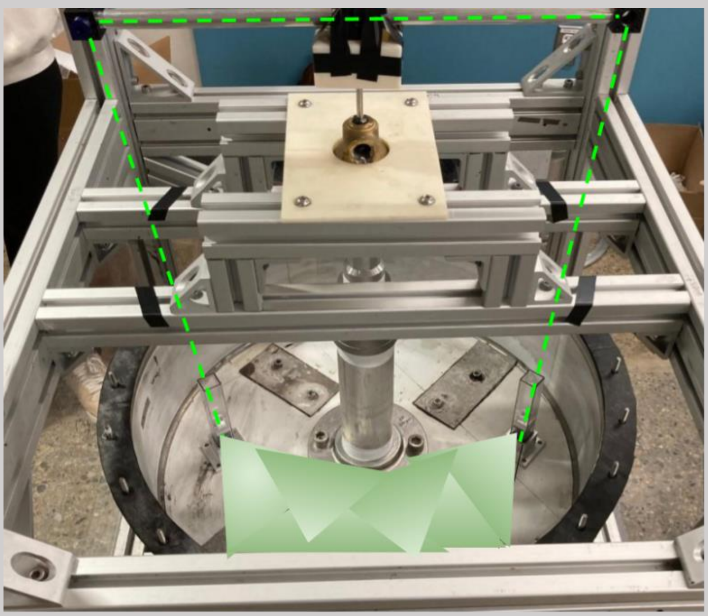

Figure 5. Final assembly with laser components sketched. To make laser sheet visible on capstone day, tank will be filled with smoke and then spun up.

At the time of this document, the team is still in the process of aligning the two systems so that they can be integrated together to create the desired laser path. The figure on the left shows the components of this aligned system and the planned laser path. The team is confident that the static alignment will be successful upon the completion of a few minor components. The team is optimistic that the alignment will hold when the tank is spun up in a demonstration on capstone day. To test this out, the team will fill the rotating tank with photographic smoke so observers can identify the plane of interest an distinguish any potential vibrations, misalignments, or dark spots in the overall system.

Summary and Impact

This project will be continued by Dave and one of Professor Allshouse's PhD students. Now that the opto-mechanical setup is functional, they can run experiments and use Particle Image Velocimetry to analyze the flow. Hopefully, this will allow them to do more technical research on how best to design the spindle of the centrifuge to efficiently separate usable oil from the refinery runoff. While this technique is still far from being ready for industrial use, the team is optimistic that this system will serve as a proof of concept for CentriCrude to invest in larger systems and begin to work with refineries at scale.