Rotating Tank Flow Visualization

Northeastern University College of Engineering

Samuel Koblensky – Lauren Kreder – Justin Miller – Peter Pulai

Background (Motivation)

The separation of crude oil is an inefficient and often wasteful process, producing approximately 18 billion barrels of waste in the US annually, translating to 75 to 150 million dollars of wasted oil per day. CentriCrude Services aims to reduce this waste by developing an efficient centrifuge to extract the remaining oil from the crude oil and water mixtures. This method separates the crude in a few hours compared to gravitational separation, which can take weeks: Figure __ & __. This method of further separating reject crude oil also reduces environmental waste by increasing the percentage of oil used.

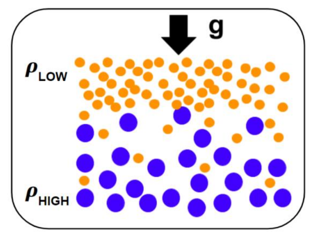


Figure __: Gravitational Separation - weeks to months

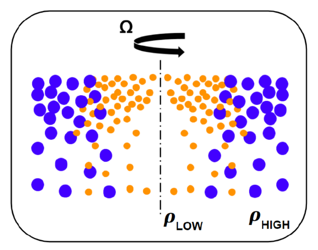


Figure __: Centrifugal Separation - minutes to hours

Problem Statement

The team's client, CentriCrude Services Inc, needs to visualize fluid flow in a centrifuge developed by a prior Capstone team. This is important because it will allow CentriCrude to validate the design of the centrifuge and ensure that the flow is behaving in an unproblematic manner. To visualize the flow, the team will develop a laser-illuminated imaging setup that integrates into the existing system.

Design Overview / Challenges

Design Concept

The design is split into an upper and lower subsystem. The upper subsystem is comprised of the stationary laser pointer and the set of mirrors and rotating arms that transfer the beam into the rotating plane of reference. The lower subsystem contains two stand alone towers enclosed in acrylic tubes designed to accept the beam from the upper subsystem and fan it into a laser sheet that illuminates the section of interest. The design concept can be seen in Figure __ below, where the laser path as it passes through each subsystem is highlighted.

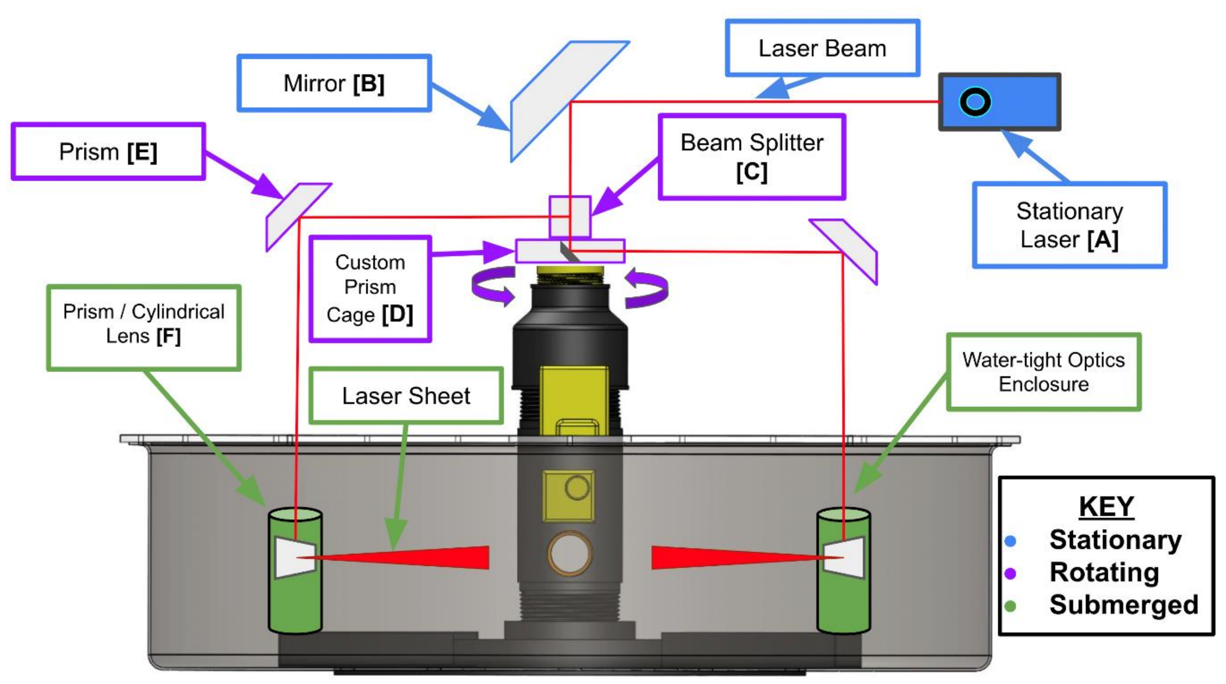


Figure __: Side view of design solution with lettered components to outline the laser path.

Challenges

This design was limited in the sense that it had to fit into the existing prototype rig. This introduced a number of challenges, including the geometry of the 80/20 rig blocking the laser path as well as maintaining the rotation of the system above a fixed rotary union. In addition, existing vibrations present in the prototype were anticipated to cause alignment issues with the optical system.

Analysis: Optical Validation

System Ray Trace

As the system rotates, mechanical misalignments can cause the optical path to deviate from nominal position. Alignment of the laser to the centrifugal rotational axis is the most critical alignment since it affects all components later in the path.

A custom MATLAB script was written to analyze how axial misalignments will affect the laser path, and to create mechanical tolerances for the system. To ensure the laser path consistently hits the beam fanning optics, the laser must be:

- Aligned to within 0.5 degrees to the rotational axis
- Centered to within 0.05 inches

The results of this study enabled selection of prism adjustment platforms and screws to meet the above tolerances.

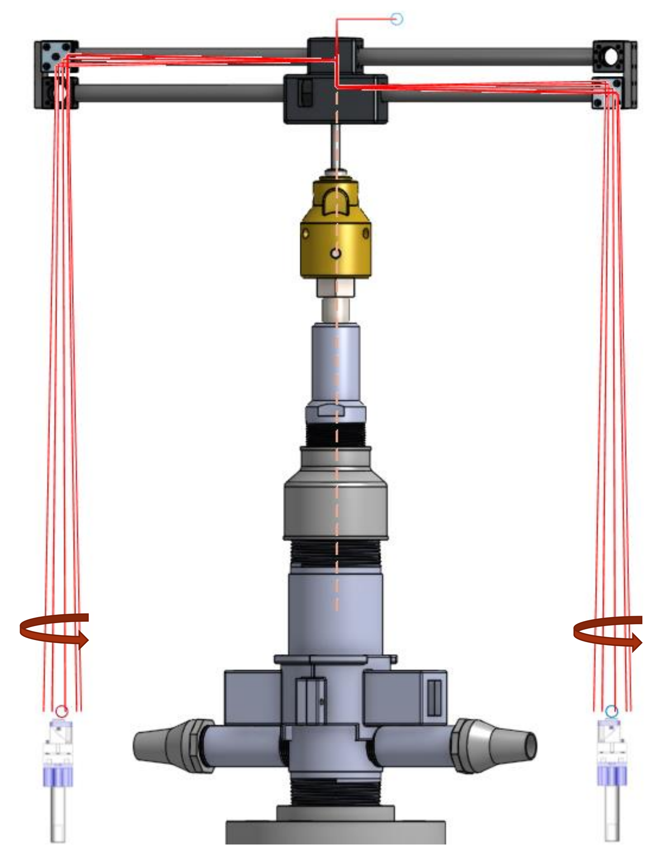


Figure #: Ray trace (red) of laser through system, overlayed over CAD. Axial misalignment causes the rays to trace circles around the nominal path, depicted by the several rays.

Beam Fanning

The laser sheet must optimize the following criteria:

- Takes up minimal space to leave flow undisturbed
- Laser sheet spreads with an angle greater than 50 degrees to cover camera FOV

Ideal beam fanning method was determined through qualitative ray-tracing in Yi-Ting Tu's Ray Optics Simulation Applet. Three options were analyzed, and cylindrical lenses were selected (Figure #):

Method	Resilience to Alignment Errors	Beam Uniformity	Evaluation
Powell Lens	Poor	Excellent	Too Sensitive
Glass Rod	Good	Poor	Too Non-uniform
Cylindrical Lenses	Good	Good	Best Option

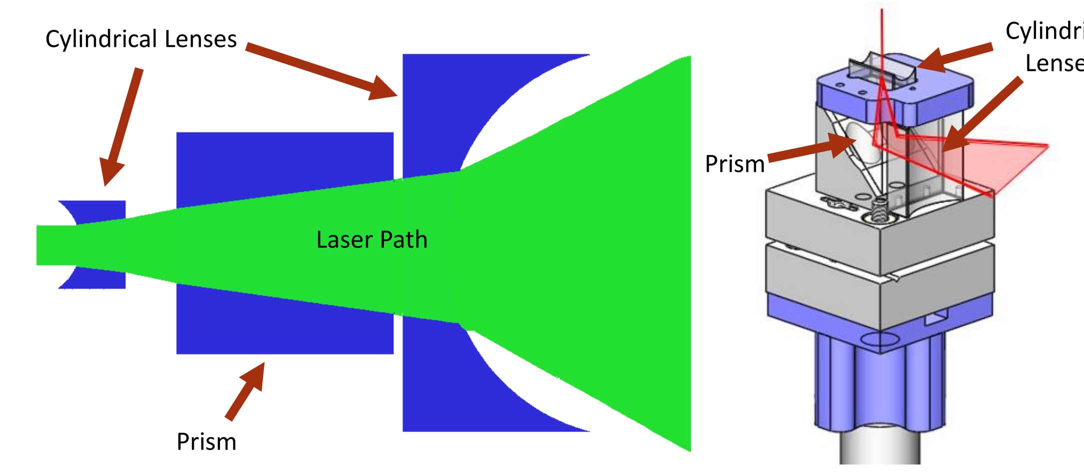


Figure #: Ray trace of laser expanding through 2 cylindrical lenses with prism in the middle (left) and physical implementation of system in CAD (right).

Analysis: Upper Subsystem

SolidWorks Finite Element Analysis

For the arm system, Thorlabs off the shelf cage systems were found to be insufficient compared to a custom arm system made of off the shelf singular rods through SolidWorks FEA. A small displacement was desired to minimize misalignment during full speed rotation.

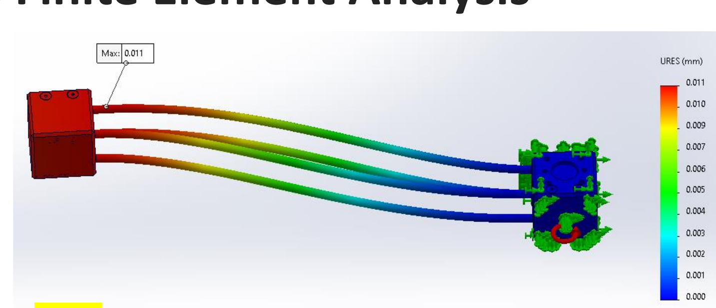


Figure __: Thorlabs arm FEA Result for displacement, showing a maximum displacement of 0.011 mm

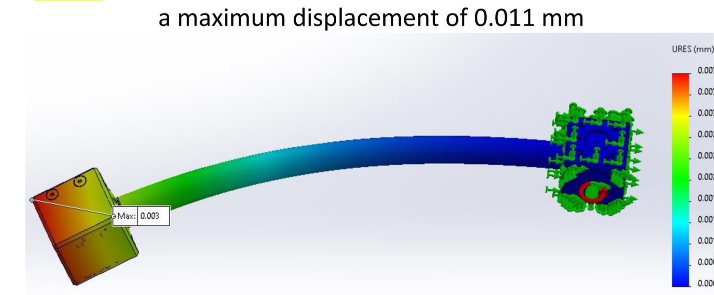


Figure __: Custom arm FEA Result for displacement, showing a maximum displacement of 0.003 mm

Analysis Result	Thorlabs Arm	Custom Arm
Maximum Stress (MPa)	0.679	0.615
Maximum Displacement (mm)	0.011	0.003

OnScale Modal Analysis

Frequency simulation

- Driving frequency of the system at 200 rpm → **3.33 Hz**
- Resonant frequency of the system from modal simulation → **28.137 Hz**
- Resonant frequency >> Driving frequency which indicates that vibration due to resonance will not occur

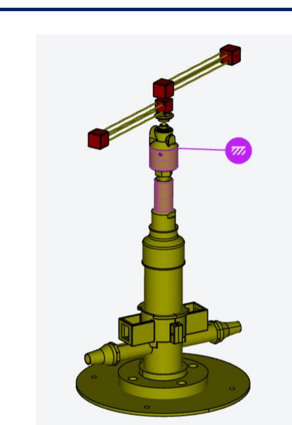


Figure __: OnScale modal analysis simplified model

Analysis: Lower Subsystem

Submerged Module Force / Moment Diagrams

This was performed from a hand calculation, as the components are simple enough to be modelled using hydrostatic equations of solid body rotation at 200 rpm.

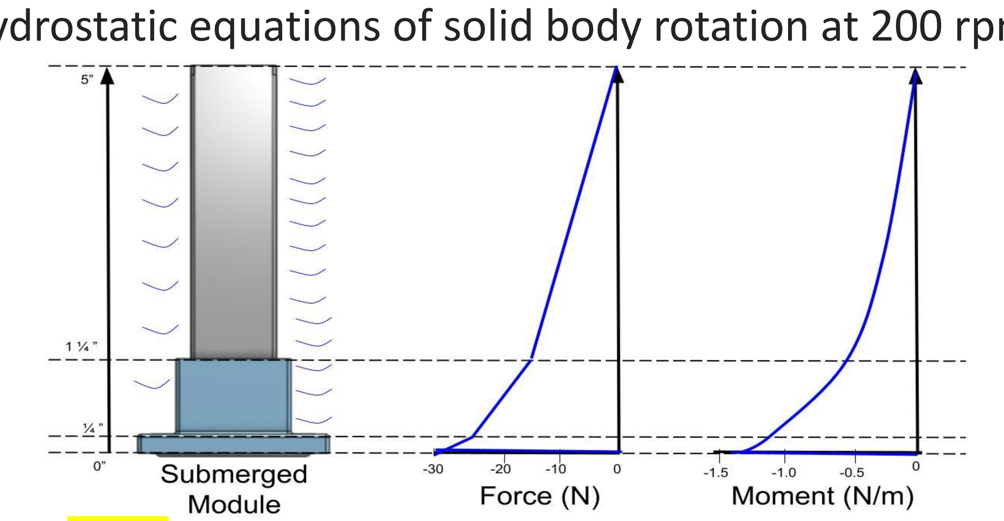


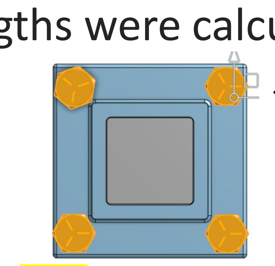
Figure #: Shear Force Bending Moment Diagram for solid body rotation at 200 rpm.

Bolt / Seal Requirements

Using the forces and moments that the modules will experience at full-speed rotation, the required seal specifications and bolt strengths were calculated.

← 18.068 N Compressive Force to seal

Figure __: Zoomed View of O-Ring Face Seal



← Bolt Stresses
σ = 237 kPa
τ = 46 kPa

Figure __: Zoomed View of Bolt Configuration

Given these relatively mild system requirements, a normal O-ring and four medium strength ¼" bolts will sufficiently exceed the requirement for safe operation.

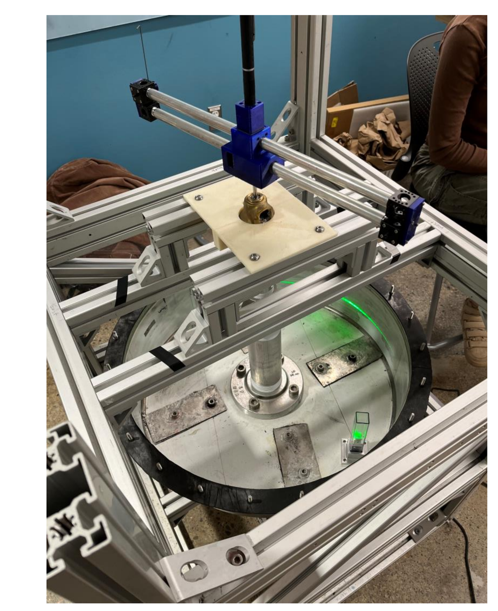
Design Validation

Optical Validation

The optical system was mounted onto the prototype centrifuge for validation. To fully assess the optical path, the tank and central axis were aligned to within 0.05 inches. The upper optical system, consisting of the split path and arms were mounted, and the lower in-tank components were placed in the drum.

The optical path was observed to successfully travel through the two branching arms to the tank, and the beam-fanning optics successfully spread the laser over the desired plane. The beam (figure #) appeared more non-uniform than desired due to poor quality of a plastic protecting sleeve around the optical tower, which can be improved by replacing this part.

To complete the optical setup, a final mirror must be mounted above the rotating arms. Currently, a laser pointer is attached directly to the rotary components as a proof-of-concept.



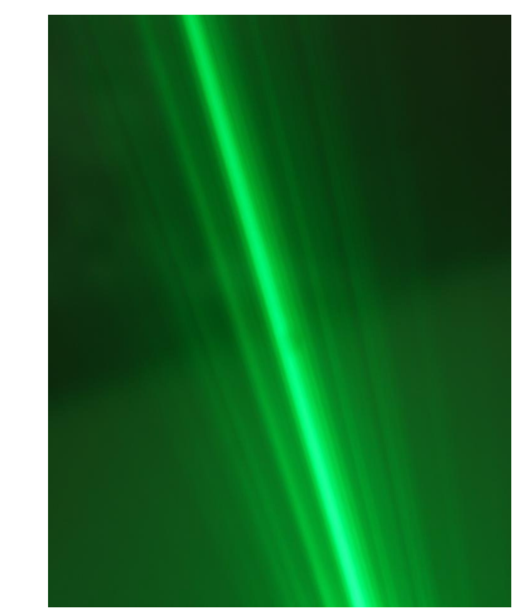


Figure #: Centrifuge rig with mounted optical components (left). The laser sheet can be seen along the back side of the drum. Top view of the laser sheet (right).

Mechanical Validation

The mechanical adjustments for the optical path were sufficient to align the two separate laser sheets. As the tank was rotated by hand, the two sheets remain in good alignment sufficient for PIV application.

To verify if the system is watertight, the drum was filled with a shallow layer of water, and the underside of the drum was observed to find leaks. No leaks were observed, so the system is assumed to be leak-tight under full operation.

While hand-rotating the system, some vibration is observed in the upper optical system. Further testing is necessary to determine if this vibration will be excited during full-speed rotation of the drum.

Future Work / Exit Strategy

The rigidity of the upper subsystem can be increased to reduce vibrations during operation. Other minor features need to be replaced for maximum functionality. For example, the square tubes encasing the in-tank posts introduce additional beam fanning and should be replaced with higher-quality components.

The project will be continued by Prof. Allshouse and his graduate students to complete alignment and run particle image velocimetry (PIV) experiments.

Acknowledgements

This project would not have been possible without the support and insight of our faculty advisor, Professor Michael Allshouse; our client, Dave Park of CentriCrude; and our design reviewers, Dr. Chuck DiMarzio from the Northeastern ECE Department and Matt Honeyman from Optikos Corporation. Thank You!