Rotating Mount for Complex Fluid Flow Research

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WESTERN MICHIGAN UNIVERSITY

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

ROTATING MOUNT FOR COMPLEX FLUID FLOW RESEARCH

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December 4, 2018
ACKNOWLEDGEMENTS

This project was made possible thanks to the guidance and knowledge of Dr. Tianshu Liu, our faculty mentor, as well as the enduring support of David Moussa Salazar throughout countless hours of wind tunnel testing. We would also like to thank David Middleton for all the 3D prints used in this project, Chris Odom and Patrick Dell at MicroMo for their help in selecting a motor and controller, and Michael J. Konkel as well as everybody at the Student Projects Lab for their aid in the fabrication of the aluminum mount. Last, but not least, we would like to give a big thank you to Amanda Hoger in the Mechanical and Aerospace Engineering Department for her assistance in ordering all the supplies needed for this project.
DISCLAIMER

This Senior Design Project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations who choose to use this material do so at their own risk.
ABSTRACT

Fluid flow around rotating objects is mathematically complex and there is currently limited experimental data on the subject. To make Western Michigan University capable of this research, a rotating wind tunnel mount was developed. The mount design was integrated into the existing setup at the Applied Aerodynamics Laboratory (AAL) to allow seamless transitions between different research projects. Non-rotating and rotating disk prototypes were created from 3D-printed materials to test the mount’s capabilities. Experimental data gathered from utilizing this rotating mount was analyzed to understand the aerodynamic effects on rotating disks in a fluid stream. From testing the rotating disk prototype at 15 m-s\(^{-1}\), with a disk rim to airspeed ratio of 1, and at angles of attack between 0 and 7.5 degrees, it was found that the rotation of the disk increased drag and reduced lift. While this may be due to the lack of precision in the design and data gathering, this result directly opposes studies suggesting that rotating disks in a fluid stream may reduce drag and increase lift (Nakamura, 1991). Further testing is recommended to ensure the validity of this data, as there is uncertainty on the aerodynamic effects from the mount itself and the unsteady motion caused by the imperfections in the fitment of the shaft. There is also uncertainty on the effects from the non-symmetric local velocity distribution along the surface of the rotating disk due to single-axis force measurements.
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LIMITED STUDIES have been conducted on the aerodynamic effects of skin friction on a rotating disk in a freestream. However, rotating symmetrical bodies may provide an increase in lifting forces due to increased downwash from flow vortices downstream of the disk (Nakamura, 1991). If this can be quantified robustly, the accuracy of computational fluid dynamics (CFD) software can be increased. Additionally, unmanned aerial vehicle (UAV) applications may benefit from the use of rotation due to the decreased need for operational power caused from increased rotational stability and lift. To collect empirical data for these purposes, Western Michigan University’s small wind tunnel in the Applied Aerodynamics Laboratory (AAL) must be outfitted with a mount and actuation system that will rotate a removable Frisbee while measuring the aerodynamic forces and moments produced.

Background Research

A study on the aerodynamics of a rotating disk concluded that the rotation of the disk provides gyroscopic stability that is resistant to pitch moments that typically cause a non-rotating, flat object to tumble like a leaf (Potts & Crowther, 2002). This study tested 3 disks of various cross-sections in a wind tunnel at airspeeds of 6 to 20 m-s⁻¹, at spin speeds quantified by a disk rim speed to airspeed ratio that is equal to 1, and at angles of attack between -10 to 50 degrees. The disk was mounted to an “L-shaped rig,” such that the length of the disk was parallel to the direction of gravity (Figure 1). The disk was rotated by a motor and shaft, and the aerodynamic forces were measured using a 6-component, overhead balance.

Figure 1: Potts & Crowther's L-Shaped Rig

Another study, by Nakamura and Fukamachi in 1991, offers discussion on how lift is generated on a disk by the intensified downstream vortices when the disk is rotating rather than stationary. This study tested a single disk geometry at an airspeed of 1 m-s⁻¹, at spin speeds of 0 to 3 rpm, and
at an angle of attack of 0 degrees. The disk was rotated by an electric motor and shaft that held the length of the disk perpendicular to the direction of gravity (Figure 2). Smoke-generating wire and cameras were used to visualize the flow over the surface and immediately downstream of the disk, which were illuminated by a projector far downstream of the test section.

![Figure 2: Nakamura & Fukamachi's Test Arrangement](image)

The study above examined the flow around a rotating disk using smoke-generating wire, but the results are only qualitative, not quantitative. In 2009, Woodiga and Liu’s study on delta wings utilized a global luminescent oil-film skin friction meter to obtain both flow visualizations along the surfaces of the wings as well as quantitative skin friction results. A thin coating of luminescent silicon fluid was applied to the surface of the test geometry and a camera was used to capture the flow patterns illuminated by UV light in a dark room at 25 fps. MATLAB was then used to process the images and obtain quantitative skin friction measurements. The delta wings were tested at angles of attack from 0 to 20 degrees and a free-stream velocity of 20 m-s\(^{-1}\). Although this testing was done on a stationary geometry (Figure 3), it is possible to apply this same process to a rotating disk.
Objective

A mount and actuation mechanism must be produced to test the aerodynamic forces produced by a rotating disk in the small wind tunnel at Western Michigan University’s Applied Aerodynamics Laboratory. With this design, empirical data can be collected on the aerodynamic effects of skin friction on multiple rotating disk geometries.
DESIGN PROCESS

Design Requirements

The biggest limitation the wind tunnel posed on the design of the mount was that the existing supports could not be removed and had to stay where they were so other tests being performed in the small wind tunnel could utilize them. Figure 4 depicts these two supports in the small wind tunnel.

While these supports provide a way to measure lift and drag forces, as well as adjust the pitch angle of the test geometry, they also severely restrict the amount of testing area. Because the mount must attach to the pin connections at the top of the force gauge and pitch actuator, the mount and test disk geometry can only be a maximum of six inches before getting too close to the top of the wind tunnel.

The disk and motor must also be located directly in the center of the force gauge and pitch actuator in order to obtain accurate force measurements. In addition, the mount needs to have minimal impact on the airflow around the disk to not distort skin friction oil results and force measurements.

Aside from the wind tunnel restrictions, the mount is required to provide rotational velocity in the range of 1,000 rpm up to 3,000 rpm to the test disk geometry and allow for precise control of this velocity. The disk must also be interchangeable so that testing may be done on various geometries. Finally, testing should be able to be performed at pitch angles from 0 to 15 degrees.

Conceptual Design

Multiple concept designs for the mount were considered during the early brainstorming process, the most unique of which was based on the swashplate of a helicopter. But, after gaining access to Western Michigan University’s Applied Aerodynamics Lab and taking measurements of the
mount connections and wind tunnel testing area, the design options were narrowed down to two basic concept designs. This was due to the strict space limitations in the small wind tunnel and the necessity that the design mount to the current force gauge and pitch actuator configuration.

Both conceptual designs employ a DC motor to rotate the test disk. The motor is attached to a base mount that is pin supported by the force gauge and pitch actuator. The motor in each design is wired to a PWM controller which is then connected to the wind tunnels DAQ module so that the rotational speed can be adjusted using the LabVIEW program that controls the wind tunnel. A PWM, or pulse width modulation, controller varies the average voltage signal sent to the motor by turning the signal on or off for a certain amount of a duty cycle. The longer the voltage is turned off per duty cycle, the lower the average voltage seen by the motor will be. The speed of the motor is directly proportional to this voltage. The DAQ, or data acquisition, module gathers and sorts all the data signals being sent from the system to the LabVIEW program and vice versa, allowing the wind tunnel operator to control the instrumentation and be able to see the status of the instrumentation and any measurements recorded.

The first concept design utilizes a standard DC motor. It’s offset to the side since its height would not allow the required range of pitch angles if it were mounted in-between the supports. Figure 5 shows the preliminary CAD model for this design.

![Figure 5: Concept Design 1 with Standard DC Motor](image)

The second concept design makes use of a flat, or pancake, DC motor. This motor is larger in diameter but, because of its significantly shorter height, it is possible to mount it in-between the force gauge and pitch actuator and still be able to test a large range of pitch angles. The preliminary CAD model for this design is shown in Figure 6.
The exact method for attaching the disc was still under consideration in the conceptual phase, with the leading idea being to adhere the disk to a small threaded connector that screws onto an aluminum shaft coming out of the motor. Multiple of these disc connectors could be fabricated to enable quick testing and swapping of specimens.

The size of both motor types needed to meet the torque required to rotate the disk as well as the cost of machining the mount design needed to be examined for the final design.

Motor Selection

Torque Calculations

The most important factor when deciding on a motor was the maximum torque the motor could output. Usually the continuous torque required by the application is used to select a suitable motor, but it wasn’t possible to calculate this due to the complexities of the flow and the CFD software available for use. Therefore, the start-up torque required to bring the disk from standstill up to speed was used since this would be the maximum torque seen by the motor.

It was known that Potts and Crowther used a disk rim to air speed ratio of 1, from the background research conducted, but a skin friction study using luminescent oil on a disk had never been performed before and the exact rotational speed that would produce usable test results was unknown. So, although using start-up torque rather than continuous torque would likely cause the motor selected to be overkill, this excess available torque provides a margin of safety in case the disk rim to airspeed ratio needs to be increased to obtain good skin friction oil flow images. It’s also possible that the acceleration time for the disk to reach speed would need to be changed during testing, depending on its effects on the oil flow, and reducing this time would also increase the torque the motor sees. This torque calculation may seem pointless with all these unknowns, but
it’s a good starting point and required by motor suppliers. The density of the luminescent oil can also be adjusted during testing to aid in imaging the flow patterns.

In order to find the torque required to rotate the test disk geometry, the mass of the geometry had to be found first. Knowing the dimensions of the test disk geometry and the density of the 3D printing material used, the mass of the geometry was found in two parts.

\[ \text{Equation 1} \quad m_{\text{disk}} = \frac{\pi}{4} d_{\text{disk}}^2 h_{\text{disk}} \rho \]

\[ \text{Equation 2} \quad m_{\text{shaft}} = \frac{\pi}{4} \left( d_{\text{shaft},0}^2 - d_{\text{shaft},i}^2 \right) h_{\text{shaft}} \rho \]

Using the equations above with a density of 1.25 g/cm³ for PLA, the mass of the disc was found to be 237.5 g and the mass of the shaft 6.36 g. With the mass of the disk and shaft for the geometry, it was possible to find the moment of inertia of both sections and then combine them to use in the torque calculation.

\[ \text{Equation 3} \quad I_{\text{disk}} = \frac{1}{8} m_{\text{disk}} d_{\text{disk}}^2 \]

\[ \text{Equation 4} \quad I_{\text{shaft}} = \frac{1}{8} m_{\text{shaft}} \left( d_{\text{shaft},0}^2 + d_{\text{shaft},i}^2 \right) \]

\[ \text{Equation 5} \quad I_{\text{geometry}} = I_{\text{disk}} + I_{\text{shaft}} \]

With the masses known from equations 1 and 2, the moments of inertia for the disk and shaft were found to be 0.479 g-m² and 1.86E-6 g-m², respectively, giving a moment of inertia of 0.479 g-m² for the entire geometry. Assuming the maximum speed that would be used for testing is 3,000 rpm and using the same start-up time as the wind tunnel turbine of 5 seconds, the angular acceleration of the disk was found to be 62.8 rad/s² using the equation below.

\[ \text{Equation 6} \quad \alpha = \frac{\omega}{t} \]

Finally, having the moment of inertia and the angular acceleration of the geometry, the torque required to rotate the geometry was found using the equation below. This is also the torque output required by the motor.

\[ \text{Equation 7} \quad T = I_{\text{geometry}} \alpha \]

Finding a max torque of 30.1 mN-m immediately ruled out the use of a flat DC motor as their stall torques are only 2-4 mN-m, in this size range, which would only be able to provide a rotational velocity of 300 rpm with an acceleration time of 5 seconds. A flat DC motor with a high enough torque would be way too large for this application so a standard DC servomotor was decided upon.

**Wind Tunnel Results for Axial Force Requirements**

Since these motors are typically used at speeds around 30,000 rpm and skin friction testing will be performed at speeds potentially as low as 300 rpm, motors with an integrated gearbox were considered. Although an integrated gearbox slightly increases the length of the motor, it makes it possible to control the motor at lower speeds. Looking at motors with integrated gearboxes
revealed that they could only handle 1 N axial and radial loads at the shaft. This low force was concerning, so testing was conducted on the static geometry in the wind tunnel. The drag and lift forces can be found in Table 1 and Table 2 and were calculated using Equation 8 and Equation 9 from the Force Measurements section.

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Drag (N)</th>
<th>Lift (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.36</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>0.46</td>
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<td>0.58</td>
</tr>
<tr>
<td>15</td>
<td>0.46</td>
<td>0.88</td>
</tr>
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</table>

<table>
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<th>Angle of Attack (°)</th>
<th>Drag (N)</th>
<th>Lift (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.86</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.87</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>0.92</td>
<td>0.03</td>
</tr>
<tr>
<td>9</td>
<td>0.92</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>0.97</td>
<td>0.06</td>
</tr>
<tr>
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<td>1.01</td>
<td>0.26</td>
</tr>
<tr>
<td>15</td>
<td>1.04</td>
<td>0.12</td>
</tr>
</tbody>
</table>

After reviewing the data, it was found that the motor would experience radial forces greater than integrated gearbox motors are rated for. Consulting the Engineers at MicroMo led to the selection of a motor with internal analog halls paired with a motion controller. This motor could withstand 5 N axial forces and 15 N radial forces, making it strong enough for the loads observed on the disk during testing. Although the motor with analog halls and motion controller was more expensive, the project was estimated to use only a third of the budget, so this price increase was acceptable.

Summary

The motor selected for the rotating disk mount was a Faulhaber brushless DC servomotor from the 3242-BX4 series with a MCBL 3006S motion controller. Figure 7 and Figure 8 show the motor and controller, respectively.
With a height of 44 mm and diameter of 32 mm, this was the smallest motor available that met the disks torque requirement and had analog halls. The motion controller was more expensive than a speed controller but doesn’t require the adapter that the speed controller does, so it ended up coming out to the same price. It is also smaller than the speed controller in combination with the adapter, with a width of 65 mm and a height of 58 mm.

Mount Design

Motor and Wind Tunnel Limitations

The mount must be pin connected to the wind tunnel supports and be able to house the selected motor with dimensions of 32 mm in diameter and 44 mm in length. The motor should ideally attach to the mount at the top plate of the motor with 6 screws but can be clamped by the base if needed. The motion controller with dimension of 58 mm by 65 mm needs to be as close as possible to the motor for accurate speed control, therefore should also attach to the mount. The mount design also needs to be minimally intrusive in the test space to not cause drag and disturb the flow around the test geometry.
Conceptual Designs

The original conceptual design for the mount was to be machined out of aluminum so that the motor could be positioned between the force gauge and pitch actuator, maximizing the distance between the mount assembly and disk geometry and minimizing interference with the airflow around the disk. However, after selecting a motor and taking measurements at the wind tunnel, it was found that positioning the motor in-between the supports would not allow the required range of pitch angles for testing. To solve this problem, the mount was extended so that the motor is positioned above the supports. Figure 9 depicts this design concept. It was modeled in Autodesk Inventor and includes 6 holes to connect the top plate of the motor to the mount along with a cutout for the shaft, pinholes at the bottom to connect the mount to the wind tunnel supports, and holes on one side to connect the motion controller.

![Figure 9: Isometric View of Machined Mount Design](image)

Presenting the mount design to the College Machine Shop at Parkview campus revealed a backlog of a couple months before work could begin on the mount followed by a lead time of one month. On top of that, the tooling and labor costs were estimated to be hundreds if not thousands of dollars. This did not conform with the budget or timeline of the project, so a new concept for the mount had to be considered.

A suggestion was made to fabricate the mount at the WMU Student Projects Lab using common stock shapes like rectangular tubing and U-channel that can be cheaply purchased. Studying the machined mount design, it was obvious that the main body of the mount that contains the motor could be fabricated out of a piece of rectangular tubing. A U-channel welded to the bottom was suggested to provide a place to attach the mount to the pin supports but for design simplicity, two holes were instead added to the bottom of the rectangular tube so that it could be bolted to the existing wind tunnel mount. This way the mount would have a perfect fit with the wind tunnel supports since the U-channel didn’t come in the exact size required and spacers would need to be
used. **Error! Reference source not found.** depicts this revised mount design that attaches to the existing wind tunnel mount pictured in Figure 11.

![Isometric View of Final Mount Design](image1)

**Figure 10: Isometric View of Final Mount Design**

![Existing Wind Tunnel Mount](image2)

**Figure 11: Existing Wind Tunnel Mount**

During assembly of the mount, it was found that the wrong CAD was provided for the motor and the analog halls slightly increased the length, making it too tall to fit inside the mount. To solve this issue, a channel was cut into the top of the mount to provide clearance for the motor shaft during insertion of the motor.

**Materials and Resources**

The motor mount was made from 6061 Aluminum rectangular tube with ¼” wall thickness and outer dimensions of 2” by 3” that was purchased from McMaster-Carr. A vertical mill and bandsaw were used in the Student Projects Lab to fabricate the mount. M3-.50 screws and bolts were purchased from Lowe’s to attach the motor and controller.
Summary

Although the final mount design is not ideal and could be improved significantly with more time and funding, the question arises of would the massive increase in cost to machine a mount be justifiable for the scope of the project? The conclusion reached at this time is no. And recommendations made at the end of this report provide possible improvements to the mount that would make it more aerodynamically efficient than its machined counterpart.

Shaft Design

The shaft connects the motor and disk geometry and drives the rotation of the disk. The shaft must provide adequate structural strength to withstand bending moments mostly caused by drag, it must be long enough to reduce flow contamination from the motor and mount while being short enough to allow a wide range of angle of attack for the disk, and it must be easily assembled and disassembled from the motor for interchangeability. Shaft concepts must also consider how the shaft is connected to the motor and disk. The required shaft connections must be robust, aerodynamic, and intuitive.

Conceptual Designs

An aluminum shaft with shaft couplers and a 3-D printed shaft-disk unit were considered for this application. The aluminum shaft would connect to the motor shaft by a shaft coupler. Two set screws would provide squeeze onto the two shafts, which would transfer the motor torque to the shaft. The disk would connect to the shaft by interference fit at the top, or with another coupler, depending on the disk material. The 3-D printed shaft-disk unit would be printed as one piece and connect to the motor shaft with an interference fit.

Decision Matrix

Both designs have drawbacks. The aluminum shaft has many parts that may interfere with the flow, but it is structurally robust. The 3-D printed unit is made of plastic that may fracture under enough bending force, but it is simple and provides less flow interference. Other important considerations are lead times and material compatibility. A decision matrix was created in order to make the best choice (Table 3).

<table>
<thead>
<tr>
<th></th>
<th>3-D Printed Unit</th>
<th>Aluminum Shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength (20)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Simplicity (20)</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Lead Time (30)</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Material Compatibility (30)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Total (100)</td>
<td>80</td>
<td>75</td>
</tr>
</tbody>
</table>
Summary

The 3-D printed unit was found to be best for this application because Western Michigan University’s 3-D printing resources provide turn-around times within hours. While the strength of the plastic material is less than the strength of the aluminum shaft, the application does not require the shaft to be aluminum. Additionally, while the plastic material is more susceptible to the heat generated by the motor than the aluminum shaft, the motor will be running for short periods of time and subjected to convective cooling.

Geometry Design

The small wind tunnel at AAL has a small test section, which limits the size of the disk. The disk must be large enough to have measurable aerodynamic effects, but small enough to fit within the test section at all angles of attack.

Non-Rotating Geometry

The intent for the non-rotating geometry was to conduct preliminary tests to select a motor that can tolerate the forces acting on the disk. The geometry was reverse engineering from the Mini Driver disk from Innova® Disc Golf (see Appendix A – Miscellaneous Figures, Figure 31). The geometry was scaled from 4 inches to 5 inches in diameter, and the lower surface of the disk was filled in to reduce turbulence for the preliminary tests. The disk geometry was mounted to a vertical plate, which connects to the pre-existing mount configuration in the wind tunnel. Error! Reference source not found. and Error! Reference source not found. show the 3-D CAD model of this geometry.

Figure 12: Non-Rotating Geometry (Isometric View)
Rotating Geometry

The rotating geometry diverges from the non-rotating geometry by removing the filling on the lower surface of the disk. The rotating design also utilizes a cylindrical shaft instead of a mounting plate. The shaft length was chosen to be 3 inches to maintain clearance between the test section walls while also staying out of the turbulent wake of the mount. The shaft is hollow to allow for an interference fit with the motor shaft, which saves on material costs when compared to an aluminum shaft with shaft connectors. Error! Reference source not found. and Error! Reference source not found. show the 3-D CAD model of this design.
Materials and Resources

Both geometries were 3-D printed using the Ultimaker S5 3-D printer at the 3-D Print Lab in Western Michigan University’s Floyd Hall. MatterHackers PRO Series PLA material was used for both prints. Post-processing of the prints consisted of warm water soaks to dissolve the support material and sanding the surfaces that were supported by this material.

Cost Analysis

The overall budget for the project was $1500. This was made possible by each group member receiving a $500 Undergraduate Research Excellence Award (UREA) from the Office of the Vice President of Research (OVPR). The largest purchases came from the servomotor and the controlling. In the end, the project ended up costing a total of $673.47, which is broken down by component in Table 4.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
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<tbody>
<tr>
<td>6” 6061 Aluminum Rectangular Tube</td>
<td>$20.70</td>
</tr>
<tr>
<td>DC Motor</td>
<td>$305.20</td>
</tr>
<tr>
<td>Motion Controller</td>
<td>$239.40</td>
</tr>
<tr>
<td>Motor/Controller Adapter</td>
<td>$20.00</td>
</tr>
<tr>
<td>Null-Modem to USB Connector</td>
<td>$18.70</td>
</tr>
<tr>
<td>DC 24V Power Supply</td>
<td>$19.99</td>
</tr>
<tr>
<td>3D Prints</td>
<td>$40</td>
</tr>
<tr>
<td>Spray Paint</td>
<td>$3.49</td>
</tr>
<tr>
<td>Screws &amp; Nuts</td>
<td>$5.99</td>
</tr>
<tr>
<td>Total</td>
<td>$673.47</td>
</tr>
</tbody>
</table>

*Table 4: Cost of Design Summary*
Final Design

The motor will be bolted to the top of the mount so that the motor will be enclosed by the mount. The controller will be bolted to the outside of the mount, this is so that the motor wires will be as short as possible. The rotating geometry will be fit onto the motor shaft through the hole in the top of the mount, where an interference fit will hold it into place. This entire unit will be installed onto the supports in the small wind tunnel and fixed there with pins. A 3D CAD model of the assembly is shown in Error! Reference source not found. through Error! Reference source not found.

Figure 16: Isometric View of Final Design CAD
Figure 17: Gantt Chart for Entire Project
CFD ANALYSIS

ANSYS Fluent was used to model the pressure on the upper surface of the disk in a freestream of 15 m·s⁻¹ (Error! Reference source not found.). No angle of attack was given to this model, and a viscous k-epsilon model with default coefficients was computed. Positive pressure represents pressure directed into the surface, while negative pressure is directed out of the surface.

![Figure 18: Top View of Pressure Contour on Non-Rotating Geometry](image)

Suction pressure was experienced on most of the upper surface due to the aggressive fillet on the leading edge. The surface near the trailing edge of the disk experienced larger suction pressure because the trailing edge is symmetric to the leading edge, which causes flow separation. These results can be compared to very similar to the images captured during the oil tests.

TEST PROCEDURE

Sample Prep

When the test disk geometry is first received from the printing lab, the surface is rough and uneven due to the printing process. The image below shows the disk geometry before any test preparation.
Skin friction oil analysis requires a test geometry with a smooth even surface, so the geometry needs to be sanded. A low grit sandpaper is started out with to even out the surface and the grit is slowly increasing until a fine sandpaper is used to make the surface smooth. At this point a mylar sticker would be applied to the surface of the test geometry but flat white spray-paint was used in this case, since it is difficult to apply a sticker to a curved geometry.

**Force Measurements**

In order to obtain force measurements on the geometry, the geometry is first mounted to the force gauge and pitch actuator in the wind tunnel. The dynamic pressure in the wind tunnel is then used to find the scalar on the speed controller in the wind tunnels LabVIEW program that corresponds to the target air velocity. Figure 20 is a screenshot of the controls interface for the LabVIEW program used by the wind tunnel. The airspeed is adjusted with the slider on the left and the angle of attack is adjusted using the dial in the center.
Once the airspeed of the wind tunnel is set to the desired speed for testing, the lift and drag force outputs from the wind tunnel displayed on the right of the control panel are observed until they reach steady-state. Once the wind tunnel is at steady-state, the voltage readings for lift and drag can be recorded. The angle of attack is then changed to the next desired test angle and the lift and drag forces on the test geometry are again recorded after waiting for the wind tunnel to reach steady-state.

Skin Friction Oil Analysis

Because skin friction oil analysis is based on imaging the intensity of illumination of the oil, precise control of the lighting in the test facility is required. For this purpose, all the facility windows are blacked out with tarps and all the lights turned off except for the UV lamps being used for testing. In a setup similar to Woodiga and Liu’s, a UV lamp is positioned on each side of the wind tunnel testing area so that they shine down on the top surface of the disk. A high speed camera with a high pass filter is positioned directly above the test geometry as shown in Figure 21. The camera is then adjusted to the correct focal length by laying a piece of paper with writing on top of the geometry and focusing on it.
Silicon fluid with luminescent particles mixed in is then applied to the surface of the test disk in a thin even coat using a sponge brush. It is necessary to let the oil rest for a minute before testing so that any brush strokes dissipate. Figure 22 shows a close-up image of the static geometry prepared for skin friction oil analysis.
Finally, the wind tunnel turbine is turned on at the same moment the camera is set to start recording. Through trial and error and studying the resulting images, the flow pattern of the skin friction oil is dialed in by adjusting the oil viscosity. The sample rate of the camera is also adjusted so the images captured show a good amount of change in flow pattern between images.
TEST RESULTS

Force Measurements

Non-Rotating Geometry (Preliminary Tests)

The non-rotating geometry was installed into the small wind tunnel using pre-existing mounting equipment. The zeroing-values for the lift and drag voltages were recorded before the wind tunnel was turned on. The geometry was then subjected to 10 m-s\(^{-1}\) and 15 m-s\(^{-1}\) of flow at angles of attack ranging from 0 to 15 degrees. The lift and drag voltages were recorded at each angle of attack and speed. The voltage data collected from this test was converted into Newtons of force using Equation 8 and Equation 9, the coefficients of which are calibration values determined by the wind tunnel operators. The lift and drag coefficients were calculated from the lift and drag values using Equation 10 and Equation 11, where \(\rho\) is the density of air (1.225 kg-m\(^{-3}\)), \(U\) is the airspeed, and \(A\) is the area of the upper surface.

\[
\text{Equation 8} \quad L = 613980V_L \\
\text{Equation 9} \quad D = 139182V_D \\
\text{Equation 10} \quad C_L = \frac{L}{\frac{1}{2}\rho U^2 A} \\
\text{Equation 11} \quad C_D = \frac{D}{\frac{1}{2}\rho U^2 A}
\]

The coefficients of lift and drag were plotted against angle of attack for both speeds to compare the aerodynamic effects at varying angles of attack (Figure 23 and Figure 24). It should be noted that in the 10 m-s\(^{-1}\) test, angles 3, 6, 9, and 12 degrees were tested AFTER angles 0, 5, 10, and 15 degrees, which may explain the variation in the data.
Rotating Geometry

The rotating geometry and motor mount assembly was installed into the small wind tunnel. The zeroing-values for the lift and drag voltages were recorded before the wind tunnel was turned on, and then the assembly was subjected to 15 m-s\(^{-1}\) of flow. The lift and drag voltages were recorded at 2.5 degrees intervals from 0 to 15 degrees. The voltage data collected from this test was
converted into Newtons of force using the Equation 8 and Equation 9. The lift and drag coefficients were calculated using Equation 10 and Equation 11.

The coefficients of lift and drag for both rotating and static tests were plotted against angle of attack (Figure 25). It is shown that lift decreases and drag increases when rotated.

\[
\begin{align*}
C_L &\text{ - Rotating} \\
C_D &\text{ - Rotating} \\
C_L &\text{ - Static} \\
C_D &\text{ - Static}
\end{align*}
\]

**Figure 25: Coefficients of Lift and Drag at Various Angles of Attack (Rotating, 15 ms\(^{-1}\))**

Due to inefficiencies in the shaft design, the rotating geometry detached from the motor at an angle of attack of 10 degrees. The geometry was not recovered from the wind tunnel, and further testing was postponed. Due to time constraints, the rotating geometry did not undergo further tests, including the skin friction oil test.

**Skin Friction Oil Analysis**

*Non-Rotating Geometry*

The geometry was fitted with a Mylar sticker after sanding the upper surface, and then it was subjected to 15 m-s\(^{-1}\) of flow at 0 angle of attack. Due to the geometry of the upper surface, the Mylar could not adhere to the entire upper surface, and only a portion of the upper surface was captured. Pictures were taken at a frequency of 10 Hz for 2,000 frames, and Figure 26 through Figure 28 are stills at 15.1, 45.1, and 90.7 seconds into the test. Darker areas indicate that the oil layer is thinner, and lighter areas indicate that the oil layer is thicker, due to the luminescent particles in the oil.
Pressure on the rounded leading edge began pushing the oil along the chord of the upper surface, creating the darker wisps seen in Figure 26. Turbulent flow on the trailing edge of the flat upper
surface began developing at this time, which spread to immediately behind the leading-edge void on the left side (Figure 27). At 91 seconds (Figure 28), the oil on the upper surface began to thin across the entire surface, seemingly reducing the turbulence on the trailing edge and breaking the leading-edge void at the 0-chord point. However, this is most likely due to the transient effects of the oil in the flow, and not a change in the skin friction on the geometry. The non-symmetric nature of this flow (across the geometry’s chord line) can be attributed to the uneven surface created when the part was sanded smooth by hand.

**Rotating Geometry**

Due to inefficiencies in the shaft design, the rotating geometry was unable to undergo skin friction oil testing. However, it was predicted that the patterns observed would be affected by the local velocity along the surface of the part. Figure 29 shows the local velocity gradient on a simple rotating plate in a freestream velocity. This depiction does not account for the complexity of the disk’s surface, specifically the filleted edges of the disk. Still, this representation provides an estimate of the flow interactions on the upper surface.

![Figure 29: Local Velocity on Rotating Plate in Freestream](image)

Since the disk rim to airspeed ratio for these tests was 1, the rim at the leftmost edge would have seen a local velocity of 30 m-s\(^{-1}\), whereas the rightmost edge would have seen a local velocity of 0 m-s\(^{-1}\). This velocity gradient would increase the skin friction on the left side of the disk when compared with the non-rotating geometries. Superimposing the results of the non-rotating geometry onto the simple rotating plate model, the 3D effect of increased skin friction along the disk’s filleted edges would result in larger lift and drag forces on the right side of the disk than the left side of the disk.
CONCLUSIONS

Design

The overall design came in well under the allotted budget of $1,500 provided by Undergraduate Research Excellence Awards. During the project planning process in spring 2018, the total expense of the design was estimated at $650. In the end, the final design came in just over that goal with a total cost of $673.

Although the motor was slightly larger than anticipated, the mount was able to be successfully modified to incorporate the motor and integrate with the existing wind tunnel mount and supports. The motor provided ample torque to rotate the disk at the required testing speeds and was fully controllable through the provided software. The motion of the disk, however, was not smooth enough for testing. The poor fitment of the 3D printed shaft onto the motor shaft caused the disk to gyrate as it rotated and eventually come loose from the motor during wind tunnel testing. The uneven motion of the disk can also be attributed to dissymmetry in the geometry’s upper surface due to uneven sanding.

The static geometry proved sufficient for skin friction oil film analysis, but clear images proved difficult to capture due to scratches in the wind tunnel’s glass window and camera lens from negligence. Outdated hardware also amplified these issues as it took over an hour to transfer images of 5 2-minute tests from the computer hard drive to a USB only to find the quality of the images to be too poor for analysis due to data compression. Also, the UV lighting and camera mount proved to be not only a hassle when trying to reposition and focus the camera, but also a serious safety concern for the both the wind tunnel instrumentation and personnel.

Aerodynamics

The non-rotating geometry generated more lift at 10 m-s$^{-1}$ than at 15 m-s$^{-1}$. The 0-degree lift coefficient decreased from 0.0375 to 0.00125, while the 0-degree drag coefficient remained near 0.025. This indicates that the non-rotating geometry is not preferable at speeds above 10 m-s$^{-1}$.

The rotating geometry experienced a larger 0-degree lift-to-drag ratio when static than when rotating. The 0-degree lift-to-drag ratio during the static test was close to 1.06, while the 0-degree lift-to-drag ratio during the rotating test was 0.902. This result directly opposes studies suggesting that rotating disks in a fluid stream reduces drag and increases lift (Nakamura, 1991). The lift-to-drag ratio also increased with increasing angle of attack at a greater rate during the static test than during the rotating test. These results may be due to the instability of the disk when rotating. The disk’s motion contained a wobble effect due to the imprecise machining of the shaft hole for the interference fit. Due to the gyration, precise steady-state averages of the lift and drag forces were difficult to capture. Additionally, the lift and drag forces in the roll-axis were not measured, but it is assumed that there are forces in the roll direction due to the non-symmetric local velocity distribution due to the rotation of the disk. The effects of these non-symmetric forces were not quantified due to the wind tunnel’s inability to measure force in that axis.
When comparing the non-rotating geometry to the rotating geometry, the non-rotating geometry was found to experience nearly a factor of 10 less force than the rotating geometry. The increase in force from the non-rotating to rotating geometry can possibly be contributed to the difference in geometry, most significantly due to the removal of the material on the lower surface of the disk to more closely match Innova® Disc’s Mini Driver, which is dish-shaped. Incorporating the dish shape increases the amount of pressure on the lower surface at all angles of attack. Another possible reason why the force increases from the non-rotating to rotating geometry was the force contributed by the motor mount itself. The motor mount has a large square frontal area with many non-aerodynamic edges and wires. The contribution of the mount on the aerodynamic force was not quantified during testing, but it is assumed to be a large factor.
RECOMMENDATIONS

Design

One of the major design concerns is the pressure fit of the 3D printed shaft on the motor shaft. The inaccuracy of the inner diameter of the 3D printed shaft required it to be drilled out so it was large enough to fit onto the motor shaft, but this caused the inner diameter to not be completely straight and symmetrical, introducing radial play into the shaft. To avoid this problem, a 5 mm diameter aluminum shaft should be attached to the motor shaft using a 5 mm to 5 mm shaft coupler. A disk geometry with proper shaft inner diameter can then be slipped onto the aluminum shaft like a sleeve. The longer dimension of the aluminum shaft of 5 cm should act as a better positioning guide for the disk geometry compared to the 1 cm shaft of the motor.

Another issue that added to the unsteady motion of the rotating disk is the dissymmetry in the upper surface of the disk geometry. This could be improved by reorienting the 3D print, so less support material is used on this critical surface and it initially comes out of the 3D printer smoother. Another recommendation is to sand the disk geometry on a lathe so that it is uniformly sanded.

The final recommendation for reducing the unsteady motion of the rotating disk is to reduce turbulence from the mount interfering with the flow over the test geometry. This could be realized by adding a 3D printed cap to the front of the mount or encasing it so it is more aerodynamic. Another option for reducing the air flow interference from the mount is to remove it from the test section by lowering it and positioning the motor in-between the wind tunnel supports. This would, however, require machining a mount, which would be expensive and possible limit the range of pitch angles that can be tested at.

Testing

Various uncertainties plagued the results of testing. Thus, it is recommended that additional testing is performed to clarify the effects of various changes between non-rotating and rotating tests. The first recommendation is to run force measurement tests on the motor mount only to find the amount of force that it generates. The result can then be subtracted from the test results with the geometry installed to clearly see how much lift and drag the geometry is generating.

The second recommendation is to conduct skin-friction oil tests to analyze the pressure differential along the span of the disk. This would give clues on how the local velocity distribution due to the rotation of the disk affects the lift and drag.

The third recommendation is to conduct tests on a simple flat disk to understand the effects of the aggressive edge fillets on the lift and drag. It was difficult to visualize the skin friction on the upper surface of the disk due to the camera’s focal range and inability to adhere a Mylar sticker. Additionally, a flat disk would focus the force measurement results on the effects of the local velocity distribution rather than the lift and drag due to flow diversion over the disk’s edges.
REFERENCES


APPENDICES

Appendix A – Miscellaneous Figures

Figure 30: Preliminary Sketch of a Motor Mount with Two Flanges

Figure 31: Innova® Disc Golf Mini Driver
Appendix B – Facilities Used

- Applied Aerodynamics Laboratory (AAL)
- Student Projects Lab at Floyd Hall (WMU)
- 3D Printing Lab at Floyd Hall (WMU)
Appendix C – Experimental Data

Table 5: Forces on Static Rotating Geometry at 15 m-s\(^{-1}\) Airspeed

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Drag (N)</th>
<th>Lift (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.4148</td>
<td>2.4866</td>
</tr>
<tr>
<td>2.5</td>
<td>2.4259</td>
<td>2.8427</td>
</tr>
<tr>
<td>5</td>
<td>2.1643</td>
<td>3.0392</td>
</tr>
<tr>
<td>7.5</td>
<td>2.1921</td>
<td>3.1006</td>
</tr>
</tbody>
</table>

Table 6: Forces on Rotating Geometry at 15 m-s\(^{-1}\) Airspeed

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>Drag (N)</th>
<th>Lift (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.5309</td>
<td>2.2502</td>
</tr>
<tr>
<td>2.5</td>
<td>2.5774</td>
<td>2.5965</td>
</tr>
<tr>
<td>5</td>
<td>2.3817</td>
<td>2.5726</td>
</tr>
<tr>
<td>7.5</td>
<td>2.3447</td>
<td>2.8145</td>
</tr>
</tbody>
</table>
Appendix D – MATLAB Scripts

Wind Tunnel Data Processing Code

clear

cl

% Read Voltage Data from Excel Worksheets
vd10=xlsread('WindTunnelTest1','Data','B3:B10');
vl10=xlsread('WindTunnelTest1','Data','F3:F10');
vd15=xlsread('WindTunnelTest1','Data','B14:B21');
vl15=xlsread('WindTunnelTest1','Data','F14:F21');
alpha=xlsread('WindTunnelTest1','Data','A3:A10');

% Zeroing Values for lift and Drag (volts)
td= 79.09e-6;
tl= 66.65e-6;

% Processed Voltage Data
Vdrag10=td-vd10;
Vlift10=vl10-tl;
Vdrag15=td-vd15;
Vlift15=vl15-tl;

% Voltage to Newtons Conversion
nd= 139182;
nl= 613980;
Drag10=nd*Vdrag10;
Lift10=nl*Vlift10;
Drag15=nd*Vdrag15;
Lift15=nl*Vlift15;

% Calculate Coefficient of Lift
r= .127;
A= pi*r^2;
rho=1.225;
v15=15;
v10=10;
q10=.5*rho*v10^2*A;
q15=.5*rho*v15^2*A;

Cd10=Drag10/q10;
Cl10=Lift10/q10;
cld10=Cl10./Cd10;
Cd15=Drag15/q15;
Cl15=Lift15/q15;
cld15=Cl15./Cd15;

% Calculate Important Aerodynamic Parameters
Local Velocity on Rotating Disk in Freestream Code

clc

clear

v = 15; % m/s
Speed = (v / 0.0635) / (2 * pi) * 60; % RPM

theta = [0:10:360] * pi / 180;
R = [0:7.9375:63.5];
[TH, Rr] = meshgrid(theta, R);
[X, Y] = pol2cart(TH, Rr);
Z = sqrt(X.^2 + Y.^2);
vr = R / 1000 * Speed * 2 * pi / 60; % m/s
[THvr, Vr] = meshgrid(theta, vr);
U = Vr .* cos(theta) - v;
V = -Vr .* sin(theta);

figure(2)
contour(X, Y, Z, 'k')
xlim([-70 70]), ylim([-70 70]), xlabel('Radius, (mm)'), ylabel('Radius, (mm)'), title('Local Velocity on Rotating Plate in Freestream')
hold on
quiver(X, Y, U, V, 'Color', 'k')
legend('Rotating Plate', 'Local Velocity')
hold off
Appendix E – ABET Questionnaires

Form 1
To be completed by student

Assessment of Student Outcome # c
ME 4800

“An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political ethical, health and safety, manufacturability, and sustainability” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As part of your design project, you are required to fill out this form and include it in your ME4800 Final Report, please include the page numbers where the questions following are addressed.

Evaluation of student outcome “An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political ethical, health and safety, manufacturability, and sustainability”

1. This project involved the design of a: system / component / process
   Description:
   Construction, fitment, shape, materials, and installation procedures of the motor mount to rotate a 3D printed geometry was designed. A test procedure was also designed to measure the aerodynamic forces on a rotating and non-rotating disk (pages 10-20).

2. The need:
   Western Michigan University’s Applied Aerodynamics Laboratory does not have the capability to conduct research on rotating objects. The ability to research rotating objects would increase the understanding of rotating objects in freestreams and their potential benefits to the aerospace industry (page 7).

3. The constraints: (discuss the constraints that were relevant to the project. At least 3 constraints must be addressed.)
   Economic:
   The design must be fabricated and tested within the awarded budget from the group’s three Undergraduate Research Excellence Awards. This totaled $1,500 (page 21).

   Manufacturability:
   The design must be able to be manufactured with the resources available at Floyd Hall. This is limited to the equipment available in the Student Projects Lab and the 3-D Printing Lab. The aerodynamic integrity of the motor mount was subsequently sacrificed to maintain simplicity in the manufacturing process (pages 15-21).
**Others:**
The design was to be used in the AAL’s small wind tunnel on pre-existing equipment. Thus, the design needed to fit within the confines of the test section, utilize the pin connections to allow the instrumentation to work, and be structurally sound so as to not fracture during testing and damage the wind tunnel (page 10).

4. Is there a potential for a new patent in your design? Explain and compare to similar patents.
   No, there is not a potential for a new patent in this design. The motor mount is specific to Western Michigan University’s small wind tunnel and would not be effective in other applications.
Form 2
To be completed by student

Assessment of Student Outcome # j
ME 4800

“A knowledge of contemporary issues” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. The Mechanical Engineering Faculty Members have defined “A knowledge of contemporary issues” as knowledge and application of new technologies or recent innovations, satisfaction of the company’s existing customers, comparison of the proposed design with the competitor’s products, well-being and performance of other employers, safety and legal issues, new standards or recent product regulations, and possibility of product patent. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to fill out this form and submit it with your final report. Please include the page numbers where the following questions are addressed.

Evaluation of student outcome “A knowledge of contemporary issues”

1. Why is this project needed now?
   Current knowledge of aerodynamic skin friction effects on rotating objects is limited. Increasing the empirical data of such effects will increase the accuracy of computational fluid dynamics software. If the effects of skin friction on a rotating body are found to provide benefits to lift and/or drag, unmanned air vehicles (UAVs) may benefit from the reduced power required to operate (page 10).

2. Describe any new technologies and recent innovations utilized to complete this project and how will it improve satisfaction of the company’s existing customers?
   Western Michigan University developed a fluid that allows the aerodynamic skin friction effects to be observed without penalizing the true effects of the body’s surface on its aerodynamics (page 7).

   How will it improve satisfaction of the company’s existing customers?
   This project will improve satisfaction of Western Michigan University’s Applied Aerodynamics Laboratory by increasing the research capabilities of the lab (page 7).

3. Identify the competitors for this type of product, and compare the proposed design with the products of the company’s competitors.
   There are no competitors for this type of product because of the custom nature of the design. Western Michigan University does not plan on selling or limiting the use of similar motor mounts.

4. How did you address any safety and/or legal issues pertaining to this project? (e.g., OSHA, EPA, Human Factors, etc.)
This project does not involve human subjects or hazardous chemicals. Safety expectations will be outlined by the procedure to operate the wind tunnel and mount, which will include OSHA outlined personal protective equipment (PPE) required.

5. Are there any foreseeable future standards or regulations on the horizon that could impact the development of the project?

There are no new standards or regulations on the horizon that will impact the development of the project. This project is small-scale and can be easily adapted to new regulations or standards that may be put in place.


No, there is not a potential for a new patent in this design. The motor mount is specific to Western Michigan University’s small wind tunnel and would not be effective in other applications.
Form 3
To be completed by student

Assessment of Student Outcome # h
ME 4800

“An understanding of the impact of engineering solutions in a global, environmental and societal context” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to fill out this form and submit it with your final report. Please include the page numbers where the following questions are addressed.

Evaluation of student outcome “An understanding of the impact of engineering solutions in a global, environmental and societal context”

1. Is this project useful outside of the United States? Explain why.
   This project may be useful worldwide if valuable data is obtained for the aerodynamic forces acting on rotating bodies. This is because UAV technology, for commercial and private use, is a rapidly growing industry worldwide and may benefit from the research we perform by improving product flight characteristics (page 7).

2. Does your project comply with U.S. and/or international standards or regulations?
   Which standards are applicable?
   This design will not be distributed beyond Western Michigan University’s Applied Aerodynamics Laboratory and will not need to comply with international standards or regulations. No US regulations currently exist with regard to creating a test rig for a wind tunnel.

3. Is this project restricted in its application to specific markets or communities? To which markets or communities?
   The application of this project is not restricted to specific markets. Its intended purpose is strictly for the Western Michigan University Applied Aerodynamics Laboratory, however, the results and empirical data collected from testing may be utilized in the aerospace and sports equipment markets or other areas of unknown applicability.

4. If the answer to any of the following items is affirmative, explain how and where, when relevant. What actions did you take to address the issues?
   N/A
Design is focused on serving human needs. Design also can either negatively or positively influence quality of life. Address the impact of your project on the following areas.

**Air Quality?**
This project does not directly influence air quality.

**Water Quality?**
This project does not directly impact water quality.

**Food?**
This project does not directly impact food.

**Noise Level?**
This project does not directly impact noise level.

Does the project impact:

**Human health?**
This project does not directly impact human health.

**Wildlife?**
This project does not directly impact wildlife.

**Vegetation?**
This project does not directly impact vegetation.

Does this project improve:

**Human interaction?**
This project does not directly improve human interaction.

**Well-being?**
This project does not directly improve well-being.

**Safety?**
This project does not directly improve safety.

**Others?**
This project directly improves the WMU Applied Aerodynamics Laboratory by increasing the testing capabilities of the small wind tunnel while also using a design that seamlessly integrates into the existing wind tunnel setup and doesn’t inhibit the quality of life of the wind tunnel operator.
Form 4
To be completed by student

Assessment of Student Outcome # i
ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report.

Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

ME 4800
Mechanical and Aerospace Engineering Design Project

For each team member:
NAME: Riley Balk

1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

A solid understanding of fundamental mechanical and electrical engineering principles was required to calculate the torque necessary for rotating the disk geometry and selecting a motor, motion controller, and power supply that were compatible with each other and the design and sufficient for rotating the disk. Both 2D and 3D CAD skills were utilized in creating conceptual designs of the mount and assembly as well as drawings referenced during fabrication. Excellent communication skills and professional demeanor were required when procuring components from suppliers, discussing the project with other group members and our faculty mentor, and presenting and reporting on the project. Exceptional leadership and planning skills were also required to keep the project on schedule. Another skill that was required was critical thinking, in order to overcome any unforeseen problems in the design process and evaluate the final design and test results.
2. Explain how you acquired or improved the skills needed for the completion of the project.

The majority of the skills utilized in the completion of this project were developed through university coursework and internship experience. I improved or acquired new skills needed for the project by teaching myself through online materials like tutorial videos and forums as well as through trial and error and just experimenting with software to see what works. But the most important way I acquired or improved skills was by asking for help, whether it be a peer, professor, or Applications Engineer at a supplier.
Form 4
To be completed by student

Assessment of Student Outcome # i
ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report.

Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

ME 4800
Mechanical and Aerospace Engineering Design Project

For each team member:
NAME: Kirsten Murphy

1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.
   I needed knowledge of low-speed aerodynamics, experience in CAD packages and ANSYS software (especially CFD), experience with developing test plans, organizational skills, and experience with 3D printing.

2. Explain how you acquired or improved the skills needed for the completion the project.
   I improved my knowledge of low-speed aerodynamics by conceptualizing and predicting the aerodynamic effects generated by a rotating disk. I acquired the ability to use ANSYS Fluent CFD software by doing online research and watching tutorial videos. I improved my understanding of Inventor by exploring the 3D Print options in Autodesk Inventor 2018. I improved my experience with developing test plans by understanding that a test should be completed after every change in variable. I improved my organizational skills by planning, prioritizing, and owning my respective work on this project.
Form 4
To be completed by student

Assessment of Student Outcome # i
ME 4800

“A recognition of the need for, and ability to engage in life-long learning” is listed in ABET General Criterion 3. Student Outcomes as one of the student outcomes to be assessed for both Mechanical and Aerospace Engineering programs. As you work on your senior design project, we ask you to answer the following questions. These questions will help you to create the ideas needed to successfully complete your project and hence your ME4800 final report. You are required to submit the completed form in the last appendix of your final report.

Your responses will be used in the Evaluation of student outcome “A recognition of the need for, and ability to engage in life-long learning.”

A well-organized team brings together the necessary backgrounds and talents needed to successfully develop and complete the design process. Each team member plays an important role on the design team. Team members must be prepared to acquire any new additional skills, and improve existing ones during the development of the project. Your answers to the questions below will be used to evaluate a) your understanding of the need for life-long learning and b) your ability to recognize the need of acquiring new knowledge/skills when required.

ME 4800
Mechanical and Aerospace Engineering Design Project

For each team member:
NAME: Viraj Patil

1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.
   I needed a strong attention to detail to create preliminary sketches for the motor mount with the design requirements taken into consideration. I also needed basic knowledge of aerodynamics for the design process and wind tunnel testing.

2. Explain how you acquired or improved the skills needed for the completion the project.

   I improved on my CAD skills from working as an Engineering Trainee at InDepth Engineering Solutions by creating the final design of the motor mount with Autodesk Inventor. I acquired machining skills from the Student Projects Lab by using a vertical mill and a band saw to fabricate the mount. Throughout the semester, I improved on my effective communication with my group members, the faculty advisor, the graduate assistant working at the wind tunnel, and the supervisors at the Student Projects Lab.
Kirsten Murphy
kirsten.l.murphy@wmich.edu
(734)-536-6076

Objective
Graduating engineering student seeking a full-time position as a mechanical or aerospace engineer. Offering 1+ years in internship experience with Flowserve Corporation to support engineering and sales in the design, selection, and testing of new product and technology.

Education
Bachelor of Science in Aerospace Engineering
Western Michigan University, Lee Honors College
Kalamazoo, MI
Major: Aerospace Engineering, Minor: Mathematics
GPA: 3.57 / 4.00

Awards
Dean’s List - College of Engineering and Applied Sciences
- Spring 2018
- Fall 2017
- Fall 2016

Senior Design Project
Title: Rotating Mount Design for Complex Fluid Flow Research
Mentor: Tianhui Liu
Description:
Fluid flow around rotating objects is mathematically complex and there is currently limited experimental data on the subject. To make Western Michigan University capable of this research, a rotating wind tunnel mount was developed. The mount design was integrated into the existing setup at the Applied Aerodynamics Laboratory (AAL) to allow seamless transitions between different research projects. Non-rotating and rotating prototypes were created from 3D-printed materials to test and revise the mount’s capabilities before finalizing the design. Experimental data gathered from utilizing this rotating mount will be used to better model the aerodynamic effects on rotating objects in fluid streams.

University Work
Teaching Assistant for Engineering Graphics Laboratory
Slobodan Urlichevik (Kalamazoo, MI)
- Instructed a laboratory of 24 students once per week to solidify manual and AutoCAD drafting techniques.
- Offered one-on-one instruction to any students who sought additional mentoring during office hours held once per week.
- Used AutoCAD 2016 to design 2D and 3D objects in accordance with ANSI drafting standards.

Computer Software Experience
- MATLAB 2018
- AutoCAD 2017
- AutoDesk Inventor 2017
- ANSYS 15.0
- Microsoft Word, Excel, & Powerpoint
- LabVIEW 16.0
- LTSpice XVII
- Minitab 17
Kirsten Murphy
kirsten.l.murphy@wmich.edu
(734)-536-6076

Internship Experience
Applied Technical Solutions Engineering Intern for Flowserve	August, 2018 – present
William Dietz (Kalamazoo, MI)
- Identify important parameters on laser wave patterns and develop an inspection procedure for laser-machined parts.
- Collaborate with Gaspar Engineering and lapping departments to agree on a standard for seal face lapping specifications.
- Analyze mechanical seal failures and recommend process and or product changes to decrease chances of future seal failures.
- Measure seal face topography using optical microscopes and metrology devices such as Tropel, Bruker, and FRT to understand failure modes and predict seal face life.

Pac-Seal Engineering Intern for Flowserve	January, 2018 – August, 2018
Joseph Allen (Kalamazoo, MI)
- Implemented a break-away torque calculation into the seal selection Toolbox to ensure that all rubber components will be able to transfer start-up and running torques with the designed compression.
- Conducted tests on competitor and trouble seals to replicate customer applications and better understand their failure observations. Wrote test reports and made seal design and application recommendations based on discussions with Pac-Seal engineers and customer representatives. Addressed quality and inspection issues for seals manufactured at Kalamazoo-Mexico by creating optical flat training documents and statistical-based inspection sampling.
- Improved the seal selection process by incorporating various mathematical checks to ensure that the seal’s capabilities are suitable for the described application.
- Supported the development of an instruction manual to standardize the mechanical seal selection process.
- Developed a 3D-Printed Plate to test the mechanical loading of a seal without pre-loading it.
- Selected custom mechanical seal configurations for customers based on their specific applications.
- Performed root cause analyses (RCAs) on failed mechanical seals and wrote concise reports on the findings.

R&D Engineering Intern for Flowserve	March, 2017 – January, 2018
Ryan Kremer (Kalamazoo, MI)
- Conducted structural analyses on test parts using ANSYS to ensure the parts’ ability to contain water at high-pressures without failure.
- Wrote test plans and test reports that explore the validity of new seal face coatings and materials.
- Performed RCAs on failed test parts to make recommendations to prevent future failures.
- Utilized various tribology equipment to analyze seal face wear and material quality.
- Research new metrology equipment and made recommendations for upgrading the optical microscope currently used by engineering.
- Created a department presentation that informs new-hires and site visitors about the capabilities and current projects at Flowserve-Kalamazoo.

Volunteer Work
- Kalamazoo Valley Habitat for Humanity Volunteer (2016)
Riley Balk
(248) 914-8085 | rileybalk@gmail.com

OBJECTIVE
Detail-oriented senior with a strong work ethic seeking a full-time job post-graduation. Offer outstanding time management, organization, and analytical skills sharpened through previous work experience and coursework.

EDUCATION
Bachelor of Science in Engineering
Western Michigan University (WMU)
Kalamazoo, MI
Major: Mechanical Engineering
Minor: Mathematics
CPA: 3.88

WORK EXPERIENCE
Engineering Intern – Order Engineering
Flowsolve
Kalamazoo, MI
June 2018-December 2018
• Automated daily, weekly, and monthly reports for active jobs and job output using Excel VBA, reducing the time required to run a report from minutes/hours to seconds
• Created training documents for writing VBA programs in Excel to reduce time wasted on repetitive tasks and increase the quality of life of colleagues.

Engineering Specialist
Summit Polymers
Portage, MI
April 2018-June 2018
Engineering Intern – Quality Lab
February 2017-April 2018
• Scanned parts with structured light scanner and used resulting point clouds to create CAD comparison color maps so the customer could see how the part geometry deviated from nominal
• Performed tests such as torsion, adhesion, lifecycle, and airflow on parts to see if they satisfied applicable specifications and composed testing reports for customers
• Headed up to 20 projects at a time, coordinating equipment use and test timing with other Quality Technicians, ensuring customer deadlines were met

IN INVOLVEMENT AND AWARDS
Undergraduate Research Excellence Award, WMU 2018
Deans List, WMU 2014-2018
Sophomore Experience, WMU 2016
Blue Oval STEM Scholarship, Ford 2015-Present
CEAS Leadership Scholarship, WMU 2014-Present

SOFTWARE PROFICIENCY
Microsoft Office Suite
Adobe Suite
MathCAD
Projects
Autodesk Inventor
Autodesk AutoCAD
SolidWorks
Rotating Mount For Complex Fluid Flow Research (Senior Design) 2019
ANSYS
LabVIEW
Romax Technology
Custom PC build and overclock 2019
MATLAB
LT Spice
Certified Amazon Alexa skill using Node.js 2018

ATOS/GOM Inspect
VIRAJ PATIL
(248) 909-8859 | Email: virajhp@hotmail.com | LinkedIn: www.linkedin.com/in/viraj-h-patil18

Conscientious and detail-oriented aerospace engineering senior seeking a full-time position after graduation. Offering academic knowledge and 3+ years proficiency in 2D and 3D CAD tools, MATLAB, and Microsoft Office. Personal attributes include the desire to learn, strong work ethic, teamwork, effective written and verbal communication.

EDUCATION
Bachelor of Science in Engineering (ABET-Accredited) Expected Graduation Date: December 2018
Western Michigan University Kalamazoo, MI
Major: Aerospace Engineering, Minor: Mathematics Overall GPA: 2.92 / 4.00

ENGINEERING EXPERIENCE
Engineering Trainee July 2018 – August 2018
InDepth Engineering Solutions LLC Troy, MI
- Gained extensive knowledge of the engineering industry and enhancing CAD design expertise with Autodesk Inventor by completing designs such as a pop-up rail for an amusement park.
- Studied engineering drawings to recreate 3D parts and assemblies.
- Utilized FEA simulations on beams in Inventor and verified the results with hand calculations.
- Modeled bus body structures such as the roof, sidewalls, and hood.

TECHNICAL SKILLS
Computer Software
Abaqus, AutoCAD, Autodesk Inventor, CATIA V5, MATLAB, Microsoft Office, and SolidWorks

Relevant Coursework
Controls Systems, Flight Test and Engineering, Flight Vehicle Performance, and Stability and Control

ADDITIONAL WORK EXPERIENCE
Crew Member May 2018 – July 2018
Burger King Farmington, MI
- Developed multitasking in a fast-paced environment by preparing burgers and drinks, maintaining the cleanliness of the kitchen and restaurant, greeting customers in a polite manner, and handling cash and coupons at the cash register.

Communication Coordinator September 2015 – April 2017
The Source (Registered Student Organizations (RSO) Design Center) Kalamazoo, MI
- Responded to clients in a courteous and professional manner and approved flyers from all of the registered student organizations and coordinated reservations for 13 display cases and 3 solicitation tables in the student union.
VIRAJ PATIL
(248) 909-8859 | Email: virajhp@hotmail.com | LinkedIn: www.linkedin.com/in/viraj-h-patil18

TEAMWORK

Mechanical and Aerospace Engineering Senior Design January 2018 – present

- Working with two other students and a faculty advisor, Dr. Tianshu Liu, to develop and design a rotating wind tunnel mount.
- Creating prototypes from 3D-printed materials and conducting numerous tests at a small wind tunnel at the Applied Aerodynamics Laboratory (AAL)
- Expanding research from experimental data on fluid flow around rotating objects.

American Institute of Aeronautics and Astronautics Student Branch January 2015 – April 2018

- Worked with 9+ members to build and test competitive RC planes.
- Team won 15th place out of 91 universities at the 2018 Design-Build-Fly Competition in Wichita, Kansas.
- Maintained a budget of $7,500 as the treasurer during the 2016-2017 academic year.

LEADERSHIP

Little Three Leadership Council September 2016 – present

- Collaborating in the planning of residence hall activities such as the Fall Fest and Super Bowl parties.
- Learning about the personalities and points of view of diverse residents.

WMU Signature: Leadership August 2014 – November 2018

- Facilitated a Fall Leadership Fair 2018 event called “Building K’Nexions” where students work in groups to construct an object out of K’Nex pieces to become better communicators.
- Participated in leadership retreats, physical activities, and workshops to develop conflict management and leadership skills.
- Improved on abilities to take initiative in goals, tasks, and my career path.
- Built an understanding on disciplinary, focus, and responsibility aptitudes.

National Residence Hall Honorary November 2016 – April 2018

- Wrote and submitted Of the Month awards to recognize the good deeds of the residents living on campus.
- Submitted names of campus staff and residents as Of the Year winners as Chief Officer of Recognition during the 2017-2018 academic year.

AWARDS AND CERTIFICATIONS

American Institute of Aeronautics and Astronautics – Student Member July 2018
WMU Undergraduate Research Excellence Award February 2018
Bronze Leaders in Action Certificate April 2015