The Mechanics of a Spiral Water Pump

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Abstract

The fundamental necessity for water is a widespread issue affecting many communities across the globe. In this project, our team sought to provide an innovative solution to this problem for a small community with access to a relatively close source of flowing water. Resultant flow rate of water was calculated to be 0.498 L/min. Stress and strain analysis on individual subsections of the system were as follows: -44.2 MPa for bending moment in the rod; -7.04 MPa for shear stresses in the rod of the axis; -8.88E-5 for shear strain in the rod ; -1.11 MPa and .429 MPa of shear stresses in the L brackets; -0.123 MPa for radial stress of spiral, -0.422 MPa for hoop stress of spiral, -2.10 MPa for bending moment of spiral, and -0.176 MPa for the maximum shear stress of the spiral pump on the rotating wheel.

The focus of the design remained fixated on water acquisition; however, further additions can be made for water purification.

1 Introduction

As engineers, our calling is to improve the quality of life for humans while implementing both innovation and efficiency. We observe problems in society in order to better understand them and to find an efficient solution using our technical knowledge. There are millions of people worldwide who struggle to find a reliable source of water each day. For this project, we aimed to solve this problem for a hypothetical community in need. We wanted to create a solution that was affordable, used commonplace and easily obtainable materials, and that was simple enough to build without overly specialized equipment.

2 Methods and Materials

Before we could begin producing concepts, we had to finalize a location to better adapt our design. Our supervisor suggested McDowell Grove Forest Preserve located in Naperville, IL as the best site for our purposes. The forest preserve offers a vast array of streams and rivers with varying depths, widths, and flow rates. We decided on utilizing a river that was about 0.70 meters deep and 15 meters wide. For sections of the river with greater depth, it would require a more extensive design with higher strengths of material, thus complicating the project. With this in mind, we chose a section of the river closer to shore with a depth of 0.23 meters. To measure the flow rate of the river over this desired section, a leaf was placed into the water while using a stopwatch to record the amount of time it took the leaf to travel a measured distance of a 3.048 meter long taut string. Using the average of three separate trials, the resultant flow rate was found to be 0.45 m/sec. Once the location and specific river was finalized, we then began the process of designing a mechanism that would be able to efficiently collect water from the chosen water supply.

3 Design

3.1 Inspiration

The inspiration for this project originated from a problem that affects countless communities across the globe: the lack of access to clean drinking water. The overarching issue of water access, or lack thereof, is problematic for many third world countries and has plenty of intricacies that each require specific attention. Some examples include sewage and plumbing, filtering, transportation, purification, and acquisition. As an engineering team, we decided to focus on the issue of water acquisition with a concentration on answering the question, "How might we provide water for a small community in a simple, affordable, and reliable way?" With this question in mind, we sought to use knowledge from a 'Strengths and Materials' mindset to spark development of a solution, thus transitioning from initial inspiration into the process of ideation.

3.2 Ideation

Ideation commenced shortly after we established the aforementioned question. We made sure to establish that no idea was too great or unfeasible in order to prevent the limitation of creativity. The first rounds of brainstorming allowed for any ideas or concepts that would relate to the issue of water access in general (see Figure 1). The following rounds began narrowing the focus to answer our established question, filtering and building on ideas from the first few brainstorming sessions. Multiple sticky notes and sketches later, our design team mutually agreed on the development of a mechanism that would provide a solution to the problem at hand: a spiral water pump.

Figure 1: Example brainstorming session

3.3 Prototype

The idea of a spiral water pump would allow for simple mechanical construction and would not require additional electrical or alternative power sources other than a given source of flowing water. We sought to design a model that offered a self-sustainable solution for a community in need of water acquisition. Since we were unable to observe an actual community and determine their case-specific problems, assumptions were made based on this hypothetical community. These included that basic building materials could be obtained and the village was located near a reliable, flowing water source such as a river. The latter assumption would allow the village to obtain water from the source without relocating or changing its course. The specifications of the pump would change depending on the elevations between the river and village, and water consumption per unit of time. Initial prototypes utilized building materials of regular office supplies such as paper, rolls of tape, rubber bands, plastic cups, and paper clips. Using these simple prototypes, our ideas were condensed into a final design. This final design of a spiral water pump was made to exemplify a concept that can be extended to various communities worldwide. Our resultant model was made up of four main components: the frame, the water wheel, the paddles, and the spiral.

Frame: Initially, the intended design for the frame of the spiral pump took the form of a cantilever that would extend over the river. The first design called for the extension of the steel axle from the dry land over the flow of water and the support of wooden planks that would hold it into place with additional mass to anchor it down(see Figure 1). A problem arose when we realized that it was not possible to fix the axle to a point while simultaneously allowing rotation due to the motion of the spiral pump. This problem with the rotating axle was solved by attaching a rotary joint to allow for rotation of the spiral pump while being connected to a stationary pipe. After the design and construction of the water wheel, it was determined that the initial concept would not be structurally stable given the parameter of the axle diameter and strength of the material required to support the weight of the water wheel itself. The moment applied due to the loading of the spiral at the end of the axle would be directly proportional to the distance from the fixed point on the land to the point at which the force due to the mass of the spiral pump was applied. To decrease this moment, it was necessary to decrease the distance from the center of mass of the pump to the fixed point of the frame. To adjust our design, we produced an initial concept of a ground frame made of wood to even the distribution of the load on the frame (see Figure 2). The rotary joint was no longer necessary for the design as this new concept allowed for the whole axle to rotate within the frame. In order to allow water to flow through the spiral pump, a PVC pipe was attached to the end of the steel rod on the same side and acted as both the axle and outflow pipe. Although the axis was given the freedom to rotate with the wheel, the actual experimentation of the frame resulted in the wheel simply rotating about the axis. The final drawing for the frame of the system is shown in Figure 3.

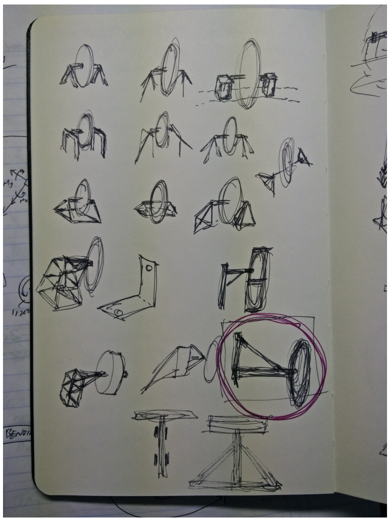

Figure 2: Cantilever Concept

Water wheel: For the water wheel component, we had to figure out how to attach both bicycle wheels rigidly so that they could spin together. Initially, we were going to fixate tensile rods on the outer perimeter of the wheels by bending the ends and drilling in screws; however, it was more efficient to use the paddles and L-brackets as the components that held both wheels together. We also had a rod that went through the axles of both wheels to hold them together, but also to provide a site onto which we could attach the frame that supports the whole build. To make the water wheel, we connected two bicycle wheels with a steel rod allowing rotation around the rod.

Paddles: For the paddle components of the water wheel, we had to figure out what material to use and how to make the paddles. We realized it was necessary to choose a material that was strong enough to withhold the forces of the water but flexible enough to work with. At the same time, this material needed to be cost effective and easy to obtain. Initially, we planned to use wood for the paddles since we thought they would be very strong. However, if the L fasteners on both wheels did not quite line up, then we would need to bend the paddles to fasten them. Since we assumed that whoever is building the paddle might not have necessary pieces of equipment, we

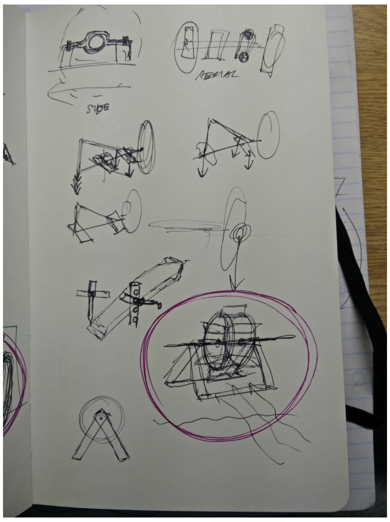

Figure 3: Ground Frame Concept

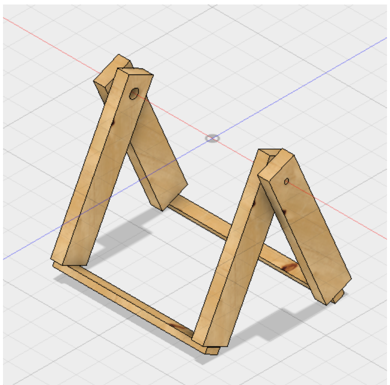

Figure 4: Final frame design

assumed that there might be problems with alignment. Thus, we decided to make the paddles with acrylic, given that it is strong but still flexible. To make the paddles, we took sheets of acrylic and cut them at a width of eight inches and a length of one foot, which was the separation between the wheels. We then drilled holes for screws on the paddles and on the bicycle rims, and attached the paddles to the wheels using L fasteners. A final drawing of the design of the water wheel and paddles are shown in Figure 4.

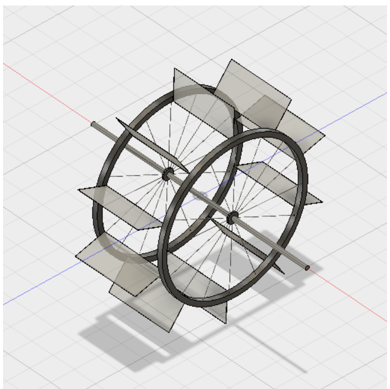

Figure 5: Final water wheel design with attached paddles and axle

Axle: For the axle of the wheel, we had to solve the problem of the spinning axle having to connect to a fixed point, or having a fixed axle and then having the outflow pipe not be aligned with the axle which brought upon the problem of the spiral wrapping around the axle. We decided to free rotation of the axle, so we refrained from connecting it to a fixed segment. To build the axle, we used a steel rod, connecting it to a PVC Tee which in turn connected to a PVC pipe. The pipe doubled as the axle that held the assembly on the frame and the outflow pipe circumventing the problem of transition between spinning. This also fixed the problem of the hose wrapping around the axle since it was allowed to rotate with the axle.

Spiral: For the subsystem of the spiral, we encountered the problem of the hose interfering with the axle of the wheel, which would prevent the wheel from rotating freely. Under the guidance of our supervisor, we solved the problem by inserting a PVC-Tee to join the hose and the axle, allowing it to rotate freely about the axle. Next, we inserted a rubber stopper inside a segment of PVC pipe attached to the end of the Tee closest to the wheel to stop back flow and separate the grease on the rod from the water. The other end was then joined to the PVC-Tee to transport the water from the pump to the desired location. The final spiral drawing is shown in Figure 5.

For reference to a list of materials and quantities used for the construction of the design, see Table 1.

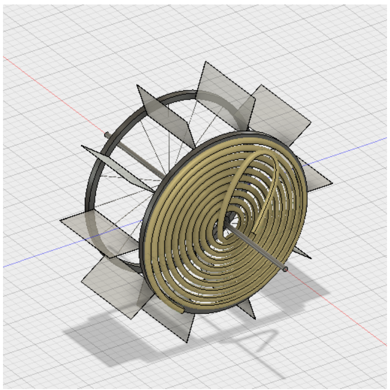

Figure 6: Final spiral design

Item	Quantity
Acrylic Sheet	1
Steel Rod	1
#10-24 $\frac{3}{4}$" screws	60
#10-24 $\frac{3}{4}$" hex nuts	60
L Brackets	20
Garden Hose	1
Planks of Wood	4
Nails	14
$\frac{1}{2}$" PVC Pipe	1
Anti-corrosive Coating Spray	1 can
Zip Ties	100
Teflon	1 roll

Table 1: Materials and quantities.

All materials gathered from Home Depot cost a total of approximately $50.

4 Results

After placing the finished pump in the river, the water wheel started spinning at a constant rate and the spiral pump began collecting and spouting water from the end of the PVC pipe. The movement of the water wheel was smooth and the frame maintained its structural integrity. The collection rate of water was determined by holding an empty half gallon container of milk to the end of the PVC pipe and using a stopwatch to record the amount of time for it to fill up completely (see Figure 8). The recorded flow rate of water from the pump system was calculated to be 0.498 $\frac{L}{min}$.

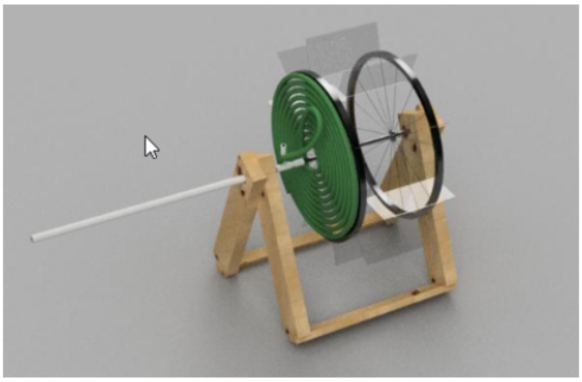

Figure 7: Final Assembly

Figure 8: Recording flow rate with finished water pump

4.1 Analysis of Rod in Frame

Stress analysis was conducted for each major part of the pump system given the conditions and resultant force of the river, which was estimated to be 22.24 N. The parts we focused on were the rod in frame, the wheel and paddles, and spiral.

The calculation for maximum stress due to bending moment at the point in the axle between the two boards was conducted using Equation 1 and shown in Figure8:

$$\begin{aligned} \sigma_z &= \frac{-M_x z}{I} \\ \sigma_z &= \frac{-23.1N*m(0.00873m)}{4.56*10^-9m^4} \\ \sigma_z &= -44.2MPa \end{aligned} \tag{1}$$

To calculate total shear stress on the rod at that point, we calculated the shear due to torsion on the rod from the force of the river and transverse shear due to the weight of the wheel using Equation 2) and shown in Figure10:

$$\begin{aligned} \tau_{zy} &= \frac{VQ}{It} + \frac{Tc}{J} \\ \tau_{zy} &= \frac{34.4N(4.44*10^-7m^3)}{4.56*10^-9m^4(0.017m)} + \frac{-0.936N*m(0.00873m)}{(\pi/2)0.00873^4} \\ \tau_{zy} &= -7.04MPa. \end{aligned} \tag{2}$$

Then, we calculated the strain due to these stresses and found that there was no axial strain

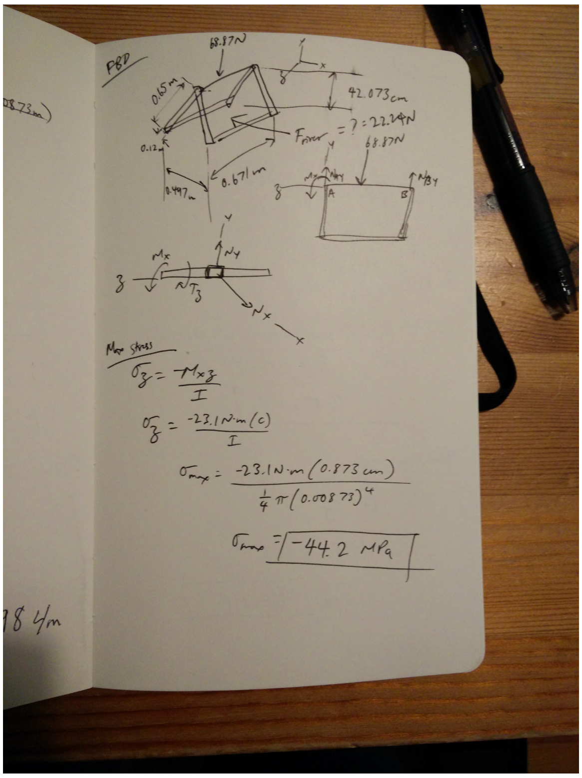

Figure 9: FBD and calculations for max stress

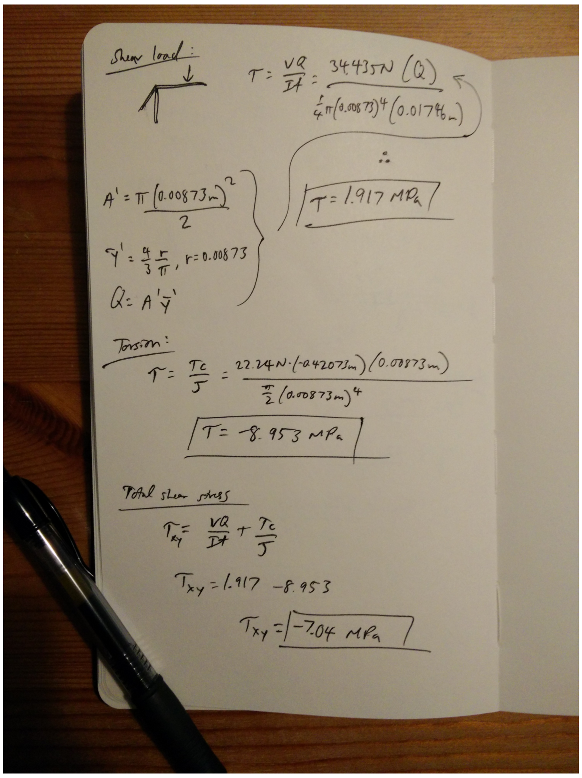

Figure 10: Calculations for total shear stress

since there was no axial stress. The shear strains were calculated in Equation 3 demonstrated by

$$
\begin{aligned}
\gamma_{zy} &= \frac{1}{G}\tau_{zy} \\
\gamma_{zy} &= \frac{1}{79.3GPa}(-7.04MPa) \\
\tau_{zy} &= -8.88 * 10^-5.
\end{aligned}
\quad (3)
$$

4.2 Analysis of L Bracket

A stress analysis was conducted for a point in the middle of one of the L brackets. Using Equation 4 we calculated the the shear stress in the x direction as follows,

$$\begin{aligned} \tau_{zx} &= \frac{V_x Q_z x}{Tt} \\ \tau_{zx} &= \frac{-22.2N(.938mm^3)}{1.25mm^4(15mm)} \\ \tau_{zx} &= -1.11\frac{N}{mm^2} = -1.11MPa. \end{aligned} \tag{4}$$

Then, we calculated the shear stress in the y direction using Equation 5 given by,

$$\begin{aligned} \tau_{zy} &= \frac{V_y Q_z y}{Tt} \\ \tau_{zy} &= \frac{4.29N(28.1mm^3)}{281mm^4(1mm)} \\ \tau_{zy} &= 0.429\frac{N}{mm^2} = 0.429MPa. \end{aligned} \tag{5}$$

Then, we calculated the strain due to these stresses and found that there was no axial strain since there was no axial stress. The shear strains were calculated in Equation 6 demonstrated by,

$$\begin{aligned} \gamma_{zy} &= \frac{1}{G}\tau_{zy} \\ \gamma_{zy} &= \frac{1}{79.3GPa}(-1.11MPa) \\ \gamma_{zy} &= -1.39E-5. \end{aligned} \tag{6}$$

4.3 Analysis of Spiral

We will analyze the sections where the zip ties are strapped to the hose and spokes, since these are the areas that will experience the most stress and strain. The hose is open ended and will experience a $\sigma_{long} = 0$. The spiral will be considered as a thick-walled cylinder as the inner-radius-to-wall-thickness ratio of $\frac{r}{t} < 10$. As a result the hose will experience a σ_{radial} and σ_{hoop} represented by the equations below:

$$\sigma_r = \left(\frac{a^2 p_i - b^2 p_o}{b^2 - a^2}\right) - \left(\frac{a^2 b^2 (p_i - p_o)}{b^2 - a^2}\right)\frac{1}{r^2} \tag{7}$$

$$\sigma_h = \left(\frac{a^2 p_i - b^2 p_o}{b^2 - a^2}\right) + \left(\frac{a^2 b^2 (p_i - p_o)}{b^2 - a^2}\right)\frac{1}{r^2} \tag{8}$$

a = inner radius,
b = outer radius
p_i = inner pressure (of water)
p_o = outer pressure (of zip tie)
r = distance from origin to element

To calculate p_i, the dynamic pressure of the flowing water in the hose will be used:

$$\begin{aligned} p_i &= \frac{1}{2}\rho v^2 \\ &= \frac{1}{2}(1000kg/m^3)(.0309m/s)^2 \\ &= 15.5Pa \end{aligned} \tag{9}$$

Assuming the F_{river} exerts a force on the paddle, to the rim, to the spoke, and lastly to the hose and zip tie, the general pressure, p_o, exerted by the zip tie upon the hose will be calculated:

$$p_o = \frac{F}{A} = \frac{22.2N}{.000121m^2} = .183MPa \tag{8}$$

Then, we can calculate σ_r and σ_h, which also represent the principal stresses:

$$\sigma_r = \left(\frac{(.00494m)^2(15.5Pa) - (.00794m)^2(.183MPa)}{(.00794m)^2 - (.00494m)^2}\right)$$
$$- \left(\frac{(.00494m)^2(.00794m)^2((15.5Pa) - (.183MPa))}{(.00794m)^2 - (.00494m)^2}\right)\frac{1}{(.00644m)^2}$$
$$= -0.123Mpa$$

$$\sigma_h = \left(\frac{(.00494m)^2(15.5Pa) - (.00794m)^2(.183MPa)}{(.00794m)^2 - (.00494m)^2}\right)$$
$$+ \left(\frac{(.00494m)^2(.00794m)^2((15.5Pa) - (.183MPa))}{(.00794m)^2 - (.00494m)^2}\right)\frac{1}{(.00644m)^2}$$
$$= -0.422MPa$$

*The negative values represent compressive stresses exerted by the zip ties.

The maximum bending stress is calculated by:

$$\sigma_y = \frac{M_y c}{I} = \frac{-0.700Nm(0.00794m)}{2.65e-9m^4} = -2.10MPa \quad (7)$$

The maximum shear stress is represented by the relation between σ_r and σ_h and is located at $r = a$:

$$\begin{aligned} \tau_{max} &= \frac{\sigma_h - \sigma_r}{2} \\ &= \frac{-0.422MPa - (-0.123)Mpa}{2} \\ &= -0.176MPa \quad (6) \end{aligned}$$

Overall, the compressive stress at the spiral is less than the stress of the other two subsystems.

5 Conclusion & Discussion

Practical improvements for future use include the possibility of doubling the intake of water by attaching an additional coil to the system. The intake would be doubled with no significant change in rpm. Due to the additional flow rate resulting from the extra coils, it would be necessary to increase the diameter of the outflow pipe to reduce the losses due to the friction of the water with the inner wall of the pipe. The most efficient angle of the paddles in respect to the river was determined to maintain at 90 degrees, maximizing the apparent area that is exposed to the flow of water. This project kept a concentration on water acquisition; however, future additions can be made to the design for the supplementary purpose of water purification.

6 References

"Thick Walled Cylinders." , Engineering Faculty of Memorial University, www.engr.mun.ca/ katna/5931/Thick %20Walled%20Cylinders(corrected).pdf. Accessed 19 Dec. 2016.

7 Acknowledgments

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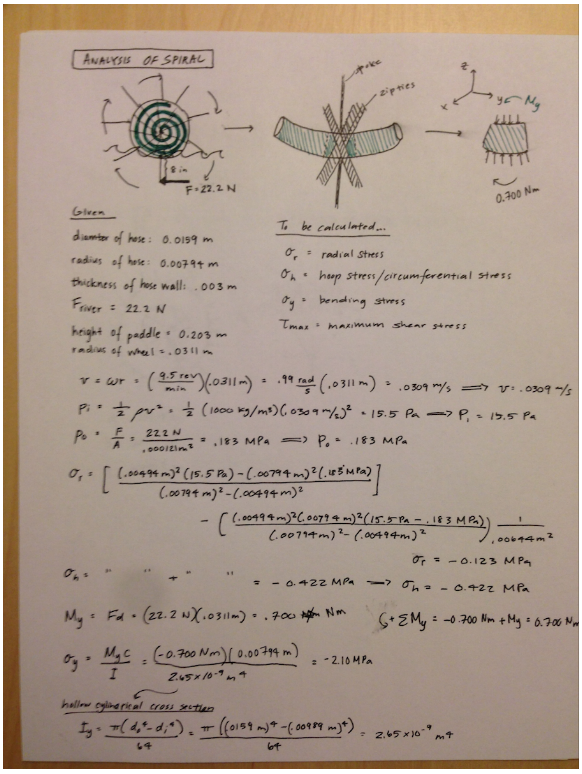

Figure 11: Calculations for Analysis of Spiral

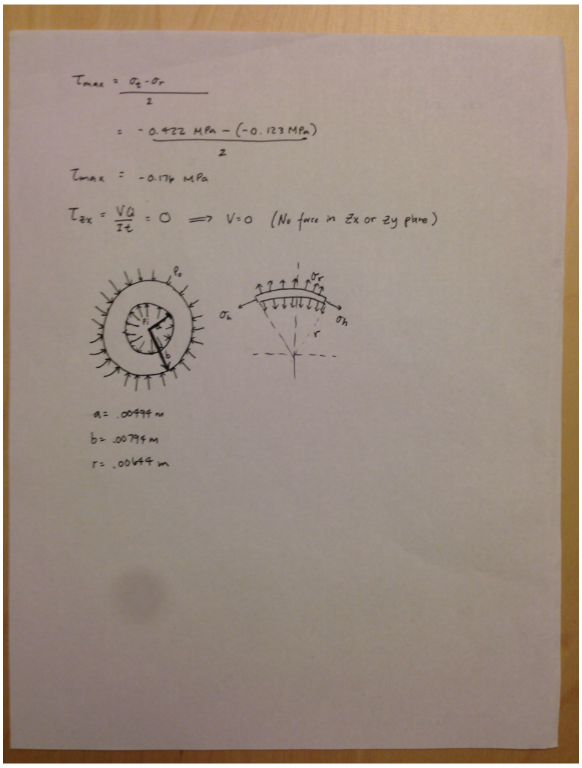

Figure 12: Calculations for Analysis of Spiral