TOW TANK FOR TETHERED HYDROFOIL

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ABSTRACT
The objective of the project was to build a small scaled version of tethered hydrofoil to compare with the model simulation provided by Dr. Mario Gomes in MATLAB. The project was divided into two teams P12462 (Tow Tank) and P12463 (Tethered Hydrofoil).

Team P12462’s goal was to create a tow tank capable of moving a platform at a constant specified speed over the top of a stationary body of water in order to recreate a river flowing around the hydrofoil.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>τ</td>
<td>Torque (in-lbs)</td>
</tr>
<tr>
<td>r</td>
<td>Radius (in)</td>
</tr>
<tr>
<td>F_D</td>
<td>Drag Force (lbf)</td>
</tr>
<tr>
<td>F_Tow</td>
<td>Tow Force (lbf)</td>
</tr>
<tr>
<td>C_D</td>
<td>Drag Coefficient</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (water)</td>
</tr>
<tr>
<td>V</td>
<td>Velocity (ft/s)</td>
</tr>
<tr>
<td>A</td>
<td>Area (ft²)</td>
</tr>
<tr>
<td>P</td>
<td>Power (hp)</td>
</tr>
<tr>
<td>m</td>
<td>Mass (lbs)</td>
</tr>
<tr>
<td>a</td>
<td>Acceleration (ft/s²)</td>
</tr>
</tbody>
</table>

BACKGROUND
The use of kites, or tethered airfoils, at high altitudes is a growing alternative to harvesting wind energy over the use of standard tower supported turbines. There are many advantages to using an airfoil over a turbine, such as a large swept area of lifting body even if when the lifting body itself is small.

The idea of the project started as a two dimensional problem based on the airfoils. After some research, Dr. Gomes came to the idea of placing a hydrofoil in a moving body of water, such as a river, in order to generate that two dimensional movement. An advantage of using this system in a river, is that the continuous flow of the water will generate the movement of the anchored hydrofoil which as a response will generate energy.

Team P12462 was asked to design, analyze, and create a small scale version of the system to be tested indoors. This was chosen because of the practical issues of proving a concept on a constantly changing environment and due to Rochester’s winter river scenarios. The objective was to create either a portable moving rig to be used next to a pool or a tow rig stationed above a usable tank.

During a meeting held by teams P12462 and P12463, the topic of using a tank or RIT’s pool for testing the design of the projects was discussed. A list with the pros and cons of each option was created and later discussed with the customer and the teams’ guide. It was decided that a tow tank was the best option, and thus starting the direction for P12462 project.
successfully design the tow tank. It will also describe the steps followed during the manufacturing and the testing stages.

CUSTOMER NEEDS/SPECIFICATIONS
The first step was to identify and understand what the customer wanted. The customer needs were originally given in the project readiness package in the beginning of MSDI. They were gradually adjusted during the process of the project through many meetings and conversations with the customer, Dr. Gomes.

The main objective given by the customer for team 12462 was to simulate a river system for team 12463’s hydrofoil to be able to collect data. This will be accomplished by the tow tank’s ability to tow a platform above the surface of a stationary body of water at a constant speed. From this specific need the project scope was identified and the team was able to start the design process.

The design process began with the discussion of whether the rig would be simulated in the RIT pool or to design and build a tow tank. Either using the pool or a tank, they both must tow a length long enough for the hydrofoil to achieve steady state. If the tank option were chosen, it must be safe for the operator and those around them, it must not damage the surroundings, it must be cost effective, and shouldn’t interfere with operation of models. Other needs that would be included in the design, involve the platform which would hold the team 12463’s hydrofoil project. The platform needs include: the platform must allow an attachment of two different instrumented systems, a set of stationary hydrofoils and a model of a translating hydrofoil systems, and it must allow for bolting of the instrumented model away from the wall of the tank. Keeping these needs in mind team 12462 was able to split up the work and start designing the sub-systems of the project.

The engineering specifications which coincide with the customer needs can be seen in Table 1. With the customer needs fully evaluated, the design can be made to meet the specifications.

<table>
<thead>
<tr>
<th>Table 1: Engineering Specifications</th>
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</thead>
<tbody>
<tr>
<td>Specifications</td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>System cost</td>
</tr>
<tr>
<td>Distance cart travels</td>
</tr>
<tr>
<td>Velocity of cart</td>
</tr>
<tr>
<td>Towing velocity variation</td>
</tr>
<tr>
<td>Max sideways deflection of rail system</td>
</tr>
<tr>
<td>Center of platform from edge of tank</td>
</tr>
<tr>
<td>Data sampling rates</td>
</tr>
<tr>
<td>Resolution of velocity data</td>
</tr>
<tr>
<td>Resolution of time data</td>
</tr>
<tr>
<td>Test setup time (by user)</td>
</tr>
<tr>
<td>Can test different models and hydrofoil sets</td>
</tr>
<tr>
<td>Compliance with accepted safety protocols and regulations</td>
</tr>
<tr>
<td>Tank is Designed so model is not restricted in its motion</td>
</tr>
<tr>
<td>Tank assembly does not damage its surroundings</td>
</tr>
<tr>
<td>Training time (1st Time)</td>
</tr>
</tbody>
</table>

CONCEPT GENERATION AND EVALUATION
Several concepts were generated and rated using various grading criteria. The first major decision was whether to use a lap pool or build a specialized tank. After discussing with team 12463 and our customer, the pros and cons were weighed and it was decided that creating a small scale tank would best serve the customer’s needs. Once it was decided to construct a tank, the next large decision was to lay out the dimensions that would be needed. Three different size tank were discussed; a small tank (1 ft wide, 0.5 ft deep, 3 ft long), a medium tank (2 ft wide, 1 ft deep, 6 ft long), and a large tank (4.25 ft wide, 1.5 ft deep, 16.4 ft long). Based on the input from all the stakeholders a metric was created to analyze each size tank. It was unclear from the metric which tank was ideal. For this reason a hybrid tank was created (2.5ft wide, 1.5ft deep and 16ft long). The metric was again analyzed with the added tank and it became clear that the new tank dimensions were best suited for all stakeholders.
The next concept that was evaluated was the decision of what kind of system should be used to move the team 12463’s system across the tank. A method was created to analyze different systems using a datum comparison. The systems to move the platform that needed to be compared were: the motor on the platform, a pulley system with a motor, cables with a winch, and a stepper motor with a screw option. The attributes used to compare these different systems were constant variable velocity, force, cost, vibration, ease of control, bi-directional, and safety. After going through the comparisons it was obvious that the best decision was to use a pulley system and a motor.

After that decision was made the motor type needed to be determined. There were a few options that were considered, such as a DC motor, an AC motor, or a stepper motor. To finalize the type of motor that would be best suited for this application, it was researched each option, keeping in mind the attributes mentioned above. It was clear that a DC motor would be best suited, since it was less costly and would do the job most efficiently. However, after many discussions it was discovered that Professor Wellin had a 3/4 HP DC motor available for use, and was only slightly larger than the planned motor power of 1/2 HP. Professor Wellin generously donated the motor, as well as the DC driver which provides speed control for the motor.

The last and probably largest discussion was the material that was going to be used for building the tank. At the beginning, the team thought about a metal support structure with glass, polycarbonate or acrylic walls, based on the previously built tanks at Cornell University, University of Saskatchewan, and California Institute of Technology. After gathering information about the various costs, the team threw away the option of a completely clear wall tank and the idea of using metal sheets and placing a window in the middle panel was then evaluated. Because of budget concerns, the team ended up changing the wall material to 3/4 inch thick plywood covered with a black 6 mm polyethylene liner.

ANALYSIS
After selection of the main components was complete it was possible to begin more in depth analysis to ensure structural integrity. Analysis was worked on individually, with each team member owning a main component.

The support structure of the tank was tested in ANSYS Workbench to find a viable design with a sufficient factor of safety as well as deflection criteria. The load cases considered included the hydrostatic force from a full tank, as well as a 200 lbf (889.64 N) point load on the top rail at center of the tank, working in the same direction as the water, to simulate someone leaning or pulling on the tank support structure. Steel angle iron was selected and used throughout the design with a yield strength of 50 ksi (345 Mpa) and a max allowable deflection of 0.03125 in (7.94E-3 m). The thicknesses and the location of the vertical supports were two things which needed to be evaluated. This was an iterative process, starting with large spacing and small thicknesses, and gradually reinforcing until structural and deflection criteria were met. It was determined that the main outside structure of the tank needed to be 2"x2"x3/8” steel angle iron to withstand the hydrostatic load and applied external forces. The interior vertical and horizontal supports needed to be 2"x2"x1/4” steel angle iron.
A similar process was also performed using initial hand calculations along with ANSYS to pick a viable wall material. The potential materials for the walls included steel plate, Plexiglas, Lexan, and tempered glass. All of these materials were modeled and tested in ANSYS to find stress and deflection values. In order to achieve minimal deflection in the tank walls, prohibitively expensive thicknesses of the materials analyzed would be necessary. Given the budget, plywood was considered as potential wall material as a more cost effective option. This material would be easy to acquire, less expensive compared to the other potential materials, and could be upgraded in the future to a more permanent material if so desired. Due to the non-isotropic material properties, ANSYS was not a viable means of analysis. Published data on the strength of plywood was consulted and used to determine that 3/4” thick plywood was required to withstand the forces applied. Due to the significantly lower cost of material, plywood was used for the final design.

Once the final decision for plywood was made, the discussion of how to waterproof the walls became relevant. A few membrane ideas were considered including rubber EPDM pond liner, fiber glass membranes, roll roofing, and 6mm polyethylene plastic. Based off of cost and availability, the 6 mm polyethylene plastic was chosen to be the waterproofing mechanism for the tank. The polyethylene proved to be a good liner until it was punctured. Once a puncture was present, the problem of patching these holes became a significant issue. Compatibility tests were done with cyanoacrylate, vinyl tape, 3M 90 Hi-Strength spray adhesive, LOCTITE Epoxy, and Gorilla tape. The vinyl tape and Gorilla tape proved to be the most compatible and were selected for further testing. The strength of the bond between the two tapes and the liner needed to be quantified. Testing samples were created of 1” thick strips of adhesive and applied to a sample of the polyethylene liner. Using force gauges the strength of the bond was quantified.

<table>
<thead>
<tr>
<th>Dimensions [in]</th>
<th>FOS Stress</th>
<th>FOS Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle Iron 2x2x.125 (Length)</td>
<td>6.42</td>
<td>2.25</td>
</tr>
<tr>
<td>Length with -100lbf point load</td>
<td>0.67</td>
<td>0.28</td>
</tr>
<tr>
<td>Length with +100lbf point load</td>
<td>0.83</td>
<td>0.37</td>
</tr>
<tr>
<td>Angle Iron 2x2x.375 with 2x2x.25</td>
<td>0.34</td>
<td>0.28</td>
</tr>
<tr>
<td>Length with -100lbf point load</td>
<td>4.39</td>
<td>1.93</td>
</tr>
<tr>
<td>Length with +100lbf point load</td>
<td>6.34</td>
<td>3.09</td>
</tr>
<tr>
<td>Length with -200lbf point load</td>
<td>2.38</td>
<td>1.06</td>
</tr>
<tr>
<td>Length with +200lbf point load</td>
<td>2.85</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Figure 3, below, demonstrates how the strength of the bond was measured with a force gauge. Based upon the results, Gorilla tape was decided to be the best choice for a patching adhesive.

Analysis of the rails and cart system was more difficult than the tank walls, not for the complexity of the system, but due to the uncertainty of the loading conditions. The loading which the cart would see during a towing event was directly related to the geometry of the cart, the geometry of the tethered hydrofoil being towed, any potential friction or binding in the rails, and was all dependent on the model of the system being accurate for hydrofoil loads and power being produced. Also due to budget concerns, a system involving linear pillow block bearings on a machined bottom supported shaft was out of the discussion, so extra care had to be taken in ensuring the lifting moment produced on the cart from the hydrofoil would not be sufficient enough to lift the cart from the rails.

Discussions with the hydrofoil team allowed for a worst case boom length, hydrofoil depth and generator K-value to be finalized. These values were then entered into the model and the torque produced on the cart from the generator was outputted, along with the forces parallel and perpendicular to the boom. These values were not constant, and varied throughout a towing event. Different times had load cases which were worse than others, dependent on the velocity of the boom as well as direction. After loads were characterized it was possible to size components of the cart.

In order to be cost effective, the cart was originally designed to ride along a section of angle iron on one side and a flat section on the other. This would mitigate binding issues due to
not being overly constrained. The most difficult challenge was that the cart needed to weigh enough to overcome the lifting moments, while also minimizing weight to reduce inertial forces shortening the usable length of track due to required stopping distance.

A later budget increase allowed an improvement of the rail design which helped to mitigate lifting concerns and allowing the team to provide a modular cart design. The cart would not ride on top of angle iron, instead it would use 80/20 Linear Bearings on both sides riding along 16ft of continuous 80/20 extruded aluminum.

Even though there was a motor provided for the project, there were still motor sizing calculations to be done. The first step in analyzing the motor was to determine the forces that the motor would be pulling. A towing force was applied to one side of the platform, and drag and frictional forces were applied to the other side of the platform. To simply the problem, friction force was assumed to be negligible. To find the tow force, equation 1 below was used. To find acceleration, velocity was divided by time, where velocity was 3.28 ft/s and time ranged from 0.25 to 2 seconds. The mass was an approximation of the total of all the equipment on the platform. The drag force was determined by assuming that a flat plate would be dragged through the water, calculating the force from equation 2, below. The drag coefficient for a flat plate and properties of water at room temperature were found in table 9.3 and A.7, respectively [1]. The area was an input parameter.

\[ F_{\text{tow}} = ma + F_D \]  
\[ F_D = \frac{1}{2} c_D \rho V^2 A \]

Once the total force was solved for, the torque was determined, in order to find the total power required to move the platform. The torque was found using the equation 3, where the radius was an input parameter. The power was then determined using equation 4 shown below, where the RPMs were found dividing the velocity by 2πr.

\[ \tau = F \times r \]
\[ P = \frac{2\pi \times rpm}{33000} \]

For a factor of safety, the maximum force was used for the final calculation, giving the required torque to be roughly 200 in-lbs, and a power of about 1/2 HP. The provided motor was a 3/4 HP motor which would support the required power. However, the motor runs at a high velocity (1750 RPMs) and a low torque, therefore a gearbox was necessary to reduce the speed and increase the torque. The gearbox needed to reduce the motor velocity to 135 RPM with a parallel shaft ratio of 12.5:1.

The next step of the motor calculations was to analyze the way the motor would be mounted onto the side of the tank. Two options were analyzed, a wooden workbench that will sit next to the tank, and a steel plate that will be welded onto the tank. The options were analyzed in ANSYS Workbench, by applying the tow force calculated and a pressure force of the weight distribution of the motor and gearbox. Also, the effects on the tank were taken into consideration. After the results were found, the wood option scored higher with a higher factor of safety; however, after talking with Rob Kraynik from the Machine Shop, it was decided that welding a plate to the tank was a better option. A piece of angle iron was added to support the weight of the equipment on the plate. Figure 4, shows the final design of the motor and its mount position on the tank.

\[ \text{Figure 4: CAD Model of Motor Mount} \]

MANUFACTURING
To get approved by the customer and the team’s guide, the team was asked to perform a miniature manufacturing demonstration. The team was asked to create a 2.5ft wide, 2ft deep and 2ft long tank. It was constructed out of the same materials as the final tank, as to not waste any part of the budget. A 4ft rail and pulley system connected to the motor was constructed to demonstrate the motor capability. In order to assure that every step used to construct the mini tank and all the learned steps the process were followed on the final production, the team created a scheduled check list. Figure 5 is an excerpt from the schedule created for final tank construction.
The steel angle necessary for the final tank was ordered to length, to ease the time of construction. Certain pieces were delivered longer than desired, due to manufacturing precision, and had to be cut to length. Every large cut (more than 1in) was performed using a horizontal band saw, while all the precise cuts where performed using a mill. The tolerance of each piece was ±1/16 in. All the metal pieces needed to be ground at a 45° angle, using a hand angle grinder, to create room for the weld to lay flush to the metal. The metal angle was assembled using a MIG welder. A final grind on all the welds was needed to eliminate the extra material left after the welding was performed.

To increase flexibility, the tank was designed and manufactured as two 8ft sections which were later bolted together. This was done so the two halves could easily be transported to their final location.

The plywood panels were cut from 8ft long x 4ft wide pieces. Smaller wall panels were installed to allow for a future window upgrade to easily be added, in the side walls or the bottom. Each individual panel was sanded and all the rough patches or holes where fixed using Bondo® in order to eliminate all the imperfections that could be a risk for the liner. All edges of the panels were also sanded, to reduce the risk of tearing the polyethylene liner.

The welded structures were cleaned, and RIT brown RustOleum paint was applied. Also, the plywood was coated with waterproof paint; the exterior sides of the panels were then painted with orange paint as the final product.

The rails were purchased in continuous lengths, so machining was not required. They were attached to the slots cut every foot along the top of the tank. This allowed for horizontal adjustment in the rails, while long bolts, nuts and lock washers allowed for vertical alignment. The only machining required for the cart was to size the length of the 80/20 used for the width of the tank; machining the 80/20 was done using the mill. The cart was then assembled using T-Nuts, connecting plates, and the linear bearings, all of which were available from 80/20. Future modifications would be simple; parts such as camera mounts, electrical cable management, and any required attachment points can be added quickly and easily due to the modular design.

**TESTING**

Tests were completed to characterize the system and to verify specifications. These included velocity, distance, start-up transient and cable wear testing. For velocity testing a distance of 8 feet was measured, and a stopwatch was used to measure the steady state travel time through this distance. This was required to find an effective pulley diameter which would convert the motor RPM to a measured cart velocity. It was also important in finding the accuracy of the measured velocity to the expected velocity. Figure 6 below shows an excerpt of the results.

![Cart Speed Test Data](image)

At higher ranges the velocity was accurate to ±0.1 ft/s (±0.03 m/s). This was a large range; however some of this was due to stopwatch inaccuracies. At lower velocities the range was much smaller and our expected velocity was much closer to the measured.

The distance testing was done to ensure that the cart’s acceleration and deceleration profiles were accurately predicted. As seen below in Figure 7, the predicted distance travelled was less than the expected in all cases. This was due to the predicted deceleration distance not accounting for the velocity of the cart. It is however important to note that at the highest velocity and longest distance of travel the cart stops within 0.075m of expected. These results are acceptable because the cart will not travel further than expected even at maximum velocity.
Initial transient testing was performed due to an issue with sudden startups. Over 50 tests were performed of translating the cart at various velocities in both directions, noting when the cart would suddenly start instead of gradually ramping up to the expected velocity. In 50 tests, the cart accelerated improperly two times. This is an issue which can be looked into further, however it does not have a major effect on testing. If a sudden startup is experienced, simply stop the motor and redo the test.

The final set of tests which were performed involved the life of the tow cable. Currently a stainless steel aircraft grade cable is being used, but it does grind on itself and make noise. A piece of paper was placed below the pulley to collect steel flakes as they wear off. There is considerable wear of the tow cable, and the recommendations section below gives further information.

RESULTS AND DISCUSSION
The following section describes our final product, shows a comparison of expected to completed specifications, and discusses potential areas for improvement.

FINAL PRODUCT
The final build is mostly complete and not without its flaws. A full 16ft long tow tank was delivered, with the following features.

- Steel angle iron and plywood walls
- Polyethylene liner
- Nylon pulley and stainless steel cable
- Preliminary pulley guards
- Permanent motor mount
- Baldor 3/4 HP Motor
- Dayton speed reducer
- Velocity motor control with LabVIEW
- DART motor controller
- Modular Cart and Rail system
- Preliminary limit switch mounting

CONCLUSION
At the end of the build process the final tank was compared to the original customer needs and specs. Most of the specifications were met except for a few which were slightly unsatisfactory. The requirement of the maximum sideways deflection of the rail system was not met due to mounting issues. The distance the cart can travel was slightly below 16ft. And the issue of potentially damaging the surroundings with leaks was not fully met.

Many of the needs were met including one of the most important. The design was successful in providing a moving platform over a stationary body of water, capable of performing fluids testing.

RECOMMENDATIONS
The following are recommendations for future improvement of the tow tank. Unfortunately, there is not enough time to implement all of these changes now, but can easily be done in the future.

1) Upgrade the plastic liner to a more robust system. Leaks have been an issue with the current liner. Potential solutions include a thicker liner of similar
material, a rubber EPDM pond liner, or a rubber roofing material which could be cut to size and applied to the inside of the tank.

2) **Upgrade tow cable and/or drive pulley.** Currently the tow cable is made of stainless steel, and is wearing at a high rate. This is in part due to the drive pulley not being grooved, and also because of the softer properties of stainless steel. A coated Kevlar cable may be a better option.

3) **Place windows in the tank walls to allow in water visibility.** In the future it would be good to have more visibility of the models being tested. This would open up the opportunity for more cameras, or entirely different testing methods, such as particle image velocimetry.

4) **Upgrade the plywood panels to sheet metal panels or glass panels.** Some of the current plywood panels are warped, or the screw holes are stripped. Improving the walls to a more permanent material would prolong the life of the tank, and could mitigate leak issues.

5) **Improve rail mounting to tank.** The rail system is currently mounted so it has horizontal and vertical positioning, but no means to account for twist in the rail along its length. Spherical washers, although expensive, could be used to solve this problem.

6) **Improve limit switch mounting and control.** The limit switches are currently not permanently mounted, and in their current setup send a 0 to the motor only while the switch is actuated, and once the switch is released returns the motor to its original speed. Changing this to cut power to the motor could dramatically improve the system.

7) **Replace pulley guards.** The current pulley guards are poorly mounted and are made of quickly bent aluminum sheet metal. These could be improved with a more elegant solution.

8) **Replace motor direction relay with one that is LabVIEW controlled.** It is very easy to have the motor go the wrong direction if you have the switch in the wrong position. It is currently external to LabVIEW control. It would be much better to operate, if LabVIEW set the direction of a tow event, not the user externally.

9) **Switch from velocity control to position control of cart.** Velocity control of the cart is less than ideal. It relies on trusting the motor controller to ramp up and ramp down based on input conditions, but the system is not consistent. More robust control over the motor would involve a LabVIEW or microcontroller control scheme for both velocity and position.

10) **Upgrade to stainless steel to reduce rust on parts.** Due to time constraints, part availability and budget concerns much of the hardware used on the tank is not stainless steel. They are for the most part at least coated, but rust may be an issue in the future being near the water.

**ACKNOWLEDGMENTS**

Special thanks and acknowledgements to everyone involved in the designing, building, and testing phases of the tow tank. Team P12642 would like to extend thanks to EPA P3, sponsor of the project, as well as to Dr. Mario Gomes, the customer.

P12642 also thanks RIT faculty Dr. Steven Day for participating on the review of the design, as well as Professor John Wellin for his support intellectually as well as his material donations. Thanks to Kelsey McConnaghy for help understand the MATLAB simulation.

Thanks to Robert Kraynik, Jan Maneti, and Dave Hathaway, members of the RIT Machine Shop where the tow tank was manufactured. Thanks to Mahany Welding Supply for donating the Miller MIG Welder, and RIT Facility Management Services for donating the primer and paint.

Lastly, thanks to Professor Ed Hanzlik for his help and guidance on this journey. It would not have been possible without him.

**REFERENCE**