WATER PROPULSION TESTING FOR MINI-BAJA

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ABSTRACT

The primary objective of this project was to assist the Mini-Baja team at the Rochester Institute of Technology in Rochester, NY in improving the water competition times for their land-water race vehicle. This was done by helping the Baja team determine the best water propulsion system available within their constraints. To fulfill this objective, the engineering team designed and built a test stand that analyzes various water propulsion options. They also determined a method for retrieving and analyzing data from each test. The final deliverable to the Mini-Baja team included both a physical test stand and the supporting software to collect and display performance data from each propulsion option.

When the finished test stand was delivered to the Baja team, it was met with full customer approval. All of the tests performed on the stand were either successful initially or were remedied successfully. In addition, all of the customer needs were met and the stand and software were delivered to the customer on time.

INTRODUCTION

Every year, the Rochester Institute of Technology Mini-Baja SAE club designs a land-water vehicle to race in competitions around the world. The goal of this project is the help the Mini-Baja team create the optimal water propulsion system for powering their vehicle during the water portions of the competition.

The objectives of the project were to design and build a testing device to examine multiple water propulsion concepts and to determine a method for retrieving and analyzing data from these tests. Improved Mini-Baja vehicle performance in water competitions was the major expected benefit from this project. In addition, the design team hoped to provide the Mini-Baja club with the ability to easily produce proof-of-concept documentation to justify their water propulsion design to judges at Baja races.

Previously, the Mini-Baja team improvised water propulsion systems without any scientific testing to prove their performance. Commercial test stands that achieve this task cost upwards of $10,000, making them unavailable to university clubs such as the Baja team. Thus, the design team was tasked with building an appropriate stand for approximately $1500. To do this, the team required a very simple design and a very specific focus on the most important elements of water propulsion.

THOERY

To begin the design process, the team first decided what the test stand needed to accomplish. It was determined that each possible water propulsion concept would be judged based on its ability to produce the most forward propulsion; that is, the most force in the x-direction. This simplified the design and helped meet cost constraints for building the test stand.
while providing the most directly useful performance data.

At the start of the project, the engineering team performed a preliminary test to measure the forward force created by the current Mini-Baja vehicle. The propulsion of the vehicle was measured both with its base design and with its current water propulsion system in place. The maximum force measurement generated by this test, 50 lb, was used as the baseline and minimum required testing capability of the test stand.

In addition, it was agreed that, while the test stand would be built by the design team with a budget of approximately $1500, the Mini-Baja team would provide all materials, such as vehicle tires, for testing each propulsion option. The $1500 budget would be sponsored by the RIT Mechanical Engineering Department.

**PROCESS**

**Customer Needs**
The list below shows the major customer needs identified for this project by the design team and the Mini-Baja club.

- Provide test stand that can produce repeatable tire/fender performance data
- Provide documentation to clearly communicate all project work done
- Provide Standard Operating Procedure for using test stand
- Ensure that test stand is safe to use
- Ensure that test stand is capable of withstanding brief exposure to rain

**Engineering Specifications**
Using the complete list of customer needs, a set of engineering specifications was determined with the aid of a House of Quality tool. This tool used the importance of each customer need and the ability of each design specification to fulfill these needs in order to prioritize the engineering specifications. The following list shows the most important design specifications for the project, along with their quantitative values.

- Maximum forward propulsion test stand can withstand (13.5 lb)
- Maximum buoyancy force test stand can withstand (55 lb)
- Standard Operating Procedure provided to Baja
- Minimum frame material strength (factor of safety of 2)
- Maximum water force tank can enclose (6.81 psi)
- Maximum test stand width (4 ft)
- All electronics are resistant to rain water

The design team used this prioritized list to focus their efforts on the project solutions that would best meet the most important customer needs.

**Solution Concepts**
To discover the best option for meeting the Mini-Baja club’s needs, the engineering team researched a broad range of solutions, both in-house and outsourced. The concepts analyzed included:

- Building and using a test stand
- Building and using a scale model vehicle and small test stand
- Testing designs directly on the Mini-Baja vehicle
- Sending designs to a tire company for testing
- Using RIT facilities to test designs
- Performing simulated tests on a computer
- Renting equipment from an outside company to perform each design test

Each of the above solutions was researched for feasibility and performance. Using the project customer needs and engineering specifications as a basis for comparison, the solutions concepts were analyzed using a concept scoring matrix.

Some concepts, including sending designs to an outside company for testing, using RIT facilities, and renting equipment from an outside company were infeasible because they simply do not exist. In addition, it was found through research that performing simulated tests would not provide accurate results, so this concept was marked as infeasible, as well.

It was determined through the concept scoring technique that the best option was to build a test stand. This is because the stand would be available for the Baja team to use at any time and could be designed to test exactly what was needed, no more and no less.

The other high-ranking concepts included building and testing a scale model and testing designs directly on the Baja vehicle. While building a scale model has the same benefits as building a full-size test stand, a model would need to be created for each proposed design in the future. This would require a significant amount of time and effort from the Baja team each time they want to try a new design. On the other hand, testing designs on the Mini-Baja vehicle requires no preparation time or cost. However, the
Baja vehicle is not always available for testing, especially during busy race weeks and during the winter months when the lakes and ponds are frozen. In addition, testing directly on the Baja vehicle involves many variables, decreasing the accuracy and repeatability of the results.

**Final Design Selection**

Using the top solution concept, building a test stand, as their model, the engineering team devised multiple possible test stand designs. These included the following, shown with sketches:

The Spring design, shown in Fig. 1, below, uses a top-mounted wheel and axle, which slides along a track on the top of the tank. The wheel pulls against a back-mounted spring, gauging the forward force.

![Figure 1: Spring Design](image)

In the Moving Tank design, Fig. 2, a side-mounted wheel and axle sit stationary on a shelf on the side of the tank. The propulsion generated by the rotating tire pushes the water in the tank, forcing the tank backwards against a force sensor at the base of the tank.

![Figure 2: Moving Tank Design](image)

The Moving Tire design, Fig. 3, incorporates a stationary tank and a side-mounted wheel and axle that attach to a rolling scaffold. The force of the rotating tire propels the wheel and axle, on their frame, forward in the tank, pushing against a front-mounted force sensor.

![Figure 3: Moving Tire Design](image)

In the Strain Gauge design, shown to the right in Fig. 4, the wheel and axle are mounted to the top of the tank on a pendulum. As the rotating wheel swings the pendulum forward, it pulls against a force sensor mounted on the back of the tank.

![Figure 4: Strain Gauge Design](image)

The Force Sensor design in Fig. 5, below, uses a stationary tank and a side-mounted wheel and axle. The forward propulsion of the wheel is captured using a water-proof force sensor mounted inside the back of the tank.

![Figure 5: Force Sensor Design](image)

As in the concept selection process, design screening and scoring matrices were used to judge the designs in an unbiased and scientific manner. The criteria for making this decision was a more detailed version of the customer needs and engineering specifications used to choose the solution concepts.

In the design screening matrix, each option above was compared to the Moving Tire design, which served as the datum for the matrix. A system of +’s, 0’s, and −’s was used to indicate whether the design in question was better than, the same as, or worse than the datum design, respectively, for each decision criteria. The Spring, Strain Gauge, and Moving Tire designs rated the highest after this analysis, but the team felt that none were perfect on their own. So, the team reassessed the best qualities of each of these designs and combined them into a hybrid design. This
combination design, called the Ultimate Hybrid, is shown in Fig. 6, below.

![Ultimate Hybrid Design](image)

Figure 6: Ultimate Hybrid Design

The Ultimate Hybrid design combined the top-mounted motor concept from the Spring and Strain Gauge designs, the use of an overhead sliding structure from the Spring design, and the stationary tank used in all three designs.

In the design scoring activity, the Ultimate Hybrid was compared to the top-rated designs from the screening activity: the Spring design, Moving Tank design, Strain Gauge design, and Moving Tire design. For this analysis, each of the selection criteria was assigned a weight based on the customer needs. Each design was then assigned a score of 1, 2, or 3 for each criterion regarding how well it satisfied that criterion. A rating of 1 indicated that the design met a need poorly, while 3 meant that the design met that need well. The score for each individual design-criterion pair was multiplied by the weight for that criterion to generate a weighted rating for each pair. The sum of each design’s scores was used to determine the best design.

Using this approach, the Strain Gauge design ranked the highest. However, it scored poorly on the criterion “Ability to test other metrics in the future”. The Ultimate Hybrid design ranked a close second and did not score poorly on any metric. In addition, the Ultimate Hybrid had very high ratings for safety, ease of use, maneuverability, ability to produce repeatable data, ability to produce accurate data, ability to test additional fixtures such as fenders or paddles, water-resistance, and ease of testing different tires. For these reasons, the team decided to proceed with this option.

Subassembly and Component Selection

Once the final design was laid out in detail, responsibility for each subassembly of the test stand was assigned to a member of the engineering team. Team members then researched possible parts to be used in their system, using a process of component screening and scoring matrices to make their final decision. These matrices utilized each part’s fit to the project’s customer needs and engineering specifications to determine the most appropriate part for each position.

As parts were selected and costs were accumulated, the team decided to make small changes to the Ultimate Hybrid design shown in Fig. 6. More, smaller rails were used in the frame to support the tank in order to increase the strength of the frame and decrease the cost. For the same reasons, the wheels and casters were removed from the bottom of the tank and replaced with frame rails that sit directly on the ground. To decrease the storage size of the test stand, the rigid plastic tank walls were replaced with a clear vinyl liner, which can be removed from the frame and folded up for storage. The liner is supported on the outside by sheets of plywood, in order to distribute the weight of the water in the tank. The final test stand design is shown in Fig. 7, below.

![Final Test Stand Design](image)

Figure 7: Final Test Stand Design

Test Stand Production

When all of the final parts were chosen and ordered, the team began to build the test stand. The stand was built in three physical subassemblies: the tank and frame, the top drive and rail system, and the electronics hardware system. In addition, another team member was responsible for creating the LabVIEW software system that would acquire and display data from the test stand when tests were performed.

The frame and tank team welded steel stock to create the frame of the test stand. The frame is able to be disassembled into two large front and back pieces and two smaller side pieces. A welding table and fixtures were utilized to ensure proper dimensions of
the frame. In addition, the metal frame was sprayed with rust-proof paint to protect it from water and abrasion. The liner for the tank was purchased from a local pool liner repair company, created from vinyl to fit the dimensions of the tank. The liner forms a 3-D box-shape that can stand inside the frame and wood supports. Finally, the wood sheets were cut to the correct tank dimensions and painted with a durable, water-proof paint. This served to protect the wood from abrasion and water damage, protect the users from splinters during handling, and give the test stand a finished look. The wood panels were then ready to be inserted between the frame and liner. In total, the frame assembly measures 8’ long, 4’ wide, and 4’ tall.

For the drive system, the team, with help from Mini Baja team members, cut all steel and aluminum stock to size and machined all custom parts. Aluminum was selected for the rails because of the unavailability of the desired shape in steel. The remaining parts were created from steel. Shaft splines were cut by Rochester Gear, Inc, to achieve more precise dimensions than the student team could provide. Welding of the wheel arm was performed by Baja team member John Farnach. The team then assembled all of the parts into the complete system and painted those parts that would be exposed to water with the same rust-proof paint as the frame.

A water-resistant enclosure was purchased to protect the electronics during testing. Once all of the electronics hardware was acquired, production of this system involved arranging and connecting the hardware inside this enclosure and cutting holes in the enclosure to allow wires to pass in and out in the correct locations. The electronics utilized include a KBCC-25 motor controller, a potentiometer, a ZB5AT44 emergency stop button with contact block, a PD-2515 dual output switching power supply, and a 4-terminal terminal block. The only electronic components not enclosed in the box are a Honeywell 4AV16F Hall sensor for checking motor speed and a LSB300 load cell for measuring the force generated by the wheel. These are located on the motor shaft and on the top of the frame, respectively.

When each subassembly was complete, the three systems were connected to form the full test stand. The frame, plywood panels, and liner were assembled in the Mini Baja loading dock, where they would remain for testing. The drive system was then mounted on top of the frame and screwed in place. The motor was attached to the drive system and affixed to the frame. Finally, the electronics box and load cell were mounted to the frame and all of the wires were run throughout the stand.

**Testing**

To test the performance of the stand, a set of test plans was written. The most likely areas for poor performance were identified through the creation of a Failure Modes and Effects Analysis, and testing was focused on these areas. Testing was performed throughout the engineering process, from component selection through production. Listed below are the tests performed, grouped by system level:

**Component/Device**
- Hall Sensor
- Motor Controller
- Signal Isolation Unit
- Liner Material
- Eyehole Strength
- DAQ Operating System Support

**Subsystem**
- Tank Water-Holding
- Rail and Runner Movement
- Shaft Alignment
- Lid Seal
- Liner Seal
- Weld Inspection
- Complete Drive System Movement

**Integration**
- LabVIEW Data Acquisition
- Wheel in Water
- Linear Bearing Load
- Linear Bearing Twist
- Structure Natural Frequency
- Frame Loading
- Electronics Wiring
- Lid Placement

**Customer Acceptance**
- Complete Test Stand Assembly

In each test plan was documented the test number and date, the test description and procedure, the equipment required, the pass/fail criteria, and the engineer responsible. If a test failed, the engineer responsible was in charge of implementing the appropriate countermeasures and repeating the test until it passed.

A master Test Plan document was created to detail the project specifications, each of the tests performed, and the customer needs and engineering specifications they address. When a test passed, its results were also documented in the master Test Plan. This document was posted on the RIT EDGE website for future reference.
RESULTS AND DISCUSSION

The final test stand product is shown below in Fig. 8. The frame and tank assembly is comprised of a painted steel frame, painted plywood supporting panels, and a 20-millimeter thick vinyl liner. The upper sliding system is made up of painted steel long rails, aluminum c-channels and bearings on which the assembly slides, and painted steel cross-members for support. Finally, the drive assembly transfers power from a 3 HP DC motor to the tire using a keyed shaft and timing belt pulleys. The motor runs off of a 180 volt power source. Various electronics, listed in the Test Stand Production section above, collect data from the mechanical subassemblies.

![Figure 8: Final Test Stand](image)

While the majority of the design and build phases of the project progressed smoothly, the team had difficulties creating the waterproof liner needed to contain the water used for each test. This item had originally been assigned little risk, because it was expected to be easy to either make or purchase, but issues with equipment availability for creating and long lead times for purchasing made this the limiting element of the process.

When the electronics were first attached to the main body of the test stand, it was discovered that the electronic controller planned for use in adjusting the speed of the motor was not compatible with the system. After discussions among the design team and with the customer, it was decided to use a manual motor control knob instead. This knob was installed on the front of the electronics box, along with a plaque marking the positions of different speeds to allow for easy use.

During the first dry trial run of the test stand, the tire was run slowly at first, and then accelerated until about 80% capacity. (Baja will routinely run the stand at about 50% capacity.) The stand ran smoothly at low speeds, up to about 30% capacity, and then it was observed that the stand began to vibrate slightly. The team hypothesized that this was the structure’s natural frequency point, because the stand quieted again at speeds above 30% capacity. However, above 60% capacity, the stand began to vibrate significantly. More weight was added to the top of the sliding structure and the vibration quieted, but did not cease. The team determined that they would add more structural support on the sliding structure to hold the motor in a more stable position. Another cross-member, installed above the frame and below the long rails, just behind the drive shaft, was also used to add more support. Between these two improvements, no vibrations were felt at any speed during the next customer trial.

In addition, during the first wet trial run of the test stand, it was discovered that a significant amount of friction was generated between the wheel and fender and the water in the tank. This added friction required so much additional power to run the motor than had been used when the tire was run during the dry demonstrations that the test stand hit the voltage limit of the power breaker at only 30% speed. For safety reasons, this breaker limit could not be bypassed, so water propulsion designs that do not create so much friction are necessary if the stand is to be run at high speeds. A picture of the tank running with the tire and fender during the first wet trial run is shown in Fig. 9, below.

![Figure 9: Tire and Fender Running During Wet Test](image)

Once the entire test stand was assembled, all of the tests performed on the stand were either successfully completed or, if a failure occurred, it was successfully remedied. Based on this and on the stand’s adherence to all customer needs, the project was deemed a success.
CONCLUSIONS AND RECOMMENDATIONS

At the conclusion of this project, and in light of the results of other Senior Design projects, it was determined by the design team that having an enthusiastic and supportive customer greatly contributed to the success of the test stand. However, the customer needs for this project were not firm and changed throughout the process, which made the project more difficult.

The subassembly integration between the frame and tank, the sliding structure, and the drive mechanism went particularly smoothly because of detailed planning and CAD drawings. The time spent in this area during the final product development stages easily paid off during the build phase. The majority of the project was completed on time thanks to the flexible and coordinated efforts of the team, as well.

In addition, significant support from experts, listed in the Acknowledgments section, below, helped make this project a success. Alone, the design team would not have had the knowledge and experience to complete this project successfully.

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