The Dual Impeller Drive System (D.I.D.S.)

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***Abstract* - This paper details the design, analysis, construction, and testing of the Dual Impeller Drive System (D.I.D.S.) which is a pumping system intended for stealth marine propulsion. This system is a positive displacement Roots style rotary pump that creates thrust by the rotation of two, three-bladed impellers. The design decisions, testing procedures, and experimental results provided a system that achieved a set of advantages over existing technology. The advantages of this design include low cavitations probability, lower SPL of operation, lower rotational speed, large range of efficient operation, and large heads over large volumetric flow rate ranges. This system was a senior capstone design project initiated and completed by two engineering students.**

INTRODUCTION

The Dual Impeller Drive System (D.I.D.S) project was the concept of undergraduate engineering seniors Sean Derrick and Jeff Rauen. It served as a multidisciplinary senior engineering capstone project at Western Michigan University (WMU). Over the course of two semesters, the project progressed from pure concept to full design, analysis, working prototype creation, testing, and evaluation. The project focused on achieving proof of concept by creating a fully functional prototype for hypothesis verification.

The project was conducted in several phases. Phase one consisted of initial research and development of the design concept. This phase included benchmark testing, reverse engineering of similar technologies, as well as the writing of an in-house computer program to determine dimensions and other critical design factors.

Phase two began when a design had been finalized and a CAD model was established. At this phase, Finite Element Analysis (F.E.A) was performed. Also, preliminary budgeting, cost analysis, manufacturing intent, and feasibility analysis were performed in great detail. At this phase multiple optimization studies were conducted along with advanced design for production methodologies. Once a finalized design was reached and tested, via computer, the prototyping method was established and carried out.

Phase three began with the D.I.D.S being built. A homemade testing rig was produced along with testing procedures. The device was tested and the data were compared with computer analysis data as well as existing propulsion systems. The project was then concluded at phase four with an optimization analysis of the design and the construction of the final presentation.

Due to this project being based on theoretical principles, there was a great deal of research conducted. First a design precedent and benchmark was established to evaluate what already existed both in the field of nautical propulsion as well as dual impeller positive displacement pumps. Once the precedent was established, design factors such as rotor geometry, hydrodynamics, and materials as well as possible components were all gathered so that a preliminary design could be created.

According to the U.S. Patent Office, no provisional or full patents have been issued for any aquatic propulsion device of this nature. Also, according to the National Science Foundation, NAVSEA, and the National Aquatic Agency, no propulsion device using two impellers is being or has been constructed or fully researched. The only research or patents granted to any similar devices were created regarding pumping and transmission of fluids in an enclosed circulation system, not for vessel propulsion. Some information has been withheld from this paper due to the project now being proprietary and patent pending.

DESIGN CONCEPT AND THEORY

The Dual Impeller Drive System (D.I.D.S) is an underwater propulsion system, which achieves thrust due to the rotation and interactive meshing of two impellers and their corresponding blades. An example of the meshed blades can be seen in Figure 1.

Figure 1
Meshed Dual Impellers

The design concept is modular and self-contained, which allows for the device to be mounted inside a vessel. Being mounted internally reduces mechanical operating noise by using the hull as a sound buffer. Being housed internally also helps to prevent the system from being damaged by external debris or impacts to the vessel.

Due to the nature of having two impellers meshing, the device achieves thrust at a relatively low rotational speed compared to current alternative simple screw devices. As a result of the low RPM thrust created by the D.I.D.S., this device would be well suited for use in submarines or any aquatic application that requires thrust while also requiring low noise, vibration, or increased directional thrust.

OPERATIONAL CONCEPT

Before the operation explanation begins, some definitions of the system will be presented. The control volume is defined as the space between the impeller blades. This control volume will change in size and shape through the entire cycle. It also is created and destroyed by the end of each cycle, with a new control volume being created for the next subsequent cycle. The D.I.D.S. operates by a four-step process detailed below. These steps are labeled as:

1. Intake Cycle
2. Inlet Transition Cycle
3. Outlet Transition Cycle
4. Thrust Cycle

The first step is to draw the working fluid into an expanding control volume. Then, the control volume is cut off from the inlet side of the system. In the third step, the control volume is opened to the outlet portion of the system. Finally, the control volume is collapsed, expelling the fluid out the outlet port of the unit. In this design, the second and third steps are overlapped to ensure that no compression is forced on the fluid, minimizing losses.

Figure 2 shows the intake cycle. Fluid is drawn into the device filling the space between the impeller blades. As the impellers rotate, the control volume expands with the blades, drawing in more fluid.

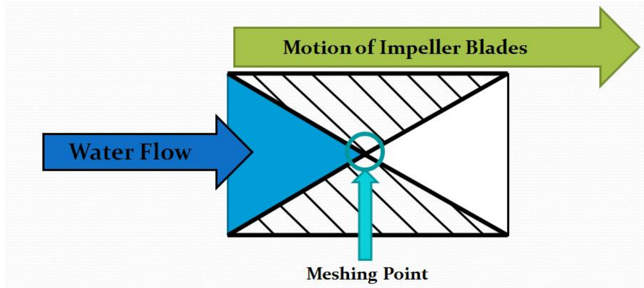

Figure 2
(Intake Cycle) Impeller Diagram

After a certain number of degrees, the blades have rotated to the point where they mesh, preventing water from flowing backwards as seen in Figure 3. During this meshing cycle, the opposite side of the impeller has opened as to not compress the trapped water and to maximize efficiency. Therefore, the moment that meshing occurs, water is being forced from the device.

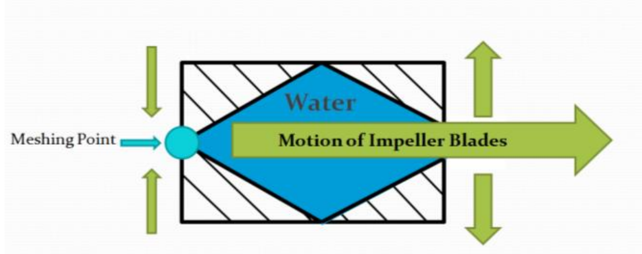

Figure 3
(Inlet/Outlet Transition Cycle) Impeller Diagram

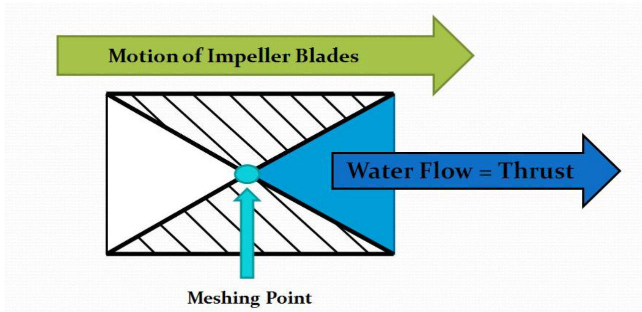

Figure 4
(Thrust Cycle) Impeller Diagram

As the impellers continue to rotate, the mesh point moves forward, driving the trapped water and creating thrust (Figure 4). There is a slight gap between the impeller blades. This tolerance gap serves two purposes. First, because water is not compressible, the blades' leading edge creates a hydrodynamic barrier at the mesh point, which acts to seal and prevent back flow. It also acts to prevent wear and to relieve excess water pressure, minimizing cavitations.

It should be noted that the device uses a three-bladed impeller. Therefore, the four cycles stated above are continuously ongoing, producing a constant amount of thrust and minimizing pulsing. The degree of twist that the impeller blades have is designed in such a way as to simultaneously conduct all four cycles.

RESEARCH AND DEVELOPMENT

During the research and development phase of the project, multiple approaches were taken in order to both study the concept's feasibility as well as to refine the concept to create an optimal end product. To aid in the research, a conventional Root-style dual impeller supercharger, meant for automotive performance, was reverse engineered in order to establish a baseline for the design.[1] A conventional supercharger was used because it has some similar technology and principles. The charger uses dual impellers to move a working fluid pressurizing it.

However, supercharger design is not meant for liquids, such as water, and is designed to redirect flow 90 degrees from its input. The D.I.D.S not only has to move water, but it also has to move it 180 degrees from its input and do so efficiently and forcefully enough to generate a large amount of thrust.

An in-house design and analysis program was developed in order to optimize the design for operation in water and to help design the curvature and twist of the impeller blades. As stated above, unlike conventional superchargers, the D.I.D.S must not only channel and pressurize a fluid but do so with enough force to generate thrust for a vehicle. Therefore, it must be extremely efficient and possess correct tolerances for water use.

In-depth research was conducted in the fields of positive displacement pumping systems and involute geometry in order to both identify and maximize the performance of the impeller blades. Multiple design iterations were made to help refine the concept. The final D.I.D.S. design consisted of several sub-components and systems. The entire device was designed to be entirely self-contained so that it could be placed inside of a vessel for propulsion. This would both protect the device and reduce the mechanical noise of operation. [2-5]

The final design included an integrated gearbox and inlet assembly. This subsystem would allow an external power source, such as an electric motor, to power the system, yet not restrict fluid to flow into the system. This subassembly mated with the rear outlet manifold to hold the entire device together. This outlet manifold directed the outflow of fluid to prevent and reduce losses. Due to the nature of the impeller, the outlet manifold had to be designed to capture outlet water from various vectors. As stated before, the impellers conduct multiple cycles at different intervals. Therefore, thrust can and will be produced at multiple locations along the impellers' cross sectional area.

The final design also included a specialized body construction which formed around the impellers to help increase their efficiency. The body acted to channel fluid, prevent dead space, and keep the working fluid as tight to the impellers as possible. [6]

IMPELLER DESIGN

Using the reverse-engineered data as well as the analysis program, we were able to determine the scale and flow rate which would be best. For ease of manufacture, testing, and logistics, it was determined that the overall diameter of each impeller should be 64mm, which was half the scale of the original design. Along the axis of the impellers would be a 10mm center bore which was figured into the design to accommodate the drive shaft.

Also driving our calculations was a desire to maintain a 4,000-5,000mm^3 or 4.0 – 5.0cm^3 volumetric flow rate per cross section of the impellers. Figure 5 shows the theoretical cross section of a single impeller. The solid dark lines represent the area of the impeller and are marked as Blades 1, 2 and 3. The light grey circle represents the overall area which the impeller could occupy during a revolution on its axis and are marked as the area between defined blades.

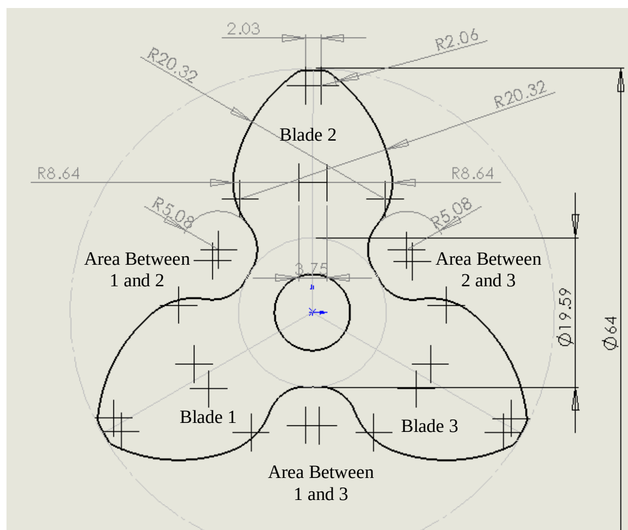

Figure 5
Impeller Cross Section

To accommodate the desired volumetric flow rate, the area between one set of blades would have to be at minimum 800mm^2. With such an area, a meshed set of impellers would have a minimum volume of 0mm^3 at the mesh point and a maximum volume of 1,400mm^3.

With a minimum area of 800mm^2 between blades, a combined pair of impellers would have a total available volume of 3200mm^2 + 1400mm^2 at the interval at which the blades mesh. This would create a maximum area of 4,600mm^2 at any given point down the length of the impeller. Therefore, for any given distance the impellers travel, 4,600mm^2 of fluid would be displaced.

The cross-section was further modified to accommodate water by increasing the radius at which the rear edge of the blade meets the main support of the cross-section. This can be seen in Figures 5 and 6. This feature was increased from 4mm to 5.08mm. The increase was necessary because at a sharper radius, water would become trapped between the two blades as they mesh together. Due to water's incompressibility, this trapped pool of water would both wear away at the impeller blade as well as reduce efficiency by adding resistance to the rotation of the blades.

The finalized impeller cross-section is a tri-involutes design. This means that due to the complicated twist angle of the overall geometry, each blade needs to have three distinctive curves to allow a blade to follow the curvature of its meshing component without colliding with its mate. This tri-involute allows for a very efficient mesh area in a water environment. The tri-involute would allow for the blades to rotate and mesh with high tolerance without interfering with one another and causing damage. A tolerance of 0.025 to 0.075 mm was designed into the cross-section.[7-9]

Using the computer analysis program, it was determined that a rotational spline of 210° would be needed for a length of 121mm in order to obtain a flow of 1.5 liters per minute while being run at 20 rpm. Using SolidWorks CAD software the determined cross-section, length, and rotation spline generated the impeller blades.

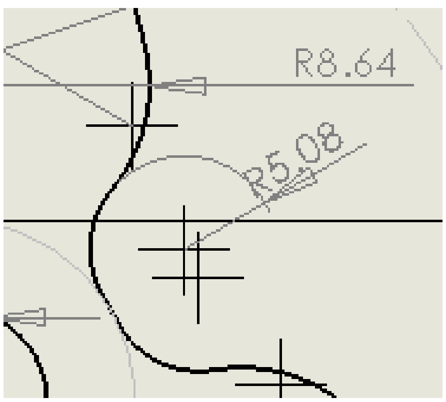

Figure 6
Impeller Cross Section (enlarged)

This CAD model can be seen in figure 7. A rotation of 210° is a full 60° more than the analysis supercharger. This more aggressive rotation is due to the density and incompressibility of the water which the overall system would have to pump.

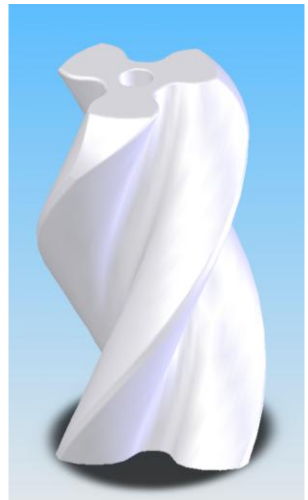

Figure 7
Impeller CAD Model

The trailing outlet end of the impeller blades were rounded and tapered to fit the outlet manifold geometry. This feature was added to increase efficiency by reducing the turbulence water would undergo during the transition from the impellers to the open space of the manifold. Combined with a slight taper in the body, this feature also adds in the directionality of the water flow, thus increasing the pressure gradient of the water entering the manifold. Using the CAD model, a more detailed analysis of the displacement pocket, or the space water would occupy during a cycle, was then initialed. Figure 8 shows an example of the pocket space.

For our determined impeller sizes, the impellers must be located 42.75mm apart from one another. This distance allows for the impellers to fit together with no clearances whatsoever. During manufacture, the positioning of this axis will have to be set as a basic dimension and as a datum. Tolerances for these locations are limited. If set apart any further than 0.075mm, the impeller blades will not function to their optimum level. Using these locations, gearing locations were then determined.

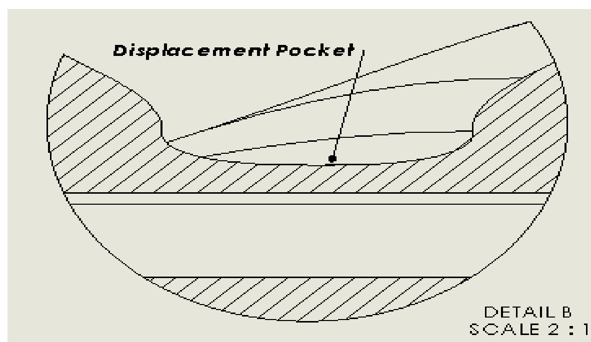

Figure 8
Impeller Cross Section Design

An early problem emerged at this point in the design. The input from a motor, in order to run the system, could not be directly fed into an impeller. This method of direct input was used in the analyzed supercharger design. The supercharger is designed to direct air flow 90° from the inlet to the outlet. Our design allows water to flow with near zero degrees redirection. By tying the input power directly into an impeller shaft, such as a supercharger does, the power input would block the inlet. Our solution to the problem was to move the input shaft down and away from the inlet and the impeller shaft axis. By moving the power input, any water is then less restricted to flow into the impellers. An example of a super charger power input verses the D.I.D.S. input can be seen blow in Figure 9.

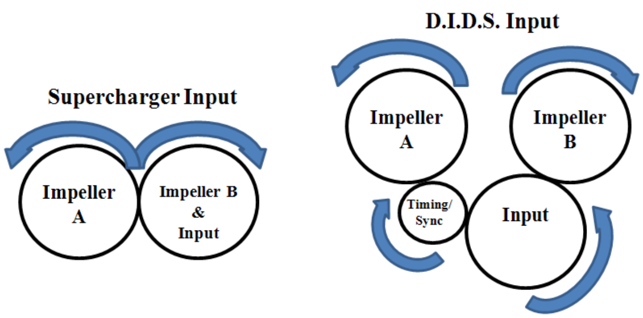

Figure 9
Power Input to Impellers (Supercharger vs. D.I.D.S)

Once the gears' sizes were fully finalized, a re-evaluation of the positioning of the gears was conducted in order to fully locate the synchronizer gear and driver gear. This re-evaluation can be seen in Figure 10. During this evaluation, the pitch diameters were placed together to insure full meshing of the gears. The finalized center distance and overall dimensions were then compared to the required inlet geometry to prevent interference with flow and the operation of the impellers' intake. The compared geometry met all requirements and then became the final design. At this time, GD&T of all components was done, along with a fit analysis to make sure that the prototype would be constructed with minimal effort.

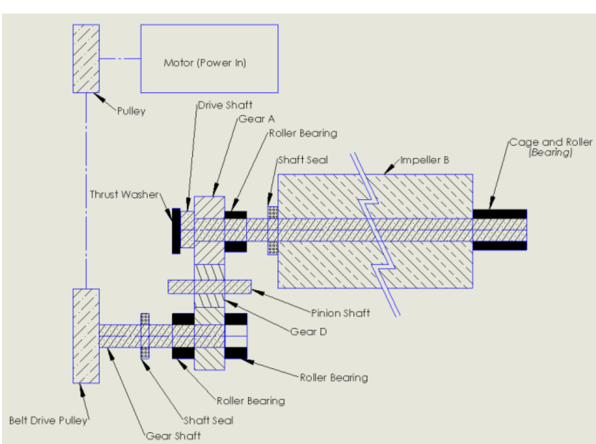

Figure 10
Gear Power Layout (Left side Impeller)

Figure 11 is a model of the gear cover. The gear box was divided into two halves for easy maintenance and assembly. The cover shown also illustrates the integrated inlet manifold that was discussed earlier.

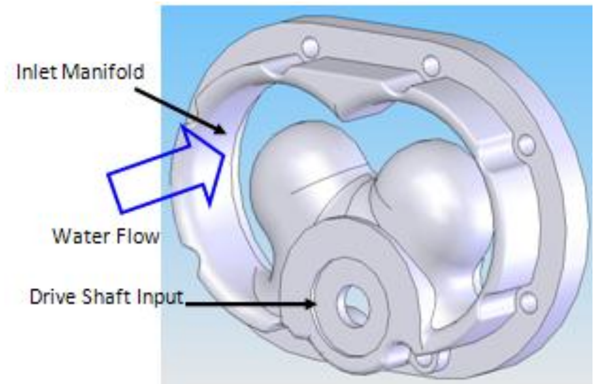

Figure 11
Front Gear Cover/ Inlet Manifold (CAD Model)

One of the most critical components to both design and to build was the outlet manifold. This component played a critical part in determining efficiency as well as the amount of thrust that would be achieved. The outlet manifold served to redirect the thrust coming from the impellers and to do it with as little restriction as possible. During its initial design, flow simulation software was used in order to design the most efficient manifold possible. As seen in figure 12 Fhe software was used to determine the point where the majority of flow would take place.

From these simulations, the internal contours of the manifold were redesigned to optimize the flow characteristics. These analyses showed that the majority of the flow would occur roughly 5mm off impeller axis.

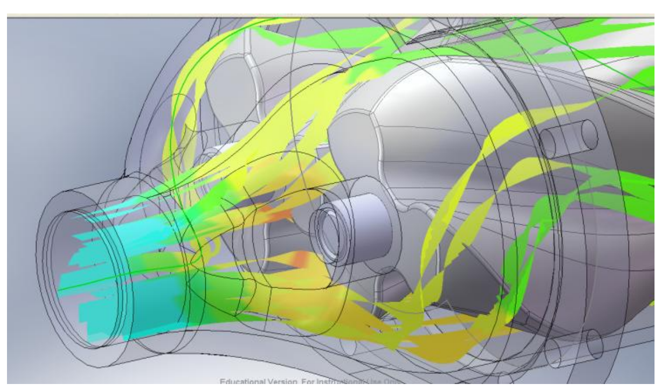

Figure 12
Initial Flow Analysis (showing max flow and stagnation)

Additionaly, the impellers were found to produce a stagnation of flow at -10mm below axis. Using this data, the center outlet was moved to correspond with the greatest amount of outflow. Also the internal curvature of the manifold was redesigned at -10mm to prevent the stagnation. An example of the changes can be seen in the Figure 13 manifold cross section.

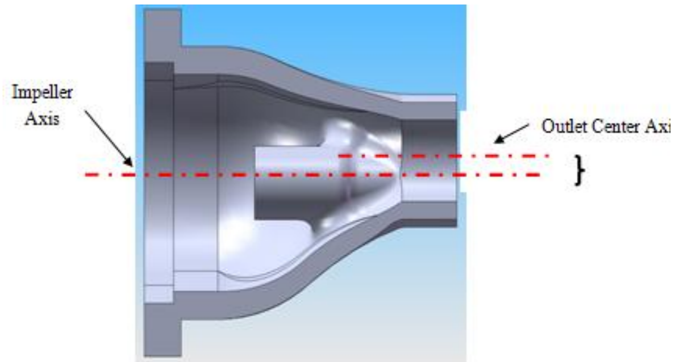

Figure 13
Outlet manifold Cross Section (showing outlet axis placement)

PROTOTYPE CREATION

In order to validate the design, a prototype was constructed. This prototype was designed to be half scale and functional. Due to time and funding constraints, the prototype was constructed of materials which could be worked with easily without compromising the design. The prototype was to be fully tested and operating at full speed. However, it was meant to serve solely as a proof of concept and not for actual use.

To help speed up the fabrication of the device, the manifold and impellers were constructed in ABS plastic using an SLA rapid prototyping machine. Due to the porous nature of the SLA process, the parts were coated in an epoxy to both seal and add strength. Due to the use of this material, testing would have to be conducted using fresh water and not saltwater. [10-11]

The gear box and its integrated inlet manifold were designed to be made from Delrin Acetal Copolymer. CAD data of the gear box sections were used to create an advanced CNC tool path in-house at Western Michigan University. The tool path was then given to Rocket Industries, Inc., who volunteered their machines in order to make the parts.

For safety and testing, the body of the D.I.D.S. needed to be clear. That way dye tests could be run in order to see how water flow behaved in the device. Also a clear body would allow easy detection if the impellers jammed or became damaged. An aluminum mandrel was fabricated and polycarbonate was then heat shrunk and partially vacuformed. The mandrel created two halves of the body which were then ultrasonically welded together to form a water tight seal.

All other components of the D.I.D.S. were either ordered via stock parts or were created on-site out of aluminum. Also due to time constraints, the main gear drive, which would link the electric motor to the D.I.D.S, had to be exchanged for a belt drive to prevent damaging the electric motor. The final prototype can be seen in Figure 14.

Figure 14
Half Scale Prototype (Assembled Isometric View)

TESTING AND VALIDATING

Since the D.I.D.S. is a new design, the testing phase was critically important. Very precise and developed methods would be needed and utilized to repel criticism of the system's abilities. Large quantities of supporting data would be needed to validate and prove the system. Statistical design of experimentation along with multiple data collection were used confirm that results were not anomalies for falsified. Additionally the statistical data collected was used to both control and monitor the process.

Due to the unique nature of the device and tests to be run, a testing bench was created. The testing bench, which can be seen in Figure 15, was constructed from plexiglas and wood. Rather than fully submerging the device, it was split between two bodies of water; that way tests would represent design conditions of the device being fitted to a naval vessel. Two tanks were fabricated to represent the bodies of water. The main tank was constructed to be 190 liters while the secondary tank held 150 liters. The secondary tank was sealed for pressure tests while the main tank remained open to atmospheric pressure. A 50mm diameter tube was used to bridge the two tanks and was affixed with a flow value so that flow restriction tests could be conducted. Measuring equipment was affixed to both the D.I.D.S. device as well as the tube connecting the device to the secondary tank. These instruments measured pressure, volumetric flow, temperature, and turbulence. Finally the test bench also included a temperature heater which maintained the water inside both tanks at 21 degrees Celsius so that temperature rises or falls, caused by the machine, could be identified. Finally a digital video camera and it was used to record turbulence and flow tests.

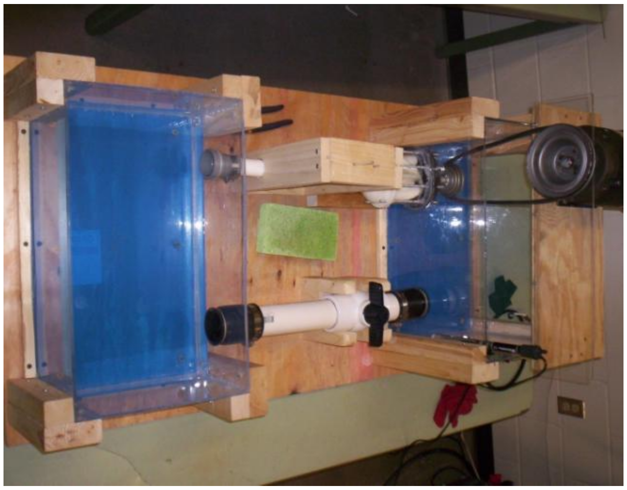

Figure 15
D.I.D.S Testing Bench

In prototype testing, the durability of the system is unknown past calculations and simulations. This means that the probability of failure is high. Therefore, when testing prototypes, it is very common to begin with low load tests. This way, the maximum amount of data is gathered before the prototype is placed in a situation where it may fail, particularly were only one prototype was available.

Tests were conducted using constant data acquisition system; the recording equipment was activated before and after a test was run. This way, if the prototype broke during the warm up or cool down phase, information regarding the moment of failure and time around that event would not be lost. Constant data acquisition gives a great deal of insight into redesign, modes of failure, and even the characteristics of operation.

Performance mapping of the device took place in multiple steps and multiple tests were conducted. During testing, the following were calculated or tested:

- Flow Mapping
- Pressure Head Mapping
- Thrust Characteristics
- Efficiency
- Turbulence (Dye Testing)

Results

Due to proprietary and patenting reasons, exact performance and figures cannot be fully covered in this paper. However, proof of concept was successfully accomplished. The device performed as expected. The recorded results were a great deal larger than what was originally calculated and designed for. Originally it was calculated that at a half scale, the design should produce a flow rate of 1.5L per minute when run at 50% of its designed RPMs with a 1Hp motor. However, the device managed to obtain this flow rate at 25% of its RPMs. The design RPM's are a full 70% lower than that of typical external propellers. Furthermore, proof of concept was established due to the combination of both the low RPM operation by reducing the likelihood of cavitations in the system caused by the low pressure gradient on the impeller blades.

Additionally, the pressure head recorded by the sensors, at the device's output, was found to be greater than expected. During stepped up testing procedure, the pressure head had risen so greatly that the pressure being generated in the secondary tank forced the tank to rupture at 50% of its thrust.

Finally, the efficiency of the device was determined to meet expected calculations. Although the efficiency was found to be below that of jet and propeller propulsion units, the efficiency of the D.I.D.S. was less than 10 percent less efficient than current conventional means. Dye testing reveled that little to no turbulence occurred in the inlet and impeller sections of the device. However, some loss occurred in the 10 percent boundary of the impeller outlet manifold junction. Once corrected and redesigned, it may be possible for the system to match existing technology in efficiency.

Conclusion

The Dual Impeller Drive System project was a complete success. The concept of dual impeller propulsion was validated and proven by not only meeting but exceeding performance expectations. It was able to produce a great amount of thrust at extremely low RPMs compared to standard propeller systems. Furthermore, it was able to do so internally, thereby allowing it to be mounted inside of a vessel.

Further proving the validity of the D.I.D.S. is the fact that the device is compact, low maintenance, and easily manufactured. A working scale prototype was able to both meet and exceed expectations within two weeks of prototype fabrication beginning. The design is currently undergoing additional redesigns and provisional patent verification.

The D.I.D.S design project stands as a great representation of the engineering educational system in place in the United States. This project was the culminating project of two undergraduate engineering students. The project was worked on almost exclusively by the students from concept creation to final testing. Skills used by the students for this project included hydrodynamics, finite element analysis, computer programming, reverse engineering, metallurgy, material science, rapid prototyping machines, advanced design for production, and machine design methodology along with involute mathematics and testing procedures. A senior design project that permits and encourages students to propose and follow a concept, fully utilizing the engineering design process from start to finish, is a valuable opportunity and provides extensive learning and professional development.

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