Boat Flooding Control: Design and Autonomous Based Design

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Executive Summary:

This system is an automatic mechanical flooding control system that ensures that water levels in a small scale performance boat are kept as low as possible. This system operates via the rotation of an elliptical valve within a tube made from PVC plastic parts. The ellipse normally rests at an angle to the flow, sealing the tube and preventing flooding of the boat. A spring is used to force the ellipse into this position. When enough water attempts to exit the boat, the spring will displace and the valve will rotate to parallel with the flow, allowing the excess water in the boat to leave. Testing was performed with the boat in normal operations to examine the efficacy of the system. This testing revealed some flaws. However, it also reveals a viable system to solve the problem of excess water. An ease of modification and low cost allows for optimization of the system and further tests to determine if widespread use in small performance boats should be pursued.

I. Introduction

Project Scope

All boats regardless of type can take in water that is displaced by the hull movement when a portion of that water is directed inboard. All ships have a drainage to prevent water from sinking the vessel. Dinghies; small sailboats meant for use by one to three people, frequently run into the problem of taking on water given that their decks are open(displaced water is inadvertently propelled inboard over the open decks). The 420 is one such dinghy. 420s used in collegiate sailing are drained by the use of handheld bailers, an inconvenient process which hinders performance of other tasks crucial to competition. 420s can be drained on land via a stern drainage hole which is plugged by a tennis ball tensioned with shock cord during water operation. This project involved the design and testing of a drainage system utilizing the preexisting stern hole. The project yielded a novel design based on designs seen in other applications.

Technical Literature

Selecting the right type of valve is crucial in designing a drainage valve in a boat. The valve must allow for the highest amount of flow out but also not permit flow into the boat. Given the size of the boats and drain hole, size, weight and complexity are also important factors to consider

In order to choose the correct type of valve, a sense of the hydrodynamic system must be developed. The smallest scale is the valve itself. This can be broken down into the concept of the force of a wave on a vertical wall, taking the simplest form of valve as some sort of swinging gate. Once this force is understood and can be accounted for, more complex valve geometry can be added. The second hydrodynamic scale to understand is the motion of the excess water in the boat. This can be described as liquid within a rigid body, in this case the boat. This excess water moving in the boat is the water intended to flow out of the valve.

These hydrodynamic elements shows that oscillation needs to be accounted for in a valve design. This oscillation also presents another challenge in its irregularity. The relative small size of the boat means that the water will experience frequent collisions, increasing its turbulence and altering periodic motion. This means that the valve design must not rely on constant pressure through it to work. This present a challenge as given the boat's stature in the water, outside water pressure will also be a factor. [1]

Valve handbooks give a variety of valve types, although in an industrial setting. There are two groups of valves which pertain to a boat drain valve. These are an on off valve and a non-return valve. An on off valve, or block valve, has two states, one where flow is permitted and one where it is not. A non-return valve limits the flow to one direction. Two types of valves which could work in a part manual part automatic system are butterfly and diaphragm valves. [2][3] In both the diaphragm and ball cases a successful non-return valve has been implemented. The diaphragm case allows for more control as design of the diaphragm can be used to calibrate the valve to a desired exit force/flow. However, the diaphragm requires that force to work and given the irregular and oscillatory nature of the flow, may not always work as desired. The ball design doesn't have the same control and also limits the outgoing flow with the presence of the ball, but works well given the oscillatory flow.

Given the flaws of previous designs, a new design should be developed. A combination of the butterfly and diaphragm valve designs would be ideal.

Research on material design determined that aluminum plating was best for the valve design, as the aluminum both strong against corrosion properties of natural water and provides easy machinability.[4] Corrosion is a major factor in metals in aeronautics and shipbuilding as metal degrading and rust can lead to decrease in performance or overall failure of system performance.[5]. Plastic springs exist, but they were determined to be too light and flimsy to be used effectively compared to metallic ones.

Design Requirements

There are three design requirements for this drainage system. This first is that the system will prevent water flow into the boat at all times. This will also be referred to as acting as a plug or plugging. This plugging function of the system is required at all environmental conditions the boat may face. Given that the boat currently operated with such a plugging system, the drainage system designed needs to be able to replicate that function. The second design requirement is to allow water flow out of the boat given certain environmental conditions. This will be referred to as drainage. The certain environmental conditions are wind speed of at least 10 knots and water level in the stern of the boat of water reaching the entrance to the system. The drainage function of the design is meant to operational at higher wind speeds. This is for two reasons. The first is the increased water intake of the boat at higher winds speeds due to the impact of the hull upon the waves spraying water into the air which is then blown into the boat. The second is the hull shape of the Z420 which is lower in the water farther forward in the boat. This means the floor of the boat slopes away from the system. This requires high speed to allow water to flow to the stern of the boat when the boat accelerates. The final design requirement is that the system avoids impeding the normal operation of the boat. The boats used for college sailing are using in competition where the speed and maneuverability of the boats are of utmost importance. The design needs to not impact the speed and maneuverability so as to preserve the performance of the boat in competition. These design requirements were obtained using previous knowledge of and experience in the operation of the Z420 sailboat.

II. Design Description

To describe how the design works, it is best described as a butterfly valve. This valve is useful due to its simplicity. A butterfly valve consists of a gate in a pipe which rotates about a shaft to allow flow. This design uses the same concept. This design uses predetermined PVC pipe sections as the pipe and machined aluminum as the gate in the butterfly valve. A spring is added to add force to one end of the gate to provide a resisting moment. This helps keep the system in a closed position to prevent flooding. The gate is shaped to rotate in only one direction to let water drain out of the boat when forced upon from the inside. The spring force is calculated to ensure that the system will neither rapidly oscillate nor be too strong as to not open.

The main design of the system consists of three parts: the valve, the pipe and the spring system. The first component is the valve itself. This valve will facilitate the movement of water towards the outboard end of the hull while preventing movement of water inboards. The second component is the fixture. The fixture is the housing for the valve which will secure it to the hull. The third component is the spring. The spring ensures that the valve behaves in a manner which is consistent with the valve’s function. The valve is the key component towards a usable drainage system.

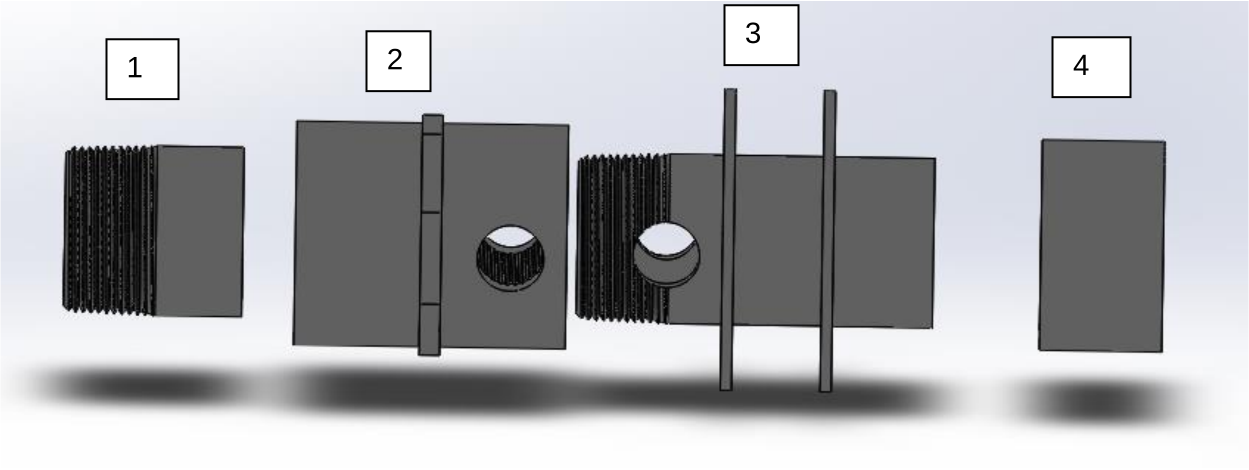

Figure 1: Sections of the Tube

The main part starts with the chassis of the design: the tube. The tube design consists of four PVC pipe sections. The tubes two functions are to provide a conduit for drainage out of the boat and a fixture to mount the system to the boat. The main section of the pipe is the piece that will extend through the hull, indicated by 3 in Figure 1. This is the main sections through which water will exit the boat, and therefore is also where at least half of the valve will sit. One either side of this pipe section are two pipe adapter sections indicated by 2 and 4. These sections have a few different functions. The first is attaching to the main section and providing pressure to the hull to prevent the system from moving. The second is extending the length of the overall tube system, providing impedance of water helping eliminate excess flooding. Both sections 2 and 3 will contain through holes to house bearing to mount the valve shaft. Section 1 extends the tube farther into the interior of the boat, helping to gather more water for drainage when required. The design also shows two rubber gasket rings to help secure the tube to the hull. Given the nature of the fit, these were not required.

The valve consists of eight parts: two aluminum elliptical plates that make up the majority of the surface to water contact, two plastic clips that holds the elliptical plates and shaft together, a center shaft that provides an axis of rotation for the valve, bearings for the shaft to rotate on and to connect the valve to the tube, and shaft collars to prevent lateral movement of the shaft.

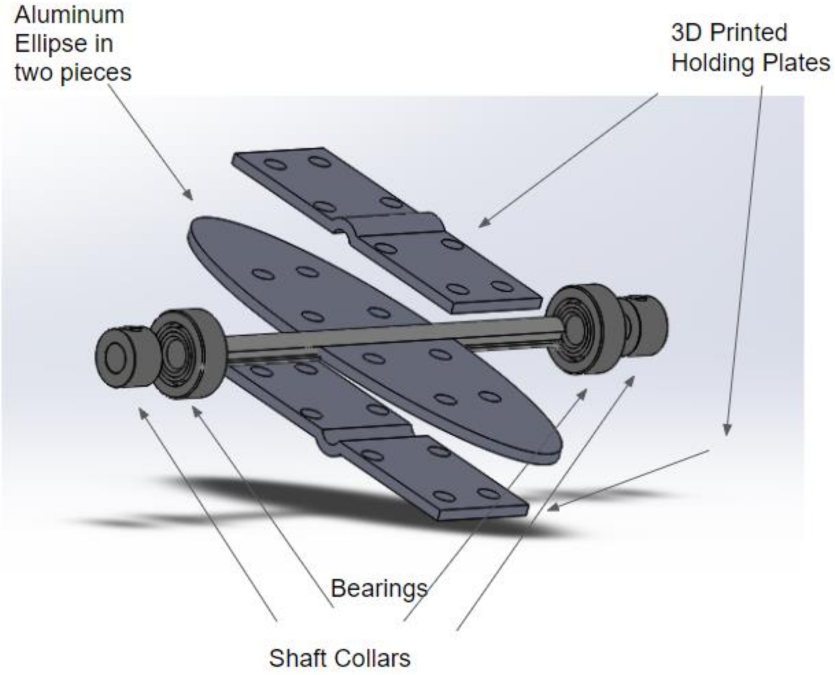

Figure 2: Exploded View of Valve

The valve design is modeled after the gate in a butterfly type valve. Many butterfly valves use a circular gate in a cylindrical tube. This type of gate allows for complete rotation of the gate about the shaft. Given the desire to limit flow, an elliptical gate is used instead.

The profile of the gate when viewed along the pipe appears that of the same as a circular gate. However, instead of being normal to the flow, it is angled to the flow. The minor axis of the ellipse is the same, spanning the complete distance across the pipe. The major axis of the gate is three times as long to create this elliptical shape. This elliptical shape will not rotate completely around the shaft axis as the geometry of the ellipse will not allow it as at a certain point the wall of the fixture will prevent the ends of the ellipse from moving any further.

A complete seal needs to be maintained to accomplish the plug aspect of this valve. Any inflow of water must be stopped by the valve. Rubber EPDM cord will be used to cover the edge of the ellipse to create such a seal. The valve is designed so that there is no space between the valve and fixture. Putting rubber in this space will provide a material that can compress and expand to cover the gap depending on the pressure to close the valve.

The other requirement is a method to secure the elliptical valve to the shaft. This can be accomplished with two different procedures. The first is to put two keys at one hundred and eighty degrees across from each other the shaft. The middle section of the ellipse can be cut out, making the ellipse into two pieces. Each piece of the ellipse can be fed and glued into the keys, creating a connection.

To hold this connection, two clips are needed, shown on the top and bottom of the valve. Aligned holes can be drilled on each of the clips and the valve pieces. Bolts can then be fed through these holes and nuts installed so that the clips compress the valve pieces and shaft to keep the mechanism together. During manufacturing, the keys on the shaft were found to be unnecessary as the clips with bolts were able to keep the valve together.

The valve works by react when enough water pushes the inboard side of the bottom valve plate, causing the valve plates to rotate around the shaft and release water from the interior to the exterior of the boat.

The spring system works right after by valve back to its original position. This valve type typically allows for flow in both directions. In this case, however, flow is only desired in one direction. This necessitates some form of opposing force keeping the valve closed in ordinary use. The opposing in this design is supplied by a compression spring. The water force will on the valve will be calculated and an appropriate spring made of corrosion resistant aluminum chosen to balance that force.

The spring was designed to be a compression spring pushing upon the outboard end of the valve back down to its desired position closing the tube. There was a few thoughts on how to implement a spring system, but the general design was to insert and glue the spring to a hole through the tube and to glue the other end of the spring to the valve.

Analysis started after the general CAD designs were made. It started with handwritten calculations, then worked to CFM simulations.

The first step towards the calculations started with the free-body diagram of the system. This was used with the spring pushing the system instead of pulling the hatch into its natural position. This method was used to calculate the length needed for the plates for the system to work. Leaving the plates too short would have left the system too sturdy, making it difficult to work in the first place. Leaving the plates too long would have made the system too flimsy, triggering on the littlest amount of water. This was also used to calculate the spring force needed.

The calculations started with the mass of the water. The weight of the water was calculated by taking the surface area of the ellipses and treating the water as a cylinder cut through its length on an angle. The volume of this half cylinder easily found, as the equation for a volume of a cylinder can be divided by two. Afterwards, the value of density of saltwater and freshwater are used to find the mass of the water.

The desired spring force, the next important factor, was found by calculating the equation for spring force, which is the multiplication of the spring constant and the displacement of the spring. The last factor needed was moment of inertia of the plates themselves. However, given the thickness of the plates being less than a tenth of an inch, this was considered negligible compared to the spring force and force of the water. After getting the forces needed, the calculation of moments was used to solve for the spring constant. The plate length was taken from the geometry of the design for a length of 4.74 inches. The spring chosen was a small spring that had an overall diameter of .1406 in and a wire diameter of .01 in.

The dimensions of the valve are affected by the dimensions of the fixture which in turn is affected by the dimensions of the hull. The width of the valve is as wide as the pipe which contains the flow, to create a seal. The valve is as short as desired, but at an arbitrary length to fit within the fixture. The overall dimensions are as small as possible as so to not impede on the operation of the boat.

There were two improvements were made after the completion of the intended design. The first was changing the location, operation, and securing of the spring. Initially the spring was meant to be used in compression. However, the given the spring needed to be weak enough to allow the valve to rotate, a small spring was necessary. This small spring deformed under compression, meaning that is did not resist rotation well. So, the spring was moved to the upper inboard end to both operate in extension and not impede flow. Finally, the spring was anchored using the coils of the spring after glue proved to be ineffective. Two holes were drilled, one on the inboard end of the valve and one through the ceiling of the tube directly above the hole in the valve. A blind rivet was fed into the diameter of the spring and used to push the spring through the tube. The blind rivet was then inserted into the tube hold. The size of the rivet head prevents the rivet from being pulled into the hold. The last coil of the spring was wrapped around the rivet head to anchor the spring to the rivet. The last coil of the other end has the wire fed into and pulled through the hole drilled into the inboard end of the valve to anchor it there. The installation of the spring in this location meant that Section 1 of the tube as shown in Figure was removed from the design as the spring wouldn't allow it to be placed as intended.

Figure 3: Final Spring System

The second improvement was the addition of a rubber shoe to the end of the elliptical valve. One of the key aspects of the valve design is the perfect geometry needed to create a seal to plug the tube. During the manufacturing process, it was difficult to create the valve with such precision. As result, there were gaps in the tube. To remedy this, some of the unused rubber gasket was used to create a shoe for the end of the ellipse to close almost all of the gap. The shoe was sized by installing the valve without the shoe and estimated the gap needed to be filled. The shoe was attached to the valve using glue. The glue worked more effectively connecting rubber and metal than the metal and metal of the spring and valve.

Figure 4: Rubber Shoe attached to the Valve

III. Testing and Evaluation

Simulation

Computational Fluid Dynamics is a great method to calculate the movement of fluids around a surface inside conditions like a pipe. However, the limitations were immediately noticeable when experimenting to get the proper length size. For one, the CFD program did not permit the valve to fully block off the path of water, which defeated one of the main objectives of the project. Secondly, despite it showed by water would act in a pipe, the fact that water is not flowing through the pipe using pressure is also a huge difference. The biggest difference was the fact that there was no way to implement the spring system into the design. However, there was some merit to using CFD for design purposes. For one, it gave a determination of what influence valve length has on the system efficiency. Secondly, it showed how water acts when the valve slightly opens and how the spring system location could affect it.

Practical Testing

Practical testing was done using a Z420 belonging to the George Washington University. This testing consisted of three different tests; testing with the boat out of the water, testing with the boat stationary in the water, and testing with the boat moving through the water.

A. Dry Testing

Dry testing here refers to the hull and not the valve itself. Z420s are stored on land when not in use and travel using dollies and launched using a boat ramp. The first test performed was done with the boat sitting on the dolly. This allowed for testing of the integrity and functionality of the valve without risking excessive flooding of the boat. The valve was first tested against the force of a garden hose with variable pressure. The spring proved tough to displace even with the highest flow rate from the hose but did manage to deform enough to allow drainage. The valve was also tested by putting water into the boat and inclining it to see if the water would drain out. This worked better as there more uniform flow out of the hull than a stream of water from the hose.

B. Stationary Testing

After testing the ability of the valve to let heavy flow out of the boat, the boat was put in the water to test the ability of the boat to prevent flooding. First the boat was left to sit in the water under its own weight. This determines the overall feasibility of the design. Flooding in a unweighted boat would mean the system would work under no conditions. Then, force was applied to the transom to depress the system to determine the point at which water would flood into the boat. This testing was performed to determine the critical point at which the valve would start flooding. Finally, two people moved into the boat in normal crew positions to determine if there would be flooding. This test, like the unweighted test, would help determine feasibility of the design. Crew weight can be adjusted in the Z420, so this test also helps determine optimal crew placement for function of the system.

Figure 5: Stern level during unweighted stationary test

C. Active Testing

The active testing i.e. testing of the system while the boat moved consisted of two parts. The first was normal boat maneuvers and operations. This testing was used to evaluate the impedance of the system on movement of the rudder and the effectiveness of the valve to plug while in motion. The second test was using higher wind speeds to initiate planing of the boat to facilitate operation of the drainage system. During planing the hull generates enough hydrodynamic lift that the hull moves more on top of the water than through it. This helps drainage in two ways. The first is planing causes the boat to move at dramatically higher speeds due to a decrease in drag. This increase in speed provides the acceleration needed to allow water to flow to the stern to be drained. The second is planing raises the bow of the boat more than the rest of the boat. This changes the floor of the boat from sloping away from the system to level with the system. This also helps water flow to the stern to be drained. All active tests were done at 6-12 knots wind speed. Pseudo planing conditions were achieved at 10-12 knots wind speed.

Testing Results

Dry Testing

The system let out water during the land testing with ease. One phenomenon that was observed was flow around the valve rather than forcing the valve open. This is the result of the incomplete seal by the valve. Ultimately this phenomenon does not affect the function of the system. There is still possibility of drainage, just by a different path. The plugging function of the system remains intact.

Static Testing

The system did not let water in during the static test with the boat both unweighted and with the crew in normal positions. An important performance behavior to note is that the crew weight is typically moved forward during light wind and aft during heavy wind. This is consistent with operation of the system. During the depression test the valve started to let water in when the stern was depressed to about halfway up the tube. This makes sense given that there was no rubber shoe on the upper half of the valve and therefore water could flow through the gaps there when the water level got high enough

Active Testing

The system did not let water in during active testing except during major deceleration from maneuvers or lulls in the wind. During planing conditions at 12 knots released small amounts of water through the system but overall drainage proved difficult except at high speeds. The drainage function was largely dependent on acceleration of the boat. A more accurate spring, probably of a different material, would be called for. Plugging was successful except when crew weight was placed farther aft to test the system. Optimization of the system would increase precision of the valve for a better seal to allow complete plugging. The system did not interfere at all with normal boat operations. Extreme maneuvers may be affected. This might warrant trimming of the outboard piece.

IV. Summary and Recommendations

The system has mostly fulfilled the requirements. The plugging requirement has been completely satisfied with leakage prevented at all speeds. The impedance requirement has also been completely satisfied, with the system not interfering with performance at all. However, the drainage function of only worked under certain conditions and at moderate effectiveness

The biggest weakness appeared in the imprecision of the ellipse. This imprecision left the valve unable to close all the gaps in the tube. The valve itself blocked the water as intended, but the gaps led to a couple unfavorable effects. As mentioned before, there was a phenomenon that was observed where flow went around the valve rather than forcing the valve open. Another effect was the addition of the rubber shoe. While this show was necessary from a plugging aspect, this added more surface area restricting drainage even when the valve was in the optimal position.

Secondly, the spring system proved to be stronger than intended. Ultimately, this was in line with the design philosophy of prioritizing plugging in order to maintain the safety of using the system. The strength of the spring made it difficult for drainage to occur. This reduces the advantages of this system over the current system used in Z420s. However, testing did not occur at higher wind speeds where the system would be more effective and more warranted.

Granted, there was some major benefits of this particular design. The system, although costing more than the current plug, was relatively cost effective. This project has costed \$114.20 in order parts, plus around \$1.02 in printed plastic, estimate with a price of PLA of 17.99 per kg and a weight of one ounce per each printed piece. The PVC sections were not that expensive, the aluminum and plastic could bought in bulk with multiple devices, and the only parts that cost a lot were the bearings.

Another benefit was the relative ease of manufacturing. Aside from the ellipse pieces, the only operation required was to drill holes and use the band saw to trim down pipe sections. Although the ellipses need to be manufactured more precisely, they were easy to machine using only the band saw.

The ease of use was another strength of this design. The only requirement is to install using the preexisting hole by fitting all the pieces together with the main section in the hole with space on either side for the other sections to attach to. After that, there is no need for adjustment by the operator.

Finally, the biggest benefit of the design is the ease of modification. All of the parts can be disassembled and reassembled, so individual pieces can be modified by themselves. Different springs of different sizes and materials can be installed and removed from the system to optimize the spring force. Different ellipse lengths could also be tested.

Recommendations

As it stands, this system this system has a lot of potential for optimization. All of the parts are easily modifiable, meaning that small alterations to the product can be made. The best course of action would be to keep experimenting to make the ellipse more precise, the spring more balance, and the tube sized to fit with the hull as best as possible. Low cost for materials such as the aluminum sheet, rubber gasket, and PVC piping means that more experimenting can be done at a low cost. More expensive parts such as the bearings, shaft, and shaft collars can be reused through multiple iterations of optimization.

From a testing standpoint, there are a lot more opportunities to be explores. The system should be tested at a variety of wind speed and wave conditions and logged to get statistics on the optimal conditions for the performance of the system. This will lead to a better understanding of the effect of the conditions on the hull and system and lead to more optimization of the design. A further testing measure would to compare the performance in a variety of conditions of a boat with the system installed and a boat without the system installed. This would be the ultimate test of the systems efficacy.

V. References

1. Hughes, O. F. Paik, J. K.. “*Ship Structural Analysis and Design*. Society of Naval Architects and Marine Engineers (SNAME)., 2010 ,pp 4.77-4.81

2. Skousen, Phillip L. , *Valve Handbook*, 3rd ed., McGraw Hill, New York, 2011.

3. LLC Fisher Controls International, Emerson Process Management, *Control Valve Handbook*, 4th ed, Fisher, 2005

4. Uhlig HH, Revie RW (1991) Corrosion and corrosion control, 3rd edn. Wiley, Singapore

5. Wernick S, Pinner R, Sheasby PG (1987) The surface treatment and finishing of aluminum and its alloys, vol 1. ASM International, Ohio, p 935

VI. Appendix

Figure 6: System Mounted in the Boat

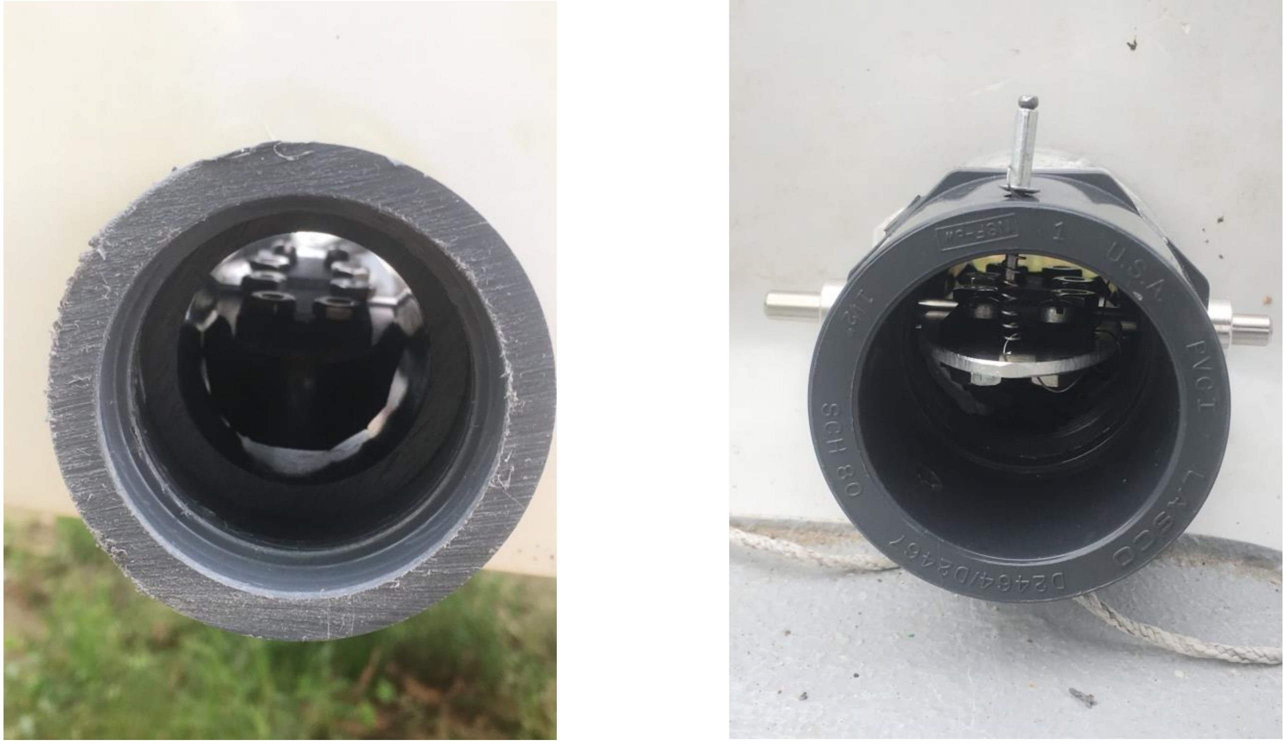

Figure 7 and 8: Inboard and Outboard Ends of the Mounted System

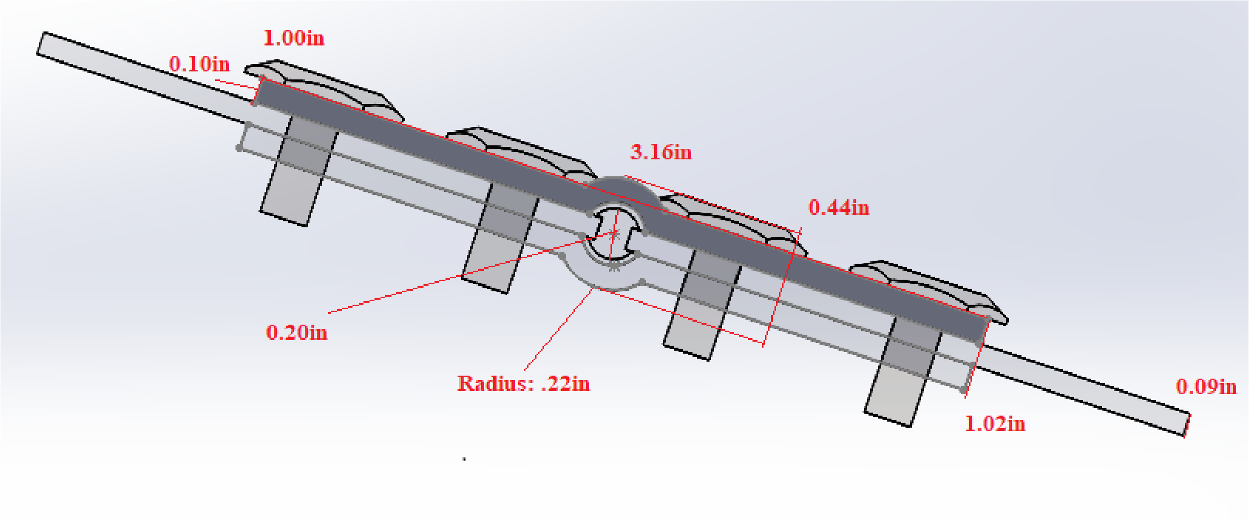

Figure 9: Side View of the Valve with dimensions

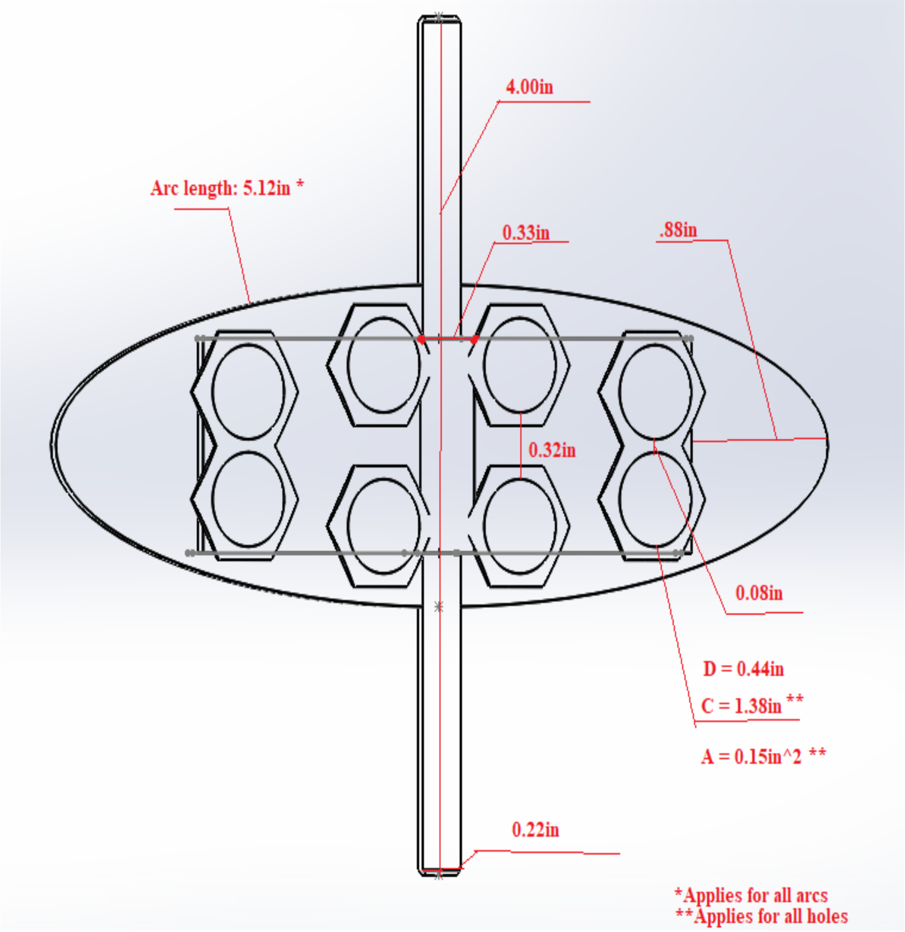

Figure 10: Top View of the Valve with dimensions and dimensions of hole locations

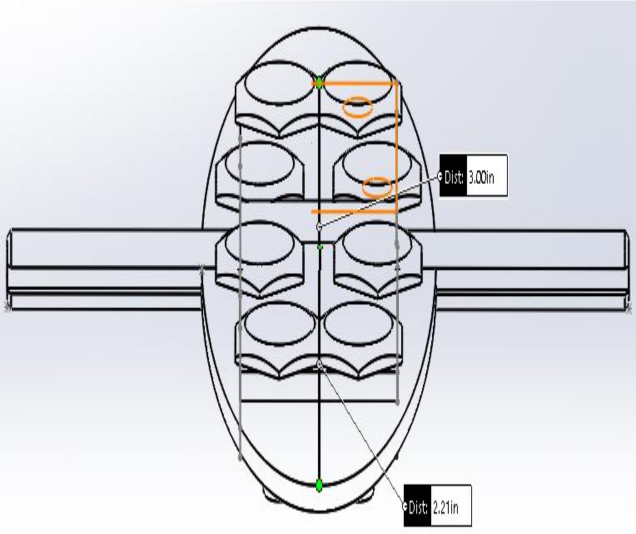

Figure 11: Front View of the Valve with dimensions

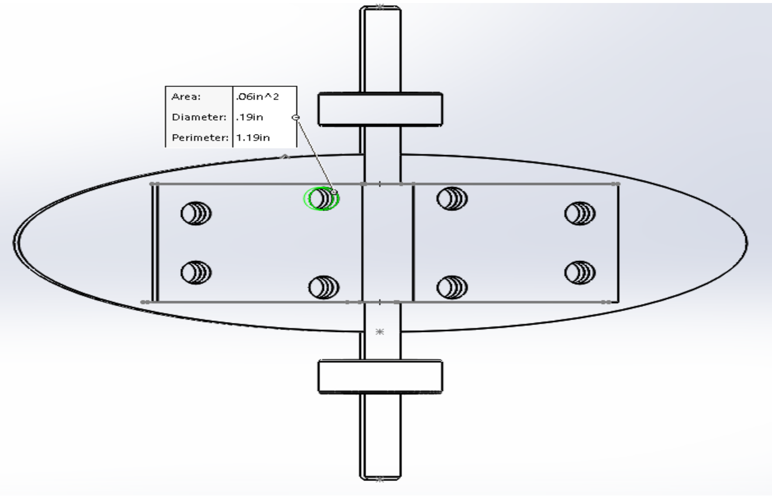

Figure 12: Dimensions of the holes on the plastic plate and ellipses

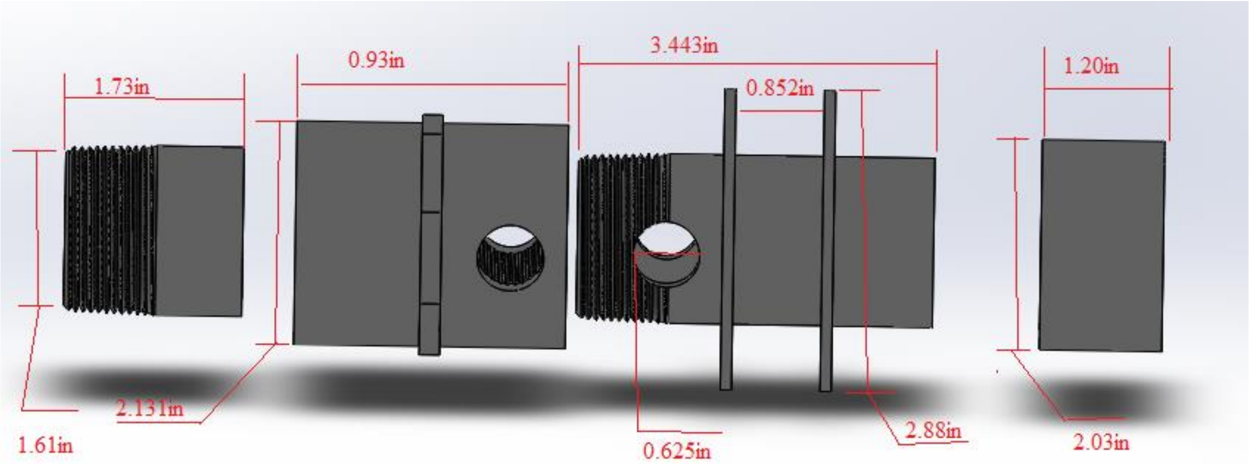

Figure 13: Tube Dimensions

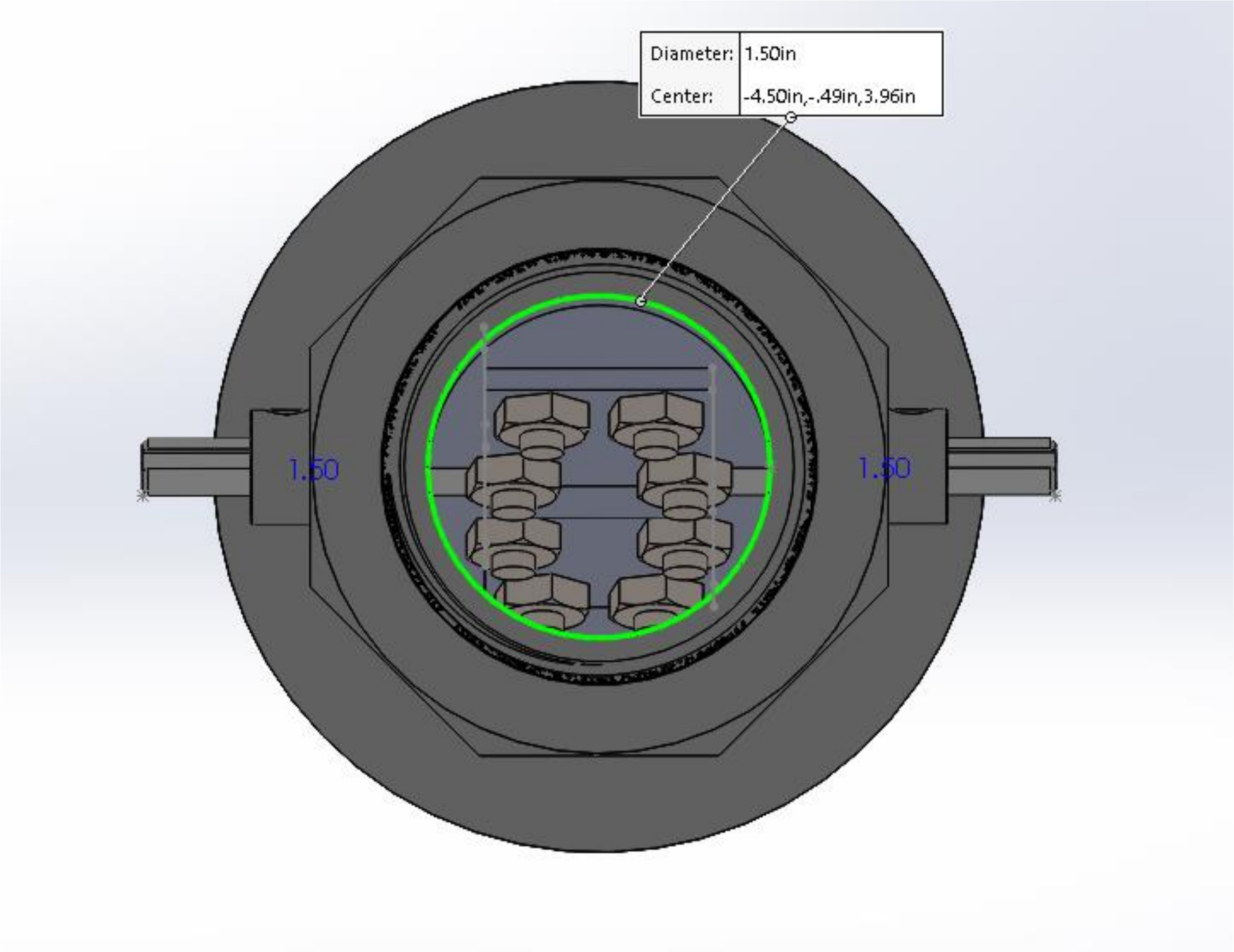

Figure 14: Tube Size

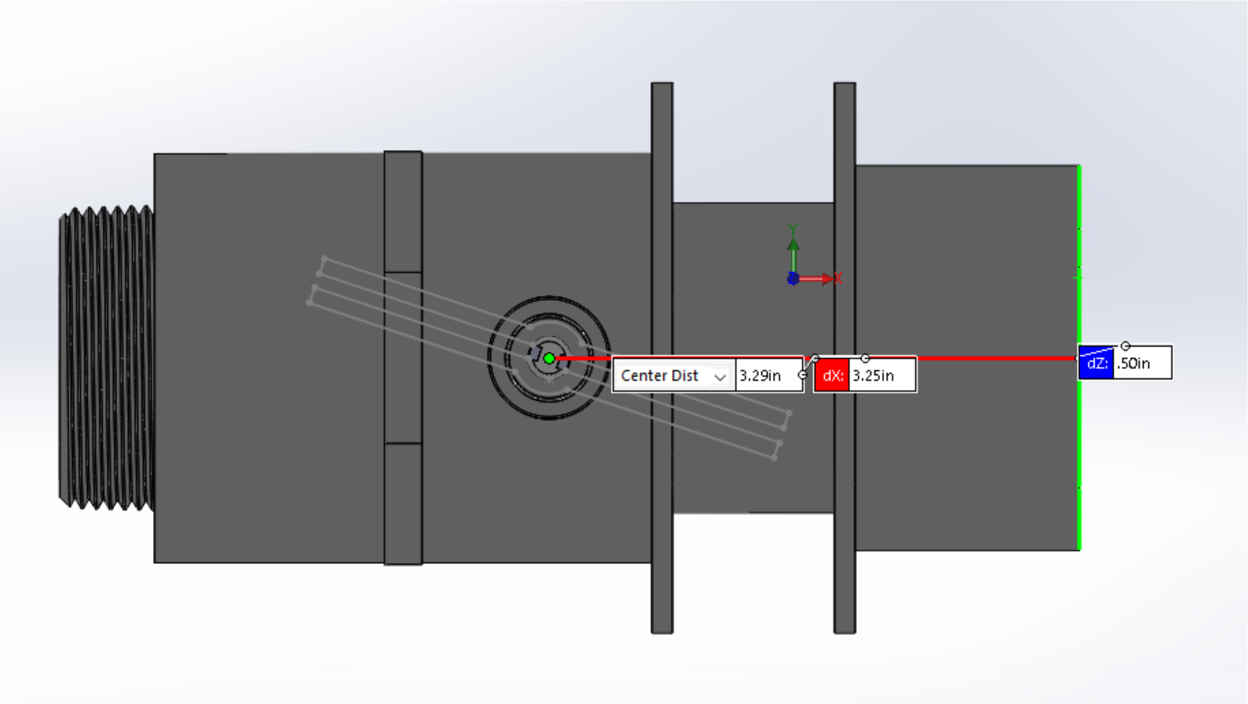

Figure 15: Bearing Hole and Shaft Location