Emergency blow simulation with the SeaPerch

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The governing component in a submarine's ability to surface and submerge is the ballast tank. A ballast tank is a device that is based on principles of buoyancy - water displaced by air in the tank allows the buoyant force to carry the vessel upward, while water intake by the tanks causes an increase in the overall density of the vessel and thus, a downward acceleration. The purpose of this project was to simulate the emergency blow feature of a submarine in an inexpensive and replicable fashion. This paper outlines the scientific concepts, the design, and the assembly of the developed ballast system as well as a description of the parameters and the results of testing said system.

Introduction

Submarines use a complex system of compressed air tanks and ballast tanks to dive and surface. Compressed air, which has a greater density and smaller volume than atmospheric air, is stored in tanks that are usually found towards the top of the submarine. In order for the submarine to surface, this air is allowed to flow into the ballast tanks which are found either towards the bottom or along the entire wall cavity of the vessel. This airflow into the ballast tanks forces water out of the tanks, thus decreasing the overall density of the submarine and allowing the buoyant force to carry it upward as demonstrated in Figure 1. This compressed air is usually reserved for a process called rapid surfacing, or more commonly, emergency blow.

A submarine's emergency blow can be initialized from hundreds of meters below the surface and usually takes only a couple of minutes to completely surface [1]. Although not a common method of surfacing in non-emergency situations, the procedure is a standard maneuver exercised regularly as a drill by submarines and their crews [2].

The goal of this project was to simulate the process of an emergency blow using the SeaPerch, a remote operated vehicle (ROV). Ideally, the size of the system would not exceed the width of the SeaPerch nor the mass of it. Also, to properly simulate an emergency blow, we need a decent surfacing velocity. Based on the max depth of the ROV (in a pool, about 3 meters) and the maximum time-to-surface desired which I chose to be 10 seconds, I then set a minimum time-average velocity of 0.3 m/s. Lastly, this project was to be done in such a way that it can be easily replicated. Several groups have developed similar systems for ROV's [3], but they are generally very complex and difficult to replicate. In the "Mathematical Analysis" section, these parameters along with a handful of scientific principles and their governing equations will be used to help determine the design and dimensions of the ballast system.

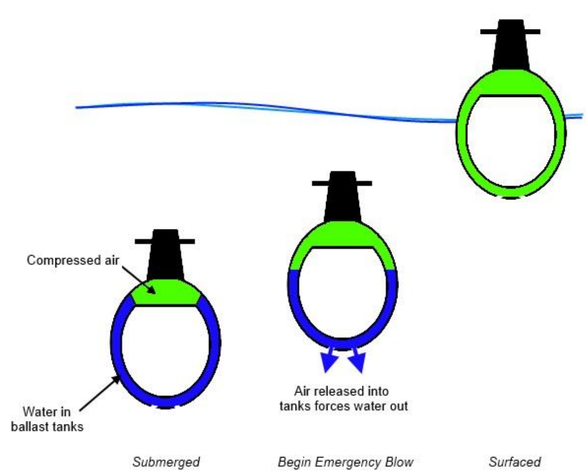

Figure 1: Illustration of a submarine's ballast system during an emergency blow.

Methods

To begin, the following preliminary concepts and designs were developed. They consist of three main components: a compressed air tank, a buoyancy tank, and a triggering mechanism that will permit air to be released from the tank into the buoyancy tank. Since the term "ballast tank" usually refers to the "sinking" part of the system and my design lacks that, I will use the term buoyancy tank from this point on.

The air tank will be made of 2" PVC. One side of the tank will be equipped with a cap customized with an air compressor fitting. This fitting will allow the tank to be filled with compressed air using a standard air compressor. The other side of the tank will have a 2"x¾" adapter and a solenoid valve through which the compressed air will be released into the buoyancy tank. This valve will be activated by a button near the SeaPerch control box. The buoyancy tank will be comprised of a balloon. The inflating of the submerged balloon will be a simple way to achieve the displacement of water. The valve will be connected by a wire ran along the tether. Note also that the floats on the standard SeaPerch design will likely be removed to maintain a neutral buoyancy.

Mathematical Analysis

There are three main physical principles employed in the design of this buoyancy tank: ideal gas law, buoyancy, and Newton's laws. There are also some principles of fluid mechanics and thermodynamics involved, but those will not be described in great detail in this paper; for more on those, see Munson 2013 and Çengel 2011. In the subsequent analyses, the figures in Table 1 will be used and calculated (note that while most of the values in the table can be found based on the preliminary design, the values for m_a, a, V_t, and v are initially unknown and are results of the following analyses).

Let's start with the ideal gas law which states:

$$\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2} \qquad \textit{Eq. 1}$$

Table 1: Description of Values and Variables Used

Symbol	Description	Value
$\boldsymbol{m_a}$	Mass of the air in system	$0.002553\ kg$
$\boldsymbol{a}$	Acceleration	$2.117\ {}^{m}/_{s^2}$
$\boldsymbol{m_v}$	Mass of SeaPerch	$.980\ kg$
$\boldsymbol{V_v}$	Volume of SeaPerch	$.00025\ m^3$
$\boldsymbol{\rho_w}$	Density of water	$999\ {}^{kg}/_{m^3}$
$\boldsymbol{V_t}$	Volume of the air tank	$0.000274\ m^3$
$\boldsymbol{V_{a_2}}$	Final volume of the air in the balloon	$0.001853\ m^3$
$\boldsymbol{g}$	Gravity	$-9.81\ {}^{m}/_{s^2}$
$\boldsymbol{\rho_{a_2}}$	Density of uncompressed air	$1.2015\ {}^{kg}/_{m^3}$
$\boldsymbol{v}$	Terminal velocity of system	$0.331\ {}^{m}/_{s}$
$\boldsymbol{A}$	Characteristic area for drag calculations	$.0465\ m^2$
$\boldsymbol{C_d}$	Drag coefficient (for cylinders)	.82

For our system let's assign the subscript "1" to correspond to initial conditions in the air tank and subscript "2" to represent conditions after the air has been released into the buoyancy tank. Let's also say that for the ballast I will use a six-inch-diameter balloon. We can also consider the temperature difference to be negligible, and Eq. 1 becomes:

$$P_1V_t = P_2\left(V_{a_2}+V_t\right) \qquad \textit{Eq. 2}$$

Solving Eq. 2 for V_t gives:

$$V_t=\frac{V_{a_2}P_2}{P_1-P_2} \qquad \textit{Eq. 3}$$

For P_1, I have learned that most air compressors have a standard operating pressure of about 114.7 psia. Our P_2 will be atmospheric pressure (14.7 psia). Air is not necessarily an ideal gas so we must multiply by a compression factor (for 114.7 psia, z=0.997). So, substituting these values into Eq. 3:

$$V_t=\frac{(14.7\ psia)\left(\frac{1}{6}\pi(0.1524\ m)^3\right)}{114.7\ psia}(.997)$$
$$=0.000274\ m^3$$

We will take this value to be the volume of the tank. The 2” PVC we will use for the tank has a nominal inside diameter of 2.067”. Based on this diameter and the volume we just calculated, we solve for the length of the tank and get 0.135m, which is approximately 5.3 inches. These dimensions are very feasible so this design meets our size goal.

Let’s also use the calculated volume to find the mass of the air in the system. The density of air at 14.7 psia is 1.2015 $^{kg}/_{m^3}$, so:

$$m_a = \left(1.2015\,\frac{kg}{m^3}\right)\left(0.000274m^3 + \frac{1}{6}\pi(0.1524\,m)^3\right) = 0.002555\,kg$$

In order to confirm that this will accomplish our goal for velocity, we use an analysis which combines principles of buoyancy and Newton’s laws. The buoyant force on an object can be described as being an upward force equal to the weight of the fluid (water in this case) that it displaces. This is true for any object, whether it be partially or fully submerged or whether it be more or less dense than the fluid. This is represented by:

$$F_B = V_0\rho_f$$

where V_0 is the volume of the object and ρ_f is the density of the fluid in which it is submerged.

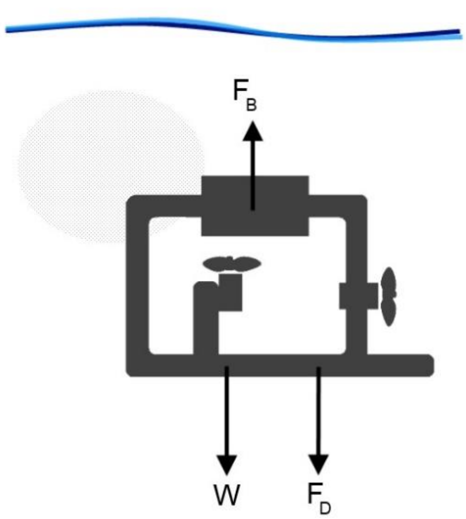

Figure 2: Free Body Diagram of SeaPerch (buoyancy tank is shown in light gray). F_B is the buoyant force, W the weight of the vessel, and F_D the drag force.

The application of Newton’s laws will be represented by the free body diagram in Figure 2 and the following equation,

$$\Sigma F = ma \qquad \textit{Eq. 4}$$

where F represents force, and m and a are the mass of the object (in our case the SeaPerch) and acceleration of the object, respectively.

The free body diagram in Figure 2 shows all the forces acting on the system which we will define as the vessel, including the air in the ballast. The buoyant force applies an upward force and both the weight and drag apply downward forces. Newton’s laws (Eq. 4) indicate that the sum of all of these forces will give our resultant acceleration times the mass of the SeaPerch. This can be modeled as:

$$ma = F_B - W - F_D \qquad \textit{Eq. 5}$$

As mentioned, we must include the mass of the air and the volume of the air when working with the above and following equations. Applying Eq. 5 to our system:

$$(m_a + m_V)a = \rho_w g(V_a + V_v) - g(m_V + m_a) - \frac{1}{2}\rho_w C_d v^2 A \qquad \textit{Eq. 6}$$

Since drag is a function of velocity and acceleration is the derivative of velocity, this is a differential equation. However, using math software and values from Table 1 I have determined that the time the vessel takes to reach terminal velocity is very small (i.e., less than 0.05 seconds), therefore, we will neglect the varying velocity during that time and use terminal velocity for v. Terminal velocity is given by:

$$v = \sqrt{\frac{2ma}{\rho_f A C_d}} \qquad \textit{Eq. 7}$$

If we plug this into Eq. 6, we can easily solve for acceleration and then for velocity.

$$a = \frac{1}{2(m_a + m_v)}\left[\rho_w g(V_a + V_v) - g(m_V + m_a)\right]$$

We substitute values from Table 1 and get:

$$a = 2.12\,^{m}/_{s^2}$$

Plugging this into Eq. 7 gives:

$$v = 0.331\,^{m}/_{s}$$

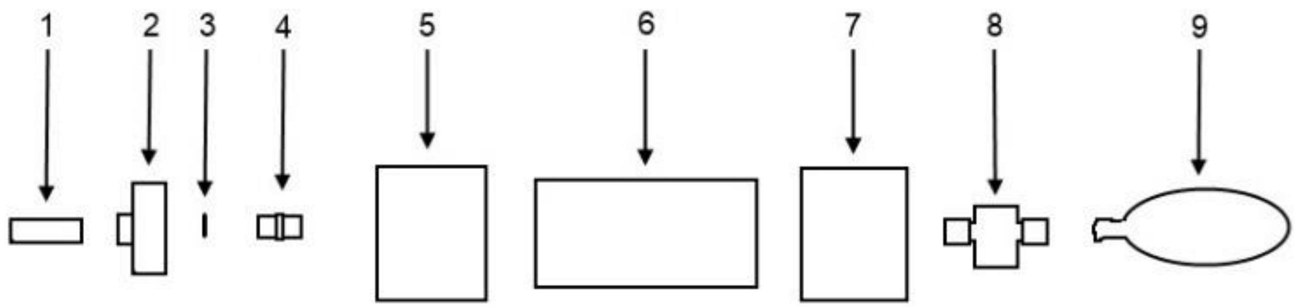

Figure 3: Exploded drawing of ballast assembly: 1) compressor coupler, 2) ABS plug, 3) O-ring, 4) connector, 5) PVC adapter, 6) 2" PVC, 7) PVC adapter, 8) solenoid valve, 9) balloon. See Appendix I for a more detailed description of each of these components.

which is just above my $0.3\ {}^{m}/_{s}$ parameter and gives me the confidence to move on with this design.

Assembly

Here, I will outline the basic steps in constructing the ballast system. See Figure 3 and tables "Materials in Assembly" and "Other Materials" in Appendix I.

1. Assemble PVC parts – use the PVC cement (16) to glue both the adapter with internal threads (5) and the 2" x ¾" adapter (7) to the main 2" PVC piece (6).
2. Apply thread tape (15) – do this to the connector (4), the ABS plug (2), and the filter side of the solenoid valve (8).
3. Drill hole in cap (2) – use the ½" drill bit to do this. Center it well. You may need to open up the hole a bit more using the drill.
4. Assemble compressor fitting – stretch the O-Ring (3) over the taped side of the connector (4), and apply a generous layer of glue (21) along the mating side of it. Press into hole in cap. Screw on the universal coupler and apply more glue on the inside for a better seal.
5. Attach wire (10) to valve – strip wire and connect one wire to each prong of solenoid valve with electrical tape. Screw taped end of valve in to the 2" x ¾" adapter.
6. Connect button (11) – cut about 5 feet of wire from the other end. Strip both cut ends. Use tape and pliers to connect white wires to each other. Solder an end of red wire to each of the prongs on button. Wrap the entire connection with tape. Attach alligator clips (12) to free end of 5' length of wire. See Figure 4.
7. Waterproof it – use the liquid tape (19) to coat the connection at the valve. Apply several thin coats and be sure to seal any gaps in the tape.
8. Attach it to SeaPerch – remove the floats from SeaPerch. Pull top crossbars in and set tank on them. Wrap a zip tie around the tank and both crossbars. Tape the wire to the tether every few feet. Stretch balloon onto the open end of the valve to complete the assembly.

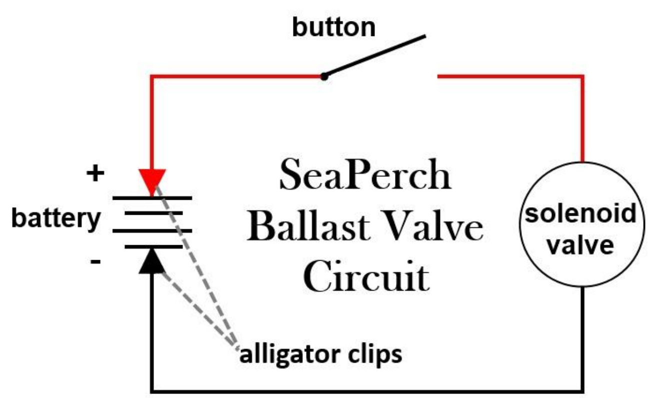

Figure 4: A circuit diagram for the simple switch circuit used to trigger the solenoid valve.

Experimental Setup

In order to test the ballast, I performed two experiments. The first test included several "dry tests". I compressed the tank and, without submerging the vessel, I pressed the button to inflate the balloon. Measurements of the circumference of the balloon were taken with a sewing-style tape measure and the diameter was calculated from that. This was done to confirm previous calculations for the mass of air needed. Benefits of performing this experiment include: 1) isolating the accuracy of our calculations for the diameter which is key in the resultant velocity and 2) doing so without the risk of damaging other parts by submerging the entire system in water.

The purpose of the second test was to confirm that the time-average velocity fit within my parameters (> 0.3 m/s). In this test, the ballast-mounted SeaPerch was submerged and sunk to the bottom of a swimming pool, its depth was measured using a tape measure, and the emergency blow was initiated. Each iteration was captured with a video camera at 24 frames per second and the footage was used to measure the time taken to surface. This frequency, though it seems low, was enough to measure time with a resolution of approximately .04 s – much more accurate than a stopwatch and sufficiently fast for this application.

Discussion and Results

Seven iterations of the first test gave satisfying results - an average balloon diameter of 6.19" was recorded, which is slightly over the desired diameter of 6". This is acceptable since an increase in diameter could only give an increase in velocity.

As for the second test, I was able to run only a very limited number of tests in the water. Even so, results show an average time-average velocity of 0.54 m/s plus or minus a systematic uncertainty of 0.09 m/s (Figure 5). In addition, with 93% confidence we can say that the following tests would also reach the goal of 0.3 m/s.

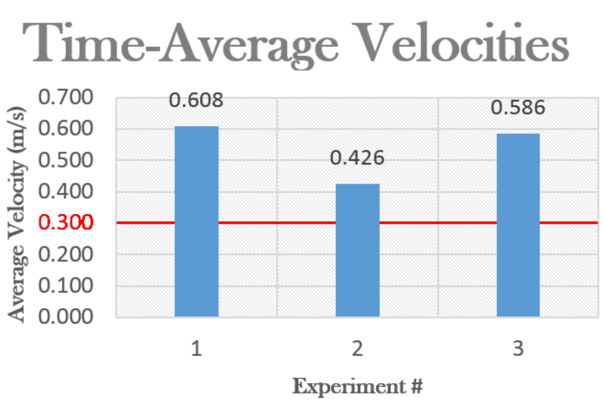

Figure 5: A chart comparing the velocities in the three experiments to the velocity prescribed in the parameters.

One concerning set of data is that of the acceleration time. Again, using the slow motion video and careful observation, I was also able to measure and collect this data. The average was approximately 0.40 s, almost eight times the calculated values. There are several factors that could cause this error, the main one being that things such as the changing volume of the balloon during inflation and the slightly negative buoyancy weren't taken into consideration in earlier calculations. Regardless of this concern, the goals were met and exceeded.

Conclusion

The purpose of this project was to develop a ballast system that would be useful in simulating a submarine's emergency surfacing maneuver. The main goals of the project were 1) that its average velocity would be at least 0.3 m/s and 2) that its width wouldn't exceed that of the ROV. As seen in the data, each of the three tests were well above the velocity goal. This was possible with a design in which the width of the ballast is only about 2" while the width of the SeaPerch is 6", so both goals were achieved and the emergency blow was effectively simulated using the SeaPerch.

Acknowledgements

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Appendix I

Materials in Assembly

Part #	Description	Notes	Vendor	Price
1	¼” Universal female coupler (for air compressor)	I recommend one that specifies “rust-free”	The Home Depot	$2.98
2	2” ABS plug with external threads	It’s a good idea to grab an extra one of these	The Home Depot	$1.00
3	M2x10 O-ring OR 012 O-ring	These can be hard to find at hardware stores. You may have to check online.	The Home Depot	
4	¼” M/M connector (for air compressor fittings)		The Home Depot	$1.56
5	2” PVC adapter with interior threads		The Home Depot	$1.27
6	2” PVC (3”)	Ask if they have scrap pieces	The Home Depot	$3.00
7	2” to ¾” PVC adapter piece		The Home Depot	$1.97
8	12V Solenoid Valve	ROB-10456 Shipping was about $5	Sparkfun.com	$7.95
9	Balloon		Dollar General	$0.85

Other Materials

Part #	Description	Notes	Vendor	Price
10	Thermostat wire	18/2 50’ is what I used	The Home Depot	$9.00
11	Button	COM-09807	Sparkfun.com	$0.95
12	Alligator clips		The Home Depot	$1.98
13	Male connector (for air compressor hose)		The Home Depot	$1.59
14	Female connector (for air compressor hose)	(optional – it depends on your air compressor setup)	The Home Depot	$1.58
15	PTFE Thread Tape		The Home Depot	$0.97
16	PVC Cement	“Christy’s” is really good	The Home Depot	$4.17
17	Solder	(optional)	The Home Depot	$7.47
18	Electrical tape		The Home Depot	$0.97
19	Liquid Tape		The Home Depot	$7.47
20	14” zip ties	This is one of many ways of attaching to SeaPerch	The Home Depot	$2.18
21	LOCTITE Glue	A similar super glue should also work fine.	The Home Depot	$7.99

Tools Needed

Pliers	Wire strippers	Phillips screwdriver
Drill	½” drill bit	Soldering Iron (optional)
Vice grips (optional)	Air compressor	