



**Design Report for**

# **Sultana**

**Submarine**

**11<sup>th</sup> International Human Powered Submarine  
Race - June, 2011**

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# 1. Introduction

Sultanate of Oman is one of the Arabian Gulf countries in the Middle East. Sultan Qaboos University (SQU) is located in Muscat, the capital of the Sultanate of Oman. The university is the leading university in the Sultanate of Oman and one of the leading universities in the region. It was established in 1986 and has been growing since then through increasing the students' intake numbers and the number and quality of the programs offered by the different colleges.

The College of Engineering at SQU was among the first colleges established in 1986. The department of Mechanical Engineering, renamed lateras the Department of Mechanical and Industrial Eng., was among the four departments in the college of Engineering back then. In 2006, the Mechanical Engineering program was recognized by ABET (Accreditation Board for Engineering and Technology, Inc, USA) as a substantially equivalent program. In 2008 the Industrial Engineering program was fully accredited by ABET.

The Mechanical Engineering program at SQU prepare its students via a combination of mathematics, physics and chemistry, courses along with engineering courses in areas such as fluid mechanics, mechanical design, heat transfer, dynamics, controls, environmental sciences, and electro-mechanical systems. An important element in the program is the design of mechanical systems. Students are exposed to this element in different courses. At their final year in the college the students are required to take a Final Year Project in which they apply what they have studied on an applied project.

The participation of SQU in the International Submarine Race (ISR) has been coordinated by the Mechanical and Industrial Eng. Dept. at the College of Engineering. The students worked on this project as part of their Final Year Project (senior project). The department felt that participating in the ISR helps in achieving academic goals through increasing the students' knowledge of design practices through involving them in a project that requires the integration of different fields in the design of the submarine.

In Fall 2008 the Vice Chancellor of SQU inquired the college of Engineering to study the viability of participating in the ISR. A committee was formed and decided that participation in the 10<sup>th</sup>



ISR, 2009, is not possible and recommended the participation in the 11<sup>th</sup> ISR in 2011. It was also suggested to send two faculty members to the ISR 2009 to have more insight about the race. Dr. Jamil Abdo and Dr. Nabeel Al-Rawahi attended the 10<sup>th</sup> ISR and they were assigned as the project's supervisors.

The project's supervisors decided to propose the design and construction of the human powered submarine as a Final Year Project (FYP) for two consecutive years. The first team, composed of three students, started in the Spring semester of 2009 and completed their work by Fall 2009. They dealt with the Hull design and general set up of the submarine. The second and the third teams; composed of three and four members, respectively; started in Fall 2009 and completed their work by Spring 2010. The fourth team, composed of six students, started in Fall 2010 and they will participate in the ISR 2011. The detailed plan is shown in table 1.

**Table 1.** Working plan and the progress made in the submarine project

Phase	Tasks	Time frame	Progress
PHASE I	<b>I-1-</b> Phase II of FYP (Human Powered Submarine 1, HPS 1) [Continuation of the FYP I that was started Spring 2009]: - Completing the design of the submarine. - Fabricating the submarine. - Testing the submarine. The committee will be following the progress of the FYP through asking the students to give two or three short presentations during the semester.	Fall '09	The theoretical part was done but no fabrication
	<b>I-2-</b> Phase I of FYP (HPS 2)[Larger group divided into two subgroups: one group for the inner (mechanisms) design and another group for the body design] : - Literature review. - Critical review of the work done by the previous group. - Looking at design alternatives. - Selecting/modifying the design. Through the use of computer simulation programs. The committee will be following the progress of the FYP through asking the students to give two or three short presentations during the semester.	Fall '09	Done
	<b>I-3-</b> Phase II of FYP (HPS 2): - Completing detailed design. - Building the submarine.	Spring '10	The fabrication of the Hull was

	<ul style="list-style-type: none"> <li>- Testing the submarine.</li> </ul> <p>The committee will be following the progress of the FYP through asking the students to give two or three short presentations during the semester.</p>		started. Internal parts were selected.
	<p><b>I-4-</b> Further testing and evaluating the built submarine more closely.</p> <ul style="list-style-type: none"> <li>- If possible start working on improving the submarine either through FYP students or Students societies/training.</li> </ul>	Summer '10	The Hull fabrication was completed and a new group started their work.
<b>PHASE II</b>	<p><b>II-1-</b> Phase I of FYP (HPS 3) and through students' societies:</p> <ul style="list-style-type: none"> <li>- Review and evaluate previous work.</li> <li>- Suggest improvements.</li> <li>- Implement the modifications.</li> </ul> <p><b>II-2-</b> Selected students will take diving course to receive diving certificates and continue practicing diving possibly with the previously built submarine.</p> <p><b>II-3-</b> Filling and sending required application forms for the ISR 2011 and sending the first part of the registration fee. (According to the new ISR manual that will be published later).</p>	Fall '10	Done.
	<p><b>II-4-</b> Phase II of FYP (HPS 3) and students' societies:</p> <ul style="list-style-type: none"> <li>- Continuing implementing the modifications.</li> <li>- Testing the submarine and finalizing it.</li> </ul> <p><b>II-5-</b> Students continue diving practices.</p> <p><b>II-6-</b> All required forms and reports for the ISR 2011 are completed and sent (according to the new ISR manual that will be published later).</p> <p><b>II-7-</b> The rest of the registration fee is sent.</p> <p><b>II-8-</b> Purchasing all necessary equipments that will be shipped with the submarine.</p> <p><b>II-9-</b> Shipping the submarine and the equipments to the USA.</p> <p><b>II-10-</b> Arranging for students' and faculty Visas.</p> <p><b>II-11-</b> Flight and accommodation arrangement for the team.</p>	Spring '11	In progress.
	<p><b>II-12-</b> Participating in the Race.</p> <p><b>II-13-</b> Returning to Oman</p>	June 2011	

Although the university administration promised to fully support the participation in the ISR, the teams managed to secure significant support from number of companies. These companies were attracted by the nature of the project and its international aspect.

Throughout the project phases the teams got valuable support and information from the ISR organizers. This includes facilitating the supervisors visit to the 10<sup>th</sup> ISR and providing valuable information and insight about the design of the submarine. The College of Engineering does not have a marine program so the teams had to rely on themselves in finding the required information from the scientific books and journals, internet, some experienced staff members in the college, and previous teams' reports. Previous teams' reports helped the teams in determining the latest work done in the topic. There are also few internet sites which helped in the design process through some free software. The teams are grateful to Mr. Claude Brancart, Chairman, International Submarine Race, ISR and Mr. Bruce M. Plazyk for their valuable support.

## **2. The submarine from a Concept to Reality**

Four teams worked on the submarine project, including the current team. The students took the project as their Final Year Project which lasts normally for two academic semesters. Each team is required to select a leader among the participating students and schedule a weekly meeting with the project's supervisors.

The first team started working on the submarine project was composed of three students. They developed different concepts and evaluated them. No one in the college had passed experience in building a submarine. Team had to search for information from different sources such as previous reports. The students' final report included the overall design of the submarine including the Hull profile, selection of a gear box and the interior design. The following team benefited much from this team work as they as they collected a lot of useful information and laid the path for improving the first design.

The second and the third teams started the work on the project about the same time. The second team, composed of three students, worked on the hull design while the third team,

composed of four students, worked on inner design (mechanisms) and propeller design. These two teams had considered the first design as one of the options and tried to come up with other alternative designs, evaluated them and then select the best one. They had more resources since by that time more reports of previous teams were available in addition to the resources found by the first team. The second team finalized the design of the Hull and built it in a fiberglass workshop. The hull was built from fiberglass. The team made sure that the design details were strictly followed. The third team completed the design of the interior components which includes the steering system, laying system, “dead man” switch, gearbox, paddling system and the propeller.

The current team, team number four, composes of six students. The tasks of this team included the following:

- a) Completing/improving the Hull construction (windows, hatch, fins,...)
- b) Improving/redesigning some of the the interior components
- c) Ordering some of the required components
- d) Testing the submarine
- e) Participating in the ISR 2011

The team redesigned almost all interior components, the hatch, the aileron, and the propeller. The steering system and the propeller have been the most challenging and time consuming. The team was able to come up with a design of an efficient propeller however; they could not find a workshop to manufacture that propeller. An existing propeller was found to be suitable for the submarine and ordered it. The team went through a diving course and got their diving licenses. They made several tests with the submarine in the university students’ swimming pool. The following sections give more details about the design of the submarine.

### 3. Configuration

The overall configuration of the hull is as follows:

- Transparent part (window): Front of the Submarine so that the pilot will see the path clearly and he will be visible by the rescue divers.
- Entrance: Top half of the submarine for an easy entering.
- Maintenance door: Upper part of the hull, between the entrance and the fins.
- Fins: Four fins near the end of the submarine, one in each side.
- Propeller: at the end of the submarine.

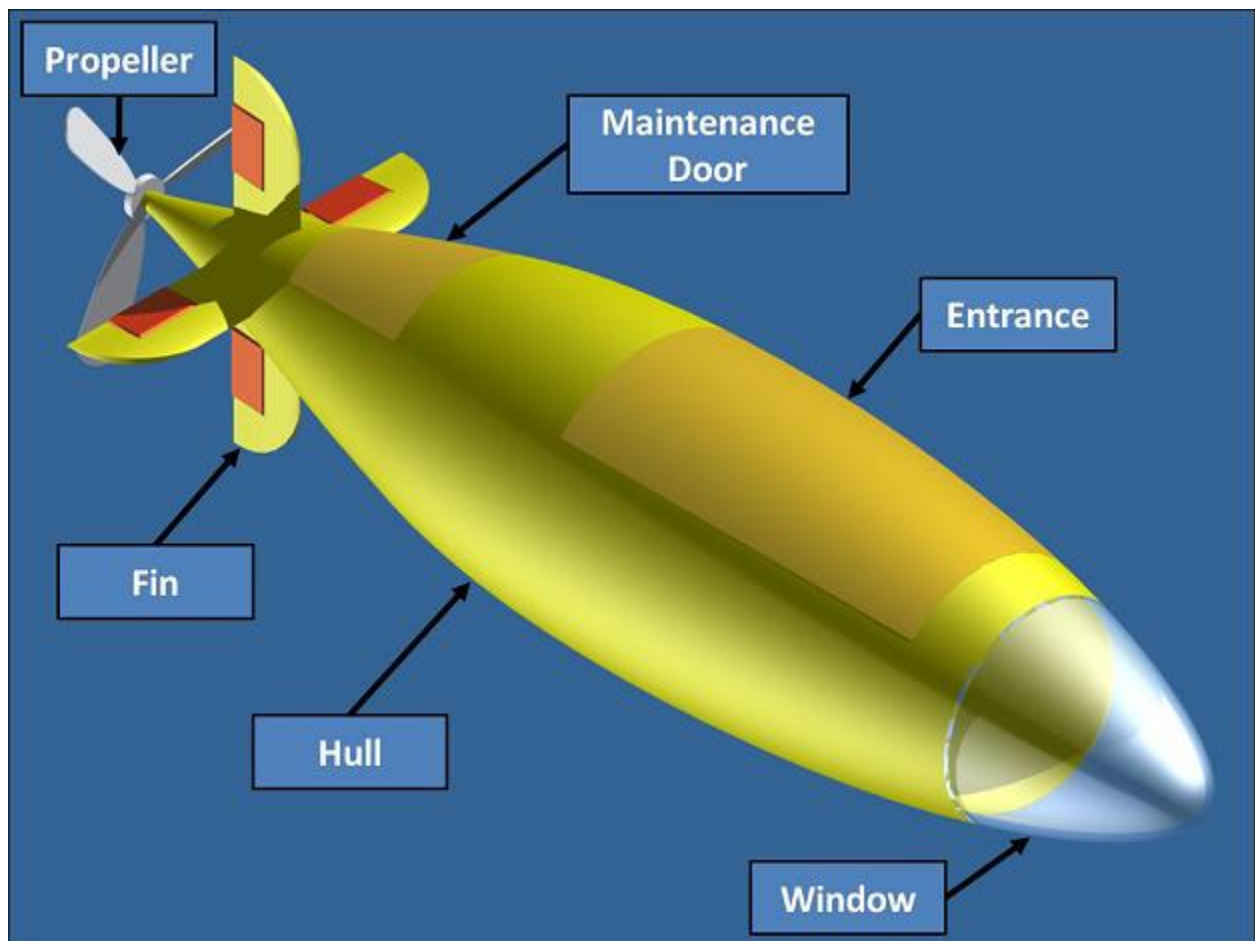


Figure 1: configuration of submarine

## 4 Hull

### 4.1 Hull Shape Design

It is known that design is an iterative process. Any feature in the final concept can be modified to get better performance. Initially, an elliptical hull was selected. However, modifications have been carried out in order to reduce the drag force further.

One of the best standards that are widely used for airfoils and submarine hulls are National Advisory Committee for Aeronautics (**NACA**) shapes. NACA shapes are divided into different groups, each one is called series. *6-series* is found to be the most appropriate for our situation since it provides an improvement over *1-series* airfoils with emphasis on maximizing laminar flow. The airfoil is described using five digits in the following sequence:

1. The number "6" indicating the series.
2. One digit describing the distance of the minimum pressure area (maximum diameter) in tens of percent of chord.
3. One digit describing the design lift coefficient in tenths.
4. Two digits describing the maximum thickness in tens of percent of chord.

The first digit should be "6" as we have 6-series shape. According to our configuration, we need to have the maximum diameter just after the middle of the hull to provide enough space for that pilot to pedal. Therefore, it is chosen to be at 60% of the chord length and therefore "6" is assigned to the second digit. Lift coefficient is zero, so the third digit has to be "0".

The last two digits can be determined from the ratio between the maximum diameter and the chord length.

Chord length needed:  $L = 3.30 \text{ m}$ ,

Maximum diameter needed:  $D = 0.76 \text{ m}$ .

Length-diameter ratio:  $r = L/D = 0.23$ .

Therefore, the last two digits are “23” and our shape is **NACA 66-023**.

The next step was to generate a sketch of the desired shape. “**Design FOIL**” software was used to accomplish this task. A view of the program interface is shown in *figure 2*.

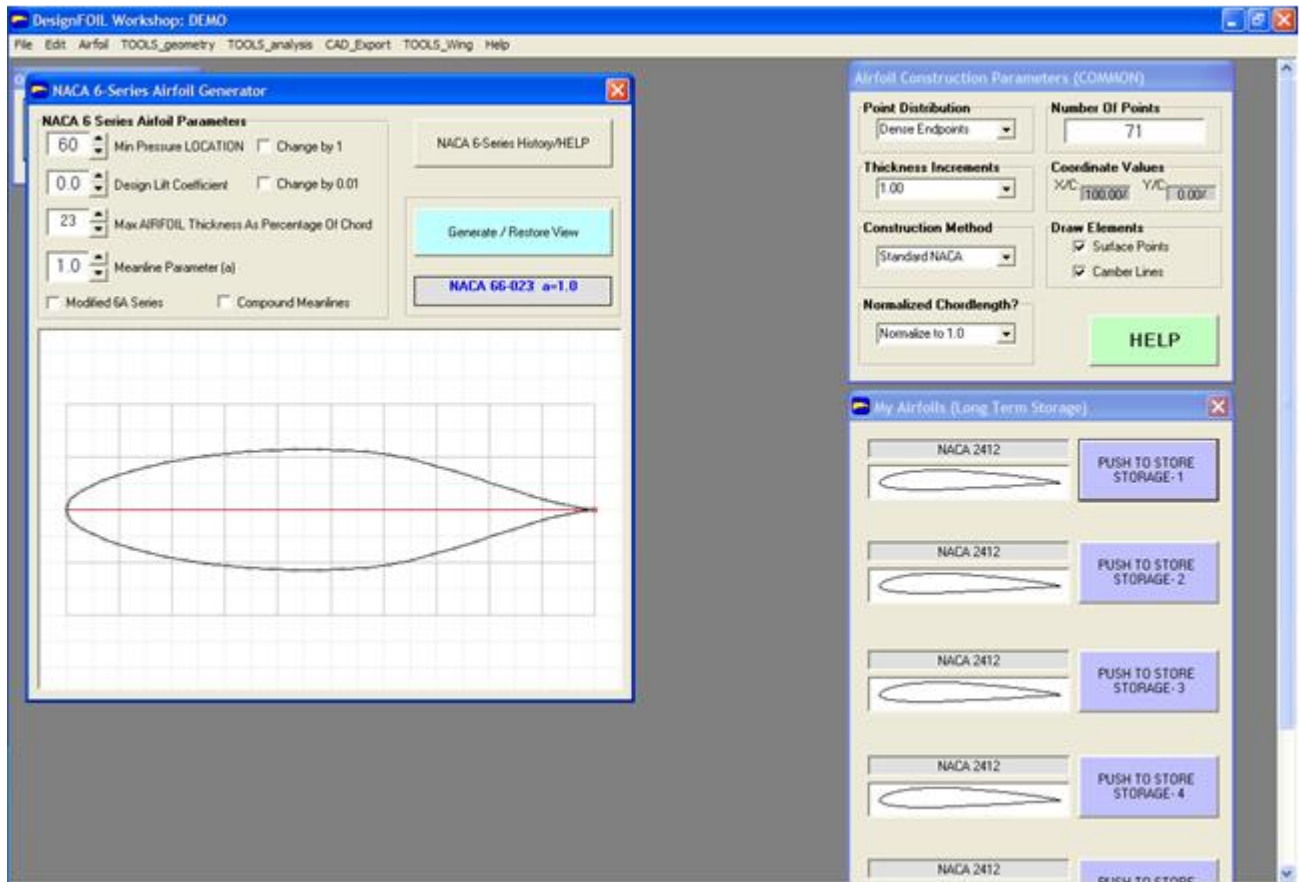


Figure 2: Design FOIL Interface

Values were entered and the shape appeared in the screen. The result was exported in two different file types: *DXF* and *dat*. *Dat* file was used to generate 2D sketches. However, the used version of the program was only demo. Therefore, the allowed number of data points was only 71 and the chord length is fixed to be 2.718277. The data are modified using *Microsoft Excel* to fit our desired chord length. The original results from Design FOIL and the extended results from Excel are listed in Appendix A. Then, the final shape was sketched using *Microsoft Math* as shown in *figure 3*.

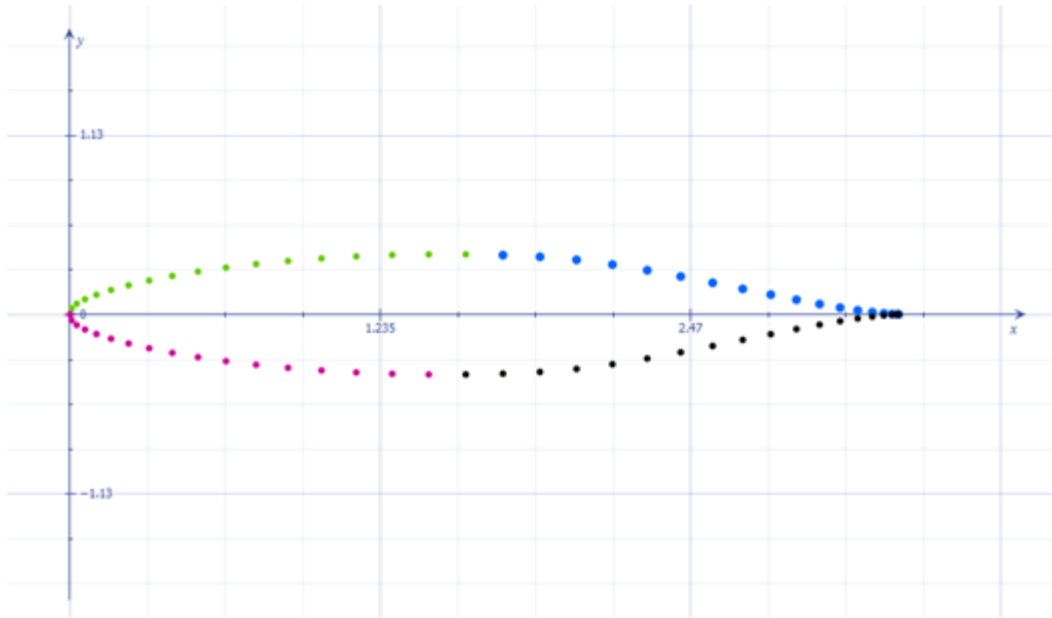


Figure 3: Submarine profile from Microsoft Math

The 3D model of the hull shape was generated in “*Inventor*” software using the DXF file generated from Design FOIL. Similar to what was done in Excel; the 2D sketch imported from the DXF file was extended to change the chord length from 2.718277m to 3.3m. *figure 4* shows the final main hull shape:

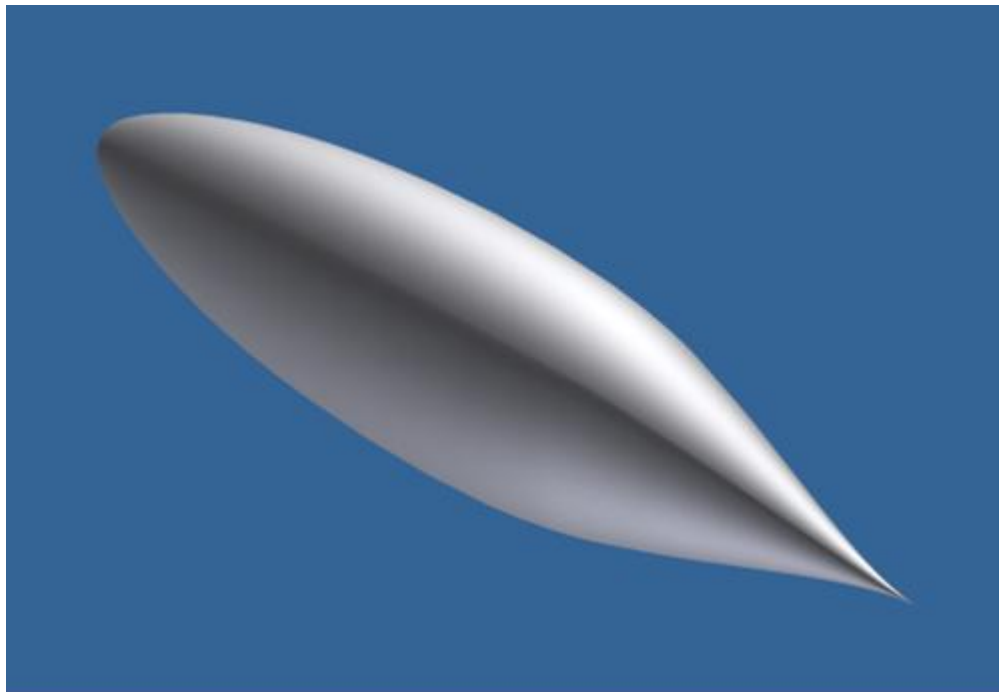


Figure 4: 3D shape of the hull



At this point the main hull of the submarine is ready. Other features like fins, entrance and window will be added next.

## **4.2 Material Selection**

The hull material was selected to be a fiberglass. It was selected depending on its suitability of the following criteria:

1. The mold ability to almost any boat design.
4. Seamless construction.
5. High strength and great durability.
6. Minimum maintenance.
7. Freedom from corrosion and rust.

## **4.3 Hull Shape Analysis**

### **4.3.1 CDF Analysis**

Computational fluid dynamics (CFD) is a branch of fluid dynamics where the flow is analyzed using numerical methods and algorithms. The fluid and other solid domains are divided into small finite elements in a process called meshing. Then properties and boundary conditions are specified and the calculation is left to computer software.

There are many different software packages that use CFD to analyze fluid flow. In this project, **ANSYS CFX v12** has been used in analyzing the fluid flow problem. However, we have kept in minds that CFX gives qualitative results. The most important output from CFX is the water pressure in the outer surface of the hull as the submarine moves at a target velocity of *8knots*. Pressure results will be exported to mechanical analysis in ANSYS. In ANSYS CFX, the analysis procedure consists of five steps: geometry, mesh Generation, setup, solution and results.

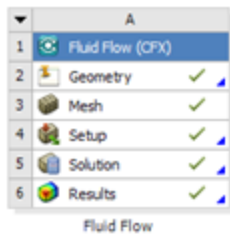


Figure 5: CFX steps

#### 4.3.1.1 Geometry

Autodesk Inventor was used to create the geometry. A water domain was modeled as a box with  $(5.0m \times 2.5m \times 12.0m)$ . Then the submarine geometry was subtracted from the water domain.

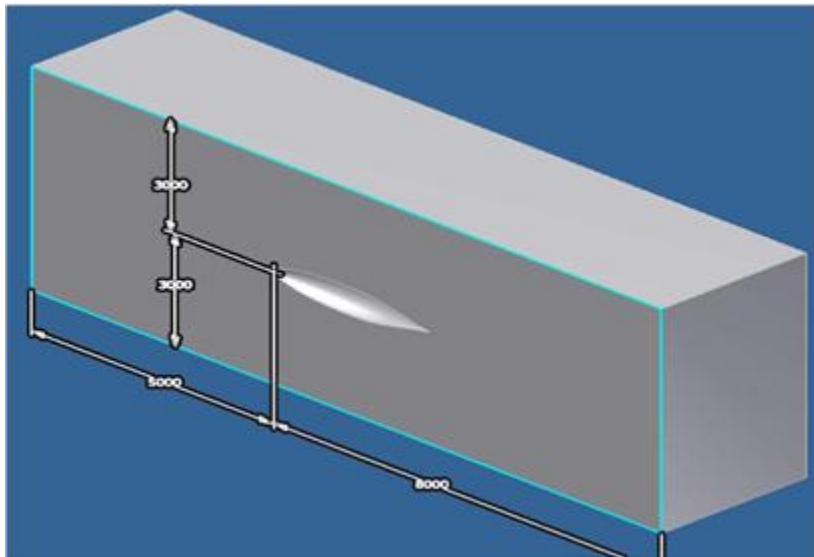


Figure 6: Geometry for CFX

#### 4.3.1.2 Mesh Generation

The next step was to generate the mesh. Surface meshing was generated followed by generating volume mesh. After the surface meshing was generated, a warning indicates that the geometry has small angles was appeared. However, this did not result in any error. The generated mesh has *35978 nodes* and *197362 elements*. All elements generated are tetrahedral

in shape. The meshing is shown in the figures 7 and 8. Small mesh size has been used for critical areas like fins and tip of the submarine.

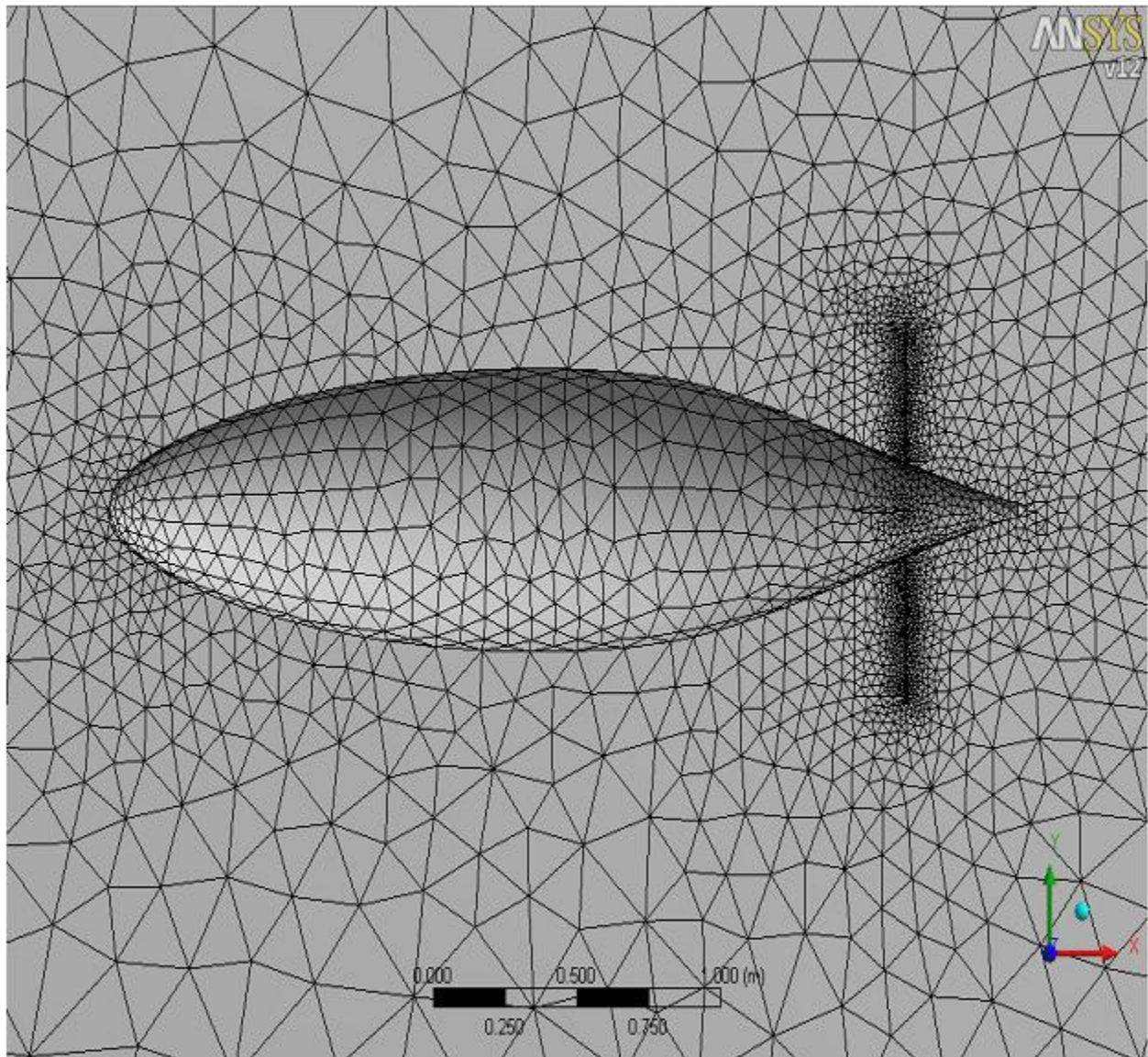
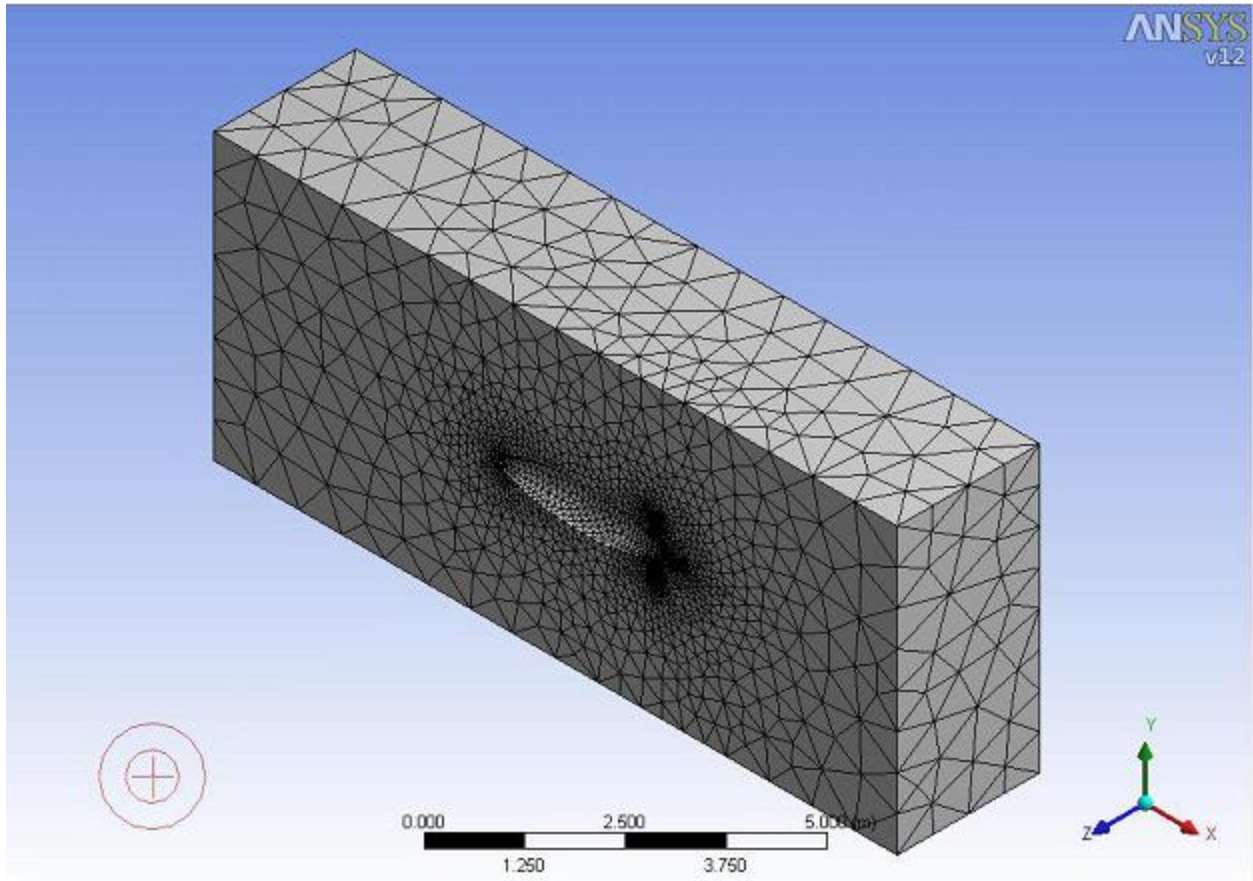


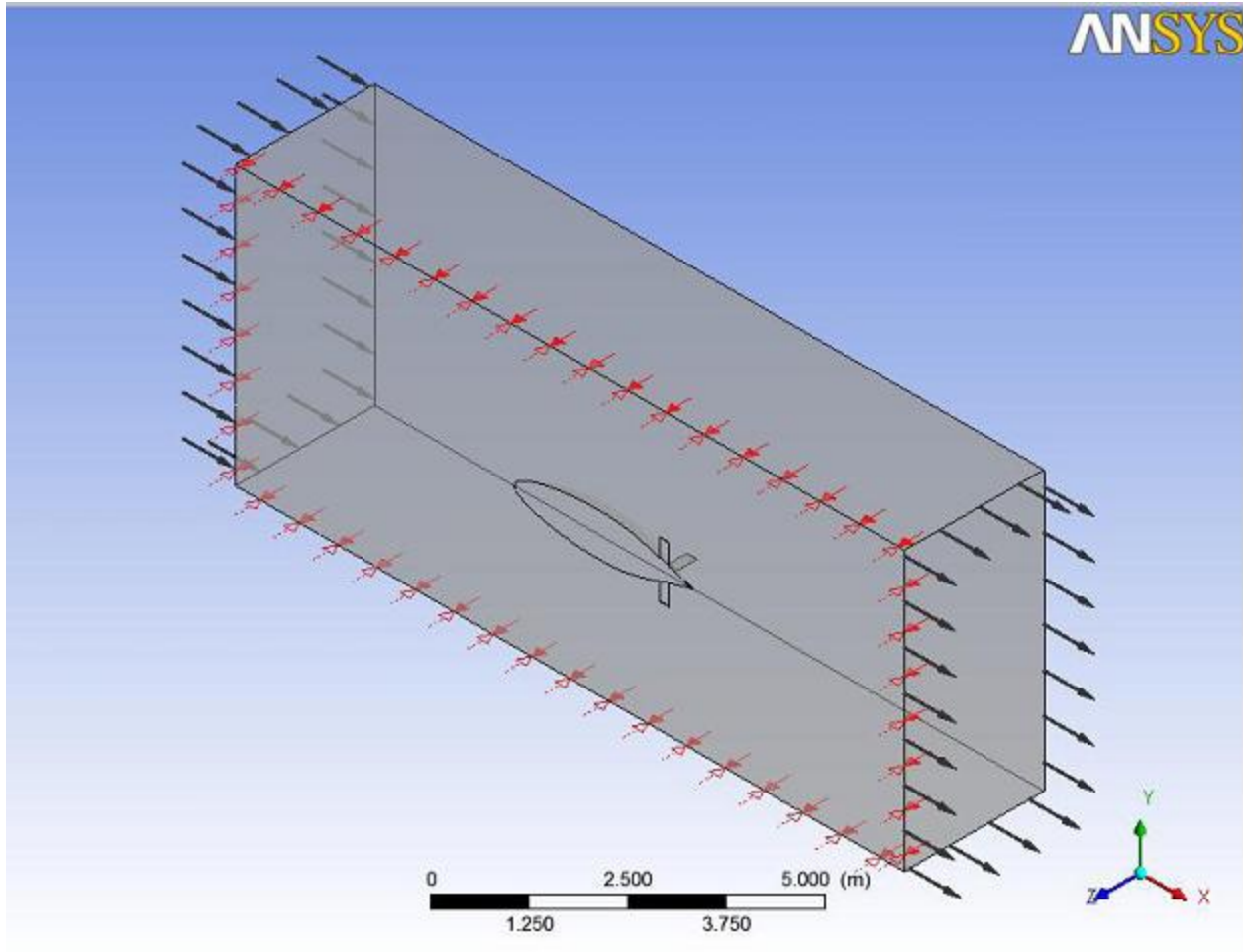
Figure 7: Meshed Geometry (1)



**Figure 8: Meshed Geometry (2)**

#### **4.3.1.3 Setup**

This stage considers the properties of the fluid and boundary conditions. The fluid was chosen to be water at  $17^{\circ}\text{C}$ . In reality the submarine moves against stationary water. However, analyzing flow patterns past a moving body with stationary fluid is dynamically equivalent to analyzing the flow patterns around a stationary body as the flow moves. The left side is set to be the inlet with a normal velocity of  $8 \text{ knots}$  and the right as an outlet with the same boundary condition of  $8 \text{ knots}$ . The front side is used as a symmetry plane. The other three sides were considered as frictionless walls.



**Figure 9: Geometry with boundary conditions**

The table below summarizes the boundary condition used in each surface.

Surface	BC type	BC value
Left side	Inlet, velocity	8 knots
Right side	Outlet, velocity	8 knots
Front side	Symmetry plane	
Other sides	Wall, No friction	
Submarine	Wall, No friction	

**Table 2: summary of the boundary condition used in each surface**



### 4.3.1.4 Solution

The software carries out the calculations needed and uses an iterative process. When it reaches an error below the specified value of ( $1.0\text{e-}4$ ), it stops the solution process. See *figure 10*.

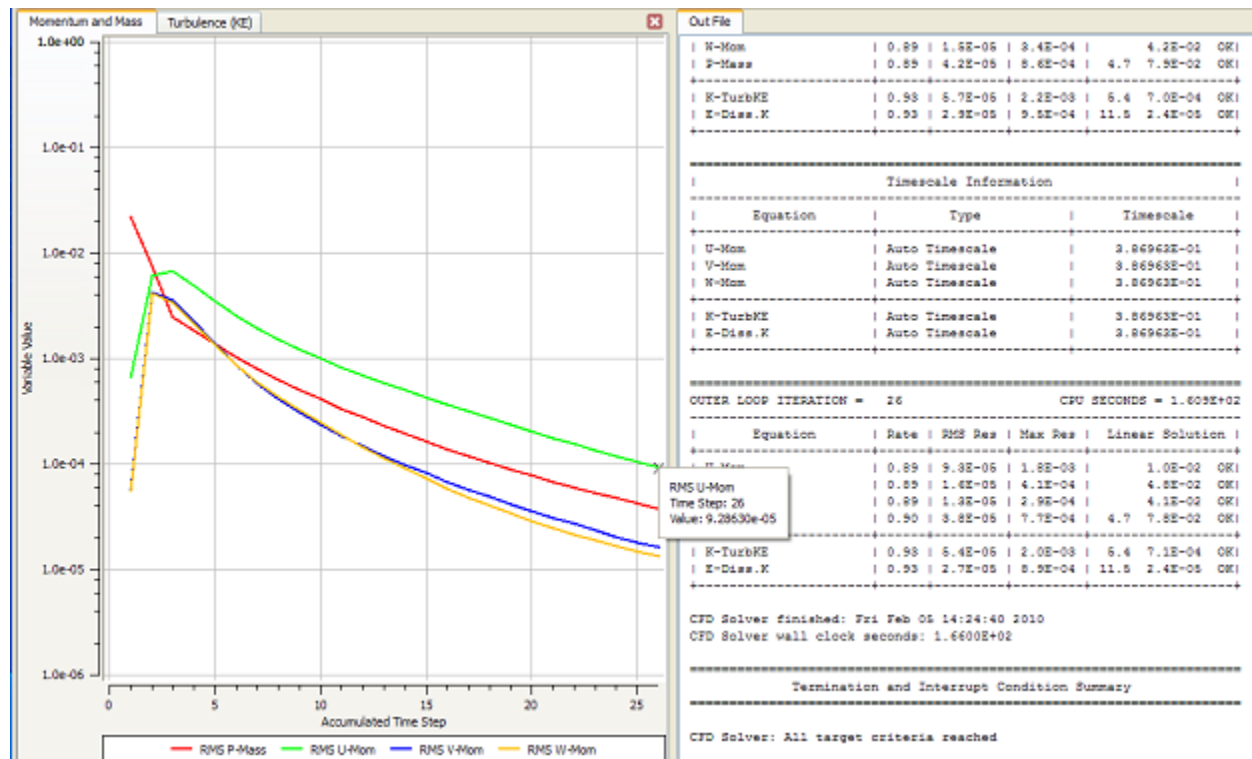


Figure 10: CFX-Solver interface

### 4.3.1.5 Results

Pressure, velocity, viscosity and other results can be viewed in this stage. Pressure results on the body of the submarine are shown in *figure 11*. The value of maximum pressure is  $8.379\text{kPa}$  at the nose of the submarine. This value is considered very logical since this region has the least area and it is perpendicular to the flow direction. This value agrees with our calculation in the parametric design section. The minimum pressure was at the region with the bigger cross section area which is located at 60% from the nose. These pressure results will be transferred to mechanical analysis.

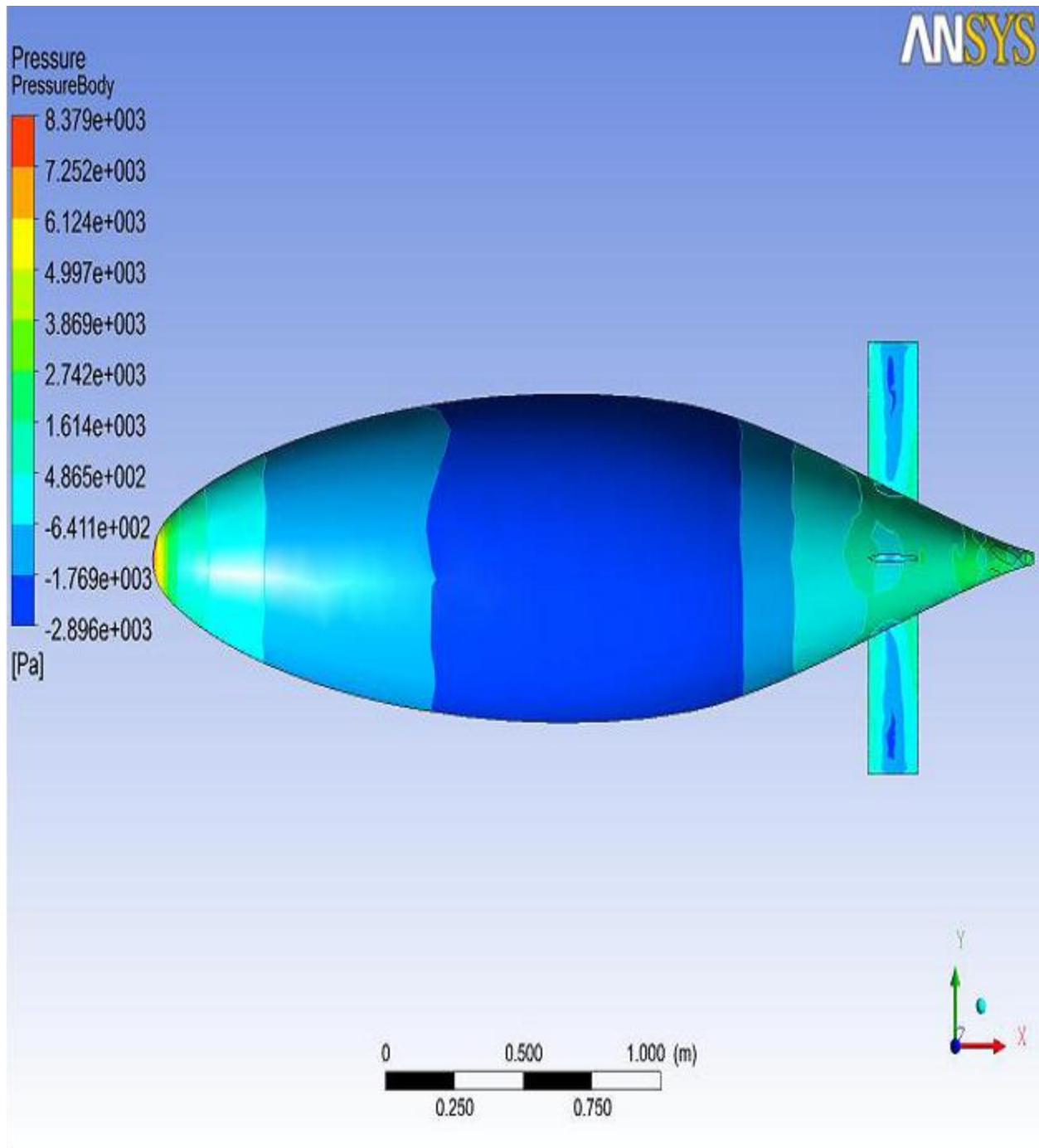


Figure 11: Submarine surface pressure

Pressure can also be viewed in the symmetry plane as shown in figure 12.

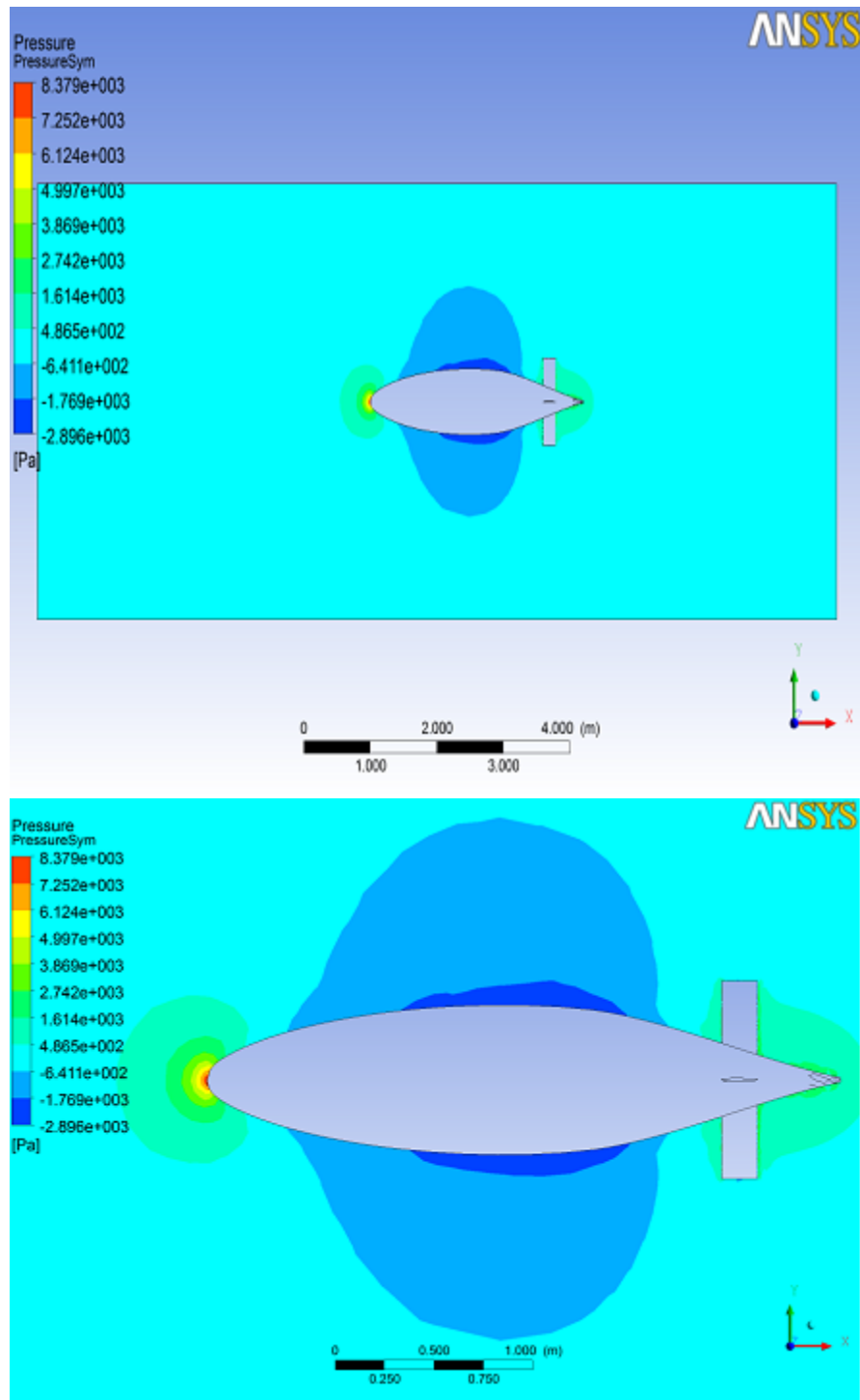


Figure 12: Symmetry plane pressure



From the velocity results shown below, the maximum velocity is at the inlet and the outlet. It decreases near the surface of the submarine as a result of the drag force.

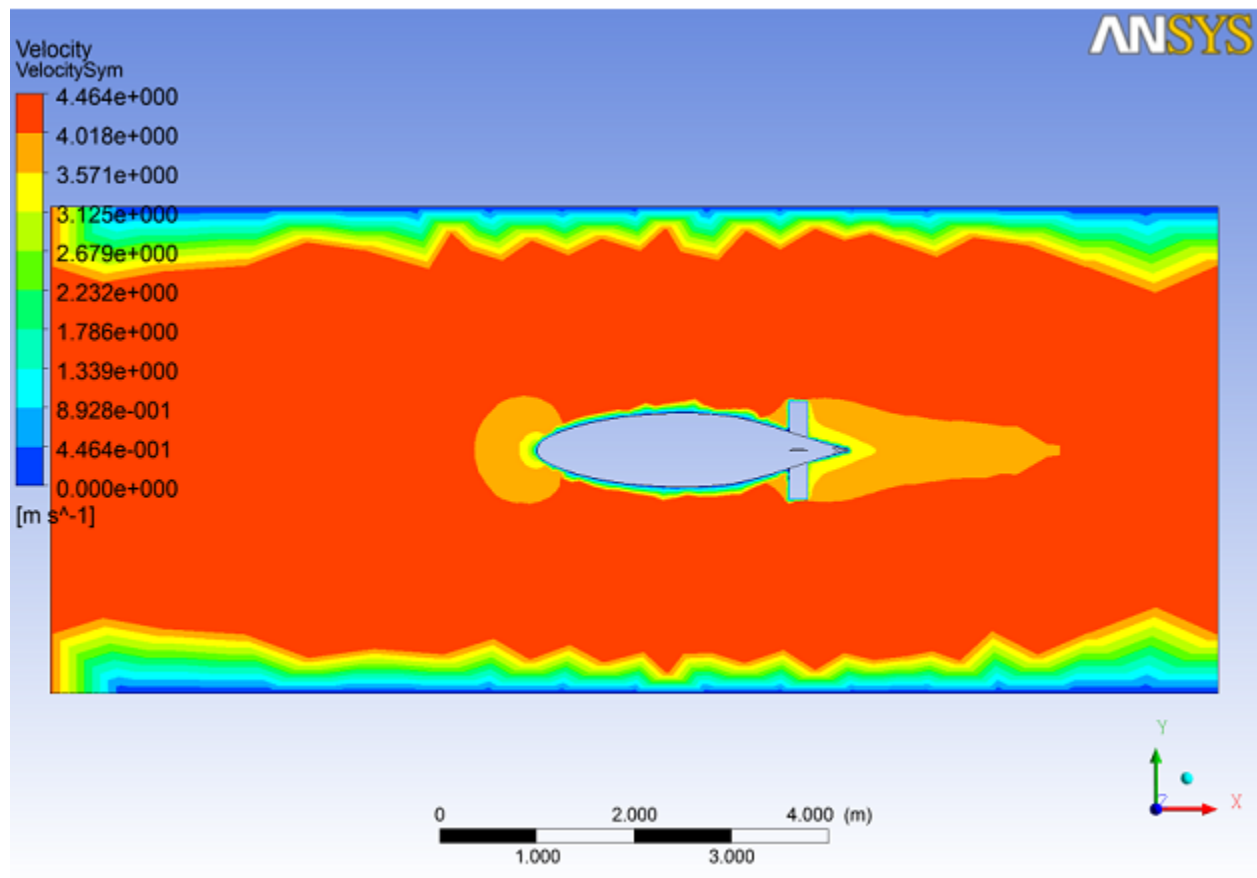
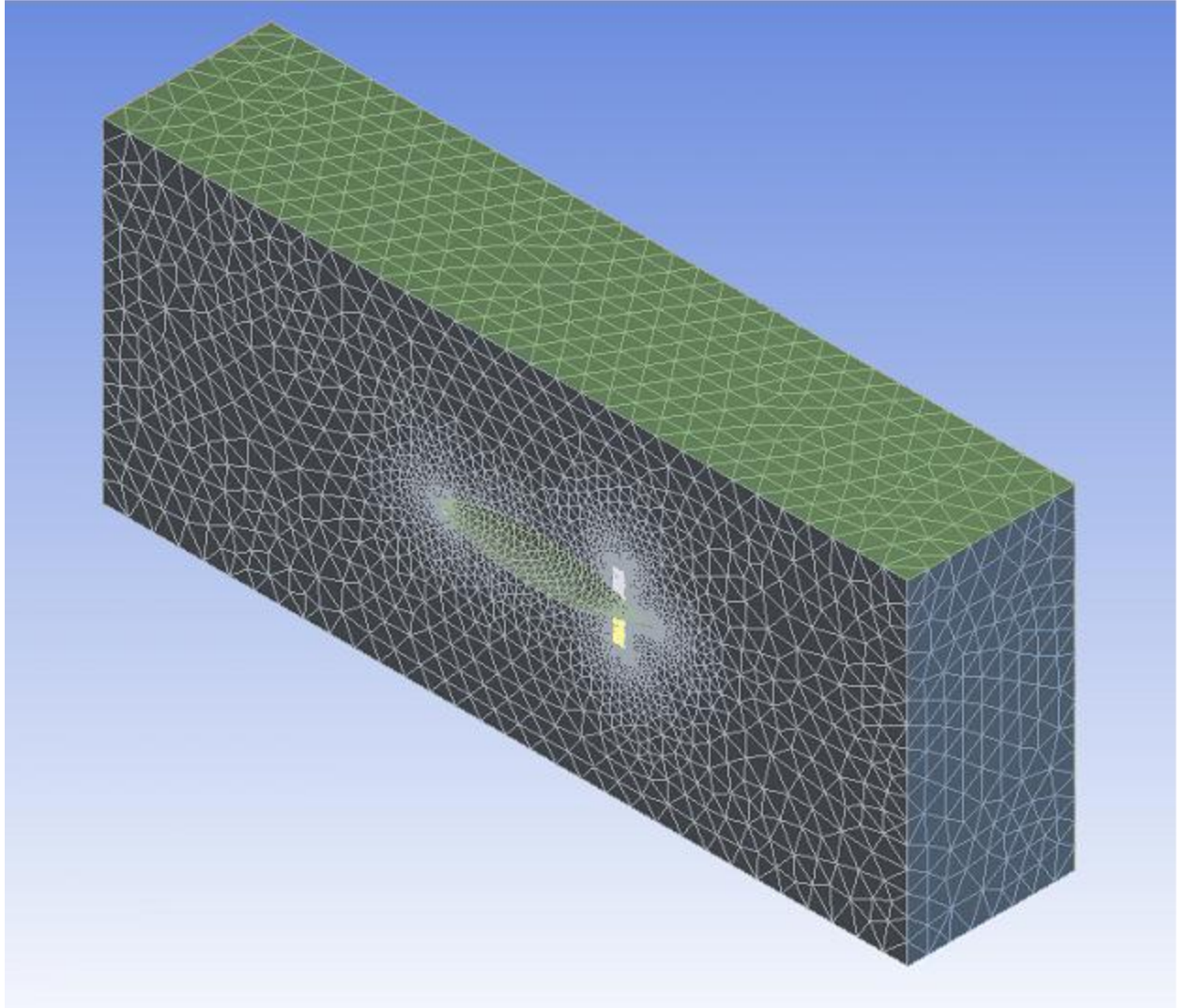


Figure 13: Symmetry plane velocity

Another analysis has been carried out using a finer mesh in order to check the solution given using the previous mesh. The new mesh has 42446 nodes and 229089 tetrahedral elements. A preview of the mesh is shown in figure 14.



**Figure 14: New meshed geometry**

With the same boundary conditions, the new results were very close to the previous result. For example, the new maximum pressure appeared to be  $8.390\text{kPa}$ , as shown in *figure 15*, and it was  $9.379\text{kPa}$ . The change is just  $0.13\%$  which is very small. This shows that the mesh is fine enough to have good results.

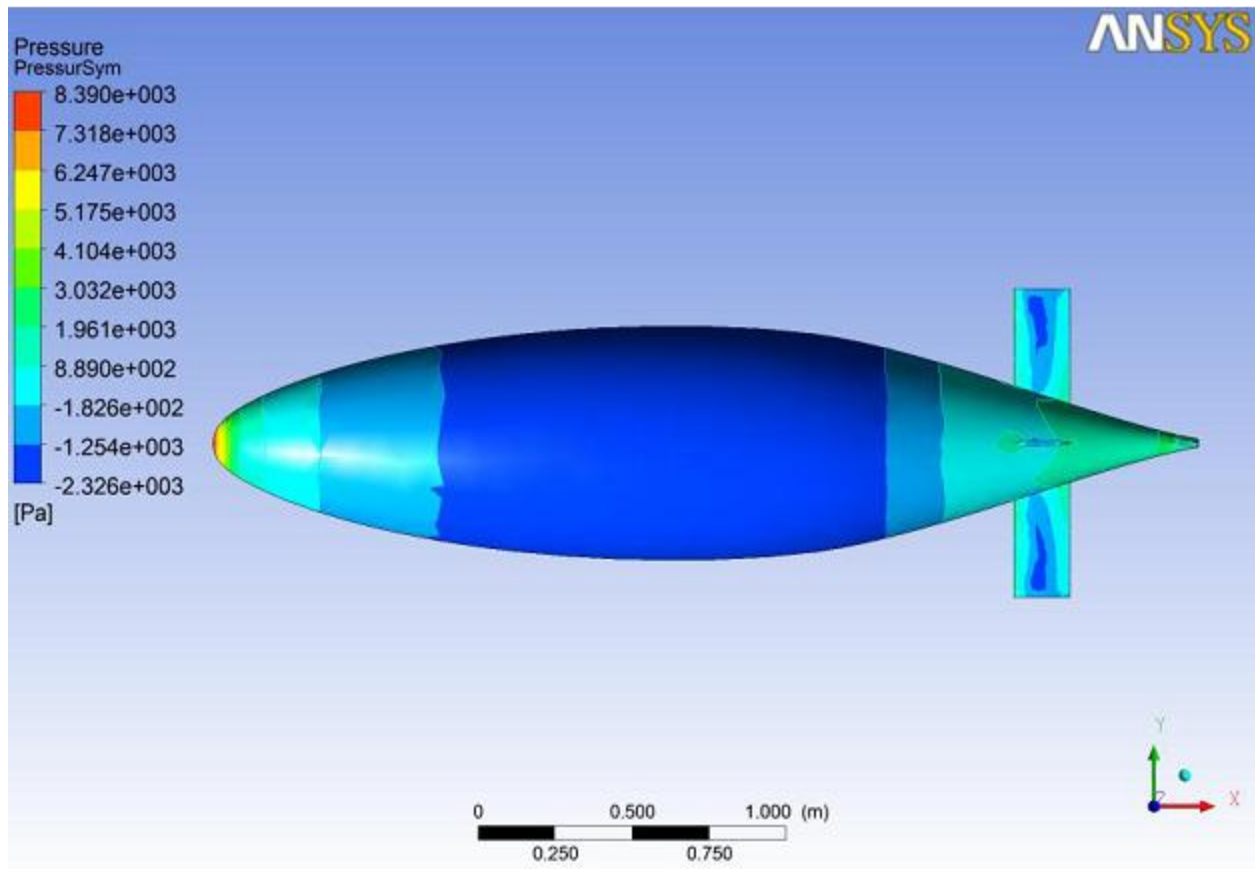


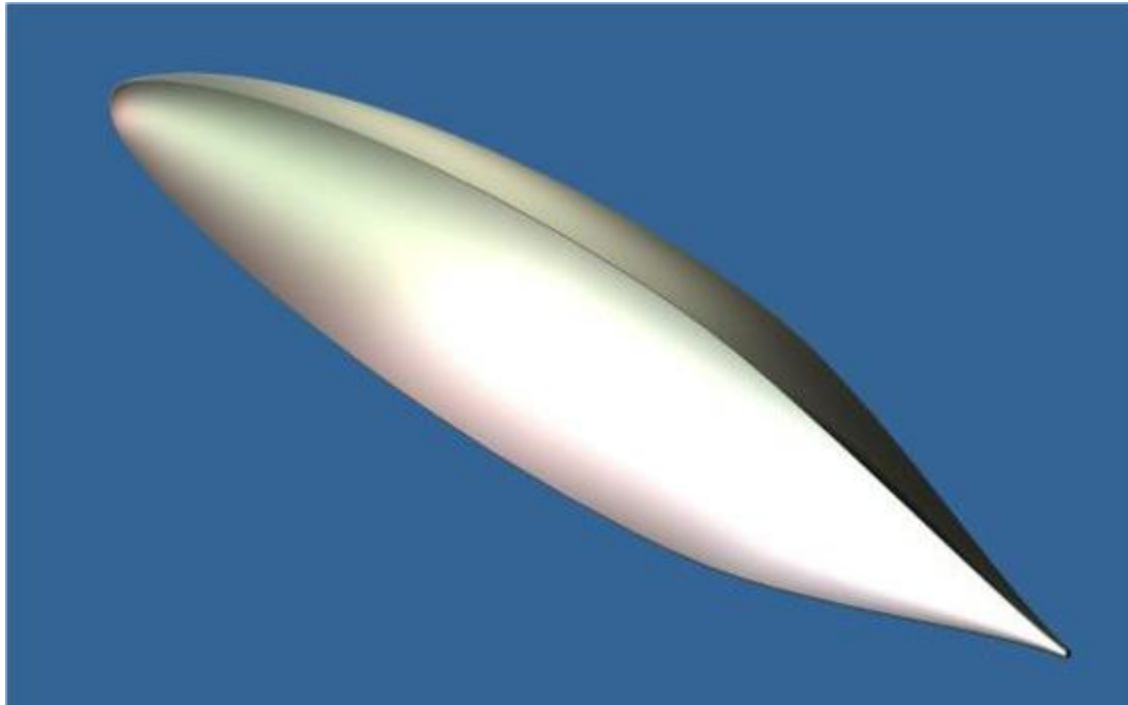
Figure 15: New pressure results

### 4.3.2 Mechanical Analysis

After CFX analysis, the next step is to perform mechanical analysis where the pressure results will be imported to ANSYS static structural analysis where the total deformation will be calculated. The figure shown below shows the two analysis types in ANSYS Workbench.

#### 4.3.2.1 Geometry:

Half of the hull was created using Autodesk inventor. It was modeled using the data provided in appendix A. The thickness of the hull was set to be 5mm. The resulted shape is shown *figure 16*. It was imported to ANSYS in “sat” format.



**Figure 16: Geometry of the hull**

#### 4.3.2.2 Material model:

The finite element model requires the material properties of the hull. Since the system under goes static analysis and in the linear elastic region modulus of elasticity and Poisson ratio of the hull material will be provided only. A fiberglass material was used for the hull of the submarine. In this FEM model, the fiberglass modulus of elasticity is  $72GPa$  and the Poisson's ratio is  $0.22$ .


Properties of Outline Row 3: Fiber			
	A	B	C
1	Property	Value	Unit
2	 Isotropic Elasticity		
3	Derive from	Young's Modulus and Poisson's Ratio	
4	Young's Modulus	7.2E+10	Pa
5	Poisson's Ratio	0.22	
6	Bulk Modulus	4.2857E+10	Pa
7	Shear Modulus	2.9508E+10	Pa

Figure 17: Material Properties window in ANSYS

#### 4.3.2.3 Mesh Generation

The same procedure done in CFX meshing was repeated to generate the hull mesh. The generated mesh has 228244 nodes and 985328 elements. The mesh is shown in *figure 18*. Surface mesh size is different in each face of the hull, as shown in *figure 19*. Finer surface mesh is used in the critical edges.

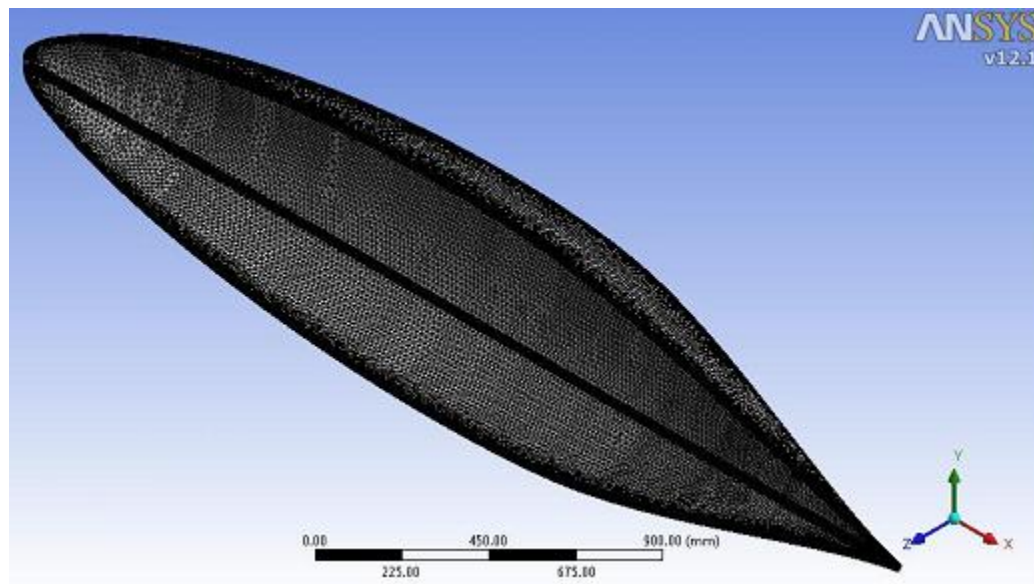


Figure 18: meshed hull geometry (1)

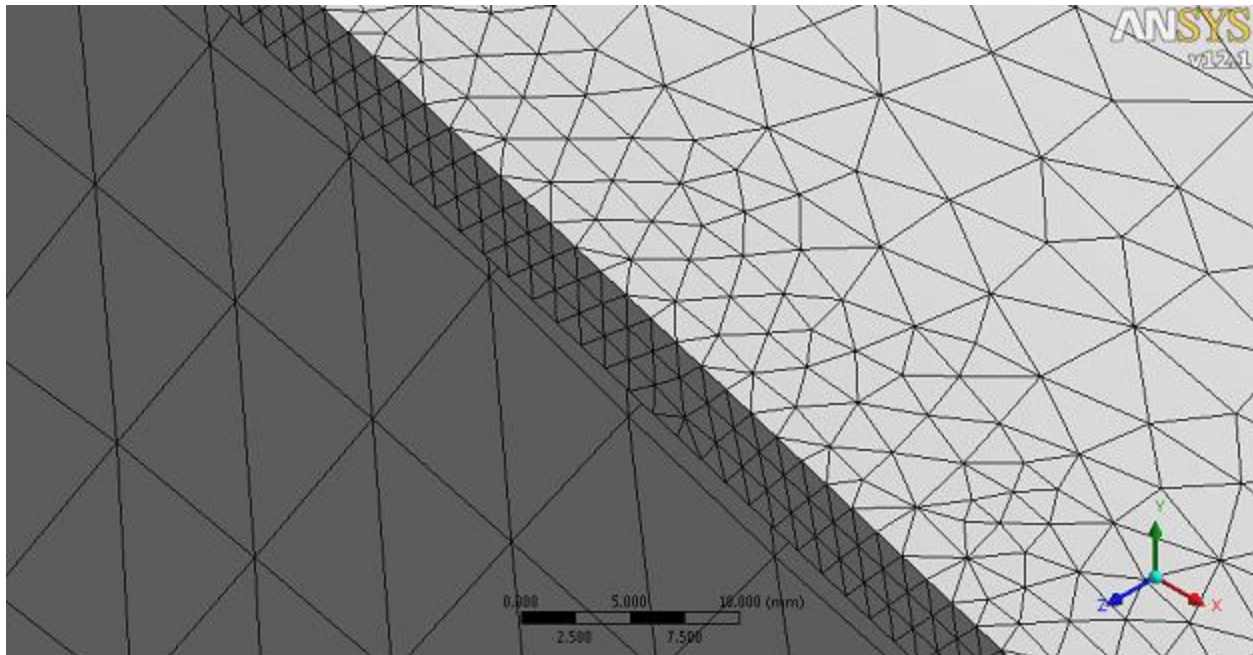


Figure 19: meshed hull geometry (2)

#### 4.3.2.4 Boundary Conditions:

There are three different loads in the hull of the submarine. There are two hydraulic pressures resulted from the weight of water column. One of them is in the outer surface of the hull, while the other one is on the inner surface. However, those two pressures are approximately the same but in opposite directions. Therefore, they will cancel each other. The third pressure is the pressure of water in the outer surface of the hull that is resulted from the movement of the submarine through water. This data will be imported from the CFX analysis done before.

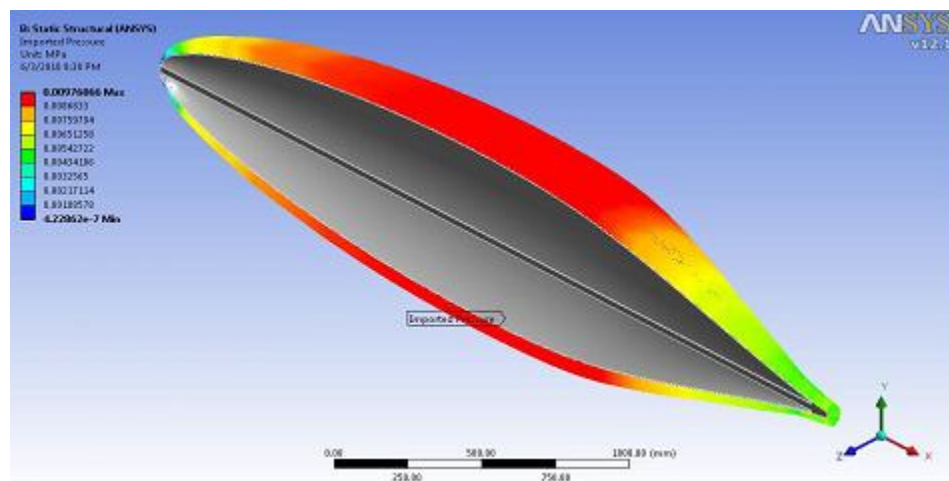


Figure 20: Pressure Imported from CFX to Static Structural



#### 4.3.2.5 Results:

Results from the static structural analysis in ANSYS were generated. The deformation is shown in *figure 21*. We can see that the maximum deflection is about 0.56mm. It is in the middle of the hull. Stress results in the hull are shown in *figure 22*. The maximum stress is about 225MPa.

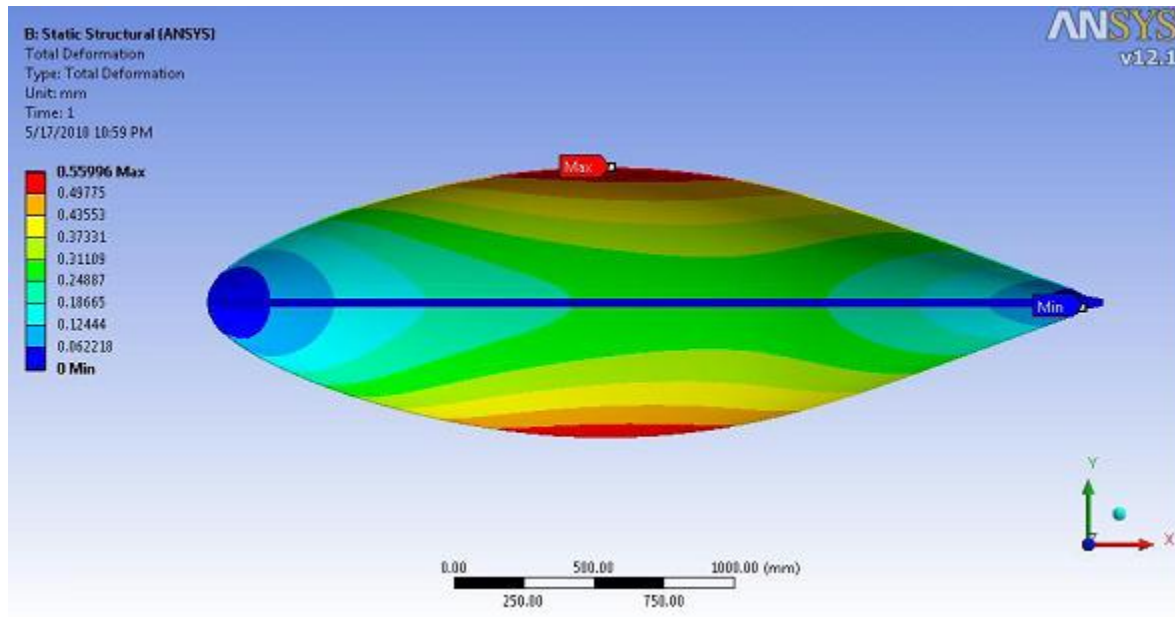


Figure 21: Static structural total deformation results

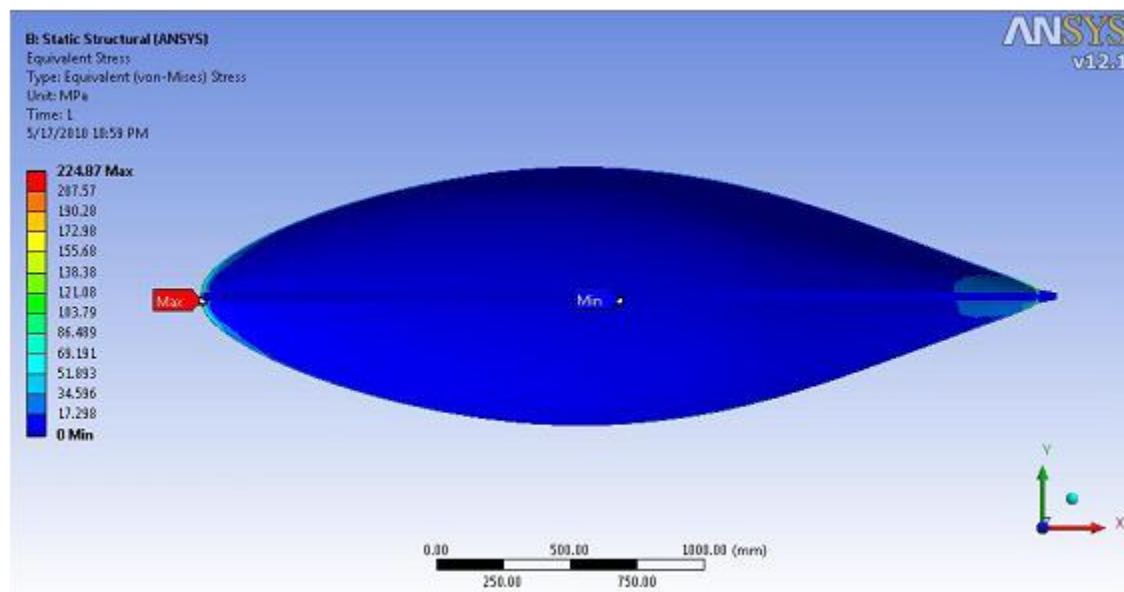


Figure 22: Static structural stress results

To check if the mesh was fine enough, another two meshes were generated to see the change in the results:

Trial #	Number of Elements	Max. Deflection
1	985328	0.55996 mm
2	1056837	0.56023 mm
3	1105244	0.56015 mm

**Table 3: Maximum deflection for changing number of elements**

It can be seen clearly that the change in the results is very small when increasing the number of elements. This means that mesh used was fine enough to get good results.

The thickness that has been used for the hull was enough to make the deflection within the safe region. However, the stress at the nose of the submarine is high. This is due to the profile of the hull which is perpendicular to the water stream direction. Transparent window will be located at the nose of the hull. Therefore, the thickness should be enough and the material used should have enough strength.

#### **4.4 Fabrication of the Hull**

The second team finalized the design of the Hull and built it in a fiberglass workshop. The hull was built from fiberglass. The team made sure that the design details were strictly followed. The team members regularly visited the workshop and observed the manufacturing process. One of the main issues in the manufacturing process is whether to choose a temporary or permanent mold. The temporary mold cost less since it will be used one time only. In the other hand, the permanent one can be used more than one time but it costs much more. After discussing this issue with the manufacturer and our project supervisors, the temporary mold was selected. The manufacturer will be responsible of making the hull, fins, entrance and maintenance door. A temporary painting of the hull was also included in the agreement. The hull will be under warranty for six months. The total cost is 3,300 R.O (about \$ 8,000).

The manufacturing process included the following steps:

1. Half of the hull profile was drawn in plywood. This profile was cut from the wood as shown in *figure 23*.



2. A cube of foam was prepared by mixing two chemicals. A reaction between the two chemicals takes place and the mixture expands gradually for 10 minutes. At the end, it takes the shape of the container. It has dimensions of 3.5×1.0×1.0m as shown in *figure 24*.
3. A steel rod was penetrated through the foam cube. It will be used to rotate the cube during the process. See *figure 25*.
4. The foam cube was fixed using the penetrated rod at a suitable height from the ground.
5. Unneeded parts of the foam were trimmed using a saw to form rough shape of the hull. See *figure 26*.
6. The plywood sheet was fixed horizontally beside the foam.
7. The foam was rotated against the plywood so that it takes the exact shape of the hull.
8. A paste was used to fill the gaps in the foam.
9. 9. The final shape was coated with special chemicals called Resin. This will make the surface very smooth before making the mold.
10. The upper half of the mold was made. Layers of fiber glass were added one by one on the upper half of the foam and given some time to dry.
11. The lower half was made using the same method of the upper half.
12. The two parts of the mold were joined using nuts and bolts. Then, they were strengthened by adding a series of pipes that are connected using fiberglass layers. See *figure 33*.
13. After the mold is dry, the two parts were separated and the coated foam was removed.
14. For each part, fiberglass layers were added to reach the desired thickness.
15. Openings were cut from the hull to form the entrance, maintenance door and window location.
16. Surface finishing was carried out to smoothen the outer surface of the hull.
17. Door hinges and locking mechanism were installed.

18. The transparent window was attached to the hull using special chemicals (fiberglass adhesives).

19. Marine paints were used for painting.



Figure 23: Plywood with the hull profile

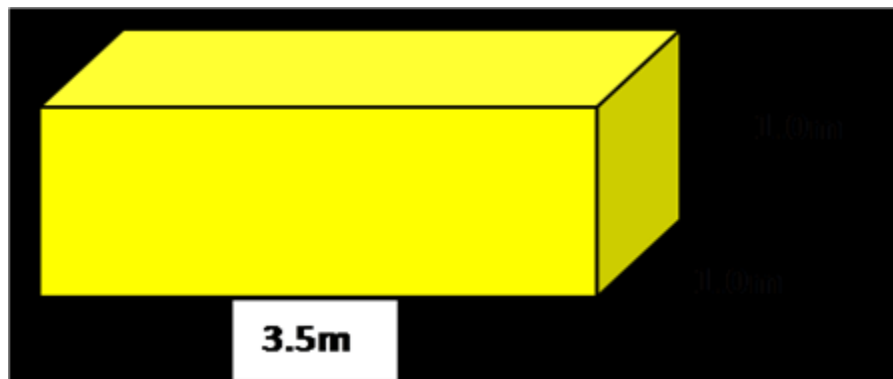


Figure 24: Dimensions of the foam cube

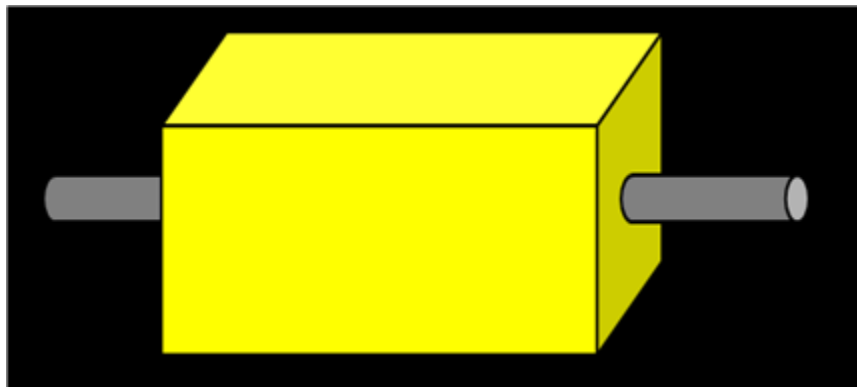


Figure 25: The foam cube penetrated with a steel rod



Figure 26: A saw was used to trim large unneeded parts



Figure 27: The plywood fixed beside the foam



Figure 28: Shape of the foam after rotation against the plywood



Figure 29: Foam surface before and after adding paste



Figure 30: Adding Gypsum to the foam surface



Figure 31: layers of fibers form the upper half of the mold



Figure 32: Forming the lower half of the mold



Figure 33: Series of pipes to strengthen the mold



## 5 Fins

### 5.1 Design of the fins

NACA shape is the best choice for the cross section area of the fin. It reduces the drag force and minimizes the turbulence of the flow. Therefore, **NACA 64-010** shape was chosen for the fin. We can see that the last two digits are “10”, because it is required to have a fin with a length of *20cm* and a maximum thickness of *2cm*.

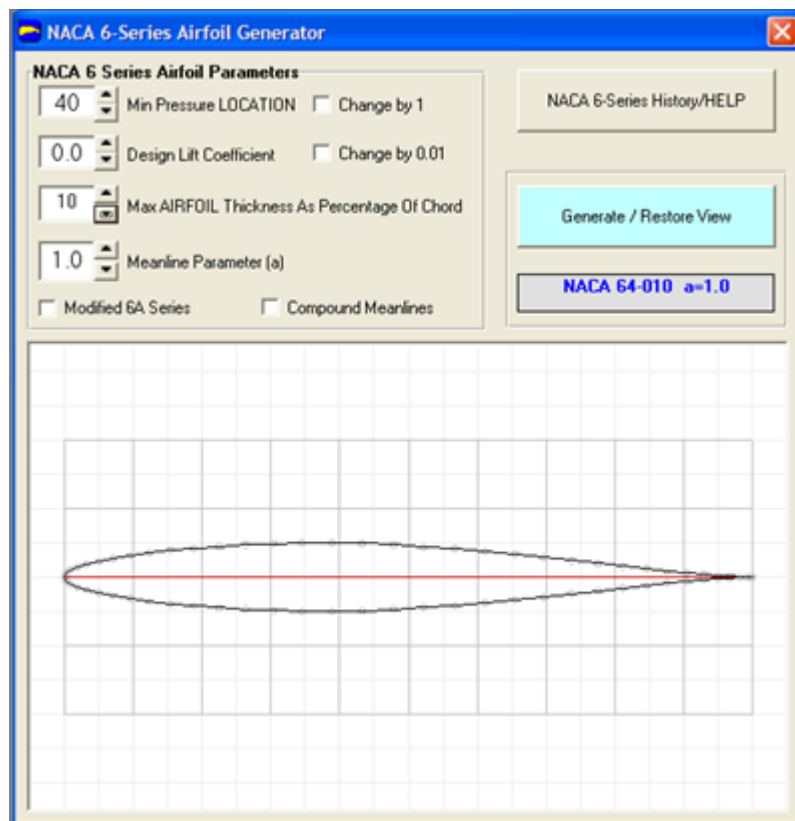


Figure 34: Design FOIL Interface

The same procedure used in generating the hull shape was repeated to design the fin. However, NACA 66-023 shape was revolved to get the hull and NACA 64-010 was extruded to get the fin *figure 34* shows the fin profile generated by Design FOIL and figures 35 and 36 shows different views of the fin in Autodesk Inventor.



Figure 35: Fin profile

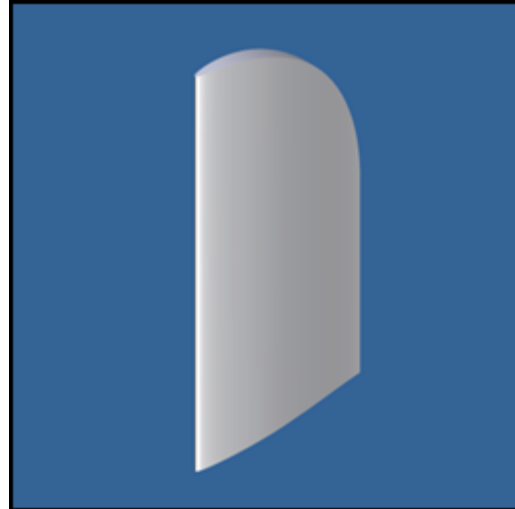


Figure 36: 3D shape of the fin

As requested from the other team (internal team), who is responsible for designing the steering system, the fins are selected to have ailerons. This type of fins, as shown in *figure 37*, consists of two parts. One part is stationary and responsible of the stability of the submarine. The other part is movable in order to change the direction of the submarine, horizontally or vertically. The fin generated previously was modified by cutting a rectangular part in the middle in order to install the aileron. The aileron is then created and installed in its place as shown in *figure 38*.

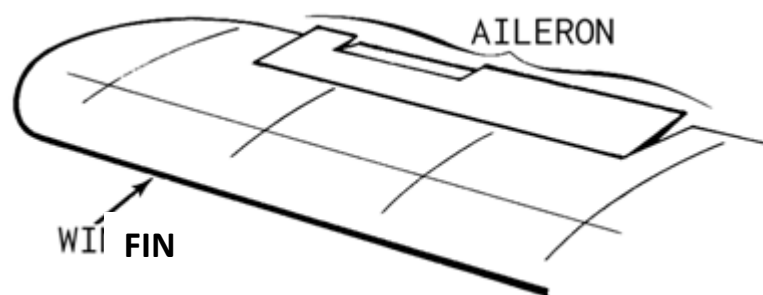


Figure 37: Fin with Aileron

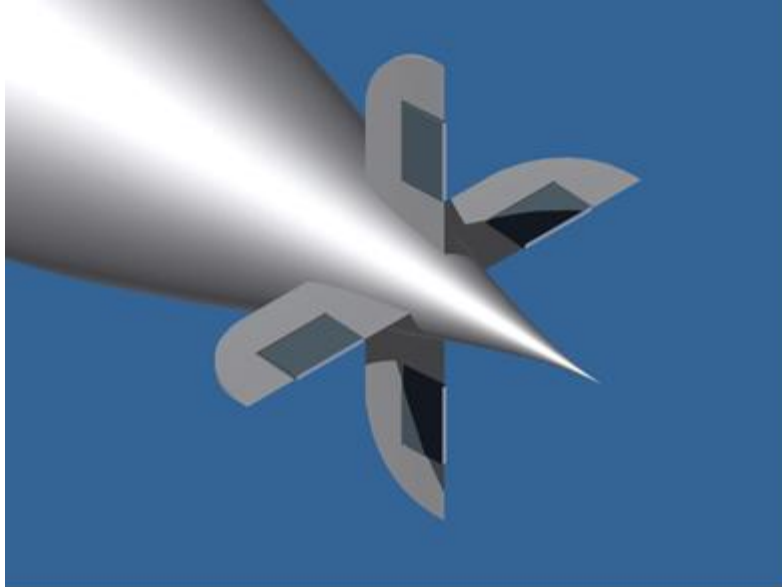


Figure 38: Fins attached to the hull

## 5.2 *Number of fins*

Based on the concept generation for the number of fins to be used, shown in table 4, we chose four fins. The fins will be placed just before the tail of the submarine where two of them will be placed horizontally on the right and left and the other two vertically on the top and bottom. Each fin will have an aileron on it where the ailerons on the horizontal fins are responsible for the up and down motion whereas the ailerons on the vertical fins are responsible for the right and left motion. More details about how the steering is connected with the ailerons are in section 10.



Feature	Importance (1-5)	Relative Importance	Concept (1)		Concept (2)		Concept (3)	
			Three		Four		Five	
			Weight	Relative weight	Weight	Relative weight	Weight	Relative weight
Easy to turn	5	0.31	3	0.93	4	1.24	5	1.55
Easy to manufacture	3	0.19	5	0.95	4	0.76	3	0.57
Less cost	2	0.13	5	0.63	4	0.50	3	0.38
More stability	4	0.25	3	0.75	4	1.00	5	1.25
Less drag force	2	0.13	5	0.63	4	0.50	1	0.13
Total	16	1		3.89		4.00		3.88

Table 4: concept generation for fins

### 5.3 Fabrication of the fins

The fabrication of the fins was done as follows:

1. The shape of the fin was drawn in plywood. Then the drawn part was cut from the wood.
2. The edges of the wood were trimmed to the exact shape of the fin.
3. Layers of fibers were placed on the surface of the wood to form a mold that has the desired fin shape.
4. Molten foam was poured inside the mold and left to dry. Then, the resulted shape was covered with fiberglass. The final result is shown in figure 41.
5. Three more fins and with the same shape were produced using the same procedure.
6. Ailerons were made using the same method used for fins.
7. Fins were attached to the hull.

At the end, the hull with its fins is ready to be transported to our workshop in SQU to install the internal mechanical components and fix the window. These components will be attached to the inner surface of the hull using a special adhesive. Then, ailerons will be placed in their positions and connected to the steering system.



Figure 39: Remaining plywood after cutting



Figure 38: Trimmed plywood



Figure 40: Fins mold



Figure 41: Final fin shape

## 6 Entrance

The entrance was previously decided to be in the upper part of the hull which makes entering easy for the submarine pilot. The length was set to be 1.0m starting at 65cm from the nose of the hull. The width is created by an angle of  $90^\circ$  from the centre line of the hull as figure 42 shows.

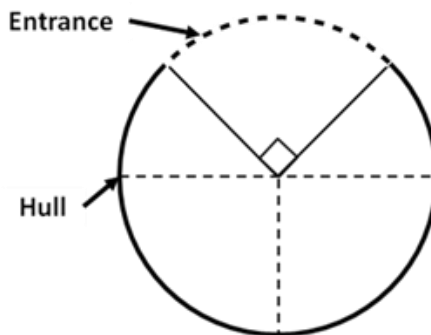


Figure 42: Cutting the Entrance location

## 6.1 Entrance location:

Table 5 shows the concept generation for position of entrance.




Feature	Importance (1-5)	Relative Importance	Concept (1)		Concept (2)		Concept (3)	
			Side		Up		Down	
								
			Weight	Relative weight	Weight	Relative weight	Weight	Relative weight
Easy to enter	5	0.42	3	1.26	5	2.1	2	0.84
Easy to manufacture	4	0.33	3	0.99	3	0.99	3	0.99
Safety	3	0.25	4	1.00	5	1.25	3	0.75
Total	12	1		3.25		4.34		2.58

Table 5: concept generation for position of entrance

## 6.2 Entrance locking mechanism:

Table 6 shows the concept generation for position of entrance.



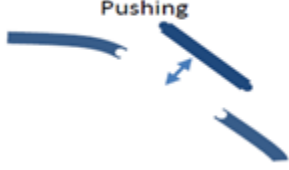
Feature	Importance (1-5)	Relative Importance	Concept (1)		Concept (2)		Concept (3)	
			Sliding		Rotational		Pushing	
								
Better holding	5	0.3	5	1.65	4	1.32	5	1.65
Smooth open and close	3	0.2	3	0.66	5	1.1	4	0.88
More stability	4	0.2	4	1.08	4	1.08	4	1.08
Safety	3	0.2	3	0.6	4	0.8	4	0.8
Total	15	1		3.99		4.3		4.41

Table 6: concept generation for entrance locking mechanism

So based on the concept generation for The Entrance location, connection with the hull and locking mechanism. Location of the entrance was chosen to be on the top, the connection with the hull was chosen to be using, while the locking mechanism was chosen to be push lock mechanism.

## 7 Window

### 7.1 Window's Location

Form the concept evaluation stage, the window is located in the nose of the hull. So, the first 50cm of the hull is considered to be the window. As a constraint the window is considered to be transparent.

Feature	Importance (1-5)	Relative Importance	Concept (1)		Concept (2)		Concept (3)	
			Up		Down		Front	
			Weight	Relative weight	Weight	Relative weight	Weight	Relative weight
Easy to see	5	0.33	2	0.66	5	1.65	3	0.99
Pilot visibility	4	0.27	5	1.35	3	0.81	4	1.08
Easy to manufacture	3	0.20	3	0.60	3	0.60	4	0.80
Easy to replace	3	0.20	3	0.60	3	0.60	5	1.00
Total	15	1		<b>3.21</b>		<b>3.66</b>		<b>3.87</b>

Table 7: concept generation for location of window

## 7.2 Window's Material and it Properties

The material used for the windows is called PMMA. Poly (methyl methacrylate) (PMMA) is a transparent thermoplastic, often used as a light or shatter-resistant alternative to glass. It is sometimes called acrylic glass. Chemically, it is the synthetic polymer of methyl methacrylate. The material was developed in 1928 in various laboratories, and was first brought to market in 1933 by Rohm and Haas Company, under the trademark Plexiglas. It has since been sold under many different names including Lucite and Perspex.

PROPERTY	ASTM METHOD	UNITS	Plexiglas® G
<b>MISCELLANEOUS</b>			
Thickness, measured		in	0.118"
Specific gravity	D792	-	1.18
Rockwell Hardness (M-scale)	D785	-	100
<b>OPTICAL</b>			
Refractive index	D542	-	1.49
Light transmittance	D1003	%	92
Haze		%	<2
<b>MECHANICAL</b>			
<i>Tensile Properties</i>			
Maximum	D638	psi	10,500
Rupture		psi	10,500
Modulus of elasticity		psi	450,000
<i>Flexural Properties</i>			
(span depth ratio 16, 0.1 in/min)	D790	psi	16,000
Maximum		psi	400,000
Modulus of elasticity			
<i>Impact Properties</i>			
Izod milled notch @ 73°F	D256	ft-lb/in of notch	0.27
<b>THERMAL</b>			
Deflection temperature under (flexural) load 3.6° F/min-264 psi	D648	°F	200
Maximum Recommended Continuous Service Temperature		°F	180-200
<b>ELECTRICAL</b>			
Dielectric strength, short time test	D149	volts/mil	500

Figure 43: Properties of PMMA

### **7.3 Window's Manufacturing Process**

Window's shaping process is as follows:

- 1 Start heating the Plexiglas with the heat gun. Aim your heat gun at the exact spot where you want the bend, turn it on low heat and begin blowing the superheated air onto the Plexiglas at the bend site. If the piece of Plexiglas is not very large, tip it on its side and hold it with your gloved hand. Blow superheated air on the point of the bend, alternating side to side. Always keep the heat gun moving slowly back and forth over the Plexiglas.
- 2 Test the pliability of the Plexiglas. While blowing hot air over the top, slowly try to flex it at the heated part. When you can easily bend the Plexiglas, you are ready for the next step.
- 3 Use the 2-inch-by-4-inch board to create the 90-degree bend. Place your 2-inch-by-4-inch board at the bending point, and while still applying superheated air, slowly bend the Plexiglas around the side of the wood.
- 4 Blow cold air on the bend point to harden up the plastic. In a couple of minutes, you'll be able to take off the 2-inch-by-4-inch board and you will have a perfect 90-degree bend.

## **8 Maintenance door**

The aim of this door is to reach the internal mechanical components easily for maintenance. It is located in the upper part of the hull between the entrance and the fins at a distance of 2.2m from the nose of the submarine. The hull cutting method is similar to the one used to create a place for the entrance. The length of this door is 40cm. The modified hull is shown below:

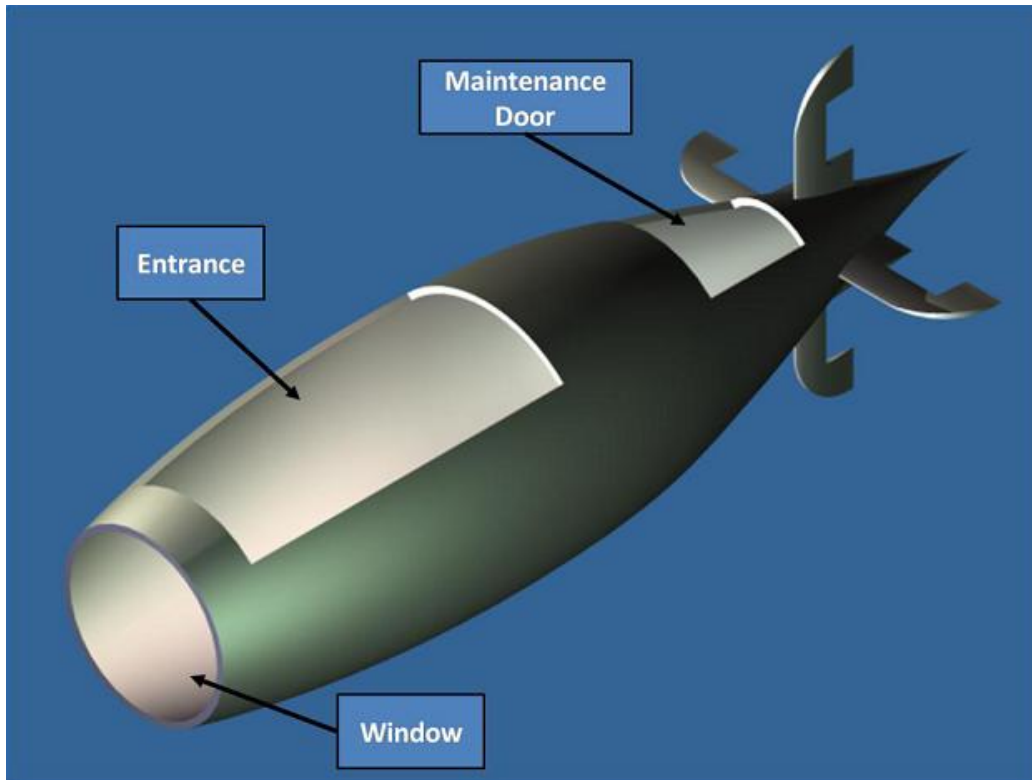


Figure 44:Figure showing location of window entrance and maintenance door

## 9 Steering system

It is worth mentioning that many teams have started implementing electronic controls. As an example, the HPS team of Virginia Tech introduced electronic controls successfully in their submarine Phantom 4 in 2001. Since then they improved and introduced more electronics in their submarines. Depth and direction are both controlled automatically.

One of the problems that face participants in the previous International Submarine Race (ISR) is the control of submarines. To avoid this problem some teams used very sensitive electronic steering control. Since this is the first time for our team to participate in the ISR, and we are not experts in electronic steering control, and the time we had was short, the team decided to design a manual steering control.



First we discuss the submarine goes up and down. As we know each fin has an aileron on it, the 2 ailerons on the horizontal fins are responsible for the up and down motion. The two ailerons are connected by a shaft, a pulley is fixed vertically on that shaft by means of nuts and bolts, and so we can predict that turning the pulley will cause the shaft to turn as well. A wire is taut around the pulley and connected to the steering. One end of the string is connected to the front side of the steering (upper string) while the other end (lower string) is connect to the tip of a shaft coming out vertically from the steering. When the rider decides to go down the steering is pushed inwards when this happens the lower string is pulled by the pulley which makes the pulley rotate forward and causes the ailerons to rotate upwards allowing the sub to move downwards. When the rider decides to move upwards the exact opposite happens the rider pulls the steering and so pulling the lower string which causes the upper string to be pulled by the pulley causing the pulley to rotate backwards and the ailerons to rotate downwards which allowing the sub to move upwards.

Next is the side turns. The two ailerons on the vertical fins are responsible for the side turns. As mentioned previously these two ailerons are also connected by a shaft, and a pulley is fixed horizontally on the shaft also by means of nuts and bolts. Like the other pulley a string is taut around the pulley.

As it can be seen from the figure 45, a sleeve is fitted through the shaft (the shaft is perpendicular to the steering) and the sleeve and the shaft lock together by means of a key. Around the sleeve is the ball bearing which is fixed from its outer surface onto the cylinder and allowed to freely rotate around its lower surface. The main function of the bearings is to maintain the main shaft horizontal and allow it to rotate.

Two shafts are connected on the right and left of the sleeve joint. Going back to the string which is around the pulley, one end of the string is connected to the end of shaft while the other end is connected to the end of shaft. When the rider decides to go the right the steering is tilted to the right and so the connection described tilts to the right as well causing the pulley to rotate clockwise (when viewed from the top) and the ailerons to point towards the left allowing the sub to move to the right. The exact opposite when the rider decides to move to

the left, the pulley rotates anticlockwise (when viewed from the top) and the ailerons to point towards the right allowing the sub to move to the left.

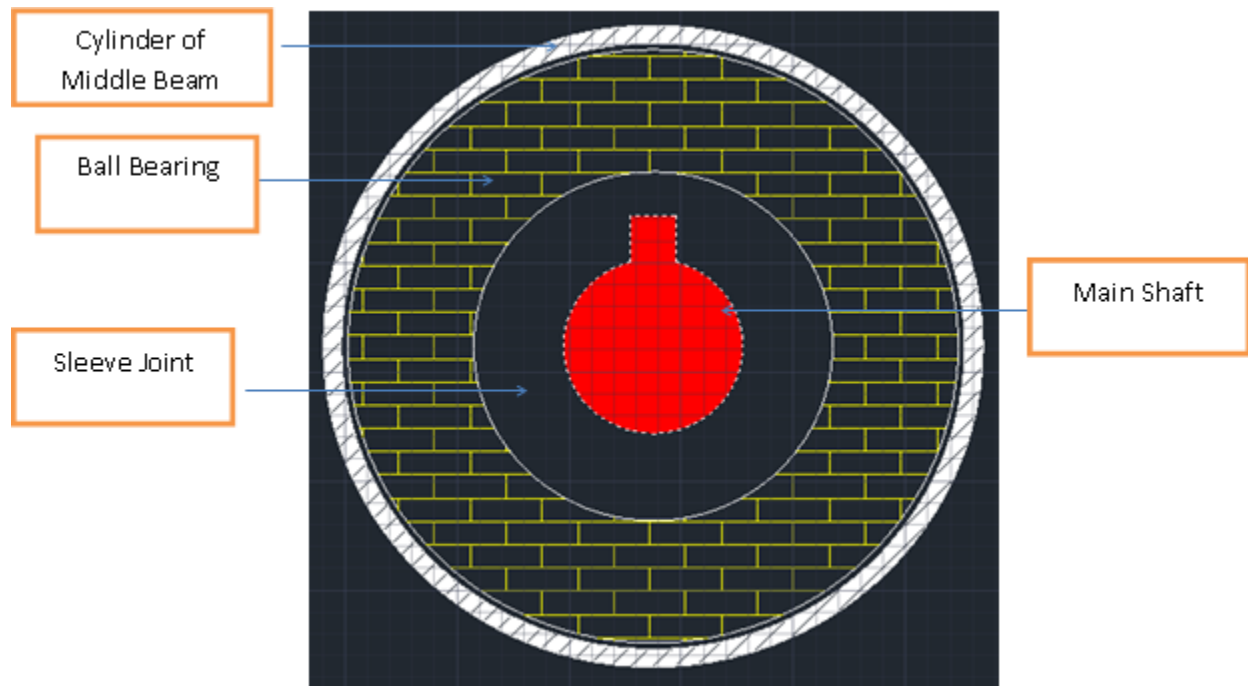


Figure 45: Figure showing cross section of part of steering system

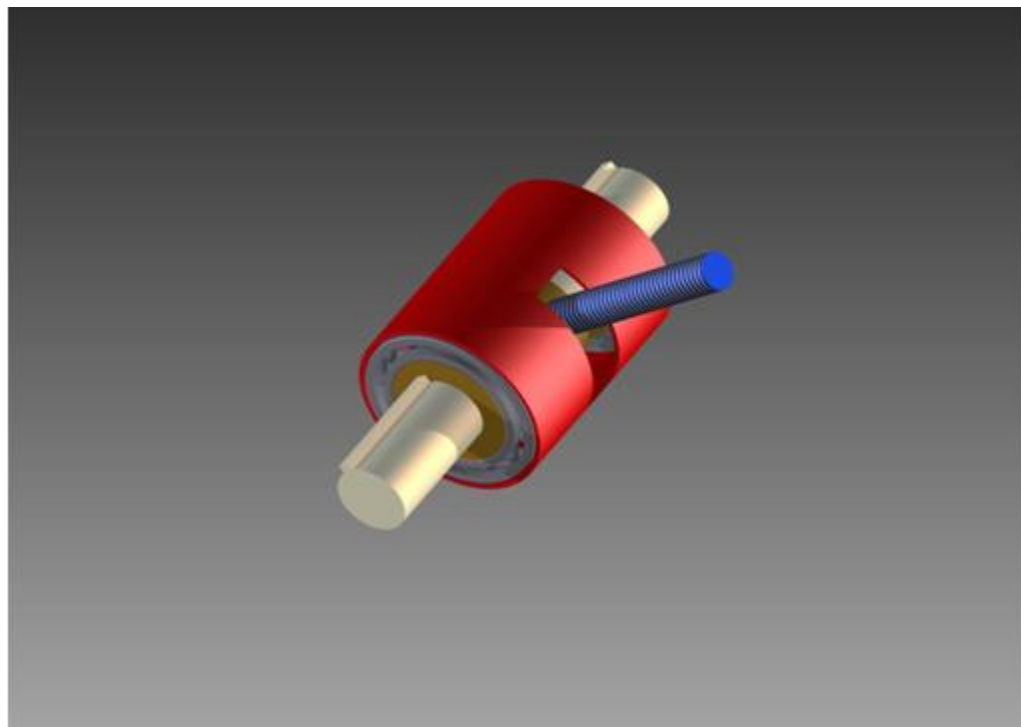


Figure 46: Configuration of steering shaft

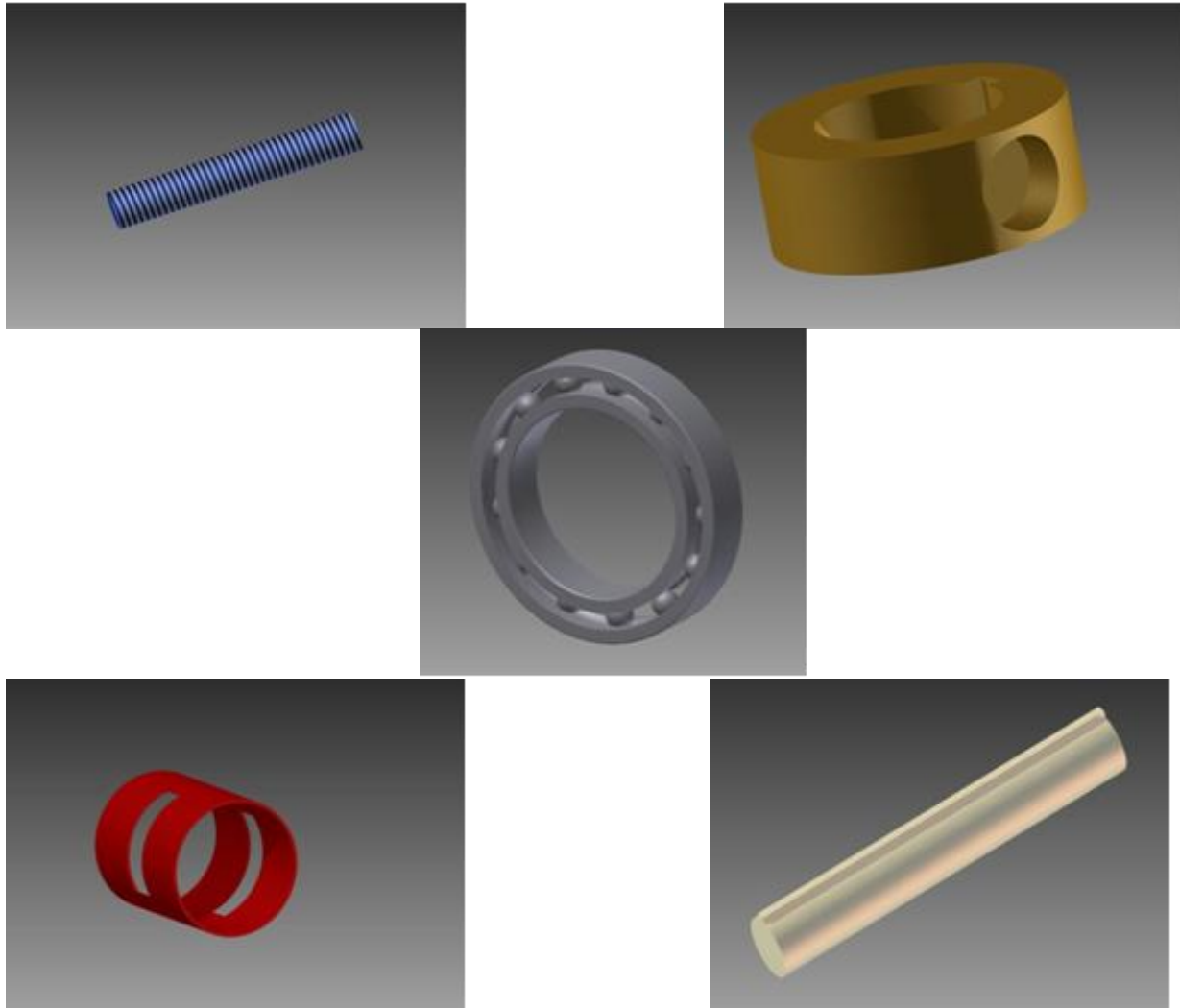


Figure 47: Top right sleeve joint, Top left horizontal shaft, Middle: ball bearing, Bottom right: main shaft, &Bottom left: Cylinder of middle beam

## 10 Propulsion system





For more stability, the team fixed both the pedals and the gearbox on a box frame that allows the load from the pilot to be converted directly to the gearbox due to less loss because of miss meshing.

### 10.1 Pedaling

Pedaling represents the only source of energy for the human powered submarine. The energy is transmitted from the pilot to the gears via a chain. For the submarine, the bicycle pedaling

system will be used since its mechanism is simple and can function properly. This mechanism also can be found in the market with the required gear ratio (2:1).

The pedaling system consists of:

- I. The **bicycle pedal** which is the part that the pilot pushes with his foot to propel the submarine. It provides the connection between the pilot's foot or shoe and the crank, allowing the leg to turn the bottom bracket axle. 
- II. The **crank set**, is the component of a bicycle drive train that converts the reciprocating motion of the pilot's legs into rotational motion used to drive the chain, which in turn drives the rear gearbox. It consists of one or more sprockets, also called *chainrings* or *chainwheels* attached to the *crankarms* to which the pedals attach. It is connected to the pilot by the pedals, to the bicycle frame by the bottom bracket, and to the rear sprocket, freewheel via the chain. 
- III. The **bicycle chain** is a roller chain that transfers power from the pedals to the drive-wheel or the gearbox in our case, thus propelling it. Most bicycle chains are made from plain carbon or alloy steel, but some are chrome-plated or stainless steel to prevent rust, or simply for aesthetics. 
- IV. The freewheel. In mechanical or automotive engineering, a freewheel or overrunning clutch is a device in a transmission that disengages the driveshaft from the driven shaft when the driven shaft rotates faster than the driveshaft. 

The condition of a driven shaft spinning faster than its driveshaft exists in most bicycles when the rider holds his or her feet still, no longer pushing the pedals. In a fixed-gear bicycle, without a freewheel, the gearbox would drive the pedals around.

**Pedaling system specifications:**

For the available bicycles, the bigger gear has 40 teeth and the smaller one comes normally with different sizes.

In our design

$$\text{Gear Ratio} = \frac{N_{\text{big}}}{N_{\text{small}}} = \frac{2}{1} \quad \Longrightarrow \quad N_{\text{small}} = \frac{N_{\text{big}}}{2} = \frac{40}{2} = 20 \text{ teeth}$$

### Why Chain?

When the system doesn't have a chain, the pedals will typically be attached directly to the drive-gear, thus limiting top speed by the diameter of the gear and resulting in designs with drive-gear as large as possible. However, using chain can enable us to reduce the size of the drive-gear for safety and simplicity in use.

#### 10.1.1 Force analysis

If the applied torque by the human ( $T_1$ ) is subjected to the pedals, the torque ( $T_2$ ) in the pinion (the gear that take the input power in the gearbox) will be equal to:

$$T_1 w_1 = T_2 w_2 \text{ And } n_1 w_1 = n_2 w_2$$

$$P_1 = w_1 T_1 \rightarrow T_1 = \frac{P_1}{w_1} = \frac{294.2}{6.3} = 46.8 \text{ N} \cdot \text{m}$$

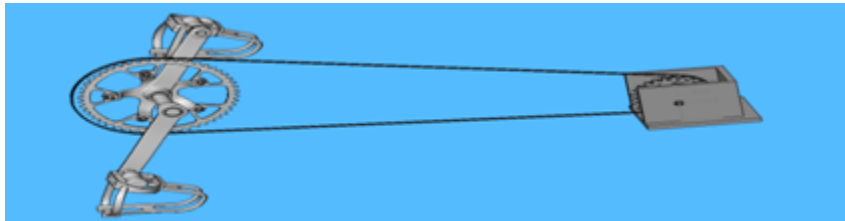
$$\text{So } T_2 = T_1 \frac{w_1}{w_2} = T_1 \frac{n_2}{n_1} = (46.8) (2) = 93.6 \text{ N} \cdot \text{m}$$

### 10.2 Gearbox

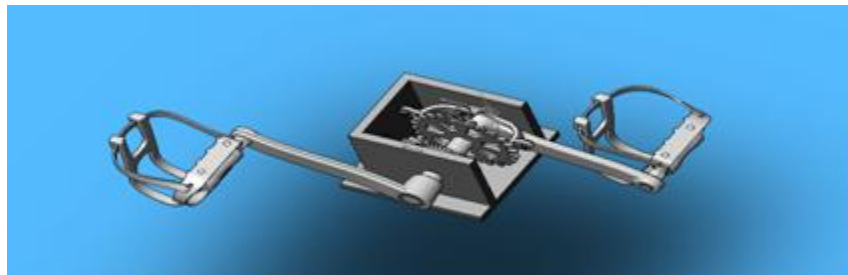
First the type of gear, since the axis of the pedals is horizontal and the axis of the shaft connected to that is mounted at 90 degrees it only made sense to use a bevel gear since that's what their used for. Second the tooth line; we had the option of using straight or spiral tooth lines. In straight bevel gears the teeth are straight and parallel to the generators of the cone while Spiral bevel gears have their teeth formed along spiral lines. However the advantage of the spiral tooth over the straight tooth is that they engage more gradually. The contact between the teeth starts at one end of the gear and then spreads across the whole tooth. This results in a less abrupt transfer of force when a new pair of teeth comes in to play. With

straight bevel gears, the abrupt tooth engagement causes noise, especially at high speeds, and impact stress on the teeth which makes them unable to take heavy loads at high speeds without breaking. For these reasons straight bevel gears are generally limited in use. So according to those results we decided that we needed a bevel gear and a spiral bevel gear in particular for our gearbox.

What we had to think of next is the gearbox pedals connection. Pedals can be connected to the gearbox directly or by means of a chain as indicated in figure 48 and figure 49. It is clear that the chain increases gear ratio however it may also occupy more space to some extent. Calculations for the Torque can be found in Appendix C.



**Figure 48: The chain connection alternative generated for gearbox pedaling connection concept**



**Figure 49: Direct connection alternative generated for Gearbox pedaling connection concept**

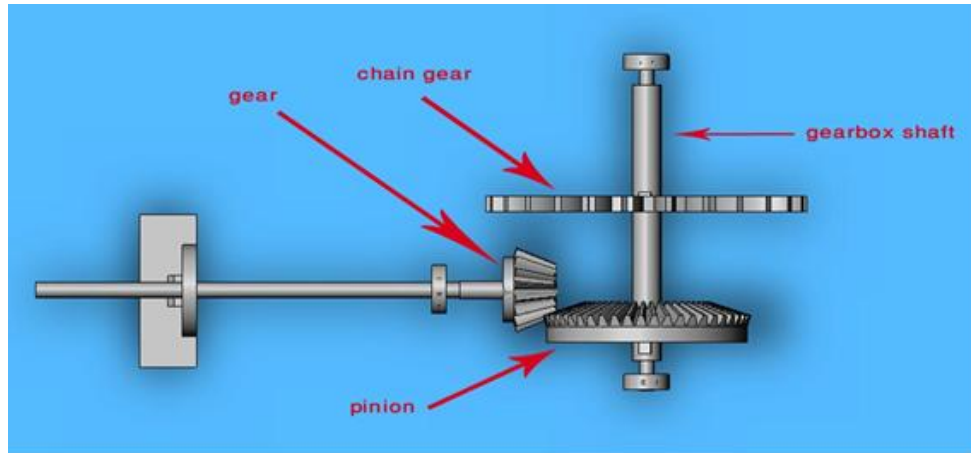


Figure 50: The configuration of the gearbox

### 10.2.1 Force analysis

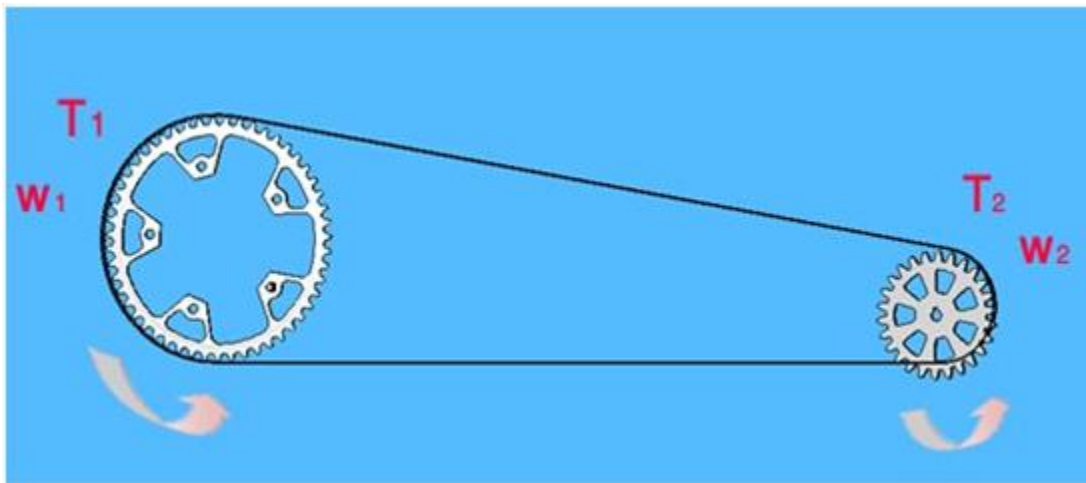


Figure 51: Torques, angular speeds in the gears moved by the chain

From the figure 51, if the applied torque by the human ( $T_1$ ) is subjected to the pedals, the torque ( $T_2$ ) in the pinion (the gear that take the input power in the gearbox) will be equal to:

$$T_1 w_1 = T_2 w_2 \quad \text{And} \quad n_1 w_1 = n_2 w_2$$

$$P_1 = w_1 T_1 \rightarrow T_1 = \frac{P_1}{w_1} = \frac{294.2}{6.3} = 46.8 \text{ N.m}$$

$$\text{So} \quad T_2 = T_1 \frac{w_1}{w_2} = T_1 \frac{n_2}{n_1} = (46.8) (2) = 93.6 \text{ N.m}$$

### 10.2.2 Gearbox design

The torque will be transmitted from chain to the shaft through the gearbox as shown in figure 52:

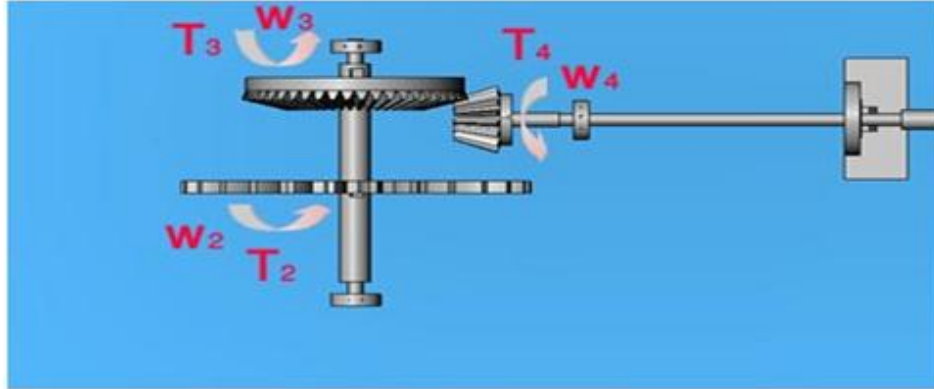


Figure 52: Torques, angular speeds in the gearbox

It is clear that the torque in pinion ( $T_2$ ) of the gearbox will be transmitted to gear (3), and then to gear (4) ( $T_4$ ) which equals to:

$$T_2 w_2 = T_3 w_3 \quad , \quad T_3 w_3 = T_4 w_4 \quad \text{and} \quad n_2 w_2 = n_4 w_4$$

$$T_2 w_2 = T_4 w_4$$

$$\text{So,} \quad T_4 = T_2 \frac{w_2}{w_4} = T_2 \frac{n_2}{n_4} = (93.6) (3) = 280.8 \text{ N. m.}$$

This torque ( $T_4$ ) will be transmitted through the shaft to the propellers.

### 10.2.3 The Calculation of Bevel Gear Wear

Detailed calculation of the bevel Gear Wear can be found in appendix.

#### Gearbox specifications:

- dimensions of 141x153x70mm
- 2 kg
- gear ratio of 3:1

A gearbox of a ratio of 3:1 which satisfied all the other parameter was found from a company called ATLANTA which is based in Germany. All the dimensions and information of the gearbox are in the figure 53 and table 8.



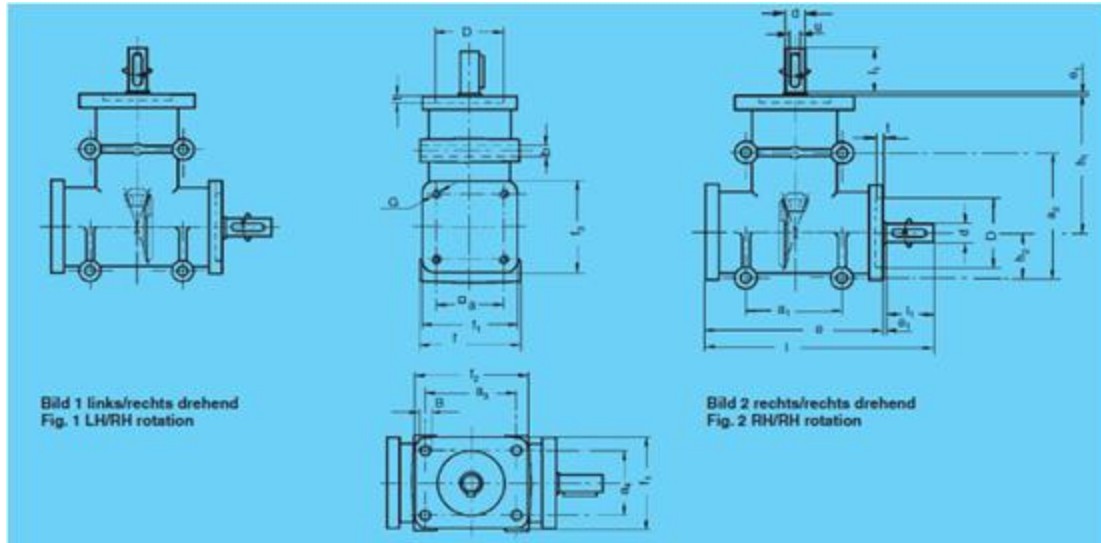


Figure 53: The gearbox dimensions

	52 07 141	52 07 191	Bestell-Nummer / Order code		52 57 191	52 57 241
			52 07 241	52 57 141		
Bild / Fig.	1	1	1	2	2	2
l	141	191	201	141	191	201
h <sub>1</sub>	90	140	140	90	140	140
h <sub>2</sub>	32	43	43	32	43	43
e	110	150	150	110	150	150
e <sub>1</sub>	1	1	1	1	1	1
f	70	86	86	70	86	86
f <sub>1</sub>	64	84	84	64	84	84
f <sub>2</sub>	64	104	104	64	104	104
f <sub>3</sub>	64	84	84	64	84	84
d <sub>1/2</sub>	14	19	24	14	19	24
l <sub>1</sub>	30	40	50	30	40	50
u	5x25	6x30	8x40	5x25	6x30	8x40
D <sup>Htr</sup>	47	62	62	47	62	62
t	3	5	5	3	5	5
a	46	60	60	46	60	60
G	M 8	M 10	M 10	M 8	M 10	M 10
a <sub>1</sub>	60	86	86	60	86	86
a <sub>2</sub>	95	86	86	95	86	86
a <sub>3</sub>	46	80	80	46	80	80
a <sub>4</sub>	46	60	60	46	60	60
B	M 8	10,5	10,5	M 8	10,5	10,5
b	8,5	11	11	8,5	11	11
z	2,0	5,0	5,0	2,0	5,0	5,0

Table 8: Info about our selected gearbox order code 52 57 141

### 10.3 Main Shaft

The team tried to find the most convenient solution for the main the shaft. Three main solutions were developed for the shaft, a 20mm Aluminum solid shaft (20S) was the first alternative and a 20mm outer diameter 15mm inner diameter aluminum hollow shaft (15-20H) was the second, and a 20mm outer diameter 18inner diameter aluminum hollow shaft (18-20H) was the third. All the shafts are 780mm in length.

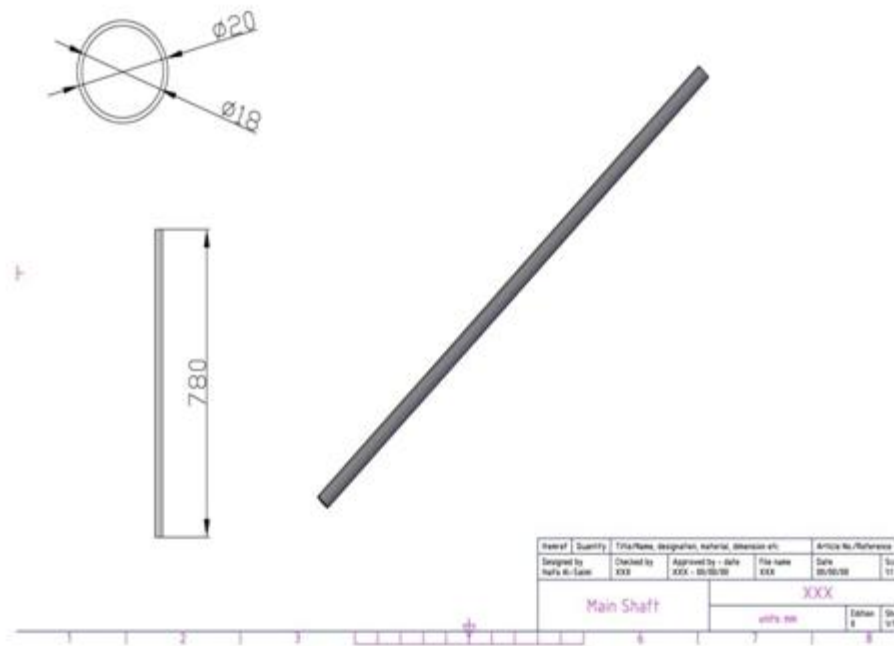


Figure 54: AutoCAD Drawing of hollow shaft inner dia 18mm outer dia 20mm.

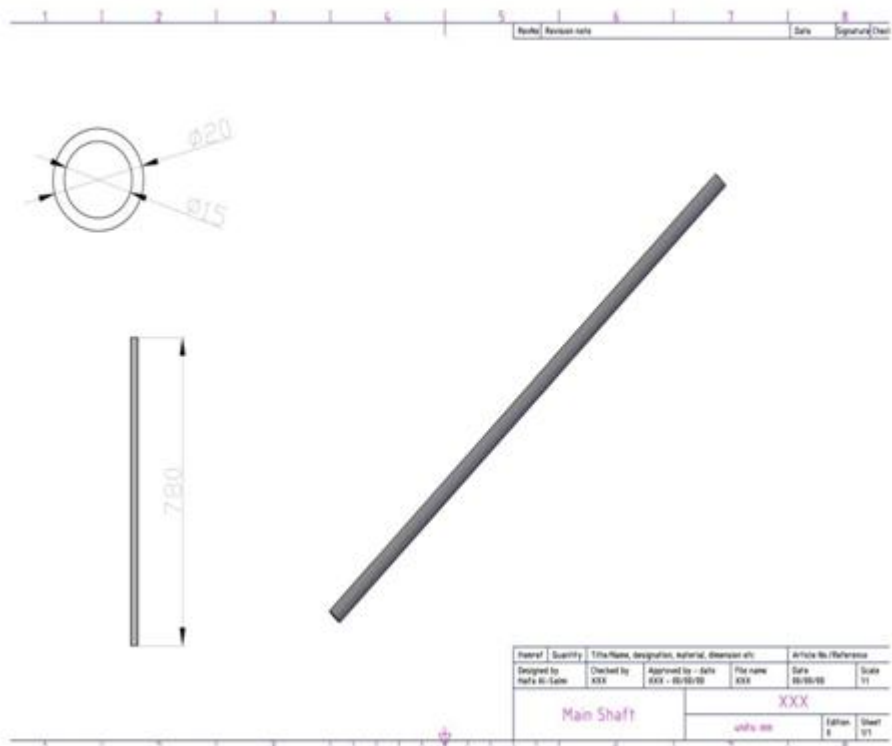


Figure 55: AutoCAD Drawing of hollow shaft inner dia 15mm outer dia 20mm

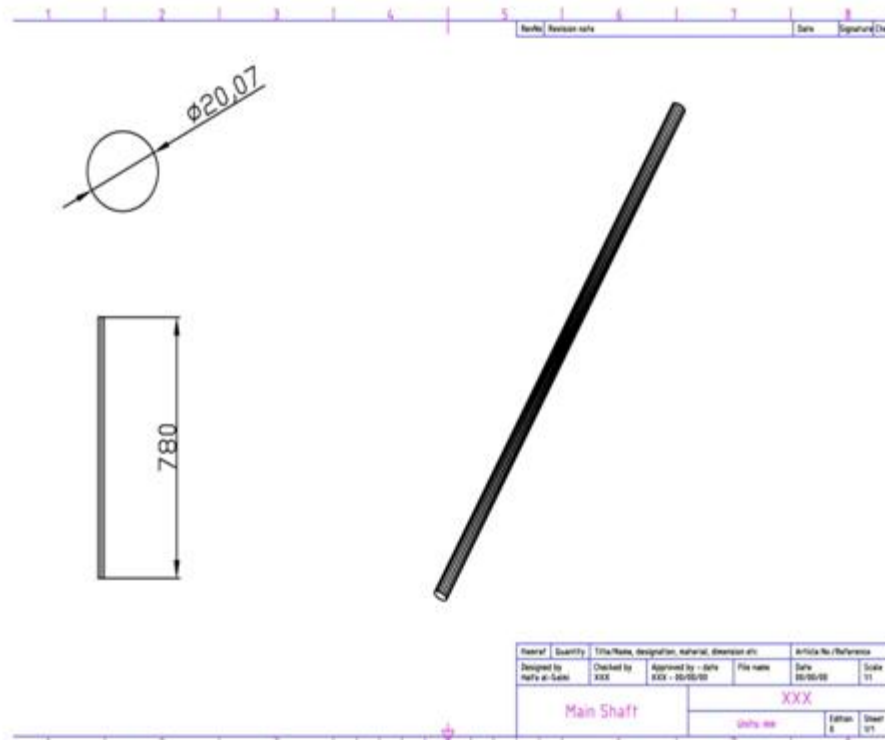


Figure 56: AutoCAD Drawing of solid shaft dia 20mm

An analysis was done for both the alternatives using ANSYS and both of the results passed. The results for the analysis are shown below:

Aluminium (18-20H):

E(Youngs modulus)=70Gpa

V(Poisson's ratio)=0.34

Length of shaft=780mm

Inner dia=18mm

Outer dia=20mm

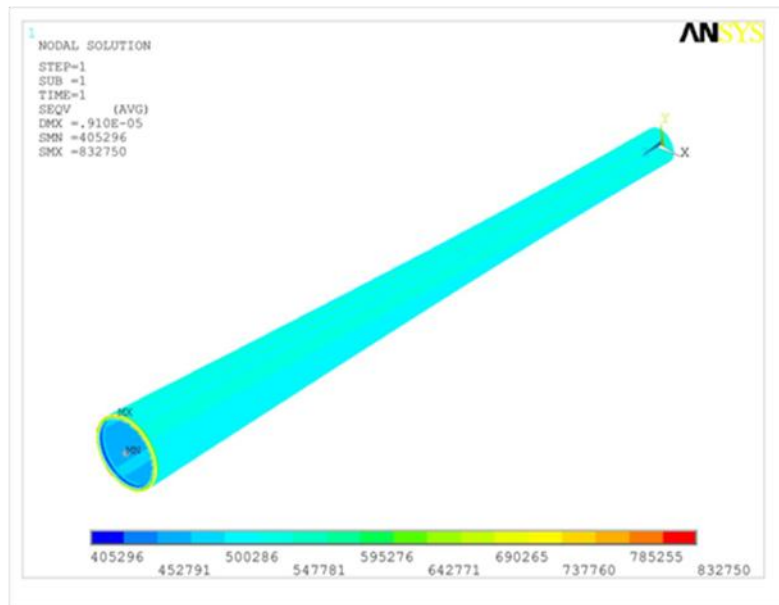


Figure 57: ANSYS Analysis for a 18mm inner dia 20mm outer dia hollow shaft

Aluminium (15-20H):

$E(\text{Young's modulus}) = 70 \text{ GPa}$

$V(\text{Poisson's ratio}) = 0.34$

Length of shaft = 780mm

Inner dia = 15

Outer dia = 20mm

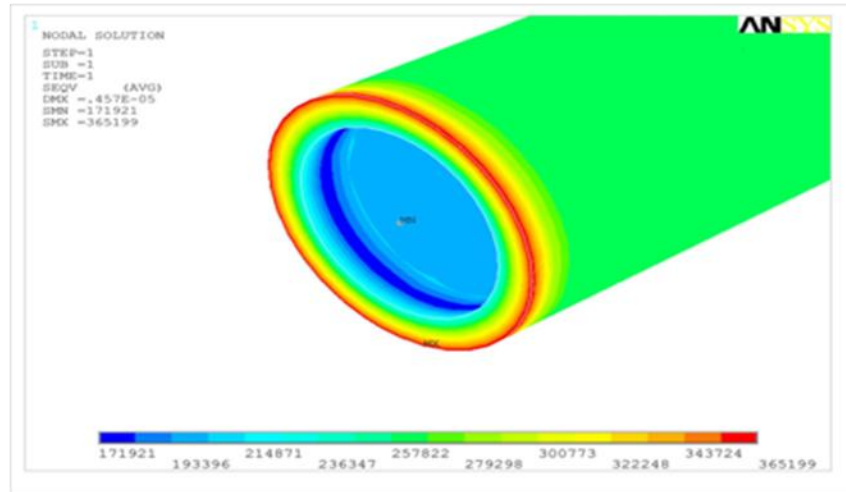


Figure 58: ANSYS Analysis for a 15mm inner dia 20mm outer dia hollow shaft

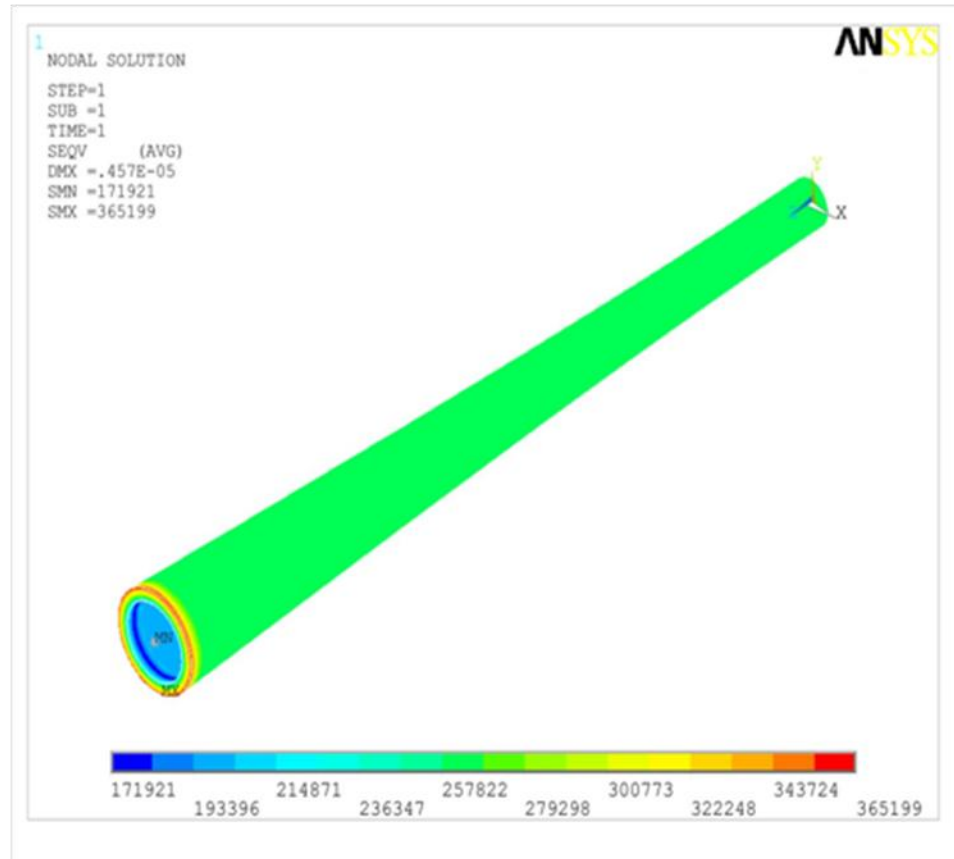


Figure 59: Close up of ANSYS Analysis for a 18mm inner dia 20mm outer dia hollow shaft

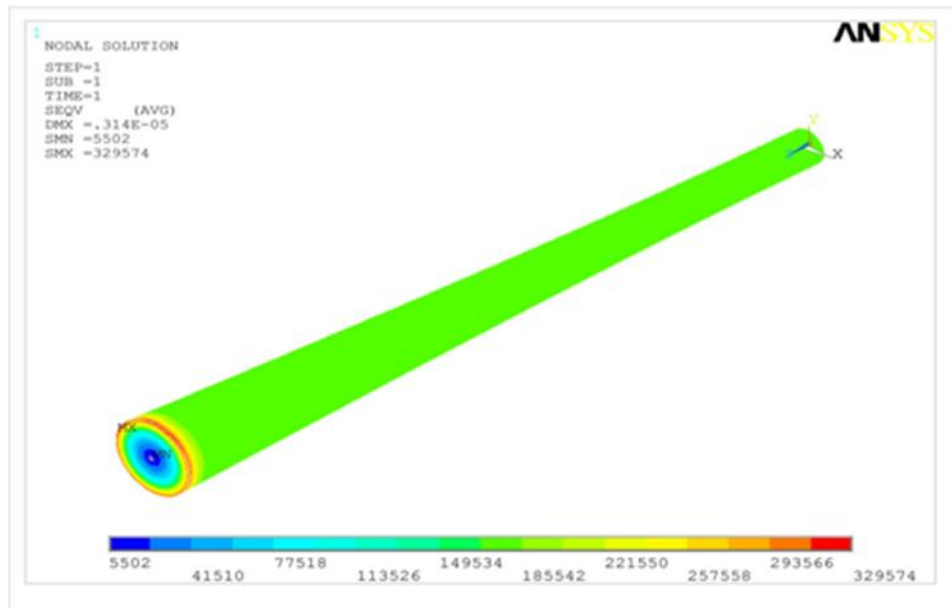


Figure 60: ANSYS analysis for 20 mm dia solid shaft

Aluminium (20S):

$E$ (Youngs modulus)=70Gpa

$V$ (Poisson's ratio)=0.34

Length of shaft=780mm

Outter dia=20mm

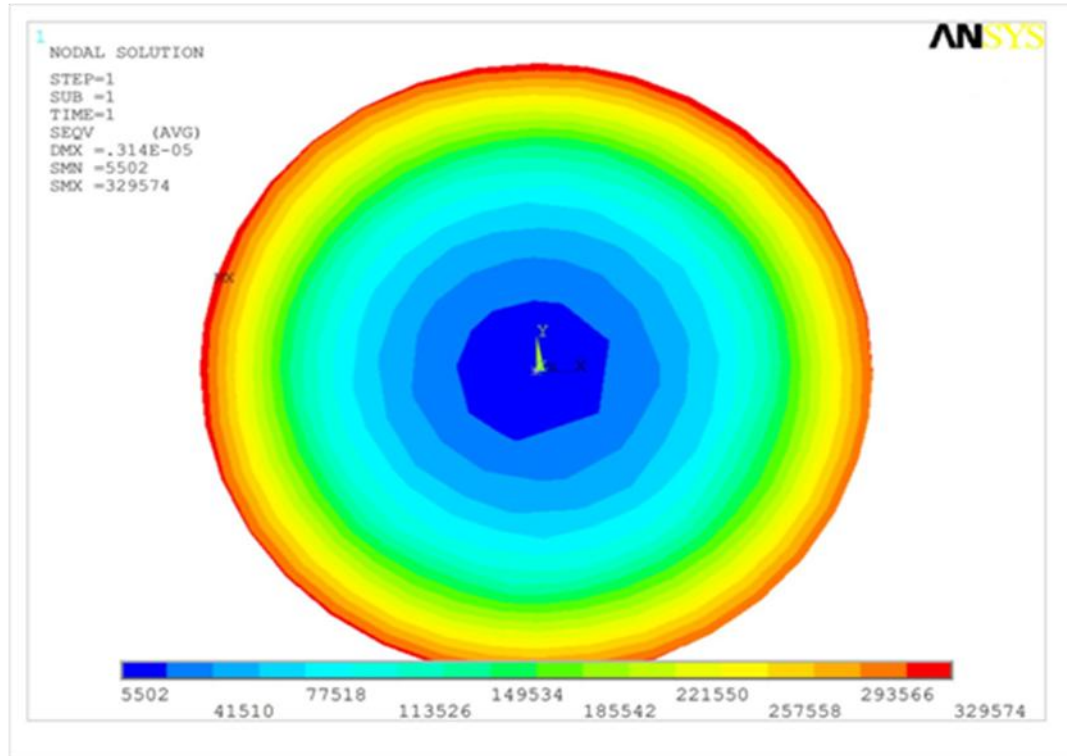


Figure 61: Close up of ANSYS analysis of 20 mm dia solid shaft

Material	Yield strength (MPa)	Ultimate strength (MPa)
Aluminum alloy 2014-T6	414	483

Table 9: Yield and Ultimate strength of Aluminium

As it can be seen from the table above the yield strength of Aluminum is 414Mpa and the max stress which appeared in our analysis for the 18-20H, 15-20H, and 20S shafts are 832750, 365199, and 329574 respectively. It is clear that none of the three shafts fail but since the 15-20H and the 20S are much stronger we excluded the 18-20H. After many group discussions the groups decided to choose the 15-20H since the results are very close to the hollow shaft but the weight is much more less for than the solid shaft

## 10.4 Propeller

In theory, the most efficient propeller would have one blade. The more blades a propeller has, the more flow around each individual blade is disrupted by the other blades. It is, however, impractical to have a one bladed-propeller because of the obvious balance problems that would result. The next most efficient solution is a two-bladed configuration which we have chosen. Professional software, JavaProp, is used to design the propeller. A screenshot is shown in figure 62. The program inputs and targets for designing the propeller are velocity, RPM, and power. The outputs are efficiency, thrust and pitch. We tried different blade angle for the same angle of attack. The highest efficiency, 92%, and thrust, 65.78 N, were at blade angle of 250.

- velocity = 4.12 m/s
- RPM = 360
- Power = 294 w

The outputs of the program are:

- Efficiency = 92%
- Thrust = 65.78 N
- Pitch = 798 mm

Enter Design Parameters and press the "Design It!" button.

Propeller Name:

Number of Blades B:  [-]

Speed of Rotation n:  [1/min]

Diameter D:  [m]

Spinner Dia. Dsp:  [m]

Velocity v:  [m/s]

Power P:  [W]

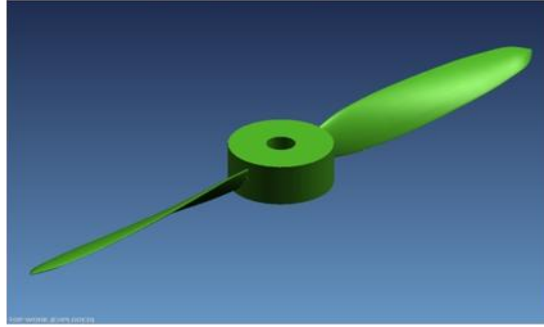
☐ shrouded rotor ☐ square tip

Propeller			
$v/(nD)$	0.981	$v/(\Omega R)$	0.312
Efficiency $\eta$	92.112 %	loading	low
Thrust T	65.78 N	Ct	0.0076
Power P	294.2 W	Cp	0.0081
$\beta$ at 75%R	25.8°	Pitch H	798 mm

Remark: The RPM setting is also used for Analysis page.

Figure 62: the input and the output of JavaProp





**Figure 63: the propeller shape from JavaProp**

A 3D printing model was prepared and depending on that the team was able to build the first propeller using CNC machine with the help of specialists. Our propeller specifications are variable Pitch, Diameter of 0.7m, Right rotation direction and 2 blades. A second propeller, HELIX Carbon GmbH in Germany, serial number of 001+002, Hub 108, type H30V 0,67m R-S-2, was ordered, according to our design and specifications.

The specifications of the HELIX propeller as mentioned in the manual are:

Strength Category 30 = 5-25 KW

Model V= variable Pitch

Diameter of 0.67m

Rotating Direction R = Right

Profile and shape S = straight shape with thin profile – depth and thickness

Number of blades 2



**Figure 64: the purchased propeller**

## 11 Wet and dry Submarine

The sub provides a wet environment for the occupant, which will require a wet suited scuba diver to operate it. Having a wet submarine provides an advantage over the dry one, first of all weight.

A submerged submarine, in a state of 'neutrally buoyancy' has to weigh as much as the weight of the water it displaces. Since the dry-hull type submarine displaces so much more water than the wet dry-hull, the dry-hull boat has to be ballasted down with massive amounts of fixed weight to achieve neutral buoyancy, and so the dry-hull submarine is much heavier due to it having to displace so much more water than the wet-hull submarine. Of course you may think that why should weight be such a big issue if both the subs perform equally well underwater. Well 99% of the time the sub is not under water it's either been displayed or transported, and of course a lighter sub would be much more convenient.

In addition to the weight issue the dry-hull boats are very susceptible to damage suffered as it is operated, transported and worked on. The greater kinetic energy (as a consequence of its greater inertia) of the heavier model will be released upon impact by breaking appendages, bending shafts, and crushing portions of the hull and superstructure. The lighter model expends less energy trying to move the brick wall and so experiences less damage.

## 12 Balancing the Submarine

When two or more forces act on an object, the result is the cumulative effect of those forces. The buoyant force is the net upward force (or uplift) exerted by a fluid on a submerged object. Gravity counters this force by pulling down on an object while the buoyant force pushes the object up. If an object's density is more than that of the liquid, it will sink (force of gravity is greater than the Buoyant force). If an object's density is less than that of the liquid, then it will float (force of gravity is less than the buoyant force). If an object's density is the same as that of the liquid, it will hover (force of gravity is equal to the buoyant force).

The forces acting on the submarine can be shown on the figure below:

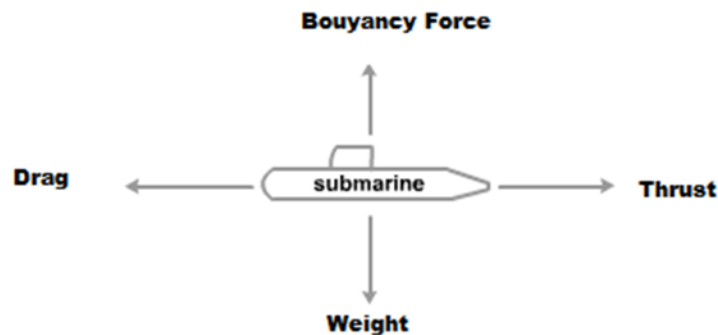


Figure 65: FBD showing forces acting on Submarine

We wanted our natural buoyancy to be at 4m under the water line to do that we attached Styrofoam to the inside of the hull by using Velcro. As to Archimedes principle” Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.”, for an object to be stable at a certain level underwater the buoyancy force has to equal the weight of the object, basically the weight of the water displaced by the sub has to equal the weight of the sub. Initially when our submarine is immersed into the water it sinks due to the weights being larger than the buoyancy force. Even though you cannot change the density of an individual substance, you can change the overall density of things that are made of several materials. Changing the density of an object can make it float or sink in a given fluid. To change the density we added Styrofoam sheets on the top surface inside the hull. Styrofoam traps air inside it air reduces the mass of the submarine and therefore its density .After adding enough Styrofoam the buoyancy force will now equal to the weight, and the sub will now have a natural buoyancy somewhere above the bottom of the pool, as more Styrofoam is added the mass of the sub is further reduced and so is the density hence, The submarine moves higher up since less water is needed to be displaced to counter the weight of the sub.

## 13 Safety Issues

There are many safety requirements that should be consider in the design of the submarine stated by the International Submarine Race (ISR) organizers. These requirements are listed below:

### 1. Submarine coloration

It is advised for the purpose of easy location that each submarine be painted with high-visibility coloration. For this purpose we choose yellow color for the submarine. Sultana is chosen to be the name of our submarine. It will be written to the hull in order to be identified in the race since numbers will not be assigned to each submarine. Propeller tips will be painted with a flashy color for easy visibility for divers.

### 2. Crew visibility

The crew face and head areas shall be visible to the safety divers at all times. For this aim a big window was installed in the front of the submarine.

### 3. Strobe marking light

Each submarine shall carry a flashing white strobe light that is visible for 360 degrees in the horizontal plane. The light should flash at an approximate rate of once per second, be visible for at least thirty feet under normal visibility conditions. To satisfy this requirement strobe marking light will installed between the entrance and the maintenance door.

### 4. Emergency pop-up buoy

All submarines shall carry a high visibility buoy that will release from the hull and float to the surface when an emergency occurs. The float shall be attached to the submarine by thirty feet of strong, highly visible line, at least 1/16" thick, so we will install a pop-up buoy in the side of the submarine hull. The crew member will have a dead-man switch that will automatically release the float in the event of disablement. This switch will be installed inside the submarine.

## 5. Crew restraint

Any method of attachment of a crew member to the submarine must have the release system that is clear therefore we colored every restrain mechanism clearly so it can be seen.

## 6. Rescue egress

The exit door that is to be used by a submarine crew for emergency egress shall be clearly marked at the location of the handle or release mechanism, so the exit door (entrance) will be painted using a flashy color. The handle or release mechanism for the exit doors will be easily accessible from both inside and outside the submarine.

All previous issues are shown in the *figure 66*

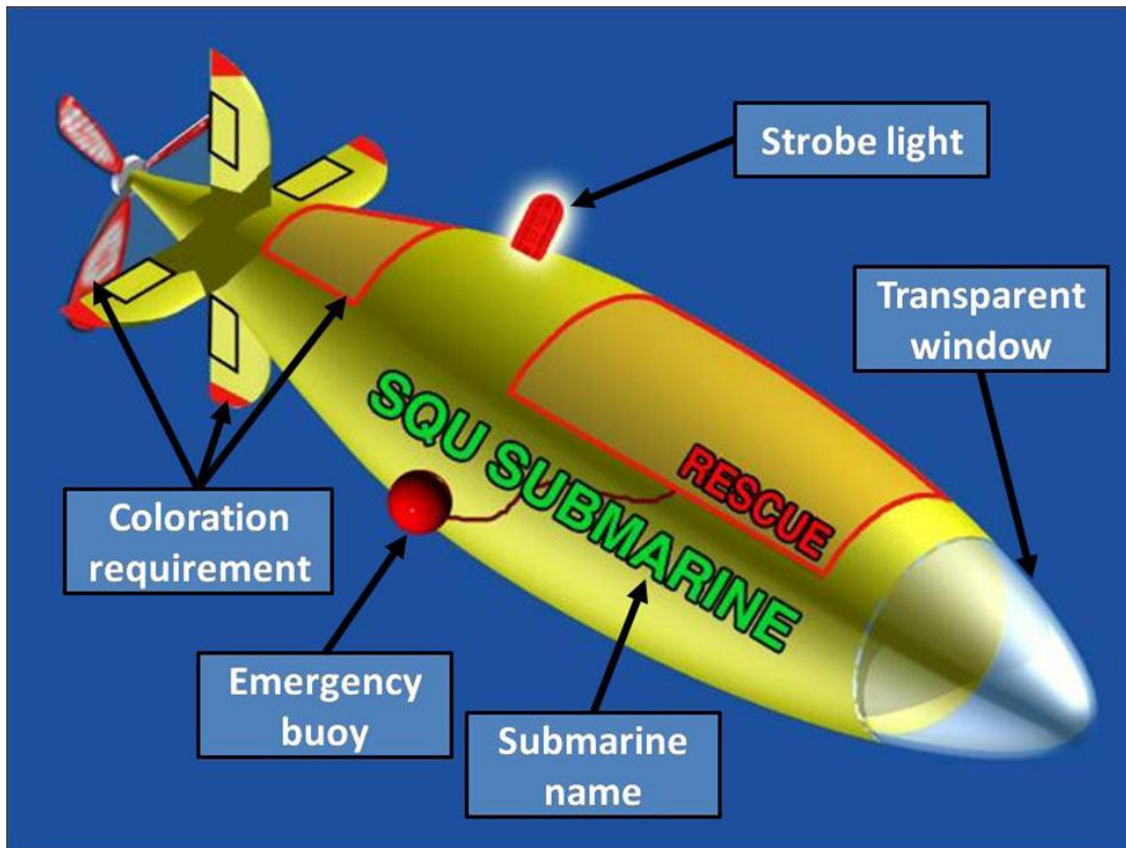


Figure 66: Figure showing safety regulations on submarine

## 14 Conclusion

The design of the submarine is completed. The submarine is constructed. We now testing the submarine and modifying it so it will be ready for the race.

The International Submarine Race is a big race started since 1989. SQU will participate this year and have the honor of being the first Arabian team to participate in this race. The project of designing and fabricating of a human powered submarine started two years ago in the Mechanical and Industrial Engineering department. This is the first Human Powered submarine made in sultanate of Oman. SQU has always been, and I'm sure will continue to be, a model for how to do a lot with a little. As a team we have successfully accomplished our first goal of making the first Omani submarine and to Participate in the 11<sup>th</sup> ISR. Our team has learned how to work together and how to deal with problems that arise during design and construction, and we have learned what skills are necessary to successfully organize and run a large group project. In conclusion, the International Submarine Race has provided the SQU Team an opportunity to become better students because of the hands on experience that has been gained from this competition.

A successful participation in the ISR 2011 is expected to have a huge impact in Oman and the Arabian Gulf. Other universities will be challenged and encouraged to do the same and enter the coming competitions. SQU is the leading university in Oman and it will be ready to assist other universities if they decided to participate in the ISR. SQU also has strong communication and cooperation with many universities in the Arabian Gulf countries. These universities have the resources and capability of participating in such competitions.

## **Appendix A**

### **Students' Groups Participated in the Project**

There have been four students' groups involved in this project through final year projects. The groups are:

**Group #1:** Spring 2009 & Fall 2009

- Sena Kobla Dorvlo
- Mohammed Abdullah Al-Ma'mari
- Abbas Abdullah Al-Dawood

**Group #2:** Fall 2009 & Spring 2010

- Haitham A. Al-Yahyaie
- Faisal A. Al-Yahyaie
- Khalid S. Al-Zuhimi

**Group #3:** Fall 2009 & Spring 2010

- Tariq A. Khashoob
- Hussain S. Al-Salmi
- Dawood S. Al-Zeidi
- Hasan H. Al-Khayat

**Group #4:** Fall 2010 & Spring 2011

- Khalid Khalifa Salim Al-Sawwafi
- Khaleel Ahmed Mohammed Al-Riyami
- Hussain Ali Hamed Al-Rashdi
- Hamed Ali Hamed Al-Amri
- Haifaa Salim Nasser Al-Salmi
- Is'haq Said Mohammed Al-Hasani

**Supervisors:** 1. Dr Jamil Abdo  
2. Dr Nabeel Al-Rawahi

## Appendix B

### Detailed Budget

#	Item	Cost (RO) - \$	Notes
<b>1</b>	<i>Construction of the submarine's Hull</i>	<i>(3,500) 9100</i>	
<b>2</b>	<i>Other Submarine's materials</i>	<i>(4,000) 10400</i>	
<b>3</b>	<i>Diving lessons and certificates</i>	<i>(600) 1560</i>	
<b>4</b>	<i>Diving equipments</i>	<i>(4,100) 10660</i>	<i>For 5 students</i>
<b>5</b>	<i>Miscellaneous</i>	<i>(1000) 2600</i>	
<i>Total</i>		<i>(13,200) 34320</i>	



## Appendix C

Torque calculations for the gearbox:

Water density  $\rho = 998.86 \text{ kg/m}^3$

Submarine velocity  $v = 8 \text{ knots} = 4.116 \text{ m/s}$

*The person can provide approximately Power = 0.4 HP = 294.2 watt*

The total mass of submarine including person and water  $m = 500 \text{ kg}$

The drag force calculated by the other group is approximately  $F_D = 486.1 \text{ N}$

Distance before the race start  $x = 30 \text{ m}$

$$C_D = \frac{F_D}{\frac{1}{2}\rho v^2 A_f} \rightarrow F_D = \frac{1}{2}C_D\rho v^2 = 486.1 \text{ N}$$

At the maximum speed where the thrust force T is equal to the drag force  $F_D$

$$\text{if, } T = F_D \text{ so } a = 0 \text{ m/s}^2 \rightarrow V_{max}$$

$$V = \sqrt{\frac{2T}{\rho C_D A_f}} \rightarrow T = \frac{\rho v^2 C_D A_f}{2} = 486.1 \text{ N}$$

Where  $C_p$  is the drag coefficient.

To calculate the maximum time required to reach maximum speed:

$$\begin{aligned}
 t_{max} &= \frac{m \sqrt{2A_f T_p C_D} a \cosh e^{\frac{A_f x \rho C_D}{2m}}}{A_f T_p C_D} \\
 &= \frac{(500) \sqrt{2(0.456) 486.1 \cdot 998.86 (0.126)} a \cosh e^{\frac{0.456 \cdot 30 \cdot 998.86 \cdot 0.126}{1000}}}{0.456 \cdot 486.1 \cdot 998.86 (0.126)} \\
 &= 4.23 a \cosh e^{1.723} = 10.189 \text{ s} \approx 10.2 \text{ s}
 \end{aligned}$$

Where A represent the surface area calculated by the other group A=0.456 m<sup>2</sup>

$$\frac{W_{out}}{W_{in}} = \frac{6}{1} \quad \text{Gear ratio: } 6:1$$

Where the rotational speed is calculated as the following:

$$P_{in} = W_{in} \cdot T$$

$$W_{in} = 60 \text{ rpm}$$

$$W_{in} = \frac{60 \times 2\pi}{60} = 6.3 \text{ rad/s}$$

$$294.2 = 6.3 \cdot T \rightarrow T_{(Torque)} = 46.8 \text{ N.m}$$

$$\frac{W_{out}}{6.3} = \frac{6}{1} \rightarrow W_{out} = 37.8 \frac{\text{rad}}{\text{s}} = 360 \text{ rpm}$$

## Calculation of Bevel Gear Wear :

Following the procedure stated in Shigley's mechanical design book based on AGMA and ANSI/ASME Standards.

Gear ratio: 3:1

$$W_1 = 60 \text{ rpm} \rightarrow n = \frac{360}{60} = 6 \text{ rad/s}$$

$$T = 46.8 \text{ N.m}$$

$$P = 0.4 \text{ HP}$$

$$\text{So, } \frac{n_1}{n_2} = \frac{3}{1}$$

- Assumptions:
  - Minimum Number of teeth for the gear ( $N_2$ )=16 teeth [4]
  - The pinion:  $N_1 = 48$  teeth
  - $N_L$  : Number of load cycle =  $10^5$  revolution
  - Pressure angle =  $20^\circ$
  - Diametric Pitch = 0.67 (module = 1.5) (P) or ( $d_p$ ) =  $1/m = N/P_d$
  - Face width =  $10/d_p = 15 \text{ mm}$

The Gear material is grade 1 steel through-hardened.

$$d_p = \frac{N_p}{P_d} \rightarrow P_d = \frac{N_p}{d_p} = 48 \cdot 1.5 = 72 \text{ mm}$$

$$\gamma = \tan^{-1} \frac{N_p}{N_G} = \tan^{-1} \frac{48}{16} = 71.565$$

$$r = \tan^{-1} \frac{N_G}{N_p} = \tan^{-1} \frac{16}{48} = 18.43$$

$$w^t = \frac{2T}{d_p} = \frac{2(\frac{46.8}{1000} N.mm)}{72} = 1.3 \times 10^3 N$$

$$w^r = w^t \tan\phi \cos\gamma = 1.3 \times 10^{-3} \tan 20 \cos 71.565 = 4.69 \times 10^{-4} N$$

$$w^\alpha = w^t \tan\phi \sin\gamma = 1.3 \times 10^{-3} \tan 20 \sin 71.565 = 1.4 \times 10^{-3} N$$

$$C_p = 2290 \text{ } pg:778 \text{ } C_p = 2290 \text{ } psi = 15789000 \text{ } Pa = 190 \frac{N}{mm}$$

**Pinion (Driving):**

$$I \approx 0.077$$

$$K_o = 1.01$$

$$K_v = \frac{A + \sqrt{200V_{et}}}{A}$$

$$B = 0.25(12 - Q_v)^{\frac{2}{3}} = 0.25(12 - 6)^{\frac{2}{3}} = 0.825$$

$$A = 50 + 56 \text{ } 1 - B = 50 \text{ } 1 - 0.825 = 40.23$$

$$V_{et} = 5.236 \text{ } 10^{-5} \text{ } 72 \frac{360}{60} = 2.26 \times 10^{-5} m/s$$

$$k_v = \left( \frac{40.2 + 3 + \sqrt{200 \text{ } 2.26 \times 10^{-5}}}{40.23} \right) = 1.0016$$

$$C_s = 0.00492 \cdot 15 + 0.4375 = 0.5113$$

$$C_{xs} = 1.5$$

$$S_H \approx 1.5 \text{ (Assumption)}$$

**Gear (driven):**

$$I = 0.077$$

$$K_o = 1.01$$

$$v_{et} = 5.236 \cdot 10^{-5} \cdot \frac{24}{1000} \cdot 6 = 7.54 \times 10^{-6} m/s$$

$$k_v = 1.0009 = 1$$

$$S_{ac} = 85000 \text{ psi} \rightarrow S_{ac} = 856 \times 10^6 \text{ Pa}$$

$$C_L = 3.4822 (10^5)^{-0.0602} = 1.74$$

$$C_H = 1 + B_1 \cdot \frac{N}{n} - 1 = 1 + 0.00898 - 0.00829 \cdot \frac{\frac{48}{\frac{360}{60}}}{1} - 1 = 1.00483$$

$$K_T = 1(Temp < 120^{\circ})$$

$$C_R = \overline{K_R}$$

$$K_R = 0.5 - 0.25 \log 1 - R = 0.5 - 0.25 \log 1 - 0.99 = 1.0$$

$$C_R = 1$$

**Pinion wear:**

$$d_p = \frac{N_p}{P_d} \rightarrow d_p = \frac{N_p}{P_d} = N_p m = 48 \cdot 1.5 = 72 \text{ mm}$$

$$C_p = 190 \sqrt{N/\text{mm}^2}$$

$$S_{ac} = 1378.952 \text{ MPa} \quad \text{table: 15 - 4 p: 778 look at page 787}$$

**Pinion contact stress:**

$$\begin{aligned} (S_c)_p &= (6_c)_p = C_p \frac{w^t}{F d_p I} K_o K_v K_m C_s C_{xc}^{1/2} \\ &= 190 \frac{1.3 \times 10^3}{15 \cdot 72 \cdot 0.077} \cdot 1.01 \cdot 1.0016 \cdot 1.00126 \cdot 0.5113^{1/2} \quad (1.5) \\ &= 190 \cdot 3.4848 = 662.114 \text{ (MPa)} \end{aligned}$$

Iteration (1): assume SH=1.5

Pinion wear strength

$$(S_{wc})_p = (\sigma_{call})_p = \frac{S_{ac} S_L S_H}{S_H K_T C_R} = \frac{1378.95 \times 10^6 \cdot 1.74 \cdot 1.00483}{1.5 \cdot 1 \cdot 1} = 1607.308 \text{ MPa}$$

Wear factor of safety:

$$(S_H)_p = \frac{(\sigma_c)_{all}}{\sigma \sigma_c} = \frac{1607.308}{662.114} = 2.4275$$

Iteration (2): SH=2  $\longrightarrow$  SH = 1.821  $(\sigma_{all}) = 1205.48 \text{ MPa}$

Iteration (2): SH=1.9  $\longrightarrow$  SH = 1.916 = 1.9  $(\sigma_{all}) = 1268.927 \text{ MPa}$

For Gear wear Just change  $k_v = 1.0009$

$$d_p = 24 \text{ mm}$$

$$S_c = 190 \cdot 6.0338 = 1146.414 \text{ MPa}$$

When  $SH = 1.5 \longrightarrow (SH)_G = 1.402$  acceptable

### Calculations of Straight-Bevel Gear Bending:

$$k_s = 0.5 \text{ (module} = 1.5\text{)}$$

$$k_x = 1.0$$

J: for pinion:

$$J = 0.19 \text{ fig: 15 - 7}$$

For Gear:

$$J = 0.3 \text{ fig: 15 - 7}$$

$$S_{at} = 44 \cdot 180 + 2100 = 10020 \text{ psi} = 68.5 \times 10^6 \text{ Pa}$$

$$K_L = 6.1514 N_L^{-0.1192} = 6.1514 (10^5)^{-0.1192} = 1.56$$

$$S_F = 1.5 \text{ (assumption)}$$

$$K_R = 1$$

Gear Bending Stress:

$$S_t = \sigma = \frac{w^t}{F} P_d K_o K_v \frac{K_s K_m}{K_x J}$$

**Pinion Bending:**

$$\text{Pinion: } d_p = N_{pm} = 48 \cdot 1.5 = 72 \text{ mm}$$

$$\text{Gear: } d_p = 16 \cdot 1.5 = 24 \text{ mm}$$

$$S_{at} = 30000 \text{ psi} = 206.8424 \text{ MPa}$$

**Pinion bending stress**

$$(S_t)_p = (\sigma)_p = \frac{w^t}{F} P_d K_o \frac{K_s K_m}{K_x J} = \frac{1.3 \times 10^3}{15} \cdot \frac{1}{1.5} \cdot 1.01 \cdot \frac{0.5}{1} \cdot \frac{1.00126}{0.19} = 153.761 \text{ MPa}$$

Gear bending strength:

$$(S_{wt})_p = (\sigma_{all})_p = \frac{S_{at} K_L}{S_F K_T K_R} = \frac{206.8428 \times 10^6}{1.5 \cdot 1 \cdot 1} \cdot \frac{1.56}{1} = 215.117 \text{ MPa}$$

Bending factor of safety:

$$(S_F)_p = \left( \frac{\sigma_{all}}{\sigma} \right)_p = \frac{215.117}{153.761} = 1.40 \cong 1.5 \quad \text{acceptable}$$

For Gear only J will Change:  $J = 0.3$

$$\sigma = 97.382 \text{ MPa}$$

Iteration (1):  $\text{assume } S_F = 1.5 \rightarrow \sigma_{all} = 215.117 \rightarrow S_F = 2.21$

Iteration (2):

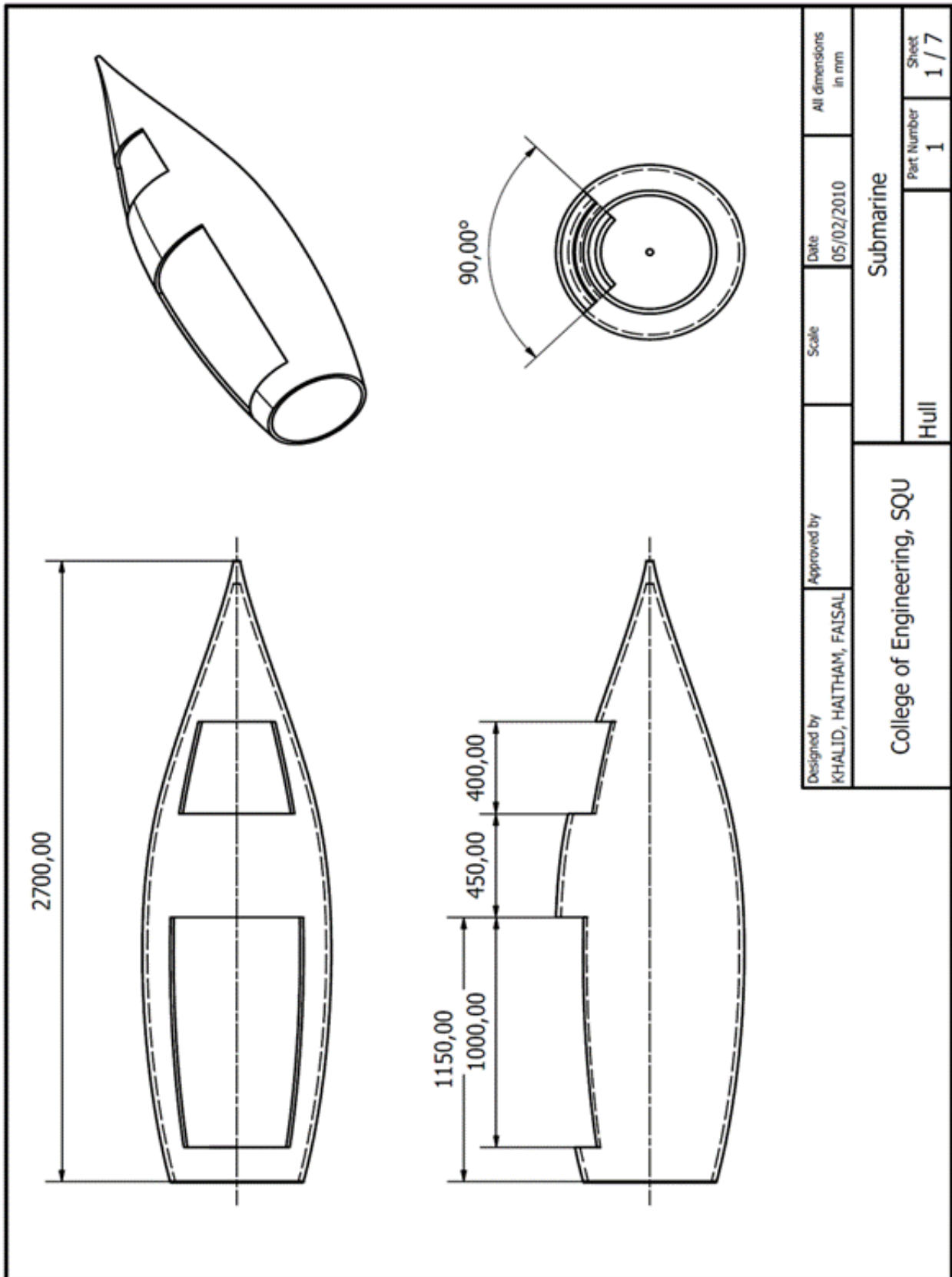
$$S_F = 1.8 \rightarrow \sigma_{all} = 179.26 \rightarrow S_F = 1.84 \approx 1.8 \quad \text{acceptable}$$

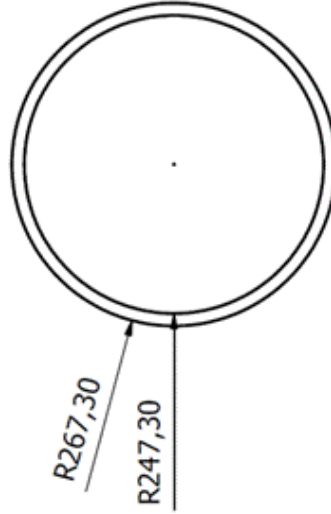
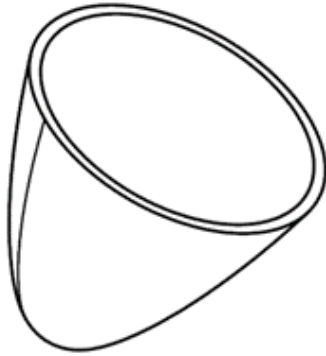
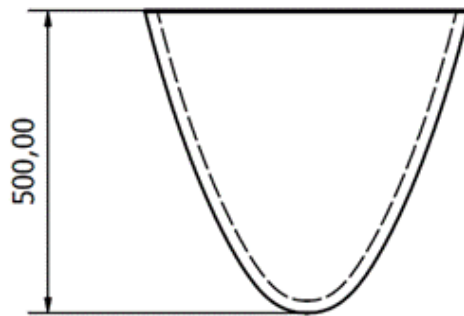
$$S_F = \frac{\sigma_{all}}{\sigma} = \frac{179.26}{97.382} = 1.84 \approx 1.8$$



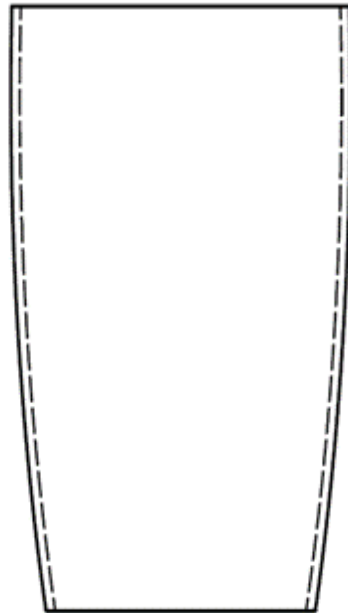
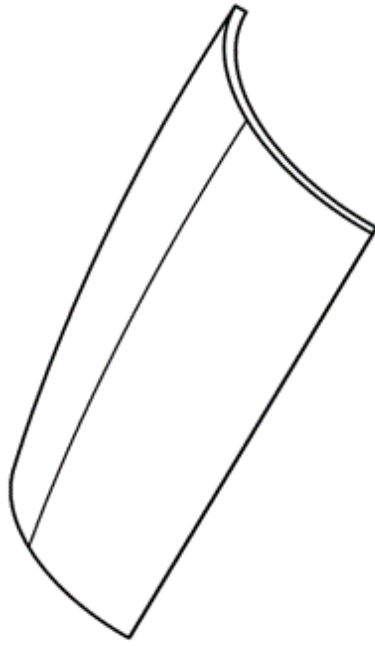
## **Appendix D**

### **Drawings**

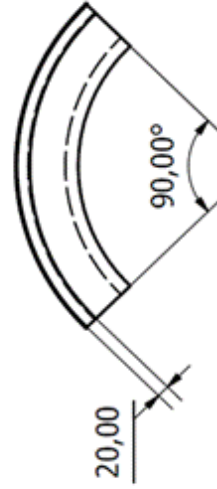
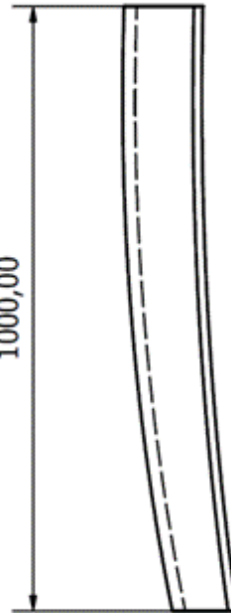




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		Window	Part Number 2	Sheet 2 / 7



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		Door			Part Number 3

