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Design, Modelling and Simulation of BLDC Motor Driven Hub less Thrusters for Underwater Vehicles

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***Abstract*:**
This paper presents the conceptual design of a hub-less thruster for Unmanned underwater vehicles, Autonomous underwater vehicle or/and Remotely operated vehicles to optimize its performance. Design requirements and critical parameters were analyzed on Solidworks and Altair Flux by rapid design prototyping methods. The software tools used to achieve the required target were vitally accounted for in the analytical procedures and designing. The design procedure encompasses Computational Fluid Dynamics (CFD) with propeller and motor parameter realization design. The amalgamation of these techniques gives output in terms of torque, power and thrust. These parameters were then compared to a commercially available thruster while incorporating the housing technique of the reference into the design thruster.

Keywords—hub-less thruster,Solidworks, Altair Flux,Computational Fluid Dynamics

I. Introduction

For marine vehicles, thrusters are indispensible part as it enables the vehicles movement. Thus modification and improvisation of thrusters vastly affectsthe technology of such vehicles. To start with the improvisation we needed a reference which fulfilled three criterions:

- Modular design, easily removable parts
- Naturally pressure resistant
- Water lubricated

All these criterions were covered by Bluerobotics T200 thruster, commercially widely used thrusters by many marine hobbyist and companies.

The aim of this paper is to design a thruster with less power to thrust ratio than Bluerobotics T200 while having all the benefits of T200.To optimize the design we went for a hub less thruster which would possibly achieve our goal.

The main benefit behind eliminating the hub is to reduce the fluid resistive force or drag created, as absence of hub leads to vortex generation of fluid stream lines which increases the water flow rate through the thruster [1]. This paper is devoted to design a potent thruster by collaborative results of CFD (computational fluid Dynamics) and electrical feasibility of the BLDC motor forming the thruster [2]. The entire process for designing and simulating the hub-less thruster is explained with a flow chart shown in Fig1.

Two software tools helped us in designing and simulation process of the thruster is Solidworks and Altair Flux.

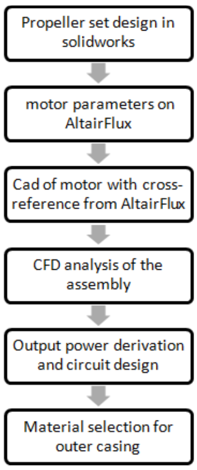

Fig1.Flow chart of the entire process

II. Mechanical Design Aspect

The design process of thrust as shown in Fig2 is subjected to Rapid Prototyping method as it takes less time and helpsanalyzing the areas need to be improvised for successive iterations of design. The cross-referencing tool to validate the result in this case is CFD(computational fluid Dynamics) of Solidworks flow simulation.

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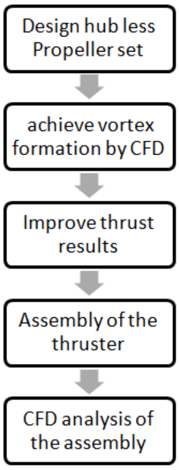


Fig2.Flow chart of the mechanical process

A. Design approach

The initial approach to the thruster design was making sure the vortex formation of the water streams occurs properly with no unwanted patterns and backlashes.The first part to be designed was the propeller which is hub-less as shown in Fig3.

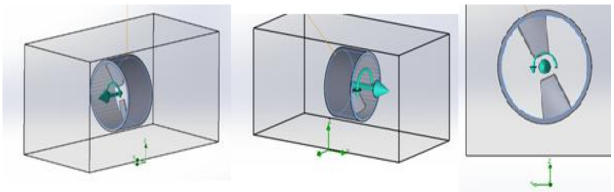


Fig3.Design approach

The initial CFD results as shown in Fig4. showsthat the vortex of the water streams is generated as the propeller rotates. The simulation was carried out by applying an angular velocity of 1500 RPM along the central axis (Z-axis) of the propeller. Here there was some turbulence and backlash in the path of the water streams so the design still required more optimization for a much smoother flow as the backlash in the above figure will cause reduction in thrust.

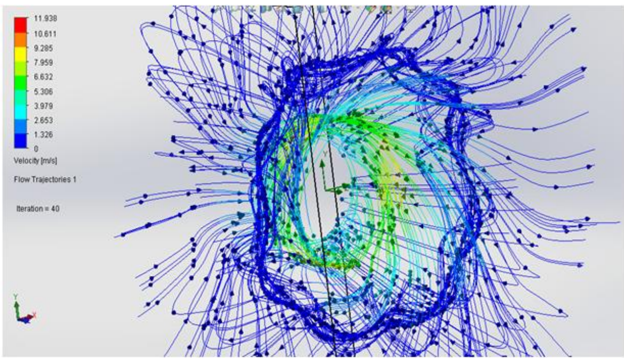


Fig4.Unclear vortex formation

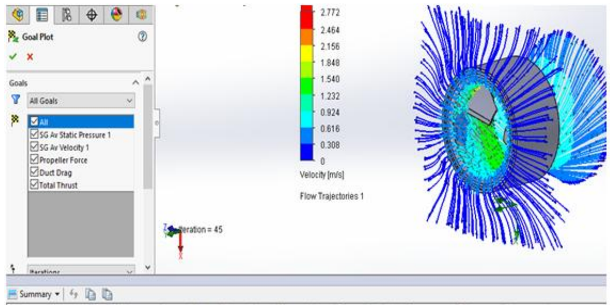
B. Breakthrough design

The model in Fig5 is the first breakthrough in the project which produced a flawless trajectory of the water streams during CFD analysis. It consists of a 2-fin propeller with a duct size of 80mm. This assembly contained the propeller, rotor body and the surface mounted magnets.

Fig5. Two fin propeller set

The Fig6 shows the flow trajectories of water streams generated using CFD in Solidworks, the flow trajectories of the water streams have improved to an optimal level. There is no backlash or turbulence in the path of the water streams and no hindrances between the inlet and outlet of the thruster. The CFD analysis of the rotor assembly was done at an angular speed of 1500 RPM or 157.08 rad/sec.

However, one challenge still remained, the amount of thrust generated by the propellers at that angular speed was not sufficient.In Fig6 result sheet, we see that the thrust generated is averaged to be 4.321 N whereas the T200 thruster could provide a thrust of 9.9 N so some optimization was required for greater thrust.



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
SG Av Static Pressure 1	[Pa]	100350.69	100474.95	100350.69	100686.11	100	Yes	335.42	550.03
SG Av Velocity 1	[m/s]	3.466	3.466	3.466	3.466	100	Yes	8.882e-016	3.466e-008
Propeller Force	[N]	4.153	4.190	4.069	4.450	100	Yes	0.382	1.143
Duct Drag	[N]	0.218	0.131	-0.010	0.291	100	Yes	0.301	0.684
Total Thrust	[N]	4.371	4.321	4.096	4.742	100	Yes	0.646	0.679

Fig6. CFD of two fin propeller at 1500 rpm

So many options were taken into consideration, such as:

- altering the profile of the propeller fins
- increasing the number of propeller fins
- changing the size and the profile of the duct

With all these options a new design needed to be implemented and verified so we began with a new set of iterations of the propellers.Fig7 is a three fin propeller designed to optimize the results from previous iteration.

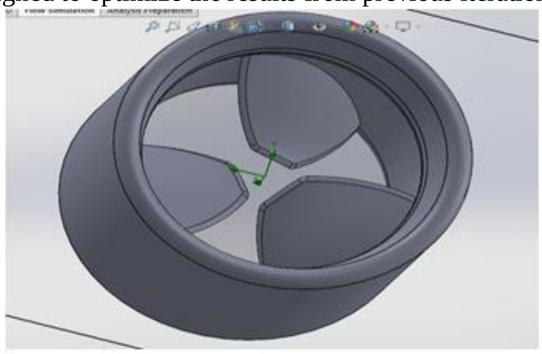


Fig7. Three fin Hub-less thruster

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The implementation of changes in the design of the propeller, changing the duct size and the propeller profile are done in the next iteration as shown in the Fig 7.

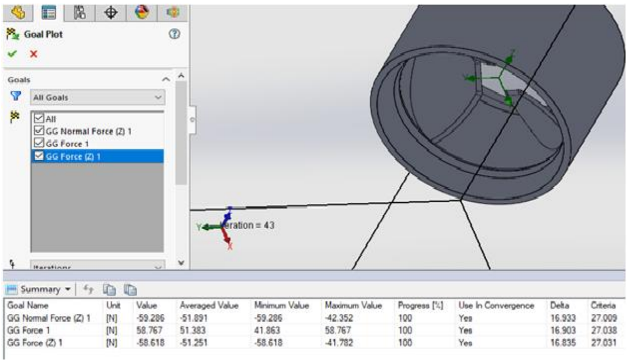

Fig8.CFD results of three fin propeller

The Fig7 shows CFD results which were tested at an angular speed of 3800 RPM or 397.93 rad/sec. Here the maximum value achieved by 3 fin propeller is 58.618 N as shown in Fig7. However, some optimization was required as the T200 could provide a thrust of 62 N at the same RPM so we went back to optimizing the design[3][4].

C. Final iteration

The last iteration was a successful design in which simulation could produce greater thrust than T200 at the same given angular velocity.In the Fig8 the design uses a propeller with 4 fins.

Fig9.Final iteration

Fig 9 shows the complete design which encloses both the stator and the rotor assemblies which is constructed with cross-reference with Altair flux along with custom ball-bearings for smooth operation.

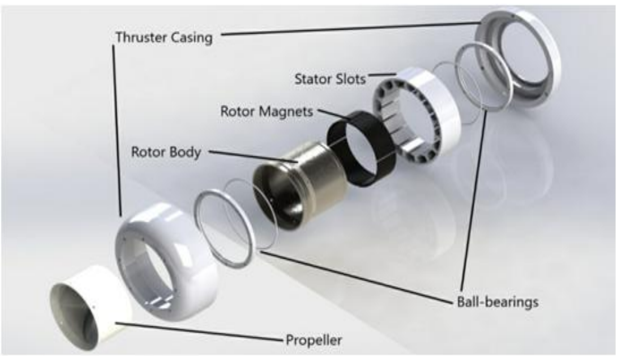

Fig 10.Exploded view of final assembly

The Final design can be broken into 4 parts as per the exploded view as shown in Fig 10:

1. The Thruster casing
2. Stator Slots
3. Rotor
4. Propeller

D. Final CFD results

The Flow Trajectories (at 3800 RPM):

Fig11. shows the flow trajectories of the thruster at 3800 rpm. There is distinct vortex formation which can be seen in the middle of thruster.

Fig12. Is a engineering drawing of the final thruster design which showcases the final thruster dimension with casing.

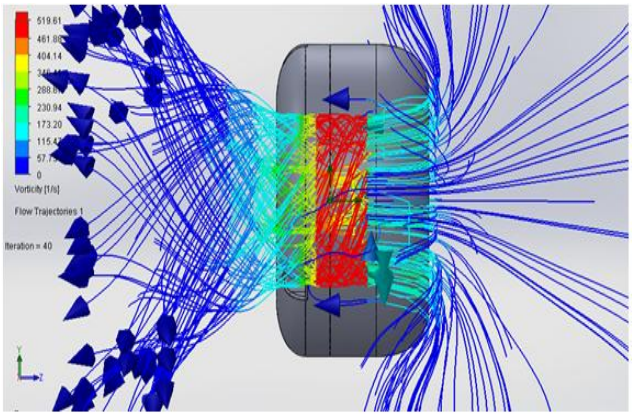

Fig11.CFD of final iteration

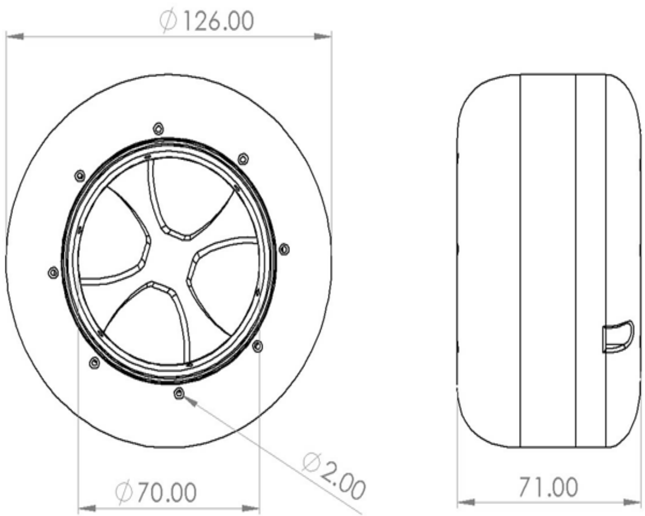

Fig 12.Thruster dimension

Fig13.shows different parameters like torque, thrust and force etc. at 1500,2000,3400,3800 RPM respectively for the final design of motor propeller set.

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Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Torque (X) 1	[N*m]	0.012	0.014	0.010	0.019	100	Yes	0.009	0.050
GG Torque (Y) 1	[N*m]	-0.007	-0.005	-0.010	0.003	100	Yes	0.013	0.049
GG Torque (Z) 1	[N*m]	-0.239	-0.274	-0.331	-0.239	100	Yes	0.092	0.417
SG Normal Force 1	[N]	9.205	10.160	9.205	11.587	100	Yes	2.381	14.007
SG Normal Force (Z) 1	[N]	9.204	10.156	9.204	11.583	100	Yes	2.379	13.998
SG Force (Z) 1	[N]	9.179	10.114	9.179	11.533	100	Yes	2.354	13.996
SG Normal Force 2	[N]	1.148	1.209	1.100	1.474	100	Yes	0.374	1.981
SG Normal Force (Z) 2	[N]	1.059	1.051	0.978	1.174	100	Yes	0.196	0.548
SG Force (Z) 2	[N]	0.989	0.970	0.894	1.094	100	Yes	0.200	0.557
Thrust 1	[N]	10.354	11.369	10.354	13.060	100	Yes	2.706	15.732
Thrust 2	[N]	10.262	11.206	10.262	12.756	100	Yes	2.494	14.289
Thrust 3	[N]	10.168	11.084	10.168	12.627	100	Yes	2.459	14.289

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Torque (X) 1	[N*m]	0.023	0.027	0.020	0.034	100	Yes	0.014	0.087
GG Torque (Y) 1	[N*m]	-0.017	-0.012	-0.018	0.003	100	Yes	0.021	0.100
GG Torque (Z) 1	[N*m]	-0.455	-0.520	-0.607	-0.455	100	Yes	0.152	0.995
SG Normal Force 1	[N]	17.549	19.094	17.549	20.709	100	Yes	3.161	32.750
SG Normal Force (Z) 1	[N]	17.545	19.087	17.545	20.699	100	Yes	3.154	33.751
SG Force (Z) 1	[N]	17.476	18.997	17.476	20.596	100	Yes	3.121	33.753
SG Normal Force 2	[N]	1.952	2.227	1.952	2.733	100	Yes	0.782	4.547
SG Normal Force (Z) 2	[N]	1.722	1.871	1.718	2.192	100	Yes	0.473	1.228
SG Force (Z) 2	[N]	1.545	1.679	1.534	1.991	100	Yes	0.457	1.254
Thrust 1	[N]	19.500	21.320	19.500	23.367	100	Yes	3.866	36.209
Thrust 2	[N]	19.268	20.958	19.268	22.812	100	Yes	3.545	33.265
Thrust 3	[N]	19.020	20.675	19.020	22.509	100	Yes	3.488	33.274

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Torque (X) 1	[N*m]	0.083	0.089	0.067	0.119	100	Yes	0.052	0.294
GG Torque (Y) 1	[N*m]	-0.053	-0.033	-0.053	0.011	100	Yes	0.064	0.229
GG Torque (Z) 1	[N*m]	-1.487	-1.644	-1.783	-1.487	100	Yes	0.296	2.820
SG Normal Force 1	[N]	54.427	58.218	54.427	62.069	100	Yes	7.643	97.534
SG Normal Force (Z) 1	[N]	54.418	58.198	54.418	62.042	100	Yes	7.625	97.741
SG Force (Z) 1	[N]	54.177	57.877	54.177	61.690	100	Yes	7.513	97.752
SG Normal Force 2	[N]	8.739	9.430	8.719	11.410	100	Yes	2.691	16.381
SG Normal Force (Z) 2	[N]	7.873	8.220	7.845	9.557	100	Yes	1.712	2.797
SG Force (Z) 2	[N]	7.397	7.697	7.359	9.015	100	Yes	1.657	2.856
Thrust 1	[N]	63.165	67.648	63.165	71.795	100	Yes	8.630	109.030
Thrust 2	[N]	62.290	66.418	62.290	70.164	100	Yes	7.874	97.046
Thrust 3	[N]	61.574	65.575	61.574	69.249	100	Yes	7.675	97.076

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Torque (X) 1	[N*m]	0.079	0.094	0.075	0.108	100	Yes	0.034	0.215
GG Torque (Y) 1	[N*m]	-0.063	-0.043	-0.066	-0.003	100	Yes	0.063	0.507
GG Torque (Z) 1	[N*m]	-1.634	-1.870	-2.147	-1.634	100	Yes	0.513	2.886
SG Normal Force 1	[N]	63.045	68.781	63.045	75.753	100	Yes	12.708	96.432
SG Normal Force (Z) 1	[N]	63.030	68.756	63.030	75.729	100	Yes	12.699	96.138
SG Force (Z) 1	[N]	62.781	68.458	62.781	75.401	100	Yes	12.620	96.147
SG Normal Force 2	[N]	6.669	7.724	6.654	9.814	100	Yes	3.160	16.637
SG Normal Force (Z) 2	[N]	5.927	6.527	5.909	8.389	100	Yes	2.480	4.939
SG Force (Z) 2	[N]	5.344	5.925	5.317	7.797	100	Yes	2.479	4.931
Thrust 1	[N]	69.714	76.505	69.714	84.192	100	Yes	14.478	109.640
Thrust 2	[N]	68.956	75.282	68.956	82.623	100	Yes	13.667	97.139
Thrust 3	[N]	68.125	74.384	68.125	81.668	100	Yes	13.544	97.171

Fig13.tabulated results of CFD at different RPM

The Table Ishowcase a comparison between the thrust values of the T200 thruster and the hub-less thruster at given angular speeds. From Table1.we may conclude that the hub-less thruster provides more thrust than the T200 thruster at given angular speeds.

TABLE I. COMPARISON TABLE

Angular Speed (RPM)	Thrust (N)	
	Bluerobotics T200 Thruster	*Hub-less Thruster*
1500	8.918	13.06
2000	15.85	22.812
3400	51.156	71.795
3800	58.995	84.192

III. MOTOR DESIGNING

In order to obtain the specific dimensions and to even select the type of motor, we have undergone a lot of trial and error method initially keeping in mind the dimensions of the propeller set CAD designed in Solidworks. The steps mentioned in Fig14.shows a simplified flow of the process involved in motor designing.

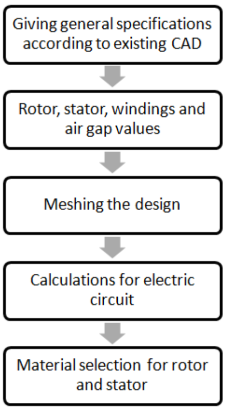

Fig14.steps of motor designing

So the first step was to finalize the number of poles and magnets shape that our fits best for our design. After deciding the rotor parameters, second step was to decide optimal parameter for stator. After fixing these parameters are cross checked in Altairflux using meshing to see if the parameters are feasible or not.[6]

When the all the rotor and stator parameters are finally fixed and cross checked, the rotor and stator is designed in Solidworks with exact dimensions and shape to develop a full assembly with casing on which a final CFD is done. The tabulated results in CFD gives torque values which required for building the circuit for the motor.

A. General Characteristics

The Table II shows different general parameters of the motor.For the sake of the fluidity of the design and enough cooling space, we have incorporated a two-layer air gap.

TABLE II. GENERAL PARAMETERS

Parameters	In (mm)
	Value
Mesh Density	0.5
Inner Radius	110
Outer Radius	140
Air Gap	1.0

These general characteristics are selected after take consideration from the CAD model of the propeller set designed in Solidworks.

B. Rotor Parameters

The Table III shows different rotor characteristics that are selected for final iteration. The shat thickness mentioned in Table III signifies the space for the propeller set.

TABLE III. ROTOR PARAMETERS

Parameters	In (mm)
	Value
Shaft Radius	
Thickness of magnet	35
Magnet pole Arc	2
External Radius	87
No. of poles	41
No. of Magnet per pole	4
	1

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There are 4 poles with 1 magnet each which provides a balance design with lesser chance of imbalance of weight and operation and increases efficiency. The shape chosen is surface permanent magnet rotor because it accommodates required number of poles and magnets in the given dimensional constraints.

C. Stator Parameters

The Table IV shows the stator characteristics that were inputted in Altairflux for final iteration. The shape of the final stator slot is "Square". We have set the value of slots in the stator as 15 so as to have a fractional slot number, which results in less cogging torque. The numbers of slots were iterated according to accommodation space in the final casing of thruster.

TABLE IV. STATOR PARAMETERS

Parameters	**In (mm)**
	Value
Shaft Radius	35
Thickness of magnet	2
Magnet pole Arc	87
External Radius	41
Number of poles	4
Number of Magnet per pole	1

D. Electric circuit design

When the motor runs at an angular speed of 3800 RPM, a torque of 1.783Nm is produced. We got this output from CAD simulation Shown in Fig15. [7]
Now using this torque formula we are going to calculate the output power.

$$P_{out} = Ts \quad (1)$$

Where,
P_{out} = Output power, W T = Torque, Nm
T = 1.783 Nm
s = Speed, rad⁄sec
s = 397.935 rad/sec
P_{out} = 1.783 ∗ 397.935
= 709.518 W

Considering our system to be ideal the input and output power will be equal.
Hence,
Input Power= Output power= 709.518W
Now assuming input voltage(V) to be 20V similar to that of Bluerobotics T200 Using the above values current (I)was calculated.

$$P = VI \quad (2)$$

Where,
P = power (W)
V = voltage (V) = 20V
709.518 = 20 × I
709.518/20 = I
I = 35.4759 A

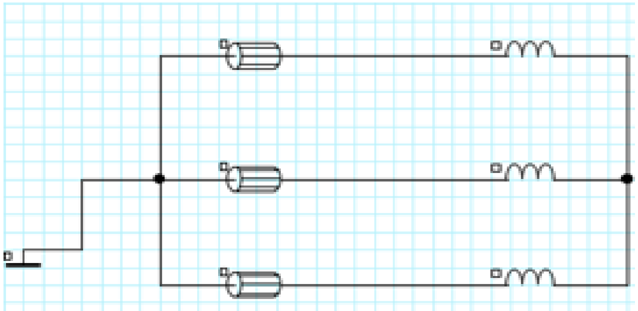

Fig1. Circuit Design in Altair Flux

The electrical circuit is used with a hall sensor for signalizing the electromagnet of motor by means of an external circuit for keeping a constant rotating motion of therotor. This increases the effectiveness in comparison to traditional motors. The circuitconsists of 3 coil conductors and 3 resistors. Coil conductors are electrical windings in the shape of a spiral, helix or a coil.

$$L = \mu \frac{N^2 A}{l}$$

L = Inductance, mH
N = Number of turns in coil
μ = Relative permeability of copper
A = Cross − sectional area of wire, cm2 l = Length of solenoid
L = 0.07356182mH
The current interacts with the magnetic fields which generates EMF. The windings in the conductor are made ofcopper of which internal resistance and inductance is calculated for the circuit shown in Fig15.

E. Meshing

We need to represent the geometry of the BLDC motor in terms of various finite elements. Meshing is an integral part of the designing process as a whole, that encompasses geometry and several finite elements together adequately to make the final design work as a single functioning unit. The reason why meshing is considered essential during early stages of designing, is because it is necessary to imbue all complex geometries divided into single and simple elements in a larger domain. The accuracy, convergence and speed of the entire simulation depend upon the meshwhich is why it is important to check the correct placement of all the components before even starting the meshing process.[8]
The meshed product in Fig15 shows the separation of various finite elements and successfully defines a geometry upon which several iterations can be implemented.

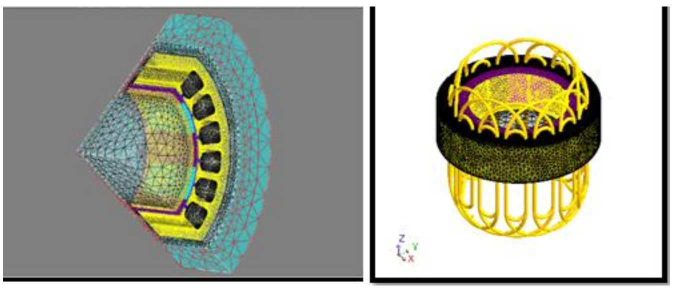

Fig15. Meshed final motor iteration

As stated previously, we have 4 poles present in the rotor design that provide a balanced approach with lower chances of imbalance of weight and operation. Each pole has magnets attached to it providingmore efficiency to the magnetic simulation. The rotor itself acts a permanent magnet in some cases; however we are having 4 dedicated poles with magnets attached to ensure maximum magnetic flux. The magnetic flux can be measured by the transient magnetic evaluation in Fig15.

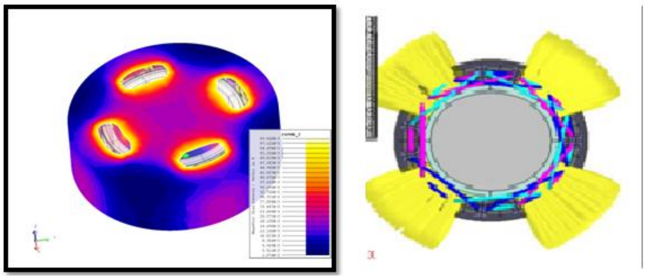

Fig 15.Magnetic analysis and direction

As we can see in the above image, the presence of 4 poles and embedded magnets is indicated by the piping red color which signifies maximum magnetic flux in the area as compared to lower flux areas depicted by blue.

F. Material selection for rotor and stator

The rotor consists of a rim with 4 pole surface mounted permanent magnets of NDFEB or commonly known asneodymium magnets.This material possesses a remnant flux density of 1.02 T and relative permeability of 1.05.

As for the stator, the material used is AISI_316LL_SS which is a code for the material Stainless Steel having a relative permeability of 1.003. One of the biggest advantages of this material is the resistance to corrosion, which is essential to sustain itself underwater.

IV. MATERIAL SELECTION

The Table V showcases different material used in different parts of the thruster. The windings and the rotor magnets are enamel coated so as to make it water lubricated.[5] This enable the designed thruster to be naturally pressure resistant as it doesn't require any type of seal for water proofing.[9][10]

TABLE V. MATERIAL SELECTION

Parts	**Type**
	Material selected
	Polycarbonate
Propeller	Polycarbonate
Casing	316 stainless steel
Ball bearings	Polycarbonate
Rotor body	NdFeB
Stator Slots	316 stainless steel
Fasteners	316 stainless steel

The windings and the rotor magnets are enamel coated so as to make it water lubricated.[5] This enable the designed thruster to be naturally pressure resistant as it doesn't require any type of seal for water proofing.[9][10]

V. CONCLUSION

The thrust results were cross-referenced with the data sheet of the Blue robotics T200 thrusters and it is observed that the hub-less thruster had a significant increase in its thrust value. According to Table VI the comparison is done to showcase the results of different parameters.The results are verified by successfully doing CFD on thedesigned thruster.

- The power to thrust ratio mentioned in Table VI indicates that for unit thrust hub-less thruster will require less power than T200 at 3800 rpm.
- According to the results the maximum thrust capability of hub-less thruster is 1.35 times more than that of T200.

In addition to these parameters the designed motor is very modular and easily maintainable as it doesn't contain any type of seal as it contains enamel coating therefore making the design naturally pressure resistant.

The BLDC motor circuit is successfully simulated to provide the required input power needed to produce the generated mechanical power output by thruster, with all the materials selection

TABLE VI. PARAMETER COMPARISON TABLE

PARAMETER	**Results of different parameters**	
	Final designed Hub-less thruster	***Bluerobotics T200***
Full throttle forward thrust Nominal (16V)	71.79 N	51 N
Full throttle forward thrust 20V max	84.19 N	62 N
Power to thrust ratio	8.42W/N	10.43W/ N

The designed thruster can be used commercially with an optimal Electronic speed controller (ESC) use or switching circuit.

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