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ANALYSIS OF AUTONOMOUS UNDERWATER VEHICLE (AUV) DESIGN AND CONSTRUCTION FROM MOTION FREEDOM PERSPECTIVE

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Abstract: *In this paper a theoretical approach of design for Autonomous Underwater Vehicle (AUV) is analyzed from perspective of motion freedom. There are consideration about propeller parameters, the number of propulsion propeller in a perspective of best manoeuvring operation in a small place, and a quick shape analysis for determining the best shape for water resistance and currents.*
Key Words: *underwater vehicle, design and construction*

1. INTRODUCTION

Many robots for underwater research was developed in last 10 years, for deep diving robots to the autonom underwater vehicles (AUV). Each of them was designed for certain features and objectives.

This paper analyzes the important steps in design of an Underwater Vehicle. In most of cases this analyzes is based on a previously developed model and added the improvements and new features. There are considerations about a quick propeller calculus. Also a design shape, it importance and testing with Computer Fluid Dynamics (CFD) methods is presented. From motion freedom perspective 3 design shape are proposed, a quick analyze of each motion freedom capability and where is that shape suppose to be applied.

2. PROPULSION CONSDERATION

There are two ways most used for underwater propulsion:

- Jet propulsion;
- Propeller propulsion (most used);

I will consider the best solution the propeller propulsion solution because it is easy to use, no needs for special body design and is low cost.

The propeller propulsion is based on a propeller blade controlled by an engine (electrical, combustion, etc.).

Definition and preliminary considerations:

Definition of power:

$$W = F \times \Delta d \qquad (1)$$

Where:

W – is the work done on an object

F – is force

Δd- are the displacement of the object

The shape of propeller and its diameter are the major determinants factor for the propulsion efficiency. The surface of the blade are a helicoidally portion. The blade act like a screw, in water a full rotation are theoretically equivalent to an axial movement at a certain distance determined by the helicoidal parameters of the blade. If a point on blade is considered, at a full rotation the blade movement of the point on the surface swept out a helicoidal surface.

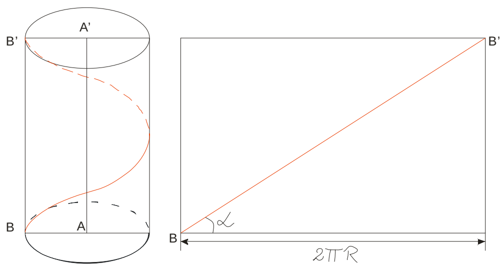


Figure 1. The face surface of a blade, radial view

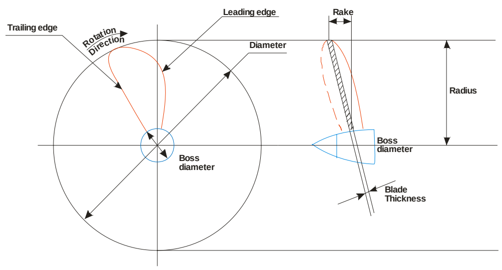


Figure 2. The face surface of a blade, axial view

If a point on blade is considered, at a full rotation the blade movement of the point on the surface swept out a helical surface.

Angle of attack is the angle between the line of reference (on a body) and the flow lines oncoming on the body.
The second important parameter of the blade is the length of the blade. The length of the blade is determined by the difference between diameter of the propeller and the boss diameter. The boss diameter is the diameter on which the blades are attached to propeller shaft.
The major forces (F) acting on any point of the blades are determined by the surface of blade (area of blade), the angle of attack (α) and velocity (V).
The force has two components:
- the force, normal to the direction of flow give the lift/displacement component (L);

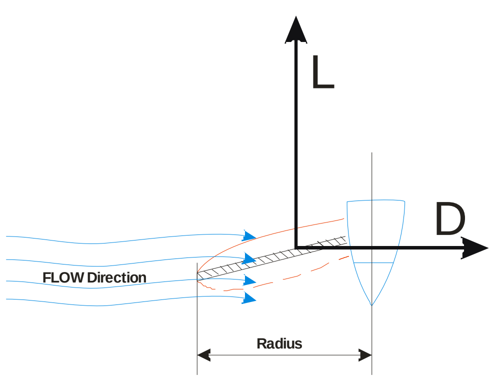


Figure 3. Forces decompositions

- the drag force – this have the same direction with the direction of flow (D);

Reynolds number is a dimensionless number used in fluid mechanics that in a given flow conditions give a measure for the ratio of inertial forces to viscous forces.

$$R_e = \frac{\rho V L}{\mu} = \frac{VL}{\nu}; \qquad (2)$$

$$\nu = \frac{\mu}{\rho}; \qquad (3)$$

where:
V – Velocity of the object relative to fluid (m/s)
L – Characteristic linear dimension (m)
μ– Dynamic viscosity of the fluid (m*s)
ν– Kinematic viscosity (m^2/s)
ρ– Density of the fluid (kg/m^3)
Conform to this we obtain from the relation:

$$\frac{F}{\rho A V^2} = f(R_n, \alpha) \qquad (4)$$

this: $$C_L = \frac{L}{\frac{1}{2}\rho A V^2}, \qquad (5)$$

$$C_D = \frac{D}{\frac{1}{2}\rho A V^2}, \qquad (6)$$

Each coefficient: lift coefficient (C_L) and coefficient of direction of flow $(C_D)$are function of Reynolds' number and angle of attack.

Propeller thrust
This is calculated for a single blade, taking an arbitrary radial section of a blade at r; the number of revolutions is N. Consider this the velocity of rotation is: $2\times\pi\times N\times r$. Note P the pitch of the blade. Theoretically, in a solid at a complete rotation the blade, advance at rate: NP. But if the blade is submerged in water, the advance rate is lower then a solid. Let's note V_a the water advance. So the difference is the "slip" ratio. Refer to this notations the slip ratio is:

$$Slip_{ratio} = \frac{NP - V_a}{NP} = 1 - \frac{J}{p}, \qquad (7)$$

Where:

$$J = \frac{V_a}{ND} \text{ the advance coefficient} \qquad (8)$$

$$p = \frac{P}{D} \text{ the pitch ratio} \qquad (9)$$

Consider the dA force of drag on blade and dL the force normal to the surface:

$$dL = \frac{1}{2}\rho C_L [V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2] b dr, \qquad (10)$$

Where:

$$V_r^2 = V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2 \qquad (11)$$

$$dD = \frac{1}{2}\rho C_d [V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2] b dr \qquad (12)$$

The thrust force T on blade:

$$dT = dL\cos\varphi - dD\sin\varphi \quad (13)$$

Where we note with:

$$\tan\beta = \frac{dD}{dL} = \frac{q_a}{q_r} \quad (14)$$

$$V_1 = \frac{V_a(1+a)}{\sin\varphi} \quad (15)$$

$$dT = \frac{1}{2}\rho C_L \frac{\cos(\varphi+\beta)}{\sin^2\varphi\cos\beta} b dr \quad (16)$$

From above we obtain the thrust and transverse forces by integrating expression along the blade:

$$dM = \frac{1}{2}\rho V_1^2 C_L \frac{\sin(\varphi-\beta)}{\cos\varepsilon} b r dr \quad (17)$$

The torque is obtained by substitute V_1 and multiply by r :

$$dQ = r dM = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\sin(\beta+\varphi)}{\cos\beta\sin^2\varphi} b r dr \quad (18)$$

The total power of thrust is proportional to TV_a and the shaft power to $2\pi NQ$.

From this consideration the efficiency is:

$$\frac{TV_a}{2\pi NQ} \quad (19)$$

and the blade element efficiency is:

$$B_{el.ef} = \frac{V_a}{2\pi NR} \times \frac{1}{\tan(\varphi+\beta)} \quad (20)$$

So, the thrust (T) and torque (Q) depend on propeller diameter (D) and the rate of advance (V_a) number of revolution (N).

So the expression can be reformulated:

$$T = \rho V^2 D^2 \left[f_{adv.coef}\left(\frac{ND}{V_a}\right) \cdot f_{Reynolds}\left(\frac{\nu}{V_a}\right) \cdot f_{Froude}\left(\frac{gD}{V_a^2}\right)\right] \quad (21)$$

The function of Reynolds' and Froude are relatively to advance coefficient are negligible so the expression can be reduced to:

$$T = \rho V_a^2 D^2 \times f_1\left(\frac{ND}{V_a}\right) \quad (22)$$

Also the torque:

$$Q = \rho V_a^2 D^3 \times \left(\frac{ND}{V_a}\right) \quad (23)$$

Total performance:

The total performance is a function of performance of the hull (here come the shape analysis), propeller efficiency, relative rotative efficiency divided by the appendage coefficient and all multiply by transmission efficiency.

$$TP = \frac{H_e \times P_e \times R_{re}}{A_e} \times T_e \quad (24)$$

where:

TP-total performance

H_e-hull efficiency

P_e-propeller efficiency

A_e-appendage coefficient

T_e-transmission efficiency

This are the steps to evaluate a given propeller efficiency and calculate the forces. Sometime we need, at a certain propeller given, to calculate the efficiency and decide if the solution is best for our mission. This steps offer in major lines an image of propulsion.

Other phenomena like cavitation and vortex are also present during the movement of blades, but to consider this it is necessary for complex mathematical analysis. Also we can't control all phenomenon's that appear in the movement of blades, most of them will be seen in small scale model analysis or adjusted after the robot/model is released.

Another way to approach these calculations is to model the propeller in software for computational fluid dynamics with we can approximate better the phenomena's appears.

3. HULL SHAPE CONSIDERATION

Most of hull shape analyses today are realized in Computational Fluid Dynamic programs (CFD).The CFD is a numerical analysis technique of fluid flow. Compared to the other analysis it is the cheapest variant. The CFD find applicability in various industry area like piping system, automotive, aeronautical, chemical sector, etc. It can be analyses at different accuracy determined by application of analysis, detail needed for designing requirements. In most of cases multiple aspects are analyzed like: hull lines, speed power requirements, flow over hull, turbulence kinetic energy, pressure planes, pressure streamlines, velocity vectors, etc.

The computational model has a working domain, and it is analyzed in following way: the solid is static and the water has the speed of flow. A rectangular working domain must be chosen where front and back faces of the domain are specified as velocity inlet and pressure outlet and the other faces is considered as wall surfaces. The model surface is discretized into a mesh structure.

At my model the speed of water is 1m/s, the diving direction is z axis of the system, the forward direction the x axis and the y axis is the axis perpendicular to the current flow.

The simulation use to solve the model

-continuity equation:

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \qquad (25)$$

-equation of moment:

$$-\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_i}\right) - \delta\overline{u_i u_j}\right] = 0 \qquad (26)$$

-the turbulence model first component: the turbulence kinetic energy:

$$\rho\frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \qquad (27)$$

-and the second component of the turbulence model the turbulence kinetic energy dissipation

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon}G_b\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (28)$$

Most important results of this simulation is:
-Velocity isosurface (fig.5)
-Turbulence kinetic energy (fig.6)
-Pressure planes (fig.8)
-Pressure streamlines (fig.4)
-Velocity vectors (fig.7)

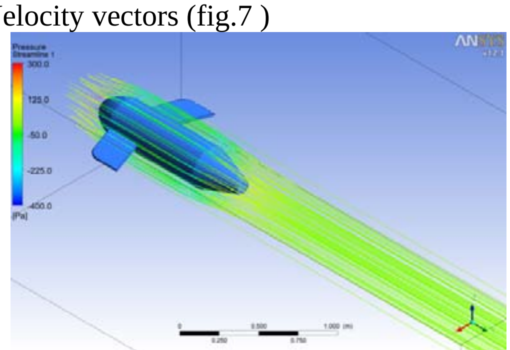


Figure 4. Pressure Streamlines

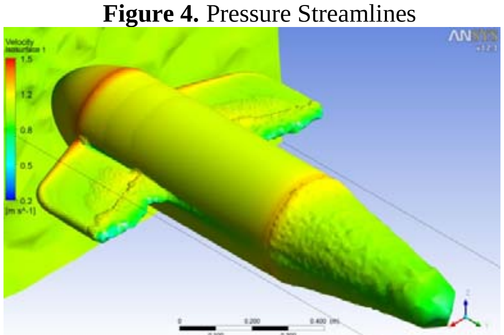


Figure 5. Velocity isosurface of submersible.

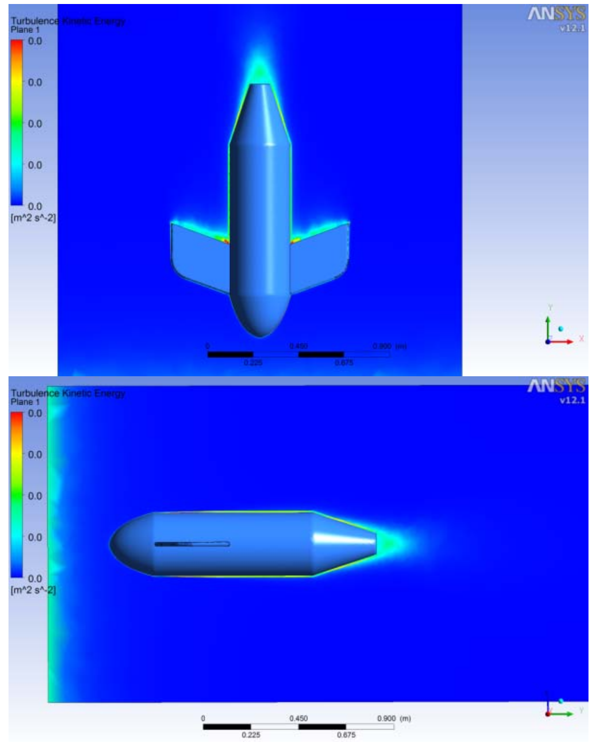


Figure 6. Turbulence kinetic energy

-Velocity is the measurement of the rate and direction of change in position of an object. The average velocity v of an object moving through a displacement during a time interval (Δt) is described by the following formula:

$$v = \frac{\Delta x}{\Delta t}$$

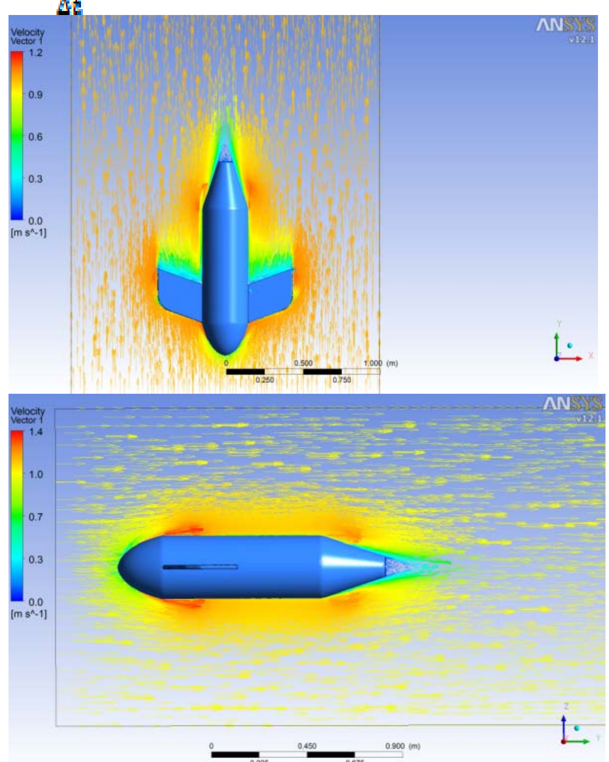
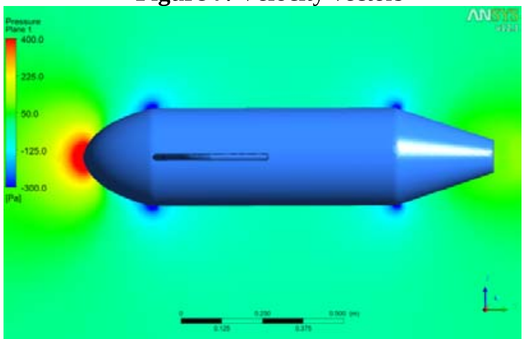


Figure 7. Velocity vectors



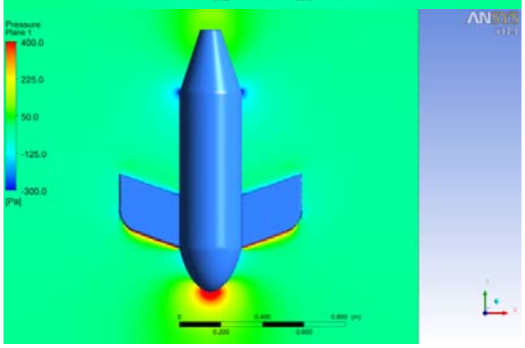


Figure 8. Pressure planes.

4. MANEUVERING CONSIDERATION

Degrees of freedom are a set of independent displacement and rotation that specify the displacement or/and the orientation of a body. In a three dimensional space a body have maximum of 6 DOF (3 displacement and 3 rotation along axis).

In three dimensions, the six DOF-s of a rigid body are sometimes described using these nautical names:

1. Moving up and down (heaving);
2. Moving left and right (swaying);
3. Moving forward and backward (surging);

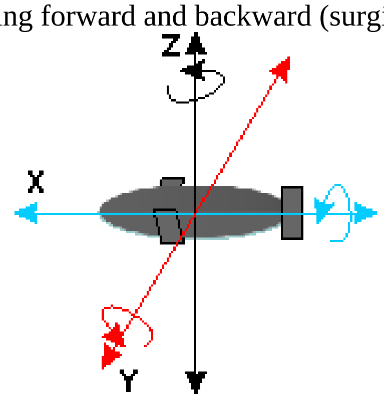


Figure 9. Degrees of freedom.

4. Tilting forward and backward (pitching);
5. Turning left and right (yawing);
6. Tilting side to side (rolling).

Most of the body on land has restricted some DOF. Take a car example: it has 2 degrees of freedom. Trains have only one because it is restricted to a rail. In water the degrees of freedom (DOF) for a body has the maximum possibility of 6: tree translation and three rotations.

First of all we must analyze the motion needed for our body (robot) and optimize from motion space perspective. If the robot is designed for move in small places and carry out a camera/sonar at least 3 degrees of freedom is needed (for dive a displacement along z axis, rotation along z axis and for move forward a displacement along x axis).

Depends on body (hull) configuration, we need to place the proper number of propeller with consideration to the maneuver space available. If the maneuver space is big the submersible robot is lend on larger water, if the maneuvering space is small the robot lend on small waters.

The maneuver space is the space in with the submersible robot can turn 360 degrees. This space depends on body/hull shape and the positioning and number of propellers mounted on body. A symmetrical submersible can reduce the maneuvering space, and also the influence of water currents which can influence the trajectory of the submersible and deviate from initial itinerary.

Best form for this is the sphere. It’s maneuvering space is the sphere. Major disadvantage is the resistance in movement for same volume shaped into a torpille form.

For example the following form will rotate along x axis at M3=-M4 speeds. Along z axis will make a complete rotation to left around a point situated at a displacement of the approximate coordinates: x=-1/2 of total length with the propeller P1 at the end of the torpille T1 at speed equal in module with P2 at the end of the torpille T2. Around the y axis a complete rotation will be executed around point situated about x=-1/7 of total length of submersible with motor M3 and M4 running of -1/3 of maximum speed and M5 running at full positive speed.

Also the weight center for a perfect equilibration of the robot must be the same with the volume center. Because of difficulty for realize this, the weight center are planed to be under the volume center of the submersible on the same z axis in most of the cases. If this is not respected the submersible robot will

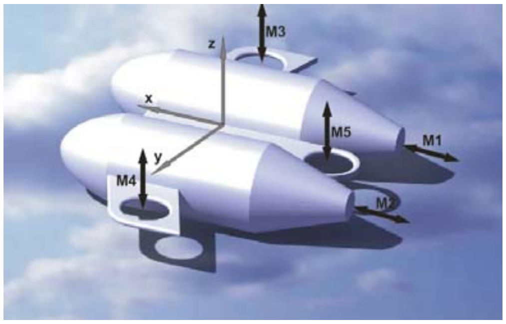


Figure 10. Shape solution one, degrees of freedom.

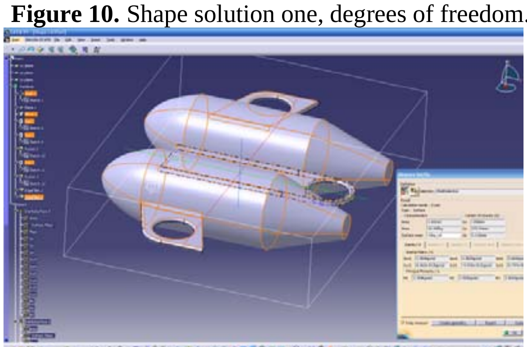


Figure 11. Shape solution one, center of weight.

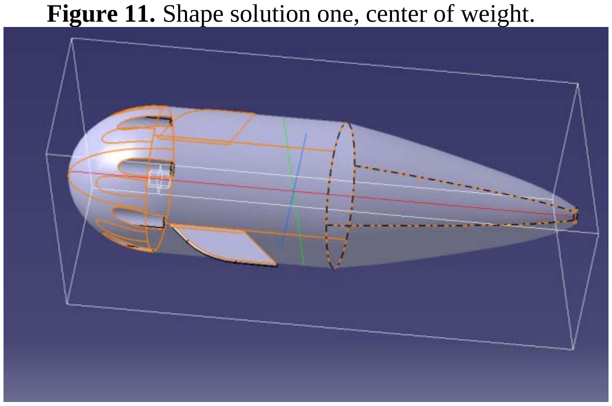


Figure 12. Shape solution two.

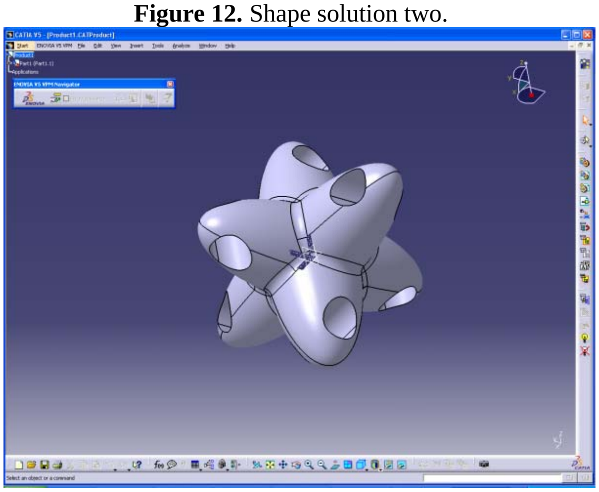


Figure 13. The solution in context from perspective of maximum degrees of freedom.

reposition itself weight center, on the position specified above, on the same vertical axis under volume center.

The second version has a large maneuver space needed. All rotation/translation are outside of the body. This is ideal for long range AUV (Automate Underwater Vehicles), but is not practical on small space lakes or spaces when maneuver operation is often required.

Another solution for best maneuvering is the following solution axed on a star structure with 6 motors. This maneuver space is the sphere in which the hull inscribes them. This type of construction has all 6 degrees of freedom. Also comparative with a sphere the displacement power needed is less on any of axis.

5. CONCLUSIONS

There are no general solutions, every solution is particularly determined for a certain type of robot.

The target of robot will determine the shape and the number of motor. If a robot is designed for purposes that need high speed then the shape of it will be designed for lower water friction resulting higher speed capabilities.

For a deep range the shape will be designed for maximum resistance at pressure minimalizing the angle of hull witch are tension concentrators.

For best maneuvering we must solve the degrees of freedom needed with the necessary number of the propulsion system.

If we consider an intermediate solution we must make some compromise to get a solution best for our purposes.

The CFD offer a simulation from where we can analyze and redesign the shape to an ideal at a very low cost and great fidelity.

The steps presented for obtain to a given propeller the representative parameters are enough for the prototype evaluation and a preliminary design parameters. There is not few cases when a underwater motor shopped earlier have to be reconsider to a robot under development and the question appear is if the existing motor have enough power for current application.

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Analiza constructiei si proiectarii Vehicolelor Submersibile Autonome (AUV) din perspectiva libertatii de miscare

Rezumat: In aceasta lucrare se prezinta o apropiere teoretica a modelarii Vehicolelor Submersibile Autonome (AUV) din perspectiva libertatii de miscare. Sunt luate in considerare parametrii elicii, numarul de motoare de propulsie in contextul unei manevrabilitati ridicate in spatii reduse si o analiza a formei si factorilor de influenta pentru a se lua in calcul acesti parametrii in reducerea rezistentei la innaintare.

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