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Steady-state Hydrodynamic Model of an Underwater Towed Vehicle

Giovanna Ambrósio de Souza
Andrea Piga Carboni
André Luís Condino Fujarra
Anelize Zomkowski Salvi
Lucas Weihmann
Thiago Antonio Fiorentin
Federal University of Santa Catarina, Joinville-SC, 89219-600, Brazil
ambrosiodesouzagiovanna@gmail.com, andrea.piga@ufsc.br, andre.fujarra@ufsc.br, anelize.salvi@ufsc.br, lucas.weihmann@ufsc.br, thiago.antonio@ufsc.br

Abstract. *One of the key factors for the effective operation of a towfish is achieving quasi-static dynamic equilibrium. Therefore, the purpose of this paper is to identify the angles of attack that promote the horizontal balance of the towfish, as well as the depth at which it is established and, to develop a communication system that allows the operator to instantly monitor the depth of operation of the vehicle during missions to confirm that data is being collected by the sensors in the designated area for study. To achieve this goal, two quasi-static hydrodynamic models are developed, one for the towfish and the other for the tow cable and, in the sequence, the modeling of the cable is coupled to the modeling of the rigid body of the vehicle to enable the identification of the angles of the hydrodynamic profiles capable of maintaining the equilibrium condition at a specific depth. Finally, an algorithm is implemented to confirm that equilibrium is achieved. This research has significant relevance in the context of ocean sciences, contributing to the advancement of underwater research, the collection of reliable data and technological development to ensure efficient decision-making to manage, preserve and regulate the use of ocean resources.*
Keywords: *Towfish, Tow cable, CFD simulation, Quasi-static dynamic equilibrium, Depth control.*

1. INTRODUCTION

Oceanic scientific research has gained significant attention in recent years, being common the use of specialized equipment designed for underwater exploration. One of the tools commonly used in scientific research is the towed system known as towfish (Cammarata and Sinatra, 2016). These non-propulsed systems function as sensor platforms, which are towed by support vessels using a tow cable.

Within the national scenario, the Federal University of Santa Catarina (UFSC) has developed a underwater towed vehicle called Towfish ECO I. This equipment serves the purpose of supporting scientific activities onboard the ECO Sailboat collecting data from the mission's location and transmitting it to a display on the vessel via an umbilical cable.

As it is a device used to reach great depths during its operation, one of the biggest challenges of its use is having the exact knowledge of the depth where this vehicle is operating. Moreover, it is essential for the operation of an underwater towed vehicle occur in quasi-static dynamic equilibrium (Cammarata and Sinatra, 2016). The control of the towfish motion is accomplished by adjusting the front control surfaces. In this sense, the vehicle's control forces and moments are due to the lift caused by the tilting of these surfaces. Furthermore, the hydrodynamic forces that act on the towfish are the tension in the tow cable, as well as the drag and lift forces of the stern stabilizer wings (Avila, 2008). In this context, to achieve the purpose of identifying the configuration that promotes the balance of the towfish at the specific depth, it is necessary to know the global hydrodynamic behavior of the system composed of the underwater towed vehicle with the tow cable, and with that, be able to properly adjust the vehicle's control surfaces. In addition, it is essential to have an electronic system capable of instantly providing the correct depth of the vehicle, so that the operator can verify if the data is being collected in the designated area for the study.

With regard to underwater vehicle behavior, it is understood that the dynamics of a underwater towed vehicle encompasses the dynamics of the rigid body and the fluid dynamics of the surrounding environment (Avila, 2008). Computational fluid dynamics (CFD) is a highly effective approach for determining the hydrodynamic coefficients of an underwater towed vehicle. CFD is a computational method for obtaining numerical solutions to problems involving the behavior of fluids. Therefore, this study has adopted numerical methods to solve the dynamic equations of the rigid body and fluid system. Using this method, it becomes possible to perform complex analyses at a lower cost compared to analytical and experimental methods, respectively (Farah and Tancredi, 2021).

In turn, the static analysis of the tow cable is of significant importance to determine the equilibrium state of towfish. Incorporating the dynamics of the tow cable into the model enables not only to include the effects of the hydrodynamic forces acting on the cable but also to represent the single propulsion force of the towfish, which corresponds to the tension in the cable at the towing point.

According to Wang *et al.*, 2018, there is a scarcity of articles on tow cable modeling. Most of the available literature focuses on two-dimensional analysis and relies on the shooting method. It is very common for authors who conduct studies on the static analysis of cables to begin their research with a two-dimensional approach, and only then proceed to three-dimensional analysis, this procedure can be found in the study by Wang *et al.*, 1993. The book by Berteaux, 1976 provides a series of solved examples for several cases of use of mooring cables, mostly in two-dimensional analysis, making it an excellent starting point for studying cable behavior. Furthermore, the shooting method involves a trial-and-error approach to solving two-point boundary value problems associated with second-order ordinary differential equations.

To identify the global hydrodynamic behavior of the system, the authors Cammarata and Sinatra, 2016, propose a methodology that combines the modeling of the tow cable and the hydrodynamic forces of the static model of the rigid body of the towfish. This integrated model enables the determination of appropriate angles for the hydrodynamic profiles, allowing the towfish to maintain a horizontal orientation at a specified depth. By incorporating the static modeling of the cable and the steady-state hydrodynamic modeling of the towfish, an algorithm is developed to search for the equilibrium configuration of the system at a specific depth. This algorithm considers the assigned angles of the stabilizer wings, the tow speed, and the length of the cable, in order to identify, if possible, the equilibrium state of system and the depth at which this equilibrium is reached.

Finally, it is known that several ocean characteristics depend on depth, such as temperature, salinity, and dissolved oxygen. The values of these variables change depending on the depth where the data is collected. Therefore, as already mentioned, it is extremely important to have knowledge of the exact depth from where the CTD probe data is being collected during a mission, in order to enable accurate analysis and provide reliable information for effective decision-making regarding the management, conservation, and regulation about utilization of ocean resources (Egan *et al.*, 2022). In that regard, to facilitate real-time transmission of the data collected by the pressure sensor, an electronic circuit employing half-duplex communication is implemented. This communication method enables bidirectional data transfer, allowing both transmitting and receiving devices to send and receive data, although not simultaneously. Consequently, the operator can instantly monitor the operating depth of the vehicle and verify if the quasi-static dynamic equilibrium condition is achieved at the correct depth.

Based on the mentioned considerations, it becomes evident that understanding the hydrodynamic behavior of the towed system is crucial to identifying configurations that facilitate the equilibrium of the towfish at the intended depth during missions. Therefore, the objective of this article is to provide an analysis of the hydrodynamic modeling, specifically in steady state condition, of the towfish with the tow cable. This modeling approach aims to determine the configurations that allow the vehicle to maintain static equilibrium at the specific depth. And to ensure that the data is being collected at the correct depth, an instant communication system is built between the towed vehicle and the support vessel.

2. METHODS

2.1 Determination of towfish hydrodynamic coefficients

In this study, the use of the numerical method was defined to solve the dynamic equations of the towfish, as previously mentioned. It is important to note that, while the numerical method offers advantages, it should not be regarded as a substitute for experimental and analytical methods. A complementary approach that uses all three methods would be ideal. Therefore, future investigations aim to experimentally validate the results obtained in this study. Furthermore, for this research, the finite volume method was adopted to discretize the investigated domain investigation. This decision was made because it is a traditional approach, in which the control volume is discretized so that the equations that model the studied problem can be applied.

2.1.1 Governing equations

Regarding the governing equations, the use of a method of numerical simulation of turbulent flows via Reynolds-averaged equations (RANS) for turbulent modeling was adopted. This method is widely employed to calculate turbulent flow and offers the advantage of not requiring significant computational resources. The RANS method involves obtaining a set of averaged equations from the Navier-Stokes equations and continuity equations.

The RANS method requires the choice of a model to represent turbulent stresses, often referred to as Reynolds tensors, which capture the influence of turbulent pressure and velocity fluctuations. In this study, the $k - \epsilon$ turbulence model was selected to simulate the flow behavior around the towfish. This model is widely used to simulate turbulent flows and yields satisfactory results when it comes to an external flow problem involving complex geometries. Moreover, it offers notable advantages, including good convergence and reduced computational consumption compared to alternative turbulence models (Wasserman, 2016).

The K-Epsilon turbulence model is a two-equation model that solves transport equations for the turbulent kinetic energy and the turbulent dissipation rate in order to determine the turbulent eddy viscosity (Siemens, 2016). Turbulent viscosity is a property associated with the flow around the Towfish, which is naturally turbulent due to its shape. In turn, kinematic viscosity is a global property associated with the control volume.

Finally, the calculation algorithm that solves the governing flow equations using the finite-volume method was defined. The selected algorithm is the SIMPLE pressure-velocity coupling and have been used the internal code of the STAR-CCM+ program. This decision was influenced by the permanent characteristics of the flow and the advantageous characteristic of the algorithm, which demands minimal computational resources. Consequently, employing this algorithm results in a quicker solution (Siemens, 2016).

2.1.2 Hydrodynamic simulation of towfish

CFD simulations were conducted to assess the forces and hydrodynamic coefficients of the towfish for different configurations of stabilizer wing angles. First, the towfish, which has a total length (L) of 0.925 m, was modeled. In addition, the simulations considered stabilizer wings featuring the NACA 0015 profile and the CTD probe. The CTD probe is utilized during missions to collect data on the conductivity, temperature, and pressure of the water column in the regions where the towfish is towed.

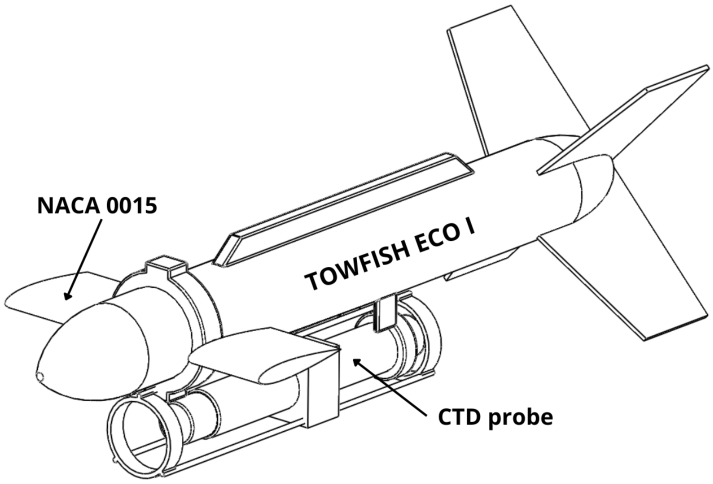

Figure 1: Geometry of towfish.

Once the geometry has been defined, it becomes necessary to incorporate it into a computational domain. This domain can be described as a section of space in which the CFD simulation solution is computed. In the case of external flows, the computational domain typically takes the form of a hexahedron and must be appropriately sized around the geometry of interest. This sizing is crucial to ensure that the assigned boundary conditions of the domain do not improperly influence the flow in the proximity of the studied geometry. In this study, the domain dimensions were established as ten times the total length of towfish in all hexahedron dimensions.

The next step is the assignment of the boundary conditions to the surfaces representing the computational domain and the geometry studied. Furthermore, it is necessary to attribute an initial value to the flow variables that corresponds to reality, including velocity and pressure. Consequently, the following boundary conditions have been proposed, which are represented in the Fig. 2: the inlet velocity was set at the frontal, side, top, and bottom regions enclosed by the domain. The pressure output region was defined as the posterior face of the domain, and the geometry of the towfish was treated as a wall surface.

The creation of the CFD simulation mesh is performed in sequence. In which, the creation of an automatic mesh with polyhedral elements was chosen, since this type of mesh is capable of providing a balanced solution to complex mesh generation problems. To optimize computational efficiency, it is advisable to employ a coarse mesh in regions that experience minimal influence from the presence of the submerged body, because these regions exhibit insignificant variations in velocity and pressure. As the mesh approaches the towfish, which represents the area of utmost interest due to substantial flow variations, progressive refinement is implemented. It is important to mention that the refinement was carried out taking into account the progressive reduction of the mesh, in order to ensure that the result found is reliable. Furthermore, to accurately capture all turbulent effects, layers of prismatic cells have been utilized around the body of the towfish. The wake region is also of paramount importance to enhance comprehension of fluid behavior around the submerged body, thus necessitating mesh refinement in this area as well. The resulting mesh used for the simulations obtained a total of cells of the order of $4 \cdot 10^7$, according to indicated in Fig. 3.

In terms of the physical configuration of the model, the following parameters have been adopted: the simulation is conducted in three dimensions, the fluid being salt water. Furthermore, the fluid is characterized by a constant density (ρ)

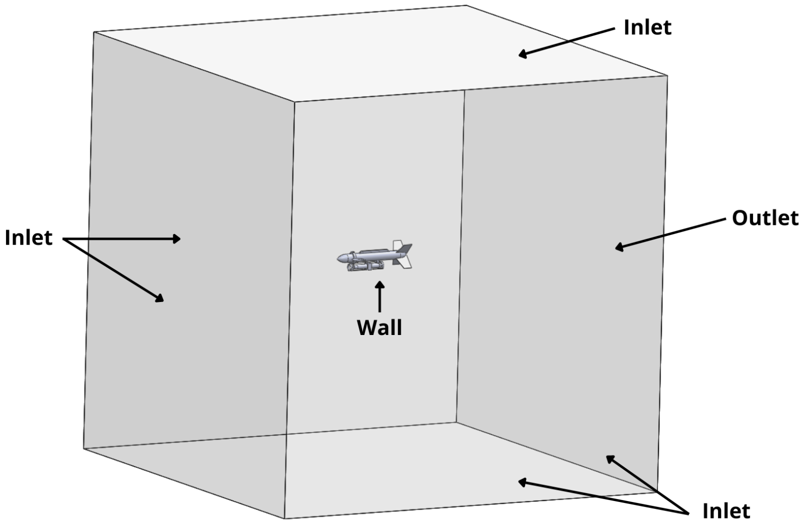

Figure 2: Boundary conditions for the towfish simulations.

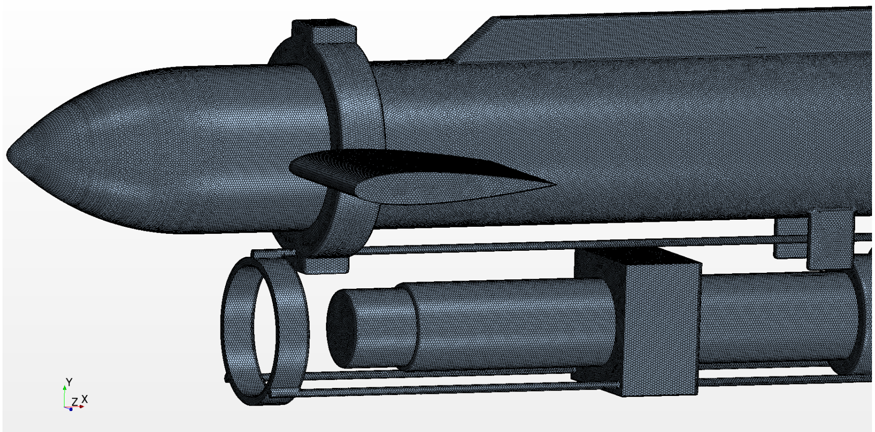

Figure 3: Mesh refinement.

of 1025 kg/m^3, a kinematic viscosity (υ) of $1,003 \cdot 10^{-6}$ m^2/s, and a dynamic viscosity (μ) of $1,002 \cdot 10^{-3}$ $Pa \cdot s$.

The flow velocity was defined in the positive x-direction, which in this case is towards the rear of the towfish. Moreover, two velocity values (v) were considered, specifically 2 m/s and 3 m/s. Consequently, simulations were carried out by varying the angle of attack of the stabilizer wings within the range of -20 to 20 degrees for both velocities.

Once the CFD model has been fully defined, the mathematical problem is solved using a numerical algorithm. The solution is obtained through an iterative process, where the initial conditions are evolved based on the specified boundary conditions, iteration by iteration. The rate of change of the solution in terms of flow variables, such as pressure or velocity, is referred to as the residual. Throughout the simulation, the residuals of each equation should progressively decrease until they reach a small value, indicating numerical convergence. In terms of convergence criteria, it is established that simulations are iterated until the residuals of continuity, turbulent energy (tke), turbulent dissipation rate (tdr), and moments in the X, Y and Z directions reach a magnitude of approximately 10^{-5}.

After the simulation is complete, the post-processing stage ensues, where the results undergo meticulous analysis to ensure a proper understanding of the flow physics. In this study, the obtained results concerning the forces and hydrodynamic moments of the towfish are presented and discussed in the dedicated section for results and data analysis.

2.2 Tow cable model

The modeling of the tow cable is based on research conducted by the authors Cammarata and Sinatra, 2016. In this way, a two-dimensional analysis of the tow cable is performed. Subsequently, the cable is integrated with the hydrodynamic forces of the static rigid body model of the vehicle. This integration aims to create a model that can accurately determine the angles of the hydrodynamic profiles necessary to maintain the horizontal orientation of the towfish at the correct depth.

The static analysis of the towline involves performing a two-dimensional modeling of the system using the shooting method for its resolution. The process can be described as follows: first, an assumption of initial condition is established, and a differential equation is integrated to obtain a solution to the problem of initial value. The final value of the solution is then used in an iterative formula to correct the initial condition. This iterative process continues until the second boundary condition is met (Filipov *et al.*, 2017).

When performing the static balance analysis of the tow cable, as depicted in Fig. 4, the forces acting on the cable are the tension of the cable, the weight force (distributed along the cable's length), the drag force and the lift force (Cammarata and Sinatra, 2016). The differential equation describing the static equilibrium equation of a cable is given by:

$$\frac{d}{dS}(T \cdot t) + F_{h\,cable} + W = 0 \tag{1}$$

Where: T is the tension of the cable; t is the unit tangent vector to the cable; $F_{h\,cable}$ is the hydrodynamic force vector, and W is the weight of the cable in water distributed along its length.

Consequently, the static equilibrium equation of the cable, in a two-dimensional scenario, the x-y plane, can be formulated as a differential equation, described as follows:

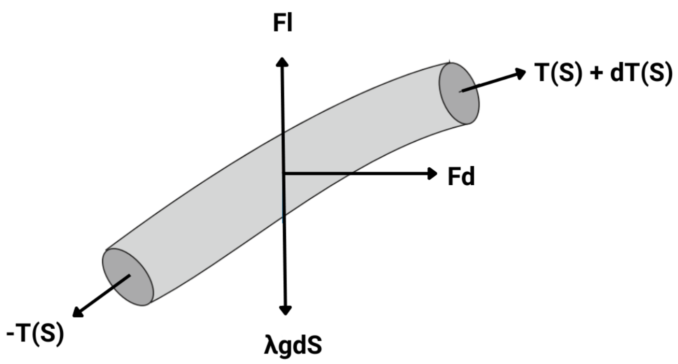

Figure 4: Diagram of tow cable static equilibrium.

$$\frac{d}{dS}(T \cdot \frac{dx}{dS}) + F_{d\,cable} = 0 \tag{2}$$

$$\frac{d}{dS}(T \cdot \frac{dy}{dS}) + F_{l\,cable} - \lambda \cdot g = 0 \tag{3}$$

Where: $\frac{dx}{dS}$ is the cosine of the angle between the tangent of the tow cable and the x-axis; T is the tension of the cable; $F_{d\,cable}$ is the drag force of the cable; $\frac{dy}{dS}$ is the sine of the angle between the tangent of the tow cable and the x-axis; $F_{l\,cable}$ is the lift force of the cable; λ represents the mass per length of the cable, and g is the acceleration of gravity.

Furthermore, by trigonometry, the following relationship holds:

$$(\frac{dx}{dS})^2 + (\frac{dy}{dS})^2 = 1 \tag{4}$$

The hydrodynamic forces, drag and lift forces, which act on the cable, are the result of the interaction with water. These forces are unknown and must be determined by performing CFD simulations for various angles of inclination. Consequently, based on the force diagram presented in Fig. 4, and considering a cable diameter of 10 mm and a weight per unit length of 2.3 kg/m, the equations used in the MATLAB code to model the tow cable are:

$$\frac{dx}{dS} - cos(\phi) = 0 \tag{5}$$

$$\frac{dy}{dS} - sin(\phi) = 0 \tag{6}$$

$$\frac{d}{dS}(T) \cdot cos(\phi) + T \cdot \frac{d(cos(\phi))}{dS} - 59.252 \cdot cos^2(\phi) - 20.904 \cdot cos(\phi) + 71.534 = 0 \tag{7}$$

$$\frac{d}{dS}(T) \cdot sin(\phi) + T \cdot \frac{d(sin(\phi))}{dS} - 84.466 \cdot cos^2(\phi) - 90.547 \cdot cos(\phi) - 23 = 0 \tag{8}$$

$$cos^2(\phi) + sin^2(\phi) = 1 \tag{9}$$

To determine the shape of the cable, the point of attachment of the tow cable to the towfish was considered to be the origin of the coordinate system. Furthermore, it is assumed that the tow speed and the forces applied at that extremity of the cable are known, being equivalent to the forces acting on the towfish during tow. Therefore, at the coupling point, the tension of the cable is equal to the resulting tensile forces Tx and Ty. Specifically, the tension in the x direction corresponds to the drag force acting on the towfish, while the tension in the y direction is equal to the sum of the vertical forces exerted on the towed vehicle. Therefore, to achieve static equilibrium, the sum of the vertical forces must be equal to zero. Lastly, the initial conditions for $cos(\phi)$ and $sin(\phi)$ come from the calculation of the angle formed by the resulting tension at the tow point with respect to the horizontal axis.

The static equilibrium equations are derived from the force diagram representing the main forces acting on the towfish, as depicted in Fig. 5. It is important to note that the shape of the initial segment of the cable is determined by the interaction of forces that act on it, resulting in a concave or convex configuration depending on the relationship between the drag force, the lifting force, and the weight force. By solving the equations that model the tow cable, it is expected that the maximum tension will occur at the end of the cable closest to the vessel (Cammarata and Sinatra, 2016). The following equations can be employed:

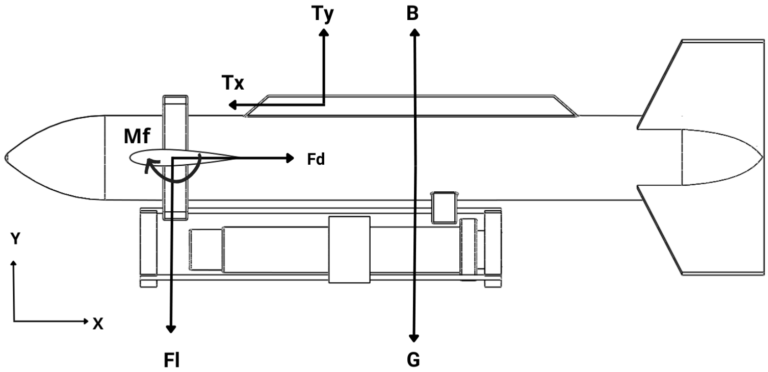

Figure 5: Diagram of forces acting on the towfish.

$$F_d - Tx = 0 \tag{10}$$

$$B - G - F_l + T_y = 0 \tag{11}$$

$$B \cdot x_g - G \cdot x_g + M_f + T_y \cdot x_t + T_x \cdot y_t = 0 \tag{12}$$

Where: B is the buoyancy force; G is the weight force; F_d is the drag force; F_l is the lift force; M_f is the moment in pitch; T_x is the horizontal component of the towline force; T_y is the vertical component of the towline force, and x_j and y_j represent the distances of the forces in relation to the stabilizer wing.

2.3 Coupling the modeling of the towfish and the tow cable

Based on the static modeling of the tow cable and the steady-state hydrodynamic modeling of the towfish, an algorithm is developed to verify, if possible, the equilibrium configuration of the towfish at a specific depth. This is achieved by defining the angles to the stabilizer wings, the tow speed, and the length of the cable.

It is important to note that the cable exhibits no lifting force in a horizontal position and that the towfish, being denser than water, naturally tends to sink. When the vehicle is immersed in water and begins to sink, it is possible to observe that the tow cable acquires a configuration characterized by an angle with the horizontal component. Consequently, this angled cable configuration generates a vertical component for the lift force. The equilibrium of the system, which is the main objective of this study, is achieved when the lifting component of the cable counterbalances the weight and buoyancy forces exerted on the towfish. By considering this condition, the differential equations governing the behavior of the cable can be solved, obtaining as a result the depth at which this equilibrium condition is achieved.

Since it is imperative that the towfish is in horizontal equilibrium during its operation, the proposed algorithm performs a final check to ensure that the condition found also guarantees horizontal equilibrium by solving the pitch moment equation. When the sum of moments is zero, the correct point of attachment between the towfish and the towline is determined, thereby establishing horizontal equilibrium for the entire system. When this final verification is implemented within the algorithm, it is expected that the equilibrium condition is discovered across a range of values applied to the stabilized wings. This variability arises because of the possibility of varying the tow cable's attachment position on the tow bar existing in the underwater towed vehicle.

The steps of the algorithm can be presented in the flow chart illustrated in Fig. 6. The algorithm's input parameters are the angle of attack of the control surfaces, the cable length, and the tow velocity. From the application of the angle in the hydrodynamic simulation for the towfish, it is possible to obtain the values for drag force, lift force, and pitch moment. Subsequently, by employing the static equilibrium equations in the x and y directions, the tension in the tow cable can be calculated at the coupling point between the cable and the towfish. With this information, the static modeling equations of the tow cable can be solved to obtain the behavior of the cable and the variation of tension along its length. Next, it is possible to use the static balance equilibrium for the pitch moment to find the position of point of attachment of the tow cable, which ensures that the towfish maintains the condition of horizontal balance. If achieving balance for the underwater towed vehicle proves unfeasible, new input parameters must be introduced into the algorithm. Therefore, the outcomes of the implemented algorithm allow for verification of the steady-state equilibrium condition for different angles of attack of the stabilizer wings, lengths of the tow cable, and tow velocities.

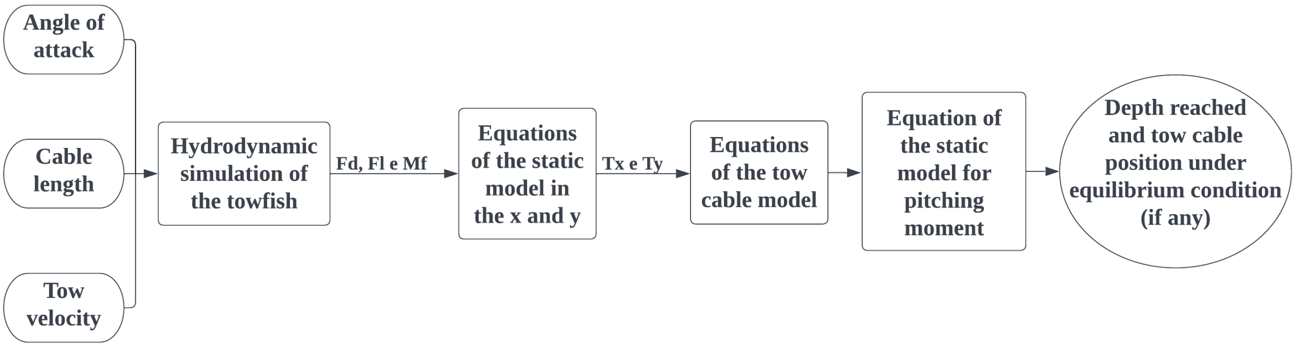

Figure 6: Flowchart of the implemented algorithm.

2.4 Half-duplex communication

As mentioned above, the development of the electronic circuit responsible for acquiring and transmitting real-time data collected by the sensor enables the operator to visualize in real time the depth of the towfish. Thus, it is possible to verify the quasi-static equilibrium condition of the vehicle at the correct depth. Consequently, the existence of a communication system between the embedded subsystem within the towfish and the embedded subsystem within the vessel that performs the towing of the vehicle is of utmost importance.

The pressure transmitter used in this system is a piezoresistive transducer. It operates by deforming its diaphragm proportionally to changes in the pressure of the environment, as it comes into direct contact with the water. Within the diaphragm, there exists a small sensor that converts this pressure variation into a corresponding electrical resistance variation. The primary objective of the developed electronic circuit is to convert this variation of electrical resistance into a depth value ranging from 0 to 200 m and to allow the real-time transmission of this depth information to the display located in the vessel. This transmission occurs through an Ethernet cable that serves not only to transmit the signal but also to provide power to the entire underwater towed vehicle system.

Taking into account the operational requirements of the towfish, which requires robust and reliable data transmission over a considerable distance in the shortest possible time, the RS-485 communication standard was adopted. This standard defines the electrical and physical specifications of the communication process, including hardware connections, operating voltage levels, device count, and maximum transmission distance.

The RS-485 standard is widely utilized in industrial applications due to its cost-effectiveness and efficient transmission speed (Kungelstadt, 2021). Within this standard, the use of half-duplex mode, which employs a pair of twisted cables that facilitate bidirectional transmission, predominates. The direction of transmission is determined by a logical signal that specifies whether the signal is being transmitted or received. Given the communication system requirements of the towfish project, which involves bidirectional data transmission without the need for simultaneous communication, half-duplex communication proved to be the most suitable approach for this application.

In Fig. 7, it is possible to observe the electronic system developed in operation with a signal generator simulating the variation of electrical resistance of the pressure sensor, half-duplex transmission through RS-485 communication from the embedded subsystem inside the towfish to the embedded subsystem in the vessel, and real-time display of the vehicle's operating depth.

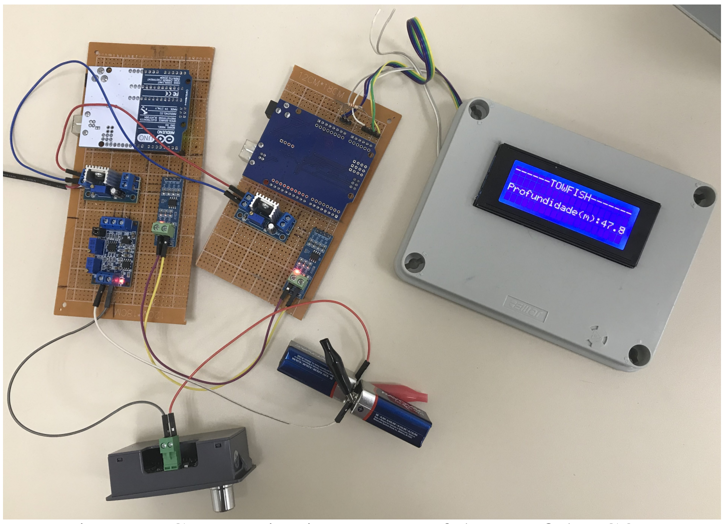

Figure 7: Communication system of the Towfish ECO I.

3. RESULTS AND DATA ANALYSIS

3.1 Result of CFD simulations of towfish

In the context of towfish simulations, by varying the inclination of the stabilizer wings between -20 and 20 degrees at a speed of 2 m/s, it is possible to obtain expressions for the drag force (F_d), lift force (F_l) and moment in pitch (Mf) as a function of the angle of attack (α). Analyzing the results depicted in Fig. 8, it can be concluded that the highest values of the drag force are observed at angles of attack with greater inclination, that is, -20º and 20º. On the contrary, the lowest drag force occurs at an angle of attack of zero degrees. As for the lifting force, there is a tendency to increase as the angle of attack increases. Finally, the moment in pitch exhibits an inverse pattern, meaning that it tends to decrease as the angle of attack increases.

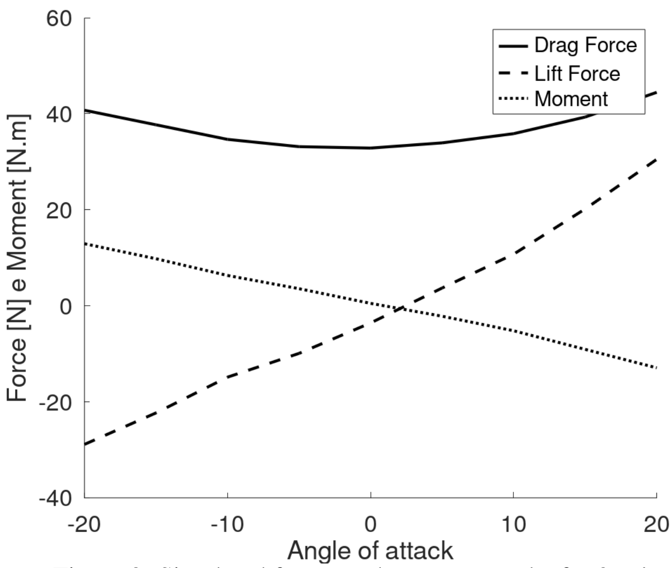

Figure 8: Simulated forces and moment results for 2 m/s.

The same analysis was performed considering a flow with a velocity of 3 m/s. The behavior of forces and moment as a function of the inclination angle of the stabilizer wings, based on the equations derived for a velocity of 3 m/s, is depicted in Fig. 9. In particular, the observed trend in the results aligns with that of the simulations conducted at a flow velocity of 2 m/s. Consequently, the same analyses mentioned above are applicable to flows with a velocity of 3 m/s as well.

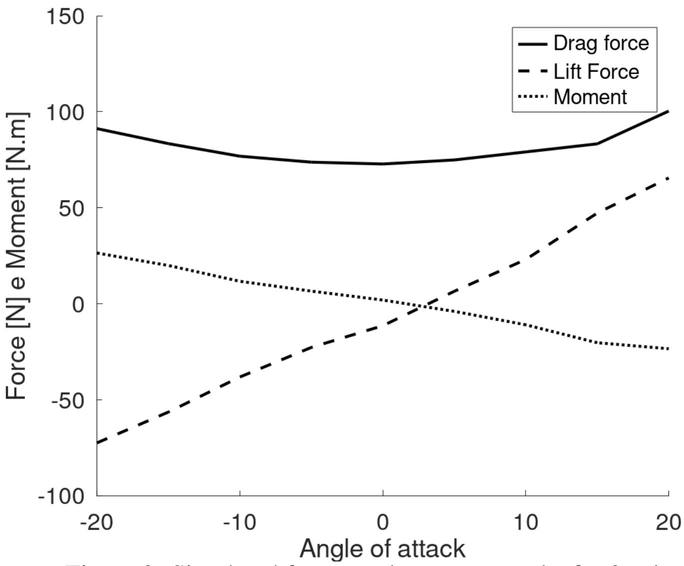

Figure 9: Simulated forces and moment results for 3 m/s.

3.2 Result of the behavior analysis of the towfish with the tow cable

The proposed algorithm can verify the equilibrium condition for the towfish, considering the angle of attack of the stabilizer wings, the tow speed, and the length of the cable. To achieve a depth of 50 m, a cable length of 150 m was adopted. In this configuration, for a tow speed of 2 m/s, equilibrium is achieved for attack angles between -1 and 8 degrees. Whereas for tow velocity at 3 m/s, the equilibrium condition is achieved when the stabilizer wing angles vary between 2 and 5 degrees.

The results obtained show that depth varies minimally for different angles of attack assuming the same tow velocity and cable length. A possible solution to solve this issue is the design of stabilizer wings with a larger surface area. With this new configuration, the lift force generated by the towfish would increase, resulting in more significant variations in the depth achieved for different angles of attack. It is important to note that the equilibrium conditions are reached with small angles of attack and no equilibrium is achieved for larger angles. This limitation can be attributed to the length constraint of the towfish tow bar, which affects the available positions to attach the tow cable to the towfish.

The cable profile under the achieved equilibrium conditions resembles the catenary shape described by the authors Cammarata and Sinatra, 2016. Figure 10 (a) illustrates the behavior of the cable when the towfish reaches equilibrium at a depth of 50 m, employing a tow cable with a length of 150 m, stabilizer wings angled at 5 degrees and a velocity of 2 m/s. Besides, for all conditions where equilibrium was reached, the tension applied to the tow cable at the end of the vessel was approximately 6×10^3 N. The variation in tension along the length of the tow cable can be observed in Fig. 10 (b).

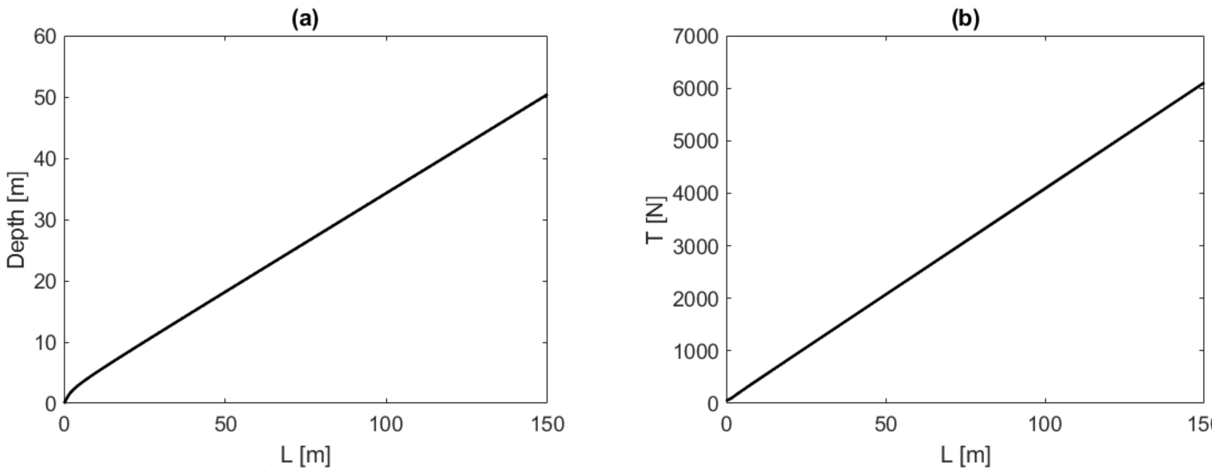

Figure 10: (a) Behavior of tow cable with length = 150 m, α = 5º and V = 2 m/s. (b) Tension along the tow cable with length = 150 m, α = 5º and V = 2 m/s.

4. CONCLUSIONS

This paper proposes modeling the global hydrodynamic behavior of the system composed of the vehicle and the tow cable and to identify configurations that promote static equilibrium at a specific depth. This understanding is crucial for the operation of the underwater towed vehicle, which is extensively used in oceanography to collect data for underwater scientific research. In addition, the communication system developed allows the operator to instantly verify the depth of the vehicle and thus ensure that data is being collected in the designated area for study. Consequently, this research has significant relevance in the context of oceanic sciences, contributing to the advancement of underwater research and technological development in this area in order to ensure efficient decision-making for managing, preserving, and regulating the use of oceanic resources.

Applying computational fluid dynamics (CFD) simulations, the hydrodynamic parameters of the towed vehicle for different angles of attack of the stabilizer wings can be determined. And, a two-dimensional model is proposed to investigate the dynamics of the behavior of the tow cable. Additionally, an algorithm is implemented to promote a global system analysis to check if equilibrium is attained within the established configurations. The results obtained enable the identification of angles of attack that promote the horizontal balance of the towfish, along with the corresponding depth where equilibrium is achieved. These results, combined with the implementation of the electronic module, provide the operator with the necessary tools to accurately adjust the towfish at desired depth, and monitor the depth during missions. Consequently, high reliability analyses can be performed with the data collected by the towed vehicle during its operational activities.

To achieve new improvements in the Towfish ECO I project, it is suggested to conduct the following tasks:

- Perform experimental tests in a test tank to validate the numerical results, obtained in this work, in relation to the hydrodynamics of the Towfish ECO I, and experimental tests at sea to validate the results obtained in this work, with respect to the global behavior of the Towfish with the tow cable;
- Study the implementation of stabilizer wings with a larger surface area, to promote the equilibrium condition at different depths;
- Implement a new algorithm, to be able to find, if possible, the angles of attack of the hydrodynamic profile necessary for the equilibrium condition to be achieved;
- From the electronic circuit implemented, develop, and design a control system to conduct the automatic adjustment of the stabilizing wings of the Towfish ECO I.

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