An Underwater Towed Vehicle to Monitor the Sicily-Malta channel

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Keywords: Underwater vehicle, Towfish, sea pollution monitoring

SUMMARY: The problem of monitoring pollution coming from oil spills assumes wide importance for the highly congested Sicily-Malta channel. Hydrocarbons, as well as other polluting substances, have a huge influence on the health status of the sea. In this paper we present the preliminary design of an underwater towed vehicle (UTV) to monitor the Sicily-Malta channel. The design of this towfish incorporates ideas for a camera, lens system and stroboscope illumination system that can be used to take images of phytoplankton and zooplankton having a size range of 100 microns up to 1 centimeter. The underwater platform includes a high definition (HD) camera for monitoring jellyfish population at different sea depths. Unlike the autonomous underwater vehicles (AUVs), an UTV is not independent and must be towed by a surface boat. This disadvantage is balanced by having a simpler design and control system and an increased payload for instruments, sensors and cameras due to the absence of heavy battery systems. In order to increase maneuverability, stability and depth control, actuated hydroplanes are used to vary the angle of attack and to change the total downward force exerted on the moving towfish. The depth of dive of the towfish is automatically controlled to a set value. Automatic control is preferred so as to reduce the work and human concentration necessary during a monitoring mission. The hydroplanes are used to control rolling and pitching of the towfish. This kind of corrective action and a means of knowing the inclination of the towfish are deemed to be necessary because of the effect that underwater currents may have on the dynamics of the towfish. In addition to active control against the rolling action, the main hydroplanes (wings) of the towfish are at a small anhedral angle in order to create a passive anti roll action by creating a corrective moment acting about the main longitudinal axis of the towfish. The stern of the towfish also carries a rudder. The rudder would mainly be used when turning and to steer the towfish away from the surface boat wake when taking surface or close to surface measurements. The towfish is towed via an umbilical cord which carries all the power supply and signal lines necessary for towfish control and data acquisition. The umbilical cord is mechanically strong enough in order to tow the underwater towfish which is subjected to hydrodynamic drag. For proper logging and mapping of pollutants and camera images it is required to know the exact position and positional depth of the towfish during a mission. The positional depth of the towfish is recorded by means of a depth sensor. The position of the towfish is found by having a Global Positioning System (GPS) on the surface boat coupled with a commercially available sonar based instrument that can be used to calculate the relative position between the surface boat and the towfish.

1 INTRODUCTION

The work presented in this paper includes work done within the project BIODIVALUE (Biodiversity and Sustainable Development in the Straits of Sicily) funded through the European Union Regional Development funds (ERDF) Italia-Malta 2013. The project aims at supporting the monitoring of pollution at sea in the straits of Sicily, hence contributing to drawing future legislation at national and European level. The harmful effects of pollution from shipping operations is not currently sufficiently monitored, evaluated and managed. The project involves the study and analysis of maritime traffic in the Strait of Sicily, the emissions produced by it and the biophysical consequences of these emissions on the local flora and fauna. The underwater towfish is being designed and developed in order to monitor the marine pollution and plankton distribution in the Mediterranean sea between Malta and Sicily. Detection of marine pollution is based on the quantities of hydrocarbons resulting mainly from seafaring vessel traffic. Other equipment that is considered for the towfish is a nitrate sensor, a conductivity, depth and temperature sensor (CDT) and a PH sensor. In order to observe quantities and distribution of phyto and zoo plankton the project aims at developing a recording camera having the capability to zoom and film these micro species of sea plants and animals. An additional camera is also added for observing jellyfish population in certain regions of the Mediterranean sea. The towfish is designed to reach a maximum depth of 50 m below sea level. A solid model of the preliminary design of the towfish is shown in Figure 1.

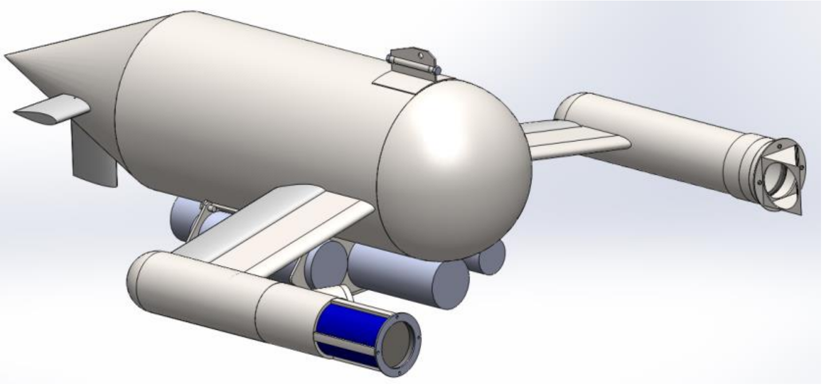


Figure 1: Solid model of the proposed towfish

Before the start of a monitoring mission the towfish is kept on the deck of the surface boat. The umbilical cord is wound on a drum connected to a manual/powered hoist. The towfish is connected at the other end of the umbilical cord. The towfish is then lowered in the sea (via a winch). So as not to foul the umbilical cord, the surface boat is driven slowly forward so that the floating towfish distances itself away from the boat. When all the cord (or part of it as necessary) is reeled out, the drum and hoist are locked and the power supply, signal and fiber optic connections are connected to their respective instruments. The mission can then start. The boat is brought up to the required speed and the towfish can then be driven/controlled from on board. At the end of the mission the boat is stopped and the positively buoyant towfish starts rising through the water until it reaches the sea water surface. The signal and fiber optic connections are disconnected from their respective instruments. The drum and hoist are unlocked and the umbilical cord is reeled in, pulling the towfish nearer to the boat. The towfish is then recovered manually or via using a winch.

2 STRUCTURAL DESIGN OF THE TOWFISH

Different possible configurations for the towfish were considered. One idea was to design a completely watertight vessel. Another idea considered a combination of watertight compartments (for creating upthrust and for placing non-water resistant equipment) and an open frame structure. After considering the watertight volume required to house all the equipment required inside the towfish it was decided to design and fabricate a complete watertight pressure vessel. The towfish consists of 3 main geometries, a cylinder, a cone and a hemisphere, shown in Figure 1. These major structural components of the towfish were designed and sized according to the EN 13445-3:2009 ‘Unfired Pressure Vessel’ European standard’ [1]. Such design involved mainly the calculation of the shell thickness for the four main components (hemisphere, cylinder, cone and the side arms/cylinders that will house the jellyfish and VPR cameras under external pressure. The main design criteria was to prevent buckling or excessive deformation of the shells. Concentrated loads such as the moment and shear load due the towing lug and hydroplanes attached to the main cylindrical and tail section were also taken into consideration. The design considers internal stiffeners in order to reduce the cylindrical shell thickness. The material considered was a pressure vessel mild steel type plate (P355N steel grade) having a minimum yield strength of 355MPa. The design by formula (DBF) method was used for the calculations.

Table 1 shows a summary of the overall dimensions and mass of the towfish components together with the minimum shell thickness required for the towfish to operate at a sea-water pressure of 0.503 MPa.

Table 1: Summary of the minimum thickness and corresponding mass for every P355N steel shell to operate at a pressure of 0.503 MPa according to the EN13445-3:2009 code

Shell Component	Mean Diameter (mm)	Length x Breadth (mm)	DBF Thickness (mm)	Mass (kg) [P355N – 7820 kg/m^3]
Cylinder (Internal Stiffener Supported)	300	600	2.0	8.84
Internal Stiffener (x3)	140	/	2.0	0.82
Hemi-Sphere	300	/	1.0	1.96
Cone	300	400	1.5	1.47
Arm (x2)	110	370	1.5	3.00
Nozzle Reinforcing Plate (x4)	295	150 x 150	3.0	2.11
Towing Lug Reinforcing Plate	304	100 x 70	2.0	0.11
Total	/	/	/	18.31

As previously mentioned, a CDT and Ph, Nitrate and Hydrocarbon sensor (each type is available as an individual piece) are to be attached to the underside of the towfish as shown in Figure 1. The decision to attach them at the towfish lowest position was taken to help maintain the towfish stable during the mission. The overall dimensions of the main cylindrical part of the towfish was decided upon based on the sensors' dimensions and length. Market research on available sensors showed that their overall shape is cylindrical. Furthermore, their length and diameter were less than (or equal to) 600 mm and 100 mm respectively. An estimate of the total sensor weight resulted to be equal to 11 kg. For sufficiently accurate data measurement to be obtained the sensors require their corresponding probes to be constantly exposed to the flow of sea-water hence the reason why they would be attached external to the body of the towfish. Consequently the length of the cylindrical part was set to the maximum length of the sensor (600 mm). Furthermore, the length of the tail cone was set to 400 mm. This dimension was decided upon in order to minimise the turbulent wake behind the towfish and so reduce drag. The diameter of the towfish was set to 300 mm in order to produce enough upthrust (approximately 68 kg) for the towfish to re-surface on its own once the mission terminates. The upthrust value could not be accurately determined at this stage since the main hydroplane structure has still to be determined at a later stage. In addition to the aforementioned three sensors, two specific cameras are required to be fitted to the towfish as described previously and as shown in Figure 1. An arm (cylindrical housing) on each side of the towfish at the end of the main hydroplanes were designed in order to house and support both the jellyfish and VPR cameras. Since the jellyfish camera can be purchased directly as a waterproof camera, it will not require additional housing but only a supporting structure, whereas the plankton camera system cannot be directly bought as a single waterproof package, hence it requires a housing to be manufactured for this application. Other positions to attach the camera system were considered, these are: to attach the jellyfish camera on the bow of the main body and the stroboscope and plankton camera on each of the arms of the towfish, while another configuration was to place the plankton camera in the bow and stroboscope in one of the arms respectively and the jellyfish camera on the other arm (Figure 2).

The former setup (Figure 2a) was ignored since the light of the jellyfish camera might interfere with the viewing path of the plankton camera, and the latter format (Figure 2b) was excluded due to optical problems of the plankton camera to focus within a shorter distance. CFD (Computational Fluid Dynamics) analyses were conducted in order to determine the best shape for the bow and a suitable position for the arms of the towfish. The analyses were carried out at a towing design speed of 12 knots and the objective was to avoid turbulence in the volume of water that is within the field of view of the plankton VPR and jellyfish camera. Figure 3 shows the turbulent intensity around the towfish for a sample different geometries of the bow. It was decided to place the plankton VPR camera so that its image path falls outside any turbulent wake which may occur due to the bow (hemispherical part) of the towfish. Because of this the main hydroplanes were shifted near to the bow so that the length of the arms are minimised as much as possible. A pair of hydroplanes were fitted to the conical tail in order to keep the pitch angle of the towfish parallel to the flow/travelling direction. This minimises drag and aligns the field of vision of the jellyfish

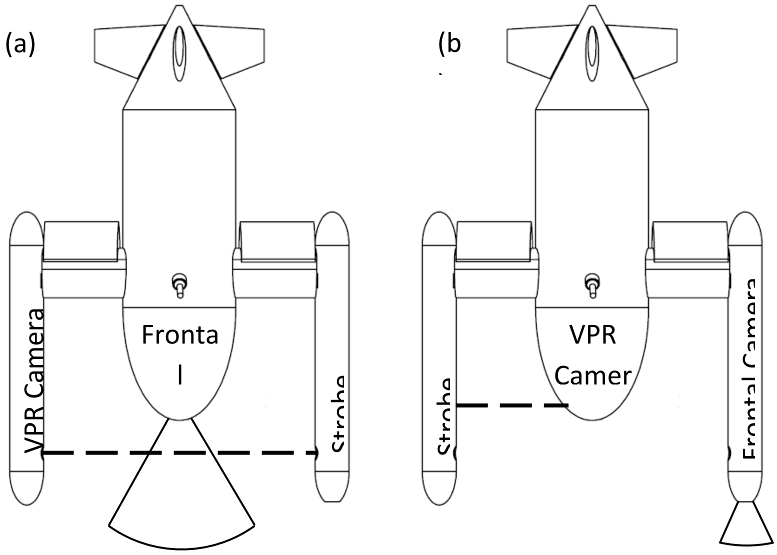


Figure 2: Two different configurations for the VPR camera, strobe and jellyfish camera

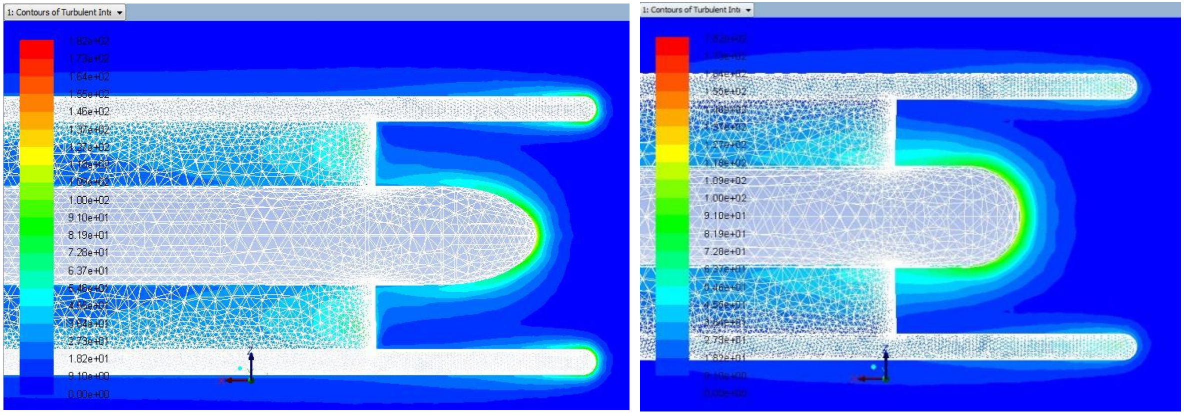


Figure 3: Turbulent Intensity around the towfish, for different shapes of the nose. The flow between the hands is less affected on the towfish with a hemispherical nose (right hand figure)

camera to being in front of the towfish. Figure 4 shows a plan view of the finalised towfish and camera setups.

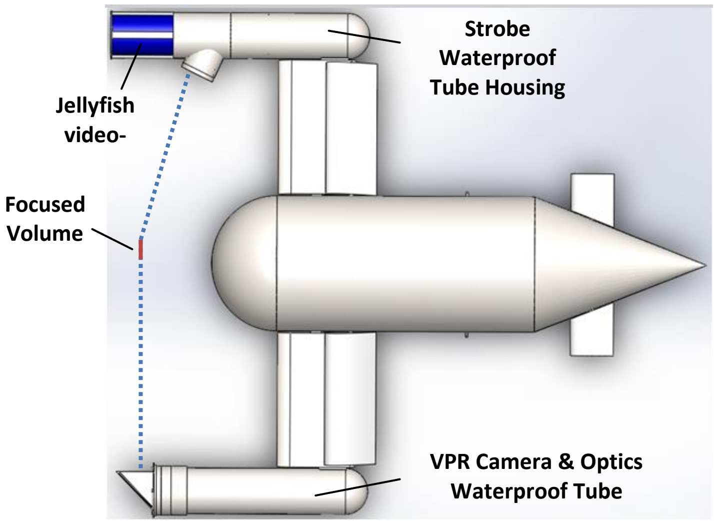


Figure 4: Towfish cameras, hydroplane and optics layout

3 DEPTH OF DIVE AND ROLLING/PITCHING ACTION OF THE TOWFISH

The depth of dive, rolling and pitching actions of the towfish are controlled by means of hydroplanes. The towfish requires the hydroplanes to be constantly controlled in order to maintain the required depth and stance. The design of the hydroplanes requires them to be streamlined at all times. Due to a sudden movement of the towfish caused by a disturbance (such as underwater turbulence or a sudden pitching movement of the surface boat whose effect will travel through the towline) it is envisaged that automatic control is used so that the towfish regains the set depth, position and orientation in the pitching direction. This way, during a mission, there is only the need of setting the required depth using the computer on the surface boat. This is achieved by using a depth sensor, a pitch and roll inclinometer and an on-board the towfish controller. Servo motors are then used to vary the angle of the hydrofoils accordingly.

There are three towfish movements that the hydroplanes need to control. These are the roll, the pitch and the depth movements. All three movements are controlled by the main wing ailerons and by the tail elevator. There are two main ailerons (connected to the main hydroplane) and they move independently one from the other so as to be able to control the roll of the towfish. As they are the largest control surface on the towfish and can create a large lift, they are also suitable to control the depth of dive as well. Pitch control, however, is achieved by both the main ailerons and the tail elevators, creating a moment that will counteract an undesired pitch angle. The motion of the rudder is independent. It is to be used when turning and to steer the towfish away from the surface boat wake when taking surface or close to surface measurements.

In order to control the angle of attack of the main and tail hydroplanes a microcontroller receives the signals from the depth sensor and from the inclinometer and calculates a suitable angle of attack by means of a PI-PID control. Stepper motors were chosen to control the ailerons due to their precision and small incremental movement. Step sizes of these motors usually are around 1.8 degrees, so the use of a gearbox is required. A worm gear with low backlash is used to further increase angular precision and to hold the hydroplanes fixed in a stationary position when the set stance parameters are reached.

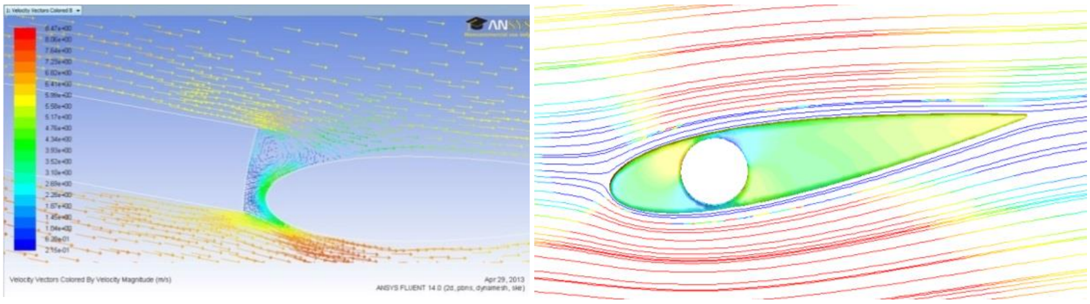
Two designs of the main hydroplanes were considered. For both of them a NACA 00XX symmetrical shape was chosen. The first design consists of a fixed structural part in front and a moving structural part at the trailing edge of the hydroplane, Figure 5-a). The fixed part would be used to support the arms and to pass the required wires from the main body of the towfish to the cameras and strobe light located in the two arms. The second design consists of only one whole rotating hydroplane. The support for the arms would also act as the axis on which the main hydroplanes rotate, Figure 5-b).

The advantages and disadvantages of both designs are various. The first design can carry a larger bending moment at the end fixed to the towfish since it can have a higher second moment of area than the hydroplane axis of the second design. Similarly following the first design ensures a more robust axle for the hydroplanes therefore reducing the incidence of the malfunction of the rotating part. The first design also caters for more hollow space to pass the necessary power and data wires between cameras and towfish main body. For the first design the gearbox/stepper motor setup can be assembled directly to the wing axle without the need of any other device or system. To implement the actuator and mechanism for the second design there might be the need for another link such as gears external to the towfish thus making it more prone for the mechanism to suffer damage from the environment. The disadvantage of the first design is that the fixed part in front of the main ailerons disturbs the water flow and makes the wing less efficient, needing more angle of attack to reach the same lift, which in turn creates more drag. For both designs an anhedral angle on the ailerons is used to provide passive control on roll. This may make the active control for roll superfluous for most of the time but will be implemented in case of major flow disturbances. Initially the choice for all the hydrofoils of the towfish had a NACA0015 (symmetric, maximum thickness = 15% length) shape. This is a common hydrofoil shape used on rudders and the reason for this being that it has a good drag/lift ratio and is still thick enough to keep structural stress within acceptable limits. The size of the hydroplanes must be enough to overcome buoyancy so as to make the towfish sink when under tow. To a certain extent the wingspan depends on the focal length of the VPR camera. This means that the parameter that could be changed in order to vary lift is the chord of the ailerons.

For the first design consisting of a fixed and a rotating part, CFD simulations of the flow around the towfish have been performed at speeds between 6 and 12 knots and a chord of 0.4m, 0.3m, 0.2m and 0.15m. It was found out that chords of 0.4m and 0.3m provide too much lift for a small angle of attack (AOA) and thus have to be avoided. Even at the lowest speed of 6 knots a small change in AOA creates a great change in lift, making the control of the towfish impossible. A small error in the AOA of the aileron would result in a large change in lift and so in a change in the depth of dive. Errors in the AOA can arise due to backlash and other mechanical clearances in the drive/gearbox mechanism. The most suitable wing chord for speeds of 6 knots was found to be 0.2m. For higher speeds, the chord of the hydrofoil has to be further reduced to 0.15m. For a forward speed between 10 and 12 knots the chord length would need to be reduced further. For the first design the aileron hydrofoils are made of a fixed frontal part that supports the arms and a rotating hydrofoil of the same thickness so that further reducing the chord of the hydrofoil might make the fixed part too thin to hold the arms of the towfish (the NACA0015 shape has a thickness/chord ratio of 0.15). A wider shape airfoil, the NACA0018, was therefore chosen, having a chord of 0.12m. The drag and lift for this hydrofoil shape for different forward speeds and different AOA is shown in Table 2.

Table 2: Drag and Lift for different forward speeds and different AOA (First design for the hydroplane)

Speed (Knots)	AOA (^{O})	Drag (N)	Lift (N)
12	-5	1695	-188
12	-10	1726	-579
12	-15	1837	-1065
10	-5	1192	-98
10	-10	1212	-408
10	-15	1288	-741



a) b)

Figure 5: a) First design: flow between the fixed wing and the aileron; b) Second design: flow on the fixed wing.

For the first design being suggested i.e. the hydroplane consisting of a fixed and rotating part it was concluded that a NACA0018 with a chord of 0.12m provides the necessary lift. In order to minimise the driving torque required to rotate a hydrofoil consisting of only one whole part the moment is normally applied at the one fourth chord length position. In the case of the first hydroplane design this consists of a fixed part and a rotating part so that the best place to rotate the hydroplane in order to minimise torque had to be calculated. Table 3 shows the torque applied at different positions along the hydrofoil centerline (cordon) for different AOAs on a NACA0018 wing having a chord length of 0.12m and a wingspan of 0.22m for the first design configuration. The maximum torque applied occurs at a position 0.035m of the chord length (0.12m) and has a value of -0.3Nm. In order to select the servomotor and driving mechanism required this torque value must be further multiplied by a factor of safety. This is done because the required torque is highly dependent on the AOA (at angles larger than 25° the torque increases rapidly) and on the precision of the aileron-axle assembly (a small deviation around the 0.035m position would greatly increase the torque required).

Table 3: Torque applied at different places of the hydrofoil centerline (cordon) for different AOAs on a NACA0018 wing having a chord length of 0.12m and a wingspan of 0.22m (First design for the hydroplane)

		Angle of Attack AOA (degrees)				
		5	**10**	**15**	**20**	**25**
Cor don (m)	**0.0325**	-0.4	-0.5	-0.9	-0.8	-1.4
	0.0350	-0.1	0.0	0.2	-0.1	-0.3

	0.0375	0.1	0.5	0.5	1.0	0.9
	0.0400	0.4	1.0	1.3	1.9	2.0

For the second design a unique rotating wing with airfoil NACA 0018 – chord/high equal to 250x345 mm, has been chosen. The plain of the wing is lowered with respect to the first design so as the rotation axis intersects the longitudinal axis of the main body. The conical surface at stern is modified, as well as the supporting skid, the stabilizers and rudder. As for the first design CFD simulations of the flow around the towfish have been performed at a speed of 12 knots. Figure 6 shows the streamlines and the pressure field all over the towfish surface when the AOA is equal to 8°.

Finally, Figures 7a-b) respectively report the total and the local (on the rotating airfoil) lift, drag and pitch torque evaluated with respect to the change of AOA of the mobile wing.

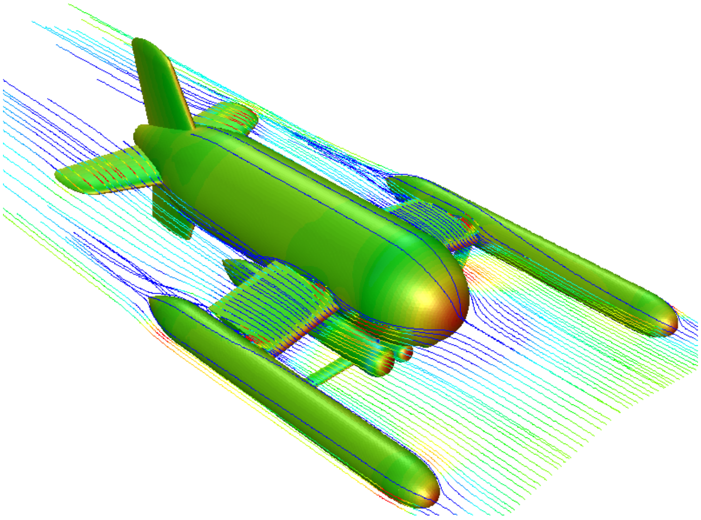


Figure 6: Streamlines and pressure distribution: AOA 8°.

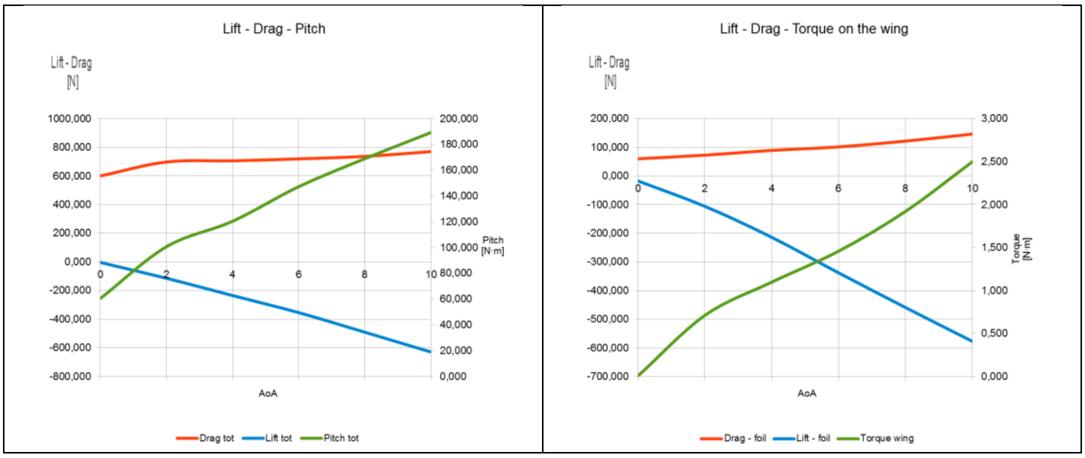


Figure 7: a) Total Lift, Drag and pitch torque; b) Lift, Drag and pitch torque for the rotating airfoil.

4 POSITION OF THE TOWFISH DURING A MISSION

For proper logging and mapping of pollutants and camera images, it is required to know the exact position and positional depth of the towfish during a mission. The positional depth of the towfish is recorded by means of a depth sensor mounted below the towfish as shown in Figure 1. For monitoring the exact position of the towfish, it is envisaged to have a GPS on the surface boat coupled with a sonar based instrument to map the position of the towfish relative to the boat. Sonar based instruments are commercially available and these can be used to calculate the relative position between the surface boat and the towfish. The method on which the positioning instrument works is called the Ultra-Short Baseline (USBL) method and is normally used for underwater positioning systems [2]. It consists of a transceiver mounted under the towboat and a transponder placed on the towfish. A computer is used to calculate the position of the towfish measured by the transceiver. A sound pulse is transmitted by the transceiver and identified by the transponder, which then sends again its particular sound pulse. This pulse is then picked up by the transceiver which measures the underwater angle and range. The transceiver contains within itself three or more transducers individually separated by a baseline of for example 100mm or less in order to calculate the angle to the underwater transponder by means of ‘phase-differencing’. USBL instruments are also found to operate under an inverted configuration (iUSBL), where the transceiver is mounted on the towfish and the transponder on the towboat. Such configuration is important in situations where an autonomous underwater vehicle (AUV) is used to perform an automatic seabed docking procedure (docking equipped with the transponder). Another commercially available positioning instrument is the DVL system [3], which provides speed relative to the sea floor or the surface of the water. Once the towfish loses the GPS signal when going underwater, the DVL system tracks the speed and heading of the towfish and, adding the distance travelled to the last GPS position, it calculates the current position with an error depending on the distance to the sea floor or sea surface.

5 POWER SUPPLY AND SIGNAL LINES

HD Cameras, sensors and actuators for controlling the towfish require a direct current (DC) electrical supply. It is envisaged that a DC power supply is available on board the surface boat and then power is transmitted to the towfish via the towline. If necessary some batteries may also need to be placed on board the towfish. It is being planned to avoid this in order to reduce the total weight and in order to reduce the need of opening up the towfish in the middle of a mission to change or re-charge the onboard batteries. Having batteries on board the towfish may imply keeping an amount of charged batteries on standby on the surface boat and this needs to be avoided.

6 TOWING CABLE ANALYSIS

The tow cable is a very important element since it has a very crucial role: it allows to tow the towfish and to feed all the electric/electronic devices inside it such as: sensors, servomotors, data acquisition boards and so on, [4],[5]. Besides the power supply, it must also grant the transmission of data provided by environmental sensors, beside a sensors that are necessary to control the towfish attitude. The best choice is to use the optical fiber for the transmission of data and a copper cable to provide power (DC), so as to avoid interferences. The choice of the optical fiber can send data in real time, as instance those coming from cameras, which require a large-bandwidth.

7 JELLYFISH AND PLANKTON VIDEO CAMERA

A video camera will be used in order to aid the gathering of information about jellyfishes. The frequency of pictures taken depends on the speed of the surface boat, and it has to be slow enough to let the volume of water photographed be completely filled with fresh sea water between one picture and the next. Knowing the dimensions of this volume and the distance travelled by the towfish, it is easy to know the density of jellyfish in any given area.

A video camera, equipped with telephoto lens and extension tubes, together with an opposing facing stroboscope (red filtered to reduce detection and disruption of plankton) needs to be used

for the imaging of plankton and other similar animals with a size range of 100 microns up to 1 centimeter. The video camera is focused approximately midway distance between the camera and the stroboscope. The strobe is used to illuminate the focused volume by a series of flashes:
both the frequency of the strobe and that of the camera must be the same because the opening of the shutter must coincide with the light pulse. The video camera and the stroboscope need to avoid any form of hydrodynamic disturbance generated by the towfish or towing cord and so it is required that such equipment is not positioned at the stern of the towfish. It is envisaged that a pair of supports, i.e. arms, attached to the hydroplanes in the middle part of the towfish, should be fixed parallel to the towfish body and projecting towards the front part of the towfish. Both the camera and strobe housings can be positioned in a way to produce the least drag by using 45° mirrors. Moreover, such cameras should not be aligned towards each other, but slightly at an angle in order for the strobe beam to be directed just past the camera, hence the resulting image of the plankton would be caused by the ‘off-axis illumination’, [6]. The manual lens let the focus to be optimized in the center of interest, both adjusting the focal length and the opening: the latter influencing the desired depth of field. Such system requires again a software interface to automatically detect the plankton distribution and even measure their respective size. The housing of the camera and strobe can be built with the required dimensions to fit the equipment. Dark colors could be used to minimize detection by the plankton and so minimise their disturbance.

8 CONCLUSIONS AND FUTURE WORK

The design of an underwater towed vehicle to monitor the Sicily-Malta channel has been proposed. The towfish must provide measurements of physical and chemical parameters pertaining the health of the sea. In order to face this task it has been equipped with different sensors such as CDT, pH, Hydrocarbon and Nitrate sensors. A camera to view jellyfishes and a system of camera/strobe to study plankton have been also included. The maneuverability and stability of the vehicle is devoted to actuated hydroplanes and a rudder. Two different designs of the hydroplanes have been considered and compared. A towline feeds the required power and exchanges control and sensor signals from the boat to the towfish and vice versa.

The final design, actually under study, will yield a prototype to be tested for the campaigns of measurement.

9 ACKNOWLEDGEMENTS

This project is being funded through ERDF (European regional Development Funds) Italia-Malta 2007-2013. The authors also wish to acknowledge the use of the ANSYS software academic research license provided to the University of Malta and the University of Catania.

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