Lat. Am. J. Aquat. Res., 44(5): 926-934, 2016
“Pathways for sustainable industrial fisheries in southeastern and southern Brazil”
P.M. Arana, P.R. Pezzuto, A.O. Ávila-da-Silva, D. Queirolo, J.A.A. Perez & C.A. Arfelli (eds.).
DOI: 10.3856/vol44-issue5-fulltext-5

Research Article

Mechanical undulating towed vehicle for collection of oceanographic data

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ABSTRACT. The need to associate the collection of oceanographic data with the use of opportunity vessels, particularly the fishing fleet, has attracted growing interest in the development of underwater equipment or vehicles fitted with multi-parameter seawater probes. Thus, four digital models of undulating tow vehicles were developed, called U-Tow, using the software program SolidWorks, to be made from fiberglass and fitted with an electronic probe that continuously gathers oceanographic data on the ship’s course, and details of the water column. The undulating system was conceived to be fully mechanical and adjustable, according to the requirements for collections performed under a wide variety of conditions stipulated by different opportunity vessels, without the need for specific training of the crew, or unnecessary occupation of space on the deck. The aim is to improve the different models presented (U-tow I to U-tow IV) in terms of their hydrodynamic, accessories for equipment protection, and ease of operation in terms of installing the probe inside the equipment.

Keywords: oceanographic parameters, opportunity vessels, continuous sampling, vertical profiles.

Vehículo mecánico ondulatorio de remolque para la obtención de datos oceanográficos

RESUMEN. La necesidad de una asociación entre la obtención de datos oceanográficos con el uso de embarcaciones de oportunidad, en particular la flota pesquera, ha despertado interés en el desarrollo de equipamientos o vehículos subacuáticos que porten sondas multiparamétricas en agua de mar. De esta manera, se desarrollaron cuatro modelos digitales de vehículos ondulatorios de remolque, denominados U-Tow, mediante el programa SolidWorks, que puedan ser confeccionados en fibra de vidrio y portar una sonda electrónica para la obtención de datos oceanográficos de forma continua, involucrando el rumbo de la embarcación y datos de la columna de agua. El sistema de ondulación fue idealizado para ser totalmente mecánico y ajustable, de acuerdo con los requisitos exigidos para que las colectas sean efectuadas en las más diversas condiciones estipuladas por diferentes embarcaciones de oportunidad, sin la necesidad de capacitación específica de la tripulación ni ocupación innecesaria de espacio en cubierta. Los diferentes modelos presentados (U-tow I a U-tow IV) buscan mejorías en términos de hidrodinámica, accesorios de protección del equipamiento y facilidades de operación en lo que se refiere a la instalación de sonda en su interior.

Palabras clave: parámetros oceanográficos, embarcaciones de oportunidad, muestreo continuo, perfiles verticales.

INTRODUCTION

Undulating samplers were first developed at the beginning of the 1960s (Glover, 1967), but their success was impeded by the lack of appropriate equipment to perform the measurements of environmental parameters, such as temperature, salinity, dissolved oxygen and inorganic nutrients, needed to interpret the characteristics of water bodies in the oceans.

In 1970, the Scottish Oceanography Laboratory signed an agreement with Plessy Marine Systems Unit (PMSU) for the development of a digital tape with enough capacity to store several hours of video over about 1,000 miles. During this same period, the PMSU began

Corresponding editor: Patricio M. Arana

Vehicle (UTV) capable of reaching depths of 5-75 m without changing the pitch or towing speed. The UTV had watertight electronic equipment capable of receiving and storing information from eight probes that picked up different oceanographic parameters. After several years of development, the "Undulating Oceanographic Recorder" (UOR) MARK 1 was created (Reid *et al*., 2003), and it was capable of operating at speeds of up to 15 knots, with undulating depths of 8-70 m; also, its depth could be altered without having to change the length of the tow cable.

Despite the differences between the various models, a pattern observed is that all three vehicles consist of three main structures: the vehicle itself, the cable, and the towing winch. The vehicles are classified in two categories: those with active depth control and those with fixed depth control.

Vehicles with active depth control (undulators) can make vertical movements while being towed horizontally. Their main advantage is the ability to measure vertical profiles of oceanic properties, associated with a high horizontal spatial resolution. Their disadvantage is their inability to achieve depths greater than 1000 m while being towed at cruising speed.

The most common types of undulating towed vehicles are the Batfish (Quildline Instruments (Canada), the SeaSoar (Chelsea Instruments, UK) and the Scanfish (Macartney A/S Denmark), with hydrofoils that can be controlled through a servomotor connected to a cable that attaches it to the vessel. The Aquashuttle (Chelsea Instruments, UK) is a fully independent vehicle with pre-programed depth control, and the Moving Vessel Profiler (Brooke Ocean Technology Ltd., Canada) has fixed hydrofoils, and depth controlled by means of a high performance winch.

Vehicles with fixed hydrofoils, and that maintain their constant depth, are controlled by the hydrodynamic forces between their weight, the speed at which they are being towed, and the length of the tow cable. The vehicles that best demonstrates this style are the Continuous Plankton Recorder-CPR (Hardy, 1939) and the Oceanographic Towed Vehicle (known as the VOR, from the Portuguese Veículo Oceanográfico de Reboque) (Faccin *et al*., 2014). The latter was the basic idea for the development of an undulator designed exclusively to collect physical and chemical data on seawater, using an electronic probe. The original idea was to propose a robust, mechanical device with low cost and easy maintenance, for use by scientific observers on board fishing and/or opportunity vessels.

MATERIALS AND METHODS

Setting up the model

The mechanical model of the U-Tow was created by modifying the original design of the VOR presented by Faccin *et al*. (2014). The VOR was made from fiberglass, 4 mm in thickness. It was 50 cm in width and 86 cm in length, with hydrodynamic stabilizing fins measuring 19 cm, based on the Undulating Towed vehicle (U-Tow) model described by Reid *et al.* (2003).

In 1939, Hardy foresaw difficulties in obtaining a fully mechanical undulating Continuous Plankton Recorder (CPR). Using the propeller to drive both the plankton collector and the deep-water undulating system would require a heavier, and more costly mechanical system. In addition, there would be difficulties in estimating the location of the organisms collected both in terms of their position in the water column and the distance traveled. This led to the idea of creating an undulating vehicle that would carry only the multiparameter oceanographic probe, without the planktonic organism collection cassette.

To calculate the reduction gearbox of the vehicle, responsible for the transmission between the rotational force of the propeller, and the translational force of hydrofoils, it was necessary to assess which factors influence the behavior of the vehicle. The equipment has a maximum depth of 200 m, based on the resistance of the multiparameter probes commonly available in the market. Therefore, as a safety margin, the maximum depth of the vehicle for the initial calculations was stipulated at 60 m. The maximum angle of attack of hydrofoils was set as 10°, to prevent the flow separating from the low pressure zone, increasing the drag and causing a decline in support strength, as this would cause the hydrofoil to act like a brake, impairing the performance of the vehicle. The angle between the tow cable and the surface of the water was taken as 60°, thus the average depth of the vehicle, *i.e.* the depth at which it will remain when being towed with zero buoyancy, will be 30 m. This depth of 30 m was used for the purposes of calculation. The angle that the tow cable makes with the surface of the water (in this case 60°) can be changed from one vessel to another; thus, the average depth can be maintained by varying the length of the tow cable, up to a maximum limit of 200 m.

Having defined the average depth of the vehicle, we then determined the undulation range at which the equipment could operate if there were no problem with water output, or operating close to the boundary layer, which would generate cavitation in propeller and impair the dynamics of the model. For this, we considered the propeller pitch and the angle of the hydrofoil.

For a propeller of 15 cm in diameter and a minimum angle of attack of at least 45°, the propeller pitch would be approximately 47 cm.

$$Ph = \frac{(d.\pi)}{(tg\beta)} = \frac{(15.\pi)}{(tg\,45^o)} \approx 47\ cm \qquad (1)$$

where: *Ph* = propeller pitch; *d* = diameter of the propeller; and *ß* = angle of attack, according to Klebanov *et al*. (2008).

It was related the range of the hydrofoil angle of attack which would result in the depth of the vehicle. Initially, the cogs of a gear were related to the angle of attack of the undulator so that each cog of the gear moved would determine an angle of the hydrofoil. A 20-cog gear was chosen, as this is the standard gear for the VOR of Faccin *et al.* (2014). So, in a system fitted with a 20-cog sprocket crown wheel and an auger screw coupled to the propeller, each turn of the wheel would turn one cog, corresponding to 2° of the angle of attack. In this way, we calculated the gear reduction needed for a given number the propeller revolutions to a given horizontal distance, for the vehicle to remain below the boundary layer, based on an average depth of 30 m. Thus, we obtained a ratio that for every 100 turns of the propeller; the vehicle would turn one cog of the main gear of the undulator, corresponding to 2° in the angle of attack of the hydrofoil (Fig. 1).

The calculated reduction would be at a ratio of 100:1, in other words, for every 100 revolutions of the propeller at the input of the gear, its output would be only one revolution, traveling only one cog on the final gear of the undulator (Fig. 2, Table 1).

Given that it is a propeller with controllable pitch, there is still a possibility that the angle of attack can be changed, in order to regulate the depth of the vehicle and its depth interval (Table 2).

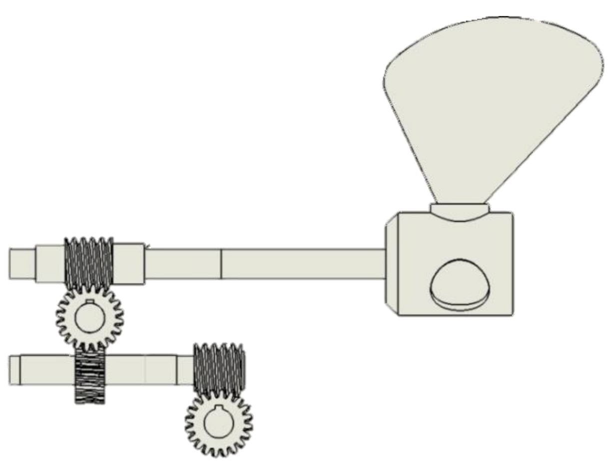

Figure 1. Propeller system with gear (input and output) to the cogged crown of the undulator.

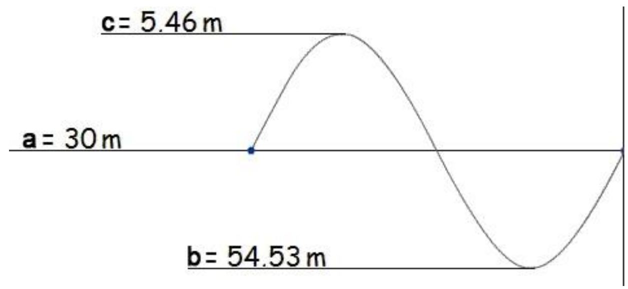

Figure 2. a) Average depths, b) maximum depth, c) minimum depth of the vehicle in a complete undulation.

Table 1. Depth related to the angle of attack for a gear of 100:1, where the total pitch refers to 100 revolutions times the propeller pitch of 47 cm.

Hydrofoil angle	Total step (m)	Depth (m)
10°	47	8.16
8°	47	6.54
6°	47	4.91
4°	47	3.28
2°	47	1.64
Total	235	24.53

Table 2. Amplitude according to the propeller angle of attack.

Angle of attack	Amplitude (m)
50°	30
55°	34
60°	42

Calculating the gear

Having defined the reduction of 100:1 (Fig. 3), we mounted the gear that would comprise the mechanical system: two gears with 20 cogs linked to two double-step auger screws. As the structure of the gearbox had to be small and lightweight, so as not to cause hydrodynamic problems in the vehicle, helical gears with auger screw were adopted as standard. According to Norton (2013), helical gears have a great advantage over straight cut gears because they have stronger, more resistant cogs, and the auger screw system is ideal for larger reductions when it is necessary to occupy a small space.

For this purpose, we performed calculations using the basic equations presented by Klebanov *et al*. (2008) for a crown with auger screw, using a spreadsheet (Table 3). The results were applied to a 3D model using the software program SolidWorks (Fig. 4).

Hydrofoil

For the hydrofoil, a similar symmetrical profile to that of NACA 0012 (Fig. 5) was chosen, as it has the ability

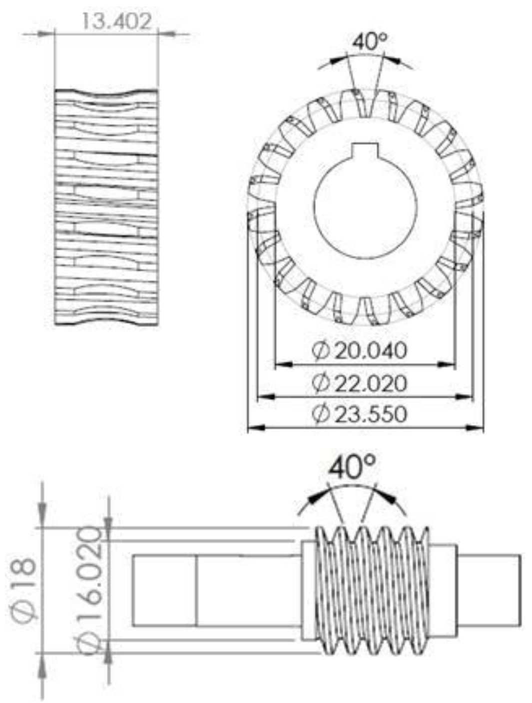

Figure 3. Cogged crown and auger screw, calculated according to Klebanov *et al.* (2008).

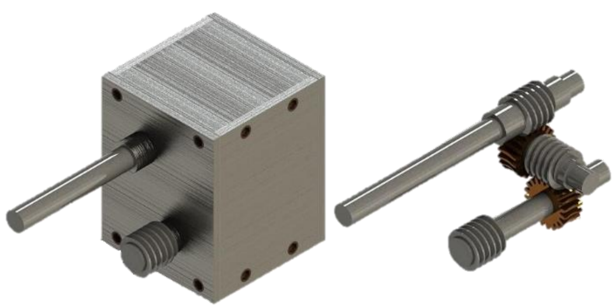

Figure 4. Simplified 3D Model of the gear (100:1) between the propeller and the undulator.

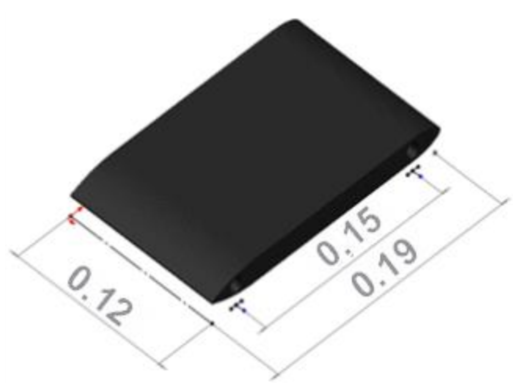

Figure 5. Isometric hydrofoil NACA 0012.

to maintain zero floatation when the angle of attack is at zero. As all the proposed models of vehicles have a flat bottom, which assists in the performance of the hydrofoil, we calculated the support strength necessary for the device to undulate vertically in the water column. Using the calculations proposed by Matveev & Duncan (2005) for untabulated profiles, we developed a spreadsheet using the SolidWorks software, in order to create a digital model of the hydrofoil.

Undulation System

With the gearbox, propeller and hydrofoils defined, we then created the undulation system, which would enable the force generated by propeller, and transmitted by the gear, to cause the hydrofoils to change their angle of attack in the trawls executed by the vessel (Fig. 6).

The system was designed on an axis, on which the gear responsible for changing the angle of attack of the hydrofoil is mounted. At the ends of this axis are two connecting rods, which convert the continuous circular motion of the axis into a linear motion. These connecting rods were dimensioned to meet the requirement of 10° of positive tilt at its highest point, and 10° of negative tilt at its lowest point (Fig. 7).

RESULTS

U-Tow I

Once all the mechanical systems had been calculated and designed, we then began to work on the creation of the first digital prototypes. The first was the U-Tow I (Fig. 8), which followed the same hydrodynamics as the VOR of Faccin *et al.* (2014).

Designed to be made from fiberglass, the U-Tow I is 83 cm in length and 32 inches centimeters width - or 69 cm in width including the hydrofoils and side shields.

Laterally, it is 23 cm to the height of the stabilization fins, and 14 cm for the body of the vehicle. The multiparameter probe is housed inside the vehicle, on a fixed support located just to the fore of the gearbox.

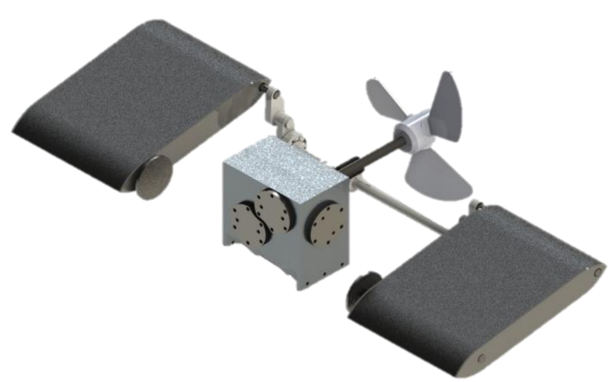

Figure 6. Complete undulation system with propeller, gear and hydrofoils.

Table 3. Calculations and formula for the crown and threaded auger screw estimated for the gearbox between the propeller and the undulator.

Crown	Symbol	Real	Calculated
Module	M	1	0.99
Number of cogs	Zc	20	20.00
Outside diameter	De	22	22.02
Primitive diameter	Dp	20.04	20.02
Widest diameter	D2	23	23.56
Wheel width	L		13.40
Radius	R		7.01
Angle of the chamfers of crown	Δ		27.26
Height of foot of the cog	A		0.99
Height of foot the cog	B		1.25
Total height of the cog	H		2.24
Propeller angle	B		8.50
Distance between axes of the crown and the screw	E		18.02
Auger screw			
Outside diameter	De	18	18.00
Primitive diameter	Dp	16	16.02
Flank angle of the filete	Γ		40.00
Formula			
P = M * N	3.11		
D2 = De + 2 R (1 - cosδ)	23.57		
De = Dp + 2 M	22.02		
E = (Dp + dp)/2	18.02		
Dp = (M * Zc) / (cosβ)	20.02		
R = E - (De / 2)	7.01		
l = 2.38 P + 6	13.40		
l = 2.15 P + 5	11.68		
h = a + b	2.24		
b = 1.167 M	1.16		
b = 1.25 M	1.25		
h = 2.167 M	2.14		
h = 2.25 M	2.22		
cosδ = (dp /de)	0.88		
γ = 29, 30, 40	40.00		
M = (de + De - 2 E) / 4	0.99		
dp = de - 2 M	16.02		
β = acos [(M * Zc) / (dp)]	8.50		
de = dp + 2 M	18.00		

At the bow of the vehicle are the tow hitches and water inputs, which allow continuous flow inside the vehicle. The water outputs are located at the stern, just below the propeller. A safety pin prevents the vehicle from lifting so that the bow is fully out of the water while it is being towed, ensuring that the hydrofoils are always submerged along with the propeller.

Using the same model of VOR, the U-Tow I is sealed at the top by a screwed lid, also made from fiberglass. This hatch is 18 cm in width and 42 cm in length (Fig. 9).

The large amount of free area inside the equipment -around 64% of the total internal volume- leads to unnecessary use of material. Therefore, the width of the vehicle was altered and the gear optimized. Another change was made to the top of the vehicle, giving better access to the probe and gear, for handing. And so, the U-Tow II was developed.

U-Tow II

The U-Tow II (Fig. 10) is 83 cm in length and 17.5 inches in width, or 54.5 cm including the hydrofoils and

Table 4. Hydrofoil support calculation table.

	Symbol	Metric	Equivalent
Π		3.14	
Area of the hydrofoil	S	0.043	0.46 (feet)
Speed	V	4.2	8.16 (knots)
Water density	ρ	1040	
Thickness of the foil	Cb	0.05	
Depth of foil	h	1	
Ratio (foil span/cable)	L	8	
Angle of attack	a	0.05	2.86 (degrees)
Curvature of the profile	f	0	
Form			
$z = (\rho / 2)\text{^}V^{2\,.\,2\,.\,Ct\,.\,S}$	z	72, 97	
$Ct = [Ki\ .\ (бCt/da)\ .\ (a + a_0 - da_0)]$	Ct	0.1850	
бCt/da = 5.5	бCt/da	5.5	
$a_0 = 1.74\ .\ f$	a_0	0	
$Ki = 1 - (5 + Cb)\ \exp(-2\ .\ h^{0.6})$	Ki	0.9256	
$da_0 = Cb / 2\ (1/ Ki - 1)$	da_0	0.0020	
$T = 0.09\ L^{0.5 - 0.04}$	T	0.2146	
$E = 0.85 + 0.16 / [(h / L)^{0.5}]$	E	1.302	
$0.02 < (h / L) < 1$	(h / L)	0.125	

Table 5. Hydrofoil support by angle of attack.

Angle of attack (°)	Support (kg f^{-1})
1	2.51
2	5.48
3	8.45
4	11.42
5	14.41
6	17.37
7	20.34
8	23.31
9	26.28
10	29.25

guards. The upper hatch is 15.6 inches in width and 54 cm in length. The lid is secured to the body of the vehicle by hinges at the front and screws at the back.

This vehicle presents better optimization of the free space, resulting in a greater economy of material. The volume of the gear was reduced by 65%, and the remaining parts are the same as in the U-Tow I.

U-Tow III

To facilitate the mounting of the multiparameter probe to the vehicle, a track system was developed, and a box that besides enabling the probe to be transported safely, is also used for placing the probe in the vehicle (Fig. 11).

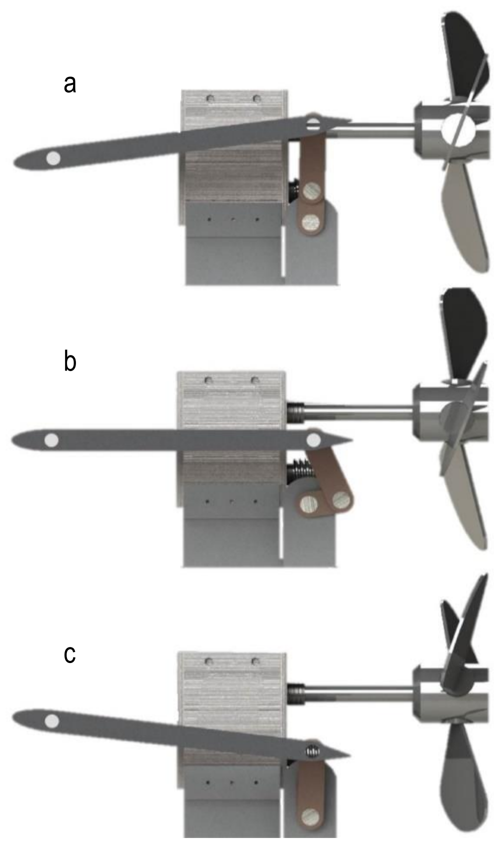

Figure 7. Movement of the hydrofoil with the arrangement of the two connecting rods. a) Maximum angle of attack, b) zero angle of attack, c) negative angle of attack.

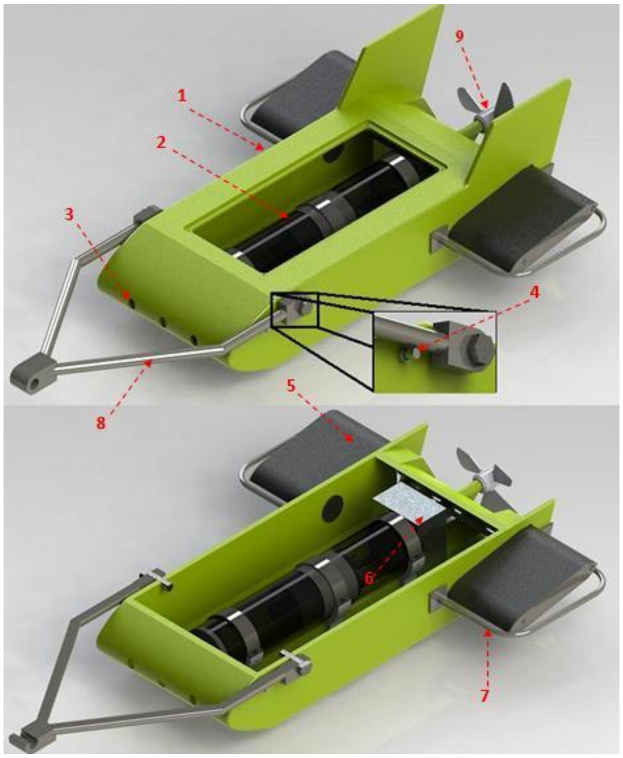

Figure 8. U-tow. 1) Body of the vehicle in fiberglass, 2) multiparameter probe, 3) hole for entry of continuous flow of water, 4) safety pin, 5) hydrofoil, 6) gearbox, 7) hydrofoil guard, 8) tow hitch, 9) variable speed propeller.

Figure 9. U-Tow I showing internal detail, and sealed.

The multiparameter probe was surrounded by brackets, and a track fitted inside the fiberglass box. This, in turn was fixed to the inside of the vehicle, forming a sliding compartment (Fig. 12).

Another modification was the addition of a guard to the bottom of the propeller, to prevent it from hitting against the edge or deck of the vessel (Fig. 13).

U-Tow IV

Improvements to the hydrodynamics of the vehicle and the probe carrying box, and the development of a chassis to fix the undulating system of the vehicle, resulted in the creation of the U-Tow IV (Fig. 14).

The U-Tow IV has the same track system for fixing the probe as the U-Tow III, but the carrying box was

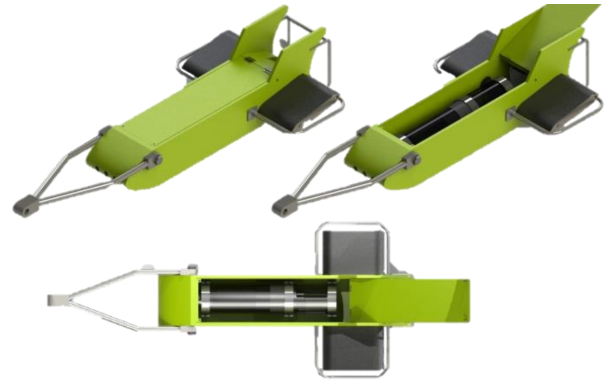

Figure 10. U-Tow II in open and closed views.

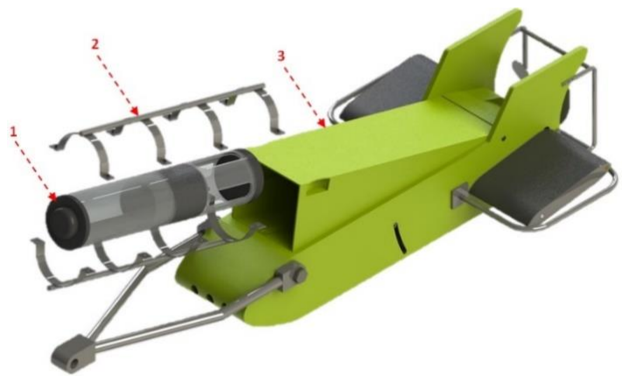

Figure 11. U-Tow III: Box for transport and mounting of the probe. 1) Multiparameter probe, 2) support and mounting track and 3) box for transport and housing of the probe.

Figure 12. U-Tow III in closed and open views.

Figure 13. U-Tow III side view.

redesigned so that it could be carried like a suitcase, and could be fitted into other vehicles to be designed in the future. The propeller guard was redimensioned so that it fully covered the bottom of the propeller at all the

Figure 14. U-Tow IV. 1) Multiparameter probe, 2) mounting track, 3) transport box, 4) propellor guard, 5) hydrofoil guard, 6) hydrofoil, 7) inputs to the continuous flow of water, 8) tow hitch.

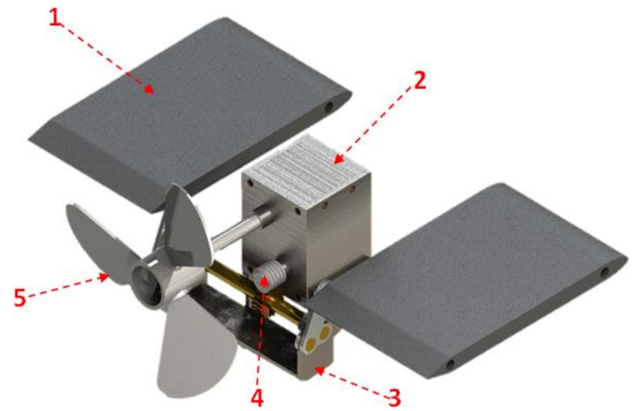

Figure 15. Undulating system with chassis for the U-Tow IV. 1) Hydrofoil, 2) gear, 3) chassis, 4) transmission of the gear to the undulators, 5) adjustable propeller pitch.

pitch angles. The chassis system was also developed, to facilitate the installation of the undulating system inside the vehicle, enabling rapid adjustments if necessary (Fig. 15).

To further facilitate the handling and installation of the equipment inside the vehicle, the size of the entry hatch was increased, to present obstructions during the on-board handling (Fig. 14).

DISCUSSION

Possible problems

The mechanical system adopted for the U-Tow is more economical than the similar servomotor used in other undulating vehicles, such as the UOR MARK 2 (Aiken, 1981). However, the mechanical system can present some failures. The first is the fact that the vehicle is unable to automatically regulate the depth, but is limited to the adjustments made on board, unlike vehicles fitted with a servomotor, which have a depth gauge that changes the angle of attack of the hydrofoils as required. Another factor is the excess weight that the mechanical structures add to the system, as in an electrical model, the propeller and gearbox are not required, further optimizing the vehicle.

A factor that could affect the dynamics of the vehicle is the zone of low pressure created by the vehicle itself as it rises in the water column with a positive angle of attack of the hydrofoils. This would generate a flow shadowing in the propeller and its cavitation, which would consequently change its depth dynamics.

Breaking of the tow cable, or a crack in the hull of the vehicle or towing structure, though unlikely, could result in the loss of the entire system including the multiparameter probes. To circumvent this problem, a hydrostatic device would be required, which emits a GPS signal, or inflates a balloon connected to a cable when the pressure becomes too high, enabling the material to be recovered by emersion.

The U-Tow is an excellent device for carrying equipment for measuring oceanographic parameters. Its mechanical system is easy to understand, and its components are easy to handle, enabling the vehicle to be used by various research institutions, with minimal training. Its compact size and adaptation enable its use on various opportunity vessels.

For further improvements to be made, it is necessary to build a prototype and perform sea trials to assess the actual performance of the vehicle and the undulating system.

ACKNOWLEDGMENTS

We thank CAPES, in the scope of the IGEPESCA Project, Sea Sciences Notice of March 9, 2009 is the financial support and the CNPq for the productivity grant, Process 305795/2014-7.

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