A procedure to estimate the hydrodynamic parameters of an Autonomous Underwater Vehicle (AUV)

Neptune SB-01 is a basic small-scale model of submarine to be used as a test platform within a cooperative submarine robotics project. After characterizing its essential components, a series of pool tests has been performed by using a simple but effective specific methodology

Giacomo Cupertino, Ramiro Dell'Erba, Giovanni Sagratella

Una procedura per stimare i parametri idrodinamici di un Veicolo Autonomo Sottomarino (AUV)

Il Neptune SB-01 è un semplice modello di sottomarino a scala ridotta il cui impiego è stato previsto come piattaforma di sperimentazione nell'ambito di un progetto di robotica sottomarina cooperante. Dopo averne caratterizzato le sue parti costitutive essenziali, si sono eseguite una serie di prove in piscina secondo una semplice ma efficace procedura

Introduction

Thanks to their easy handling and reduced costs small AUVs – Autonomous Underwater Vehicles – are witnessing a widespread and ever growing use in several oceanography applications such as, e.g., mine-recognition, and environmental monitoring of coastal and inland water basins. A number of AUVs are being specifically designed to operate in a coordinated way just like fish shoal.

Main background

Article category: autonomous robotics
Reference frame: swarm robotics
Reliability: system efficiency and economic improvement of mission management
Main limits: operative depth restricted to few ten meters and power supply limitations, resulting shorter duration of the mission
Estimated costs: about 10.000 € per vehicle

The main advantages range from the possible inspection of a given space volume in a shorter time than if made with a single machine to the opportunity to exploit a parallel architecture performing complex tasks otherwise impossible. The 'shoal-like philosophy' originates from the observation of nature. Its fundamental is a single simple-structured machine. It might get lost without affecting the survival of the shoal which is able to perform the tasks it has been assigned by a human operator anyway.

The HARNESS (*H*uman telecontrolled *A*daptive *R*obotic *NE*twork of *S*ensor*S*) project is a cooperative robotics project aimed at developing a unique system of autonomous robots into a single network of sensors. Their shoal-like concept allows them to carry out manifold joint operations. A key aspect of the project is mainly

Giacomo Cupertino, Ramiro Dell'Erba, Giovanni Sagratella
ENEA, Technical Unit for Advanced Technologies for Energy and Industry, Robotics Lab.

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underwater inter-component data exchange by acoustic wave propagation, and not only. The control system of a single machine is achieved by building, a physical model behaving as close as possible to a real one. This is called Neptune SB-01 which will be the study platform, at least in the early stage of the project. A simplified description of the basic constituent parts of the vehicle is contained in this article, as well as its geometry and electro-mechanical components, particularly focusing on hydrodynamic characteristics. Indeed, they represent the main aspect of the project specific to the use the submarine is intended to serve. Our main objective was to determine parameters of interest by simply observing its behaviour in water under specific assumptions.

We wanted this to be achieved by performing a series of pool tests with common, simple mechanical and electronic devices. Indeed this document is also aimed at proposing a methodology to evaluate the hydrodynamic parameters of any scale craft vessel in a simple and inexpensive way. Hence a series of experimental tests have been carried out in order to cost-effectively get the vehicle's hydrodynamic coefficients of drag (C_d) at various speeds as well as the value of its operating speed. Of course, before proceeding to the tests some calculations have been made allowing to formulate some preliminary hypotheses on the study model. The data and information so obtained have made the afore-mentioned experiments fully successful.

Vehicle description and main assumptions

At a first stage, the Neptune SB-1 by Thunder-Tiger has been studied out of water. This submarine model is composed of: an elliptic outer shell (figure 1), a simple propulsion system and mechanisms acting on fins and rudder, and finally a watertight cylinder inside the hull, where all the actuators converge on their corresponding motors. The moving parts consist of: propellers, two coupled fins, in phase opposition, for pitch movement (up and down in depth), a centered rudder in the stern. The cylinder also hosts a swim bladder driven by a reversible pump adjusting the immersion level of the entire hull at higher or lower depth. Each DC motor is controlled by PWM electronics except for the bladder filling/emptying pump which instead is controlled by an on/off electronic card.

Subsequently, starting from assumptions that could well approximate the actual behaviour of the object in water, preliminary considerations were made on weight distribution inside the hull, with a special focus on the heaviest loads. Then the submarine's equilibrium points 'out of water' have been observed in relation to the three coordinate axes, as well as the ballast water when the submarine is immersed in a pool at 0.5 m depth. The resulting conclusion is that the vehicle mass distribution can approximate to an ellipsoid distribution, with principal axis of inertia in the direction of the main motion shifted by a certain calculated quantity lower than the symmetry axis along the same direction. It has also been observed that the volume of water moved by this equivalent mass causes the same volume displacement of the submerged hull at the established depth. As the added mass of water tends to oppose the motion of the vehicle[1], as a result of further considerations we have adopted a volume producing an added mass of water equal to that used for calculating the inertial moments without including the mass of water induced by the fin motion. Adequate numerical values have resulted, as shown in the final extrapolation of the experimental outcomes. Indeed, the resolution of a theoretical model whose parameters are estimated on the basis of experimentally collected data gives added mass values similar to those previously assumed as a first approximation. Given the low speeds involved, for both inertial masses the correction terms of Coriolis forces[2] have been considered close to zero. So the submarine behaviour in water has been further observed assuming that the hydrodynamic forces (determined experimentally in a second moment), were essentially composed of skin friction and pressure drag[3]. The former is conside-

The Harness project

Project target: investigation and development of technologies for underwater robotics management systems.
Argument of the article: characterization of the single vehicle as elementary part of the swarm.
Description: the project aims to study cooperation aspects in a 3D swarm and solve the interaction between man and a swarm; it aims also to develop a new communication issue in an 'ad hoc' underwater network, that should allow to rise the available bandwidth of present AUVs of about hundred times.
Amount of the project: about 1,000,000 €.

red negligible compared to the latter, since the latter prevails for moderate speeds as in this case. Furthermore, considering marine currents as negligible, it has been possible to assume that the speed of the vehicle matches the speed of the flow impacting on it. Therefore the latter has always a direction coincident with the vehicle trajectory. This is exactly the reason why the tests performed will only refer to one of the three possible spatial directions: the x axis, identified as the main direction of the motion, namely the direction caused by the propeller thrust. By adopting the estimates of the diameter De of the equivalent cylinder (and the ellipsoid's too), a Reynolds number of about 100.000 has been obtained. This result allows us to state that it lies below the critical threshold corresponding to a principle of turbulent flow[4]. However, to derive the hydrodynamic forces acting along directions perpendicular to the motion (on the rudder, and on the front- and rear-fins), considering the relative speeds involved it is worth pointing out that we referred to calculations[5] always made under conditions of laminar flow over thin airfoils, so that the fluid angles of attack do not exceed 25°[6].

Experimental apparatus description

It was decided that all test would be carried out at a depth of 0.5m. Hence the submarine was completely filled with water so that it could simulate any mission. Before starting the data acquisition campaign, it was necessary to vent out as much air as possible from inside the hull. Otherwise, the many small empty spaces mostly present in the stern would not allow the hull to be fast filled with water (figure 1).

A special cableway structure ensured that the submarine would follow a straight line trajectory at the established depth. Particularly, the submarine was pulled into water by forces applied through weights attached to the structure. The entire path of Neptune was videotaped by unrolling a vertical flexible meter placed on a particular structure with a special system of pulleys. In order to better measure the speed of fall of the weight, it was decided that the single instants of the fall be highlighted with a stopwatch. Its millisecond time view was visible both on a PC monitor where the stopwatch was installed, and on the bottom wall of the laboratory through a projector. The submarine's pulling weight being known, measures could be acquired by using two systems simultaneously. A high-definition videocamera was placed on a stable tripod at the bottom of the laboratory to record the last 2.5 m of free fall. Then a photocamera was mounted on a moving part running parallel to the free falling weight along the flexible meter, so that it could photograph each second of the first part of the path (3 m approximately). The distance between the videocamera and the flexible meter was such that each pixel recorded by the device corresponded to a millimeter of linear measure. Evidently, this could be achieved by laboriously and continuously improving the viewing angle, aligning the flexible meter to the device lens, etc. By doing so, we obtained absolute parallax error completely acceptable (<0.5%). According to the existing literature, in all tests the friction force of the cord-pulley system is estimated to be around 3% of the weight force applied. The two acquisition systems are overlapped only between the 2nd and the 3rd meter of the free fall of weight. In fact their aim was precisely to detect, on the one hand, the instant when full speed was reached with the photocamera (gross acquisition), and on the other the exact value of the regime speed with the videocamera (fine acquisition), in order to validate the constancy of speed in the considered time interval. This partial overlap also allowed a double simultaneous measurement of the distance covered by Neptune as a function of time, improving measurement accuracy.

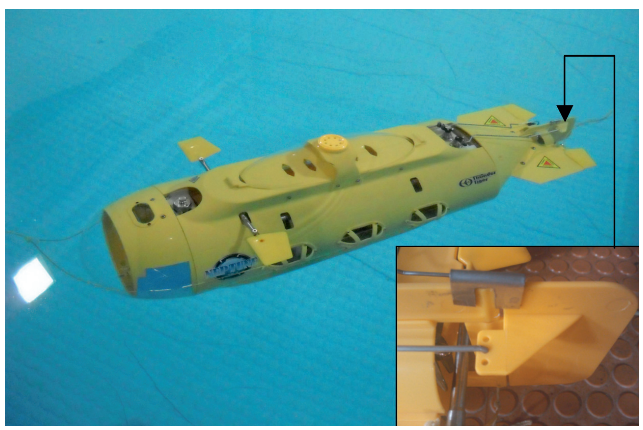

FIGURA 1 Balance positioning to dive the submarine and lock the rudder system
Source: ENEA

Running experimental tests in the pool

The tests were carried out in three sessions: evidence of the propulsion force of the submarine (static test), full speed ahead and astern, evidence of hydrodynamic resistance (drag coefficients) and maximum speed tests. The first test (figure 2) was achieved by simply fixing a dynamometer on the main frame positioned in water. The dynamometer was pulled vertically by a cord (pully-straightened underwater) strained by the submarine. With a fully charged battery, the propulsion thrust recorded was equal to +100 gr.

The second test took the longest time. The submarine was pulled with 6 different weights (m = 50, 100, 305, 450, 585 and 670 gr.). For each single weight the experiment was repeated 6/7 times. At the equilibrium position – i.e. when the applied external force net of friction (Fg-Fa) balanced the various hydrodynamic forces acting on the submarine – a constant Fidro hydrodynamic force due to the drag forces only was recorded. Hence the speed had attested on a well-precise value. [7] In this way, different coefficients of drag (Cd) were obtained for each weight. As a result, a regime speed was measured as a function of the applied force, which was the main purpose of the test. The drag coefficients are defined by the equation that is assumed to govern Neptune's motion[7]:

$$F_{idro} = F_g - F_a = \frac{1}{2}\rho C_D A_f v^2 \qquad (1)$$

where ρ indicates water density. The section (Af) quoted in (1) was calculated by counting all the pixels contained in the scanned image of the picture shown in the technical specifications of the product. Then its exact match was checked by comparing it with the real model photograph.

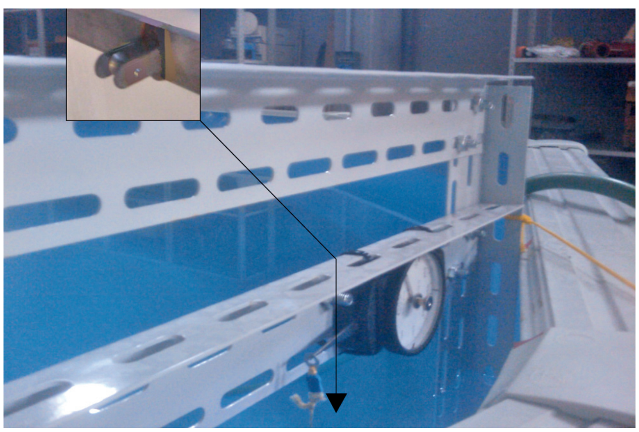

FIGURA 2 Setup for the submarine propulsion test
Source: ENEA

Finally, the third test was to determine the maximum speed the submarine could reach at a depth of about 0.5m. The experiment was carried out by using the same system of pulleys and measurement, operating the AUV in reverse manner. That is, an inextensible cord was connected between the stern of the hull and the system, with a little ring suspended to the end of the wire to keep it under tension (5gr). Therefore, with engine full speed ahead the wire coming out neatly from the conveyor tube pulled the submarine. This allowed to measure speed through the notches on the wire at known distance. In order to achieve full speed faster, it was decided to provide an initial underwater tension of 1.2 kg. Then another piece of inextensible wire was connected between the submarine's bow and a dynamometer loaded with the above force, which proved to be sufficient enough to overcome the initial inertia.

Experimental results

Starting from the equation of motion (1), the equation of balance of forces is as follows:

$$m_N \dot{v}(t) = mg - \frac{1}{2}\rho A C_D v(t)^2 \qquad (2)$$

where m is the weight mass, as described in the experimental paragraph above, m_N is Neptune's mass of, g is gravity acceleration, ρ is fluid density, A the frontal area impacting with the fluid. It should be pointed out that Neptune's mass should also include the added mass term, i.e. a certain amount of water that the vehicle drags with itself (a model widely used in fluid dynamics). Then we proceeded to solve the equation (2) in closed-form both neglecting and considering the added mass, assuming a laminar flow regime. As a following step, the C_d and possibly m_N hydrodynamic parameters were estimated by fitting the experimental data. Two methods were followed: the first one with only one family of parameters to fit (the hydrodynamic coefficients), and the second one with two families of parameters (both C_d and m_N). The data fitting process involved both speeds and the measured displacements. The different methods were compared by using

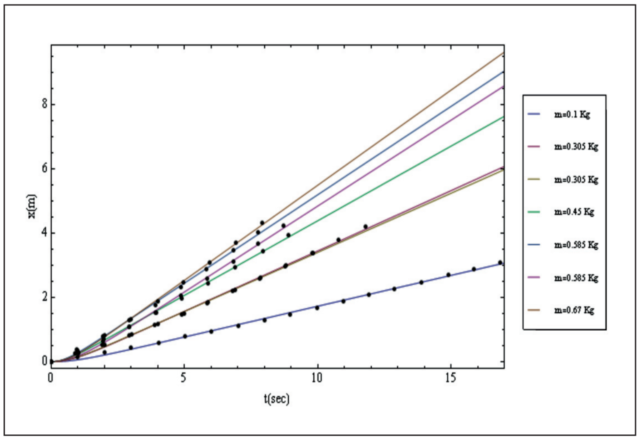

FIGURA 3 Neptune displacement as a function of the instant considered
Source: ENEA

a Gauss' hypothesis test, i.e. by calculating the chi-square divided by the model's number of degrees of freedom. Thus a total of four models were obtained.
The equation solution, with the initial condition of v (0) = 0, is the following:

$$v(t)=\sqrt{2gm}\,\frac{Tanh\left(\frac{\sqrt{AC_d g\rho m}}{\sqrt{2M_n}}t\right)}{\sqrt{AC_d\rho}} \qquad (3)$$

and integrating with the initial condition of x (0) = 0

$$x(t)=2M_n Log\,\frac{Cosh\left(\frac{\sqrt{AC_d g\rho m}}{\sqrt{2M_n}}t\right)}{AC_d\rho} \qquad (4)$$

In figure 3 experimental data are shown, together with the best fit, of the weight displacement as a function of time. It should be noted that there are two weight values reported twice showing the repeatability of the measurement.
The displacements in figure 3 correspond to the speeds shown in figure 4a. The difference between the method considering the added mass and the one neglecting it is evident in figure 4b. Here, at least for the higher speeds, the speed fit is worse when the added mass becomes significant.
Table 1 shows the estimated parameters only for the two methods where speed is fit, with and without added mass to Neptune. The difference in the Gauss' coefficients (calculation of chi-square divided by the model's number of degrees of freedom) demonstrates the best accuracy of Method 1 despite an extra parameter to be estimated. This is true only for the last two cases (larger weights or higher speeds) where the added mass becomes significant. Indeed, for latter two cases it is impossible to approximate the curves with the drag coefficient only. Note the difference in the speed limit, already visible in Figures 4a and 4b.
The drag coefficients differ by about 10%.
Ultimately, also the greater physical compliance of the

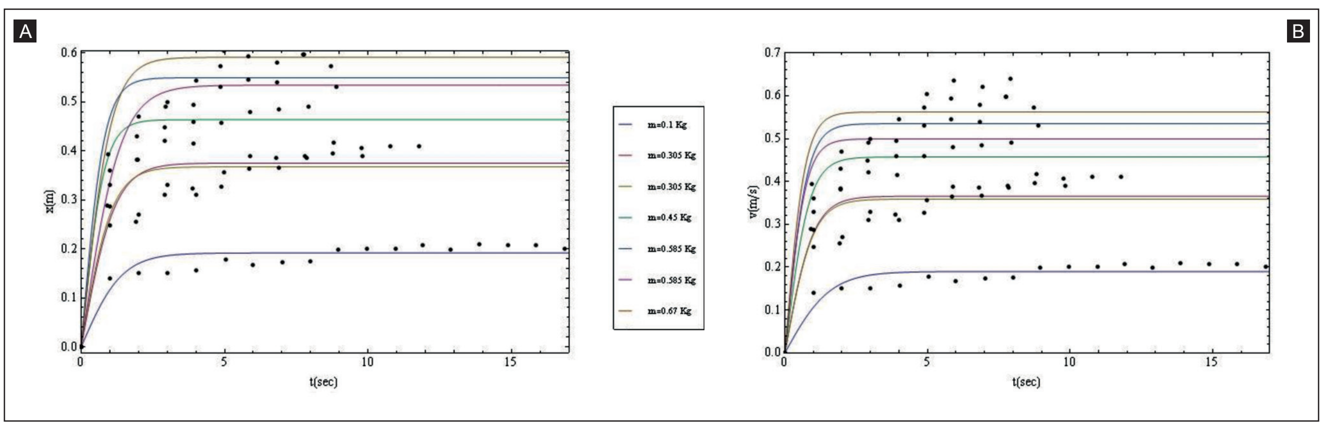

FIGURA 4 **A.** Evolution of speed of weight as a function of its fall time with added mass - **B.** Evolution of the speed of weight as a funtion of its fall time without added mass
Source: ENEA

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Mass	Coefficient value (C_d)		Regime speed (v)		Neptune Mass (m_N)		Gauss	
weight (m) [kg]	MET. 1	MET. 2	MET. 1 [m/s]	MET. 2 [m/s]	MET. 1 [kg]	MET. 2 [kg]	MET. 1 [m^2/s^2]	MET. 2 [m^2/s^2]
0.1	1.44	1.41	0.19	0.19	7.24	8.15	1.25	1.07
0.305	1.15	1.18	0.37	0.37	9.35	8.15	4.72	3.94
0.305	1.19	1.21	0.37	0.36	8.7	8.15	3.07	2.71
0.45	1.11	1.09	0.46	0.47	7.44	8.15	4.08	3.11
0.585	1.03	1.03	0.55	0.55	8.22	8.15	5.73	4.81
0.585	1.08	1.27	0.53	0.585	14.48	8.15	5.54	10.28
0.67	1.01	1.10	0.59	0.67	11.39	8.15	6.34	8.10

TABLE 1 Coefficient of Drag and regime speed with and without added mass
Source: ENEA

model led us to consider the fit made with the added mass more reliable.

Conclusions

This work was aimed at realizing the control system of a single machine, and entirely preliminary to the completion of the Harness project. The experiments results confirmed that the hydrodynamic tests may be performed by using the simple experimental setup here described, which allows to repeat experiments with very good approximation. In this work the power of engine thrust, the hydrodynamic coefficients, and the maximum speed reached by Neptune as a function of the applied thrust force have been estimated. This allowed us to understand how the motion force of the submarine opposes the system when the propulsion thrust generated by the motion of the propeller enables the vehicle to reach a regime speed. The experimental results match with the assumed theoretical model. The speed range considered corresponds to the range of the submarine's operative speed. Lower speeds are difficult to measure with this simple apparatus, and of little interest too. In this case, reaching the regime speed requires times and distances greater than those allowed by the pool used.

The next step could be trying to "accelerate" the achievement of regime speed by passing from an experimental apparatus characterized by the free fall of the weight to a more complex system. The latter would emulate the drag of the submarine by pulling it via a speed-controlled motor. At the regime speed, its speed value set at the beginning of the experiment would provide a given constant torque value necessary to determine the drag force for speeds at or below the critical value of 0.2m/s, as those read in the test method described herein. At this point the system would have the parameters to control the motors and we would expect a certain type of behaviour. The unpredictable external conditions could change the submarine's response, but as it always happens in robotics, the feedback given to the system would enable it to make the necessary corrections so that the motion may proceed as planned.

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