EXPERIMENTAL RESEARCH ON AUV MANOEUVRABILITY

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Abstract. *This work presents the main results obtained from captive and free model tests of the Pirajuba vehicle, an autonomous underwater vehicle, AUV, developed at the Unmanned Vehicles Laboratory of University of São Paulo. Those experiments are used in the validation of analytical and semi-empirical models, ASE, and CFD based methods for prediction of the hydrodynamic efforts acting upon AUV's hull and appendages. During the captive tests, carried out at the towing tank of the Institute for Technical Research (IPT), two types of multi-component strain gauge type dynamometers are used to measure the lateral forces and moment when the vehicle's model was towed at specific angles of sideslip. The free model tests used the Pirajuba AUV prototype in order perform some pre-programmed manoeuvres in a swimming pool. The embedded control architecture in the AUV is responsible for guiding the vehicle according to a pre-defined trajectory, and for acquiring the data from motion sensors. From those data, manoeuvering parameters and hydrodynamic coefficients can be estimated.*

Keywords: *AUV, submersible vehicle, towing tank, free model tests, hydrodynamic coefficients, manoeuvrability.*

1 INTRODUCTION

Worldwide, Autonomous Underwater Vehicles (AUVs) are used as assistance tools for several types of oceanographic missions (Pascoal *et al.*, 1997), pipeline inspection (Acosta *et al.*, 2007), underwater communication cable inspection (Kojima *et al.*, 1998), and in the military applications such as mining detection (Rajala and Edwards, 2006).

In the AUV design procedure, the knowledge of the vehicle dynamics is crucial for the autopilot development (Dantas *et al.*, 2010) and manoeuvrability prediction (de Barros *et al.*, 2006), being also very important on the development of more efficient (minimum drag) AUV shapes (Stevenson *et al.*, 2007; Alvarez *et al.*, 2009).

Typically, most of the uncertainties in the AUV dynamics are represented by the hydrodynamic efforts, especially when the vehicle executes high-amplitude or high-rate manoeuvres. Those manoeuvres are responsible for the effects of the flow incidence variation along the vehicle hull (de Barros *et al.*, 2008a) that should be estimated for the guidance and control systems design.

Nowadays there are a number of methods used in the prediction of hydrodynamic efforts. The minimum demand in terms of computational efforts comes from the analytical and semi-empirical (ASE) approach. It is commonly employed in the preliminary design of marine crafts, and has been adapted for dealing with AUV manoeuvrability also (de Barros *et al.*, 2008b). The ASE methods predict hydrodynamic coefficients based on the vehicle geometry. Experiments can be used to validate those predictions as well as improve the ASE formula.

Using numerical methods, such as CFD (Computational Fluid Dynamics), it is possible to achieve a better prediction than that from ASE methods in simple and complex conditions, such as the cases of high angle of attack (Tyagi and Sen, 2006) or a high turning rate (Phillips *et al.*, 2007). On the other hand, the CFD approach requires a considerable degree of expertise on grid generation and selection of numerical models, as well processing power to execute the simulations.

Despite its good potential on the hydrodynamics efforts prediction, the parameters from CFD simulations must be properly selected and validated to produce correct results. In order to do this it is necessary to collect some data from experimental tests of the specific AUV shape.

Using captive model tests in a towing tank, with a partial or full scale model of the AUV, is the most common way to obtain those types of data in a reliable form. Jagadeesh *et al.* (2009) and Azarsina and Williams (2010) performed static tests of a number of models of submersible vehicle, and presented the coefficients of normal and axial forces as well as the yaw moment as a function of the angle of sideslip. Dynamic efforts that occur during rotational motion are estimated in the towing tank through forced oscillation experiments using the planar motion mechanism (PMM). Applications of the PMM test to the estimation of AUV coefficients are reported in Kimber and Scrimshaw (1994), and Egeskov *et al.* (1994).

Regardless the type of the static test, the hydrodynamic efforts are measured by an assembly of one or more load cells, forming a multi-component dynamometer installed inside the model hull.

An alternative approach to captive model tests is the use of system identification techniques applied to experiments using self-propelled vehicles. Considering the construction of a simple dynamic model of the AUV, the system identification approach is a more concise and direct approach than the analysis based captive model tests, particularly when we compare to the PMM tests.

During the free model tests, the vehicle executes some typical manoeuvres well know in the marine fields, such as the turning and the zigzag. Using the real scale AUV, all the dynamic data (velocities, orientation, etc) acquired by its sensors are store in the embedded processing units during the tests. Applying classical techniques, such as step response or frequency response analysis, some manoeuvring coefficients can be estimated. Another option is to apply stochastic based methods, such as extended Kalman filter (Kim *et al.*, 2002) or maximum likelihood (Liang *et al.*, 2010) to estimate the vehicles hydrodynamic derivatives.

Free model tests can be used as a validation tool also in the case of checking the quality of predictions provided by other methods, such as the ASE or CFD. The vehicle response (angular rates, linear displacement, etc) is compared to that predicted by simulators based on the hydrodynamic coefficients estimated by the ASE or CFD methods.

The original application of the Pirajuba AUV is the experimental support to studies on predictions of hydrodynamic derivatives. This investigation started with the application of analytical and semi-empirical, ASE, methods to predict derivatives of the Maya AUV (de Barros *et al.*, 2004, 2006, 2008a). In a latter phase, the ASE methodology has been integrated to CFD tools in order to improve the derivative predictions (de Barros *et al.*, 2008b).

Up to now, towing tank tests at the IPT-SP, Institute for Technical Research in São Paulo, were used for the validation of the static derivatives prediction. Tests have been carried out with the bare hull of Pirajuba and Maya, and the combination of hull, hydroplanes, and the propeller duct in a number of different configurations.

The use of free model tests in the Pirajuba project is mainly proposed to include the validation of the dynamic derivatives prediction, and to reduce the costs of the experiments. Preliminary experiments have been carried out in the swimming pool of the University of São Paulo, and are planned to occur at the University basin as well. In those tests, the real scale Pirajuba AUV is employed. The vehicle performs pre-programmed manoeuvres which are implemented through the embedded controller, navigation sensors, and actuators (fins and propellers). The embedded control and guidance systems are responsible for keeping a constant depth while executing specific manoeuvres.

This work focus on the those experimental approaches that have been used for validating the predictions of hydrodynamic derivatives related to the submersible vehicles tested so far by the Unmanned Vehicles Laboratory of the University of Sao Paulo, together with the Naval and Oceanic Engineering Center (CNAVAL) of the IPT. Section 2 describes the towing tank infrastructure, and present the methodology adopted for the captive model tests. Section 3 presents the cases investigated and includes an analysis of the corresponding results. Section 4 describes the tests with the Pirajuba AUV based in pre-programmed manoeuvres. Section 5 includes an analysis of the experimental results obtained so far, and proposes future steps in this investigation of AUV dynamics.

2 THE TOWING TANK EXPERIMENTS

The hydrodynamic laboratories at CNAVAL-IPT perform tests with scale models in all areas, including propulsion performance, manoeuvrability and seakeeping. The tests presented in this paper are performed in the Tow Testing Tank laboratory that is unique in Brazil. The laboratory has a towing tank with a length of 280 m, width of 6.6 m and a depth of 4.0 m; a towing carriage, that can tow a model at a speed up to 3.5 m/s; and a high resolution PMM.

The models tested in the towing tank are manufactured in the CNAVAL-IPT Prototype laboratory. The small components of the models, such as propeller and wings, are made by a rapid prototype machine, and the models hulls and structures are manufactured by a high precision robot arm with a cutting head. Some parts of the Pirajuba model were fabricated in this facility, such as the wings and the propeller duct.

During the static hydrodynamic tests of submersible vehicles, the models are towed at a constant depth and speed by the towing carriage. In this carriage the marine craft model is attached to a rotating platform which imposes the sideslip angles. The hydrodynamic efforts are measured during the motion by a dynamometric system.

The first tests with submersibles models were conducted with a typical arrangement of the dynamometric system (Fig. 1.a), which is commonly used in experiments of marine crafts. In this arrangement the model is towed by a vertical strut attached at its middle body and the measuring unit is fixed in the towing carriage. The dynamometer system is composed by an assembly of six isolated load cells, reducing the influence between cells (cross-talk).

In order to avoid the hydrodynamic effects of the struts on the flow and in the drag measurement, some strut configurations have been adopted. One way to reduce those effects is to adopt a pair of struts in a sword shape, very slender (see, for instance, Azarsina and Williams (2010)). Other options, tested by the IPT staff is to implement a fairing structure around the strut, or to install the dynamometric system inside the model hull, isolating the vertical strut from the flow effects. The latter option is described in more details as follows.

In the arrangement using the “C” type structure, the dynamometric system is installed inside the model hull, measuring only the efforts on the hull, and it is fixed to the carriage through a sting attached at model stern (Fig. 1.b), eliminating

Figure 1. Vertical strut type arrangement (left side), and the sting (horizontal) type arrangement (right side), developed and produced at CNAVAL-IPT, attached to the Pirajuba AUV model for effort measurements during static tests.

the interference generated by the incident flow. This type of arrangements is commonly used in wind tunnels (Jorgensen, 1977), but similar arrangements are also used for AUV hydrodynamics investigations (Jagadeesh *et al.*, 2009).

3 THE CAPTIVE MODEL TESTS

For a better understanding of the experiments and results, the tests of isolated components, i.e. the calibration body (NACA missile), Pirajuba bare hull and control surfaces are presented in Section 3.1, while the tests corresponding to the combinations of bodies, control surfaces and the propeller duct are presented in Section 3.2.

The experiments described in these sections are all static tests, where the models are towed at a longitudinal velocity of 1 m/s. The axial and normal forces, and the yawing moment were measured for each sideslip angle (SNAME, 1950).

Following the example of the shipbuilding industry, the experiments were performed for both positive and negative sideslip angles; based on two main reasons. If the model-dynamometer assembly has a misalignment the measurement will provide an offset in the angle of sideslip, and this error could only be properly treated with both sides of the curve. Moreover, a change in body symmetry can be detected by a difference in the values of positive and negative efforts.

The presentation of the results is conducted in accordance with the SNAME (1950), where the forces are divided by dynamic pressure of the fluid ($1/2\ p\ v^2$) times the squared body length (L^2), and the moments by the same dynamic pressure times the cubed body length (L^3).

3.1 Individual tests

3.1.1 NACA Missile

The first experiments employed the central strut structure, and they were aimed to estimate the normal force and yawing moment in the bare hull. In order to evaluate if the effect of the strut on the measurements would be significant and to validate the experimental approach, the static test was applied to a body whose results for the same efforts had been already published.

The model chosen was tested in an wind tunnel experiment presented by Jorgensen (1977). It is a body of revolution applied in investigations related on missile aerodynamics. The tested missile (Fig. 2.a) is composed by a 0.234 m diameter cylindrical section with a ogive type nose, with a length of 1.638 m and 0.819 m, respectively. The diameter based Reynolds of this test ($Re_N = 3.4 \times 10^5$) was a slightly lower than the original test ($Re_N = 6.5 \times 10^5$). Such small difference was not considered to cause significant variations on the forces and moments to be evaluated.

The IPT towing tank experiments were conducted only with the vertical strut arrangement, with and without the faring structure, the original tests (Jorgensen, 1977) used a sting-type dynamometer, measuring only the aerodynamic efforts for positive angles of attack.

The results of the normal force coefficient and hydrodynamic center are presented in Fig 3. The hydrodynamic center was calculated by Eq. 1, where C_N is the normal force coefficient and C_M is the moment coefficient referenced in the position x_m. For a better comparison the original data are duplicated in the negative angles.

$$x_{hc} = x_m - \frac{C_M L}{C_N} \qquad (1)$$

In the normal force case (Fig. 3.a), the IPT data showed a good agreement with the reference data, without significant difference in the use of the fairing structure.

Figure 2. Models tested in IPT towing tank. NACA missile (Jorgensen, 1977) in the left side (a), and Maya/Pirajuba bare hull in the right side (b).

Initially, the comparison of hydrodynamic center showed a large difference between the original data and the IPT data, at small angles of sideslip. However, an offset in the original results from Jorgensen (1977) were detected, based on the hydrodynamic center and moment analysis. The correction was done deducing such offset value from the moment values, and the hydrodynamic center was calculated with the new moment curve.

With these treatments the hydrodynamic center (Fig. 3.b) and moment (Fig. 3.c) data presented a good agreement, considering that the near zero values are very susceptible to measurement noise.

3.1.2 Experiments Using the AUV Bare Hull

The experiments proceeded with the investigation of static efforts for the Pirajuba bare hull, that has the same external geometry of the Maya AUV (Desa *et al.*, 2007), developed at the National Institute of Oceanography in Goa, India.

The bare hull of Maya/Pirajuba (Fig. 2.b) has a torpedo-like shape composed by a nose, a middle body and a tail section. The nose and the tail shape are described by modified semi-elliptical radius distribution (Myring, 1976), having a length of $0.217m$ and $0.279m$, respectively. The middle body is cylindrical with a diameter of 0.234 m and a length of 1.246 m. Finally the bare hull presents a base-diameter of 0.057 m.

The model was towed at Pirajuba standard navigation speed (1 m/s), with a length-based Reynolds number of 1.7×10^6, with and without the fairing structure. The results are presented in the Fig. 4.

Resembling the missile case, both results presented a similar behavior for the normal force (Fig. 4.a) and the pitch moment (Fig. 4.b), but a few points showed a strange behavior. The $+20°$ and $+25°$ in normal force case, and $-25°$ in the case of the moment, do not showed the same trend as the other points, resulting in a possible error in the model alignment.

The large difference in the axial force chart (Fig. 4.c) is given by the isolation of vertical strut from incident flow drag effects.

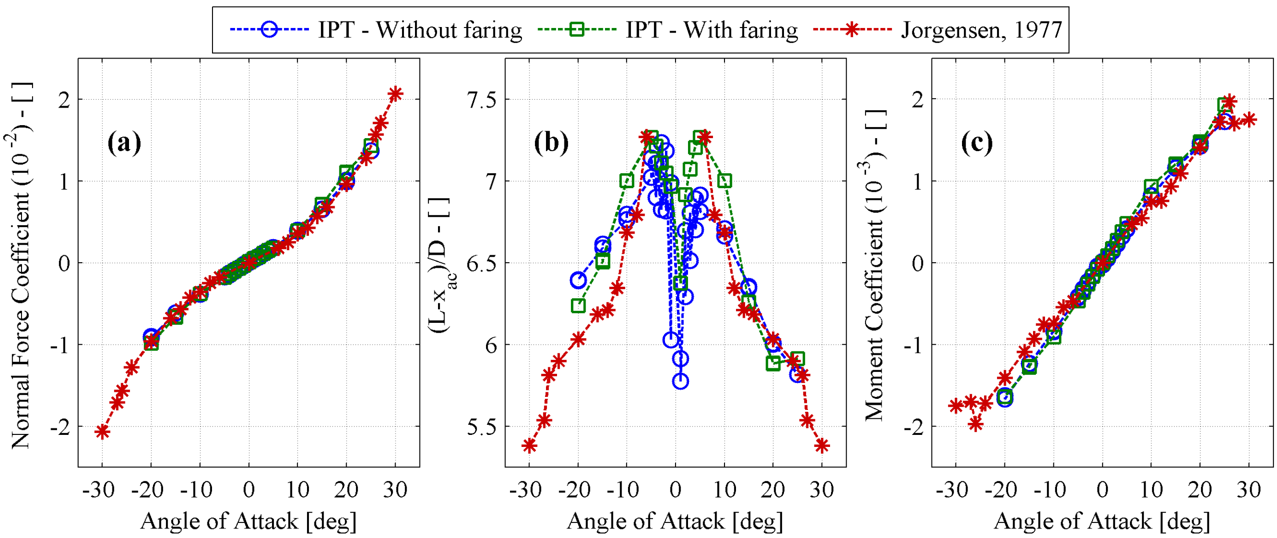

Figure 3. Comparison of normal force coefficient (a), hydrodynamic center (b) and pitch moment (c) for the results obtained from IPT towing tank and published by Jorgensen (1977), for the bare hull of an NACA missile.

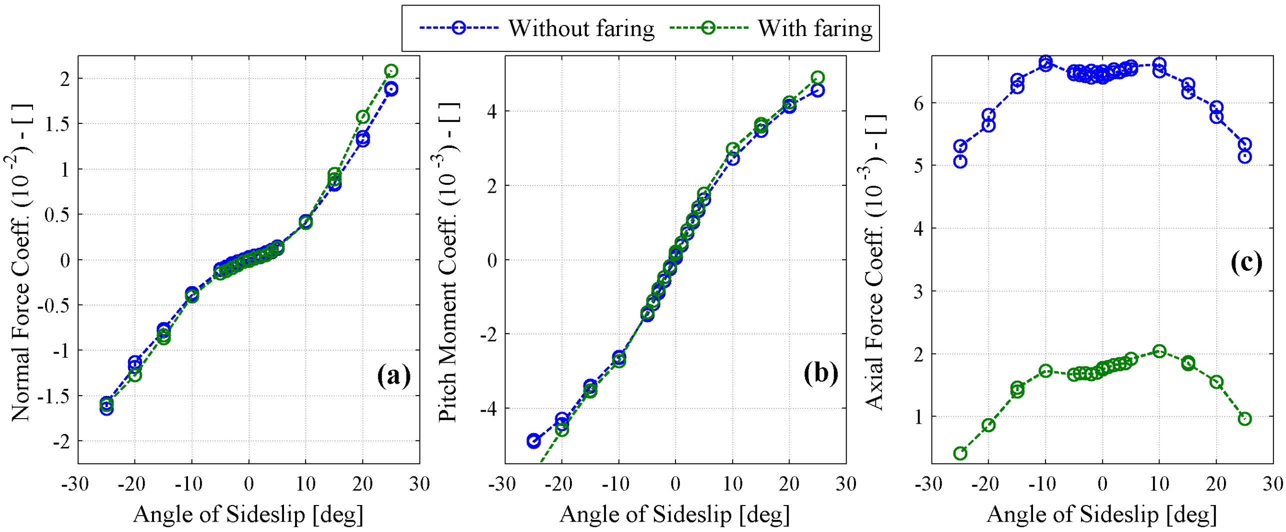

Figure 4. Normal force (a), pitch moment coefficient (b) and axial force (c) for the bare hull of Maya/Pirajuba AUV.

Some results presented in this section were used in the investigation of normal force and moment coefficients of AUVs bare hull (de Barros *et al.*, 2008a), resulting in a new application methodology of semi-empirical prediction models.

3.1.3 Experiments Using Hydroplanes

The identification of the hydroplanes hydrodynamic parameters are very useful in the vehicle stability evaluation, autopilot development and in the study of the entire vehicle hydrodynamic. In this test two hydroplanes will be investigated, the hydroplane used in Maya and Pirajuba projects, and the hydroplane which presented a better stabilization of the Pirajuba AUV under waves disturbances (Dantas *et al.*, 2010). In the second case was expected a wing that generated the same lift in the linear region and had a higher stall angle.

The Maya/Pirajuba hydroplane has a root chord of 90 mm, a tip chord of 60 mm, a semi-span of 160 mm, a null swept angle at 25% of the chord and a NACA0012 profile, giving a wing with a aspect ratio of 4.16 and area of 0.0240 m^2. The new hydroplane had a root chord of 155 mm, a tip chord of 107 mm, a semi-span of 132 mm, a rectangular trailing edge angle and a NACA0015 profile, giving a wing with a aspect ratio of 2.02 and area of 0.0346 m^2.

For simplicity only the normal force was measured in these tests. This was done because the drag generated by the controls surfaces represents less than 10% of the total AUV drag (Stevenson *et al.*, 2007), and its pitch moment is far smaller than the moment generated by the normal force of an hydroplane in the vehicles stern.

The both tests were performed by semi-wing with a large endplate (length of 1.5 m and width of 1.0 m) in the symmetry plane (Fig 5.a), to maintain the total wing aspect ratio and isolated the strut wake effects. The normal force generated by both wings are presented in the Fig. 5.b, and can be seen that the "Wing NACA015" presents the expected stall characteristics without changing the normal force slope.

In the stall region of both cases the normal force presented a hysteretic behavior, i.e. if some angles were measure in the same trial the value of a specific angle presented different values if the previous angle was larger or smaller.

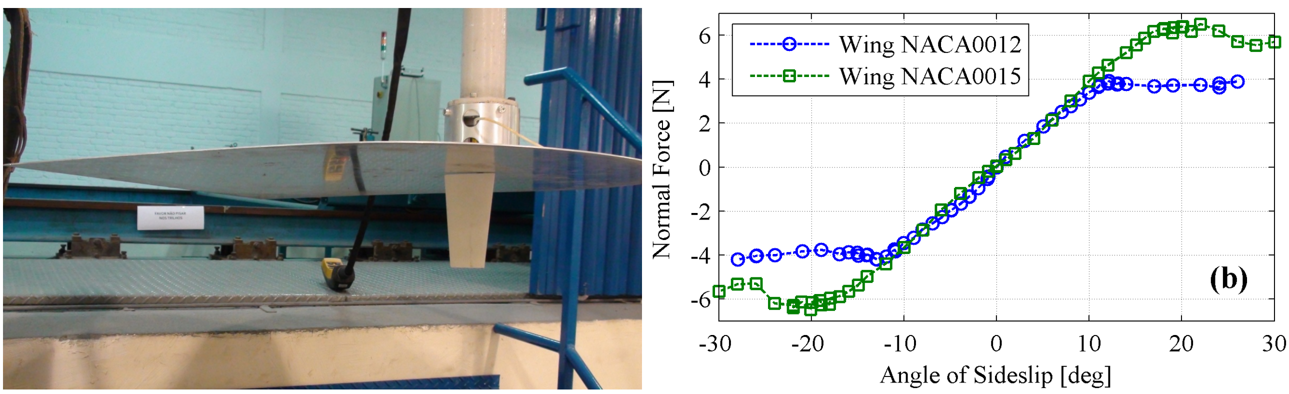

Figure 5. Assembly of hydroplane, endplate and force dynamometer (a), and wings normal force comparison (b).

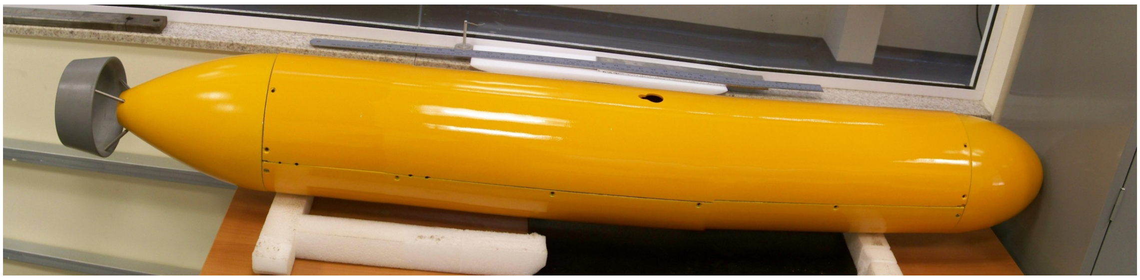

Figure 6. Captive model of AUV Pirajuba bare-hull with a propeller duct.

3.2 Bare hull with appendages

3.2.1 Body-duct configuration

The effect of an propeller duct, with and without propulsion, in the hydrodynamics parameters of the Maya/Pirajuba bare hull were studied in these experiments.

In the test without propulsion only the standard speed duct was installed 23 mm after the body base (Fig. 6). The duct has a chord of 75 mm, a internal diameter of 150 mm and a 19A section profile. The test with propulsion the Pirajuba propeller (de Barros *et al.*, 2010) was installed in the middle of the duct. The four-bladed 4-70 series Kaplan propeller-type has a diameter of 150 mm, a pitch-diameter ratio of 1.2 and a hub diameter of 30 mm.

The model was towed in both tests at same velocity of the bare-hull tests (1 m/s). On the propulsion tests the propeller generated a thrust of 3.5 N. The efforts comparison of both tests can be seen in the Fig. 7.

Without propulsion, this body-duct configuration slight increases the normal force (Fig. 7.a) and significantly decreases the moment (Fig. 7.b), i.e. the duct normal force generate a pitch moment that is amplified by its location. A similar effect was observed in the case with propulsion.

As expected the presence of the duct amplify the total axial force at zero angle of attack, but the duct also change the curvature of axial curve for low angles. Both effects were amplified in the case with propulsion. These effects can be explained by a differential stall in the both duct sides, i.e. one side stalls before the other due to differences in the local angle of attack.

3.2.2 Wing-body "T" configuration (Maya AUV)

The model of Maya AUV wing-body configuration (Fig. 8.a) was tested in order to investigates the effects on the maneuverability of the control surfaces in "T" disposition (de Barros *et al.*, 2008a,b).

The Maya AUV uses two wings in the lateral plane and one downward wing in the vertical plane, they were positioned

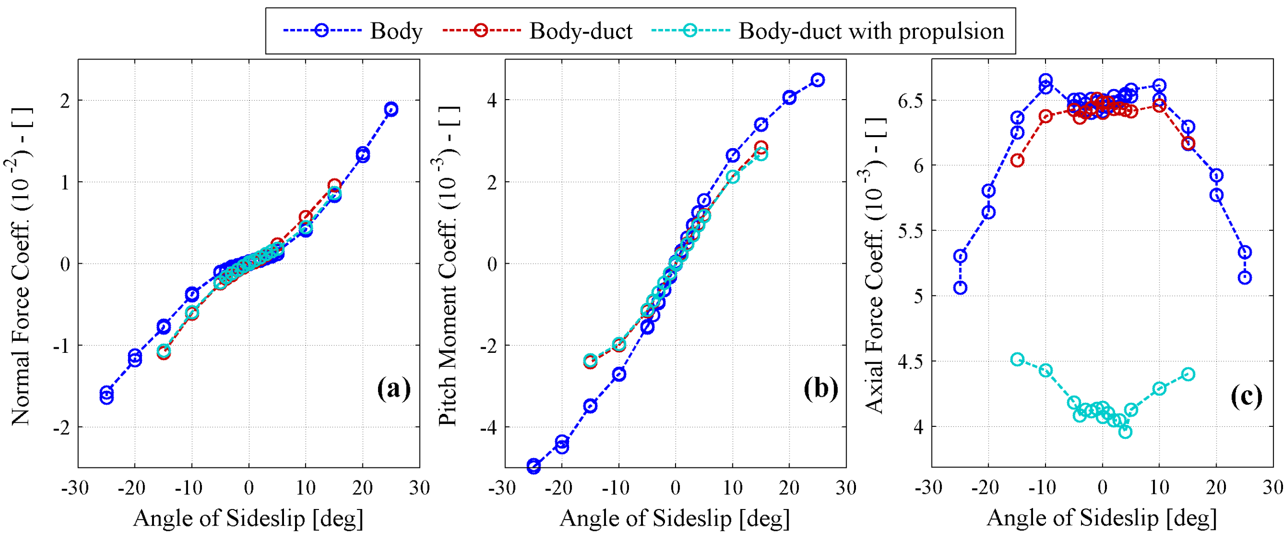

Figure 7. Normal force (a), pitch moment coefficient (b) and axial force (c) for the body-duct combination of Pirajuba AUV.

Figure 8. Captive model of Maya (left side) and Pirajuba (right side) wing-body combination.

at 1.127 m and 1.177 m, respectively, from the nose. The geometry of the wings are the same as the wing NACA0012 (presented in Section 3.1.3).

This test was also used the vertical strut dynamometer, with and without the careen system. The results for the hydrodynamic efforts in the vertical plane are showed in the Fig. 9.

The effect of this hydroplane in the entire model hydrodynamic is similar to the body-duct case, but as the hydroplane is closer to the measure center the same net moment reduction is achieved with a larger normal force.

3.2.3 Wing-body "+" configuration (Pirajuba AUV)

The first tests with Maya bare hull and the NACA0012 wings (Section 3.1.3) in cruciform ("+") configuration (Fig. 8.b) represented the initial development of the AUV Pirajuba (de Barros *et al.*, 2010). But these results were also used in the hydrodynamic investigation of symmetric body-wing combinations.

The four wings in the Pirajuba captive model were positioned at the middle section end of the bare hull (at 1.357 m from the nose or at 0.279 m from the tail end).

In 2007 the first experiments with this model were conducted using the vertical strut dynamometer, with and without the fairing structure. Different of the other tests, the efforts measure with this system (Fig. 10) presented different results, especially in the moment case (Fig. 10.b).

This behavior can be explained by the effect of the strut's wake in the upward hydroplane, locate behind the strut. In the presence of a wake the hydroplane can exhibit an irregular behavior, such as lift decrease or a stall angle variation. In both cases this effect could occur at different intensities and angles, explaining the different results.

Using the new dynamometer system (stinger) the same tests were repeated in 2009 and 2010, in order to avoid this effect and improve the results. These results can also be seen in the Fig. 10.

In 2009 the tests showed a strange behavior that was attributed to a poor orientation of the control surfaces. In 2010 the tests showed a good symmetry in all the cases and a near zero slope of normal force and pitch moment similar to the 2007 cases, but the axial force results showed a low repeatability in the lower angles.

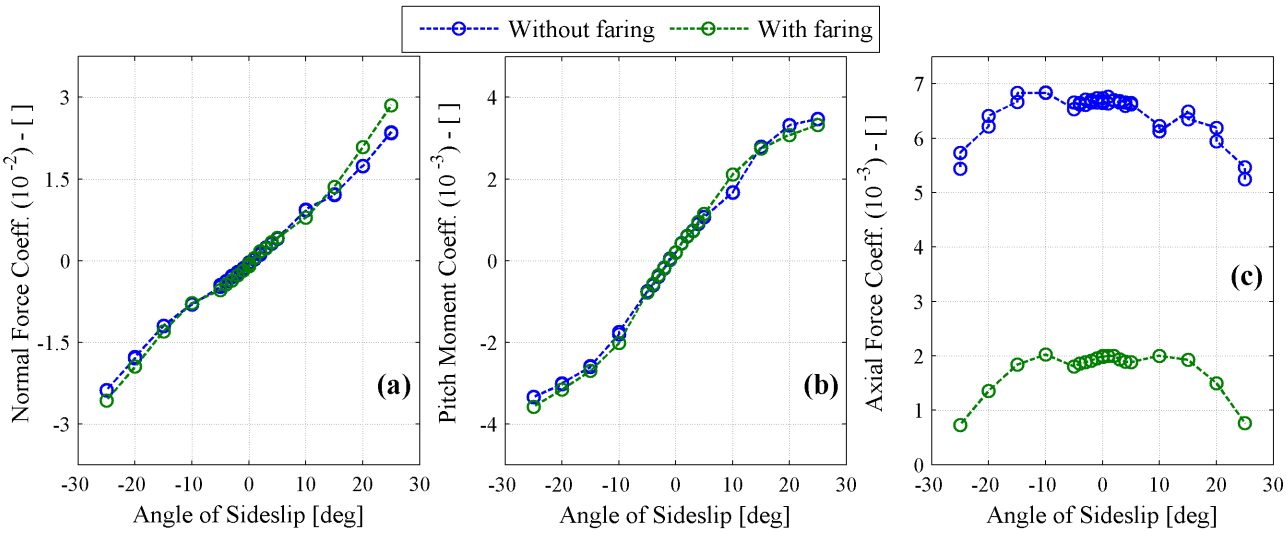

Figure 9. Normal force (a), pitch moment coefficient (b) and axial force (c) for the wing-body combination of Maya AUV.

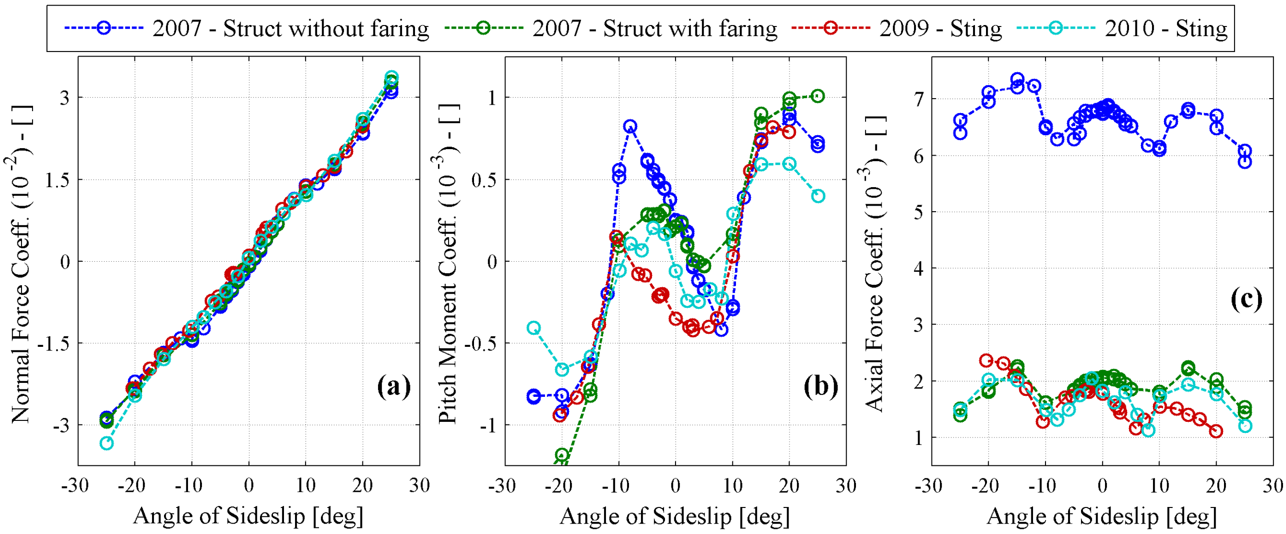

Figure 10. Normal force (a), pitch moment coefficient (b) and axial force (c) for the wing-body combination of Pirajuba AUV.

4 FREE MODEL TESTS

The free model tests were carried out with the former version of the AUV Pirajuba (de Barros *et al.*, 2010). The tests were conducted in the Sport Practice Center of University of São Paulo (CEPESUSP) swimming pool (Fig. 11).

The ideal conditions for free model tests are obtained when the AUV perform such manoeuvres with a minimum of interference from external factors. In other words, the AUV must execute the manoeuvres away from the walls (wall effect) and water surface (free surface effect), in the horizontal plane (no inclination) and at a constant speed.

Using a feedback control in the vertical plane, it was possible to stabilize the AUV's depth and trimming angle during the manoeuvres. The implemented control algorithm was based on the Linear Quadratic Regulator (LQR) theory, with a filtered feedback in the depth, inclination and pitch angular velocity.

The constant navigation velocity was achieved by a pre-calibration of the propeller rotation. This survey was conducted by a series of straight line tests, where the vehicle velocity was measured externally. More detailed information of the AUV Pirajuba sensors can be seen in de Barros *et al.* (2010).

In these tests the vehicle executes a number of zigzag manoeuvres, varying the speed of navigation (0.8-1.5 m/s), depth (0.6-1.0 m) and the amplitude of manoeuvres (5, 10, 15, 20 degrees). The better results were obtained with a 5° amplitude at 1.0 m/s and 0.85 m of depth (Fig. 12).

The heading (yaw angle) and lateral control input (rudder) for this manoeuvre are presented in the Fig. 12.a. Although the AUV had a compass, its measurement was not reliable due to the jamming of water pumping equipment (hard and soft iron effect) installed on the bottom and side of the pool, Therefore, the heading information was derived by the integration of a high precision gyro, that presents a low bias stability error for short time intervals.

In Fig. 12.b are presented the control variables. Is possible to verify the depth and the trimming angle stabilization in about 15 seconds. The elevators average level indicates a difference between the longitudinal positions if the centre of gravity and the centre of buoyance. This issue was resolved in the Pirajuba's newer version.

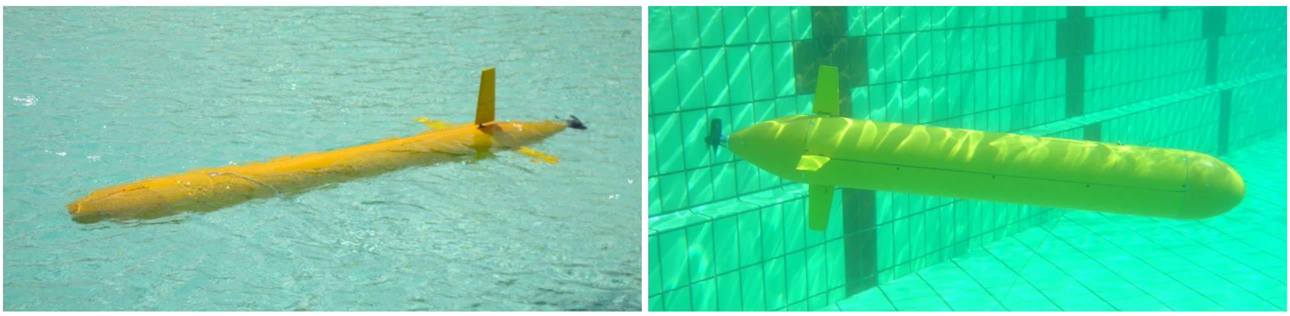

Figure 11. Free model test of AUV Pirajuba in the University of São Paulo swimming pool.

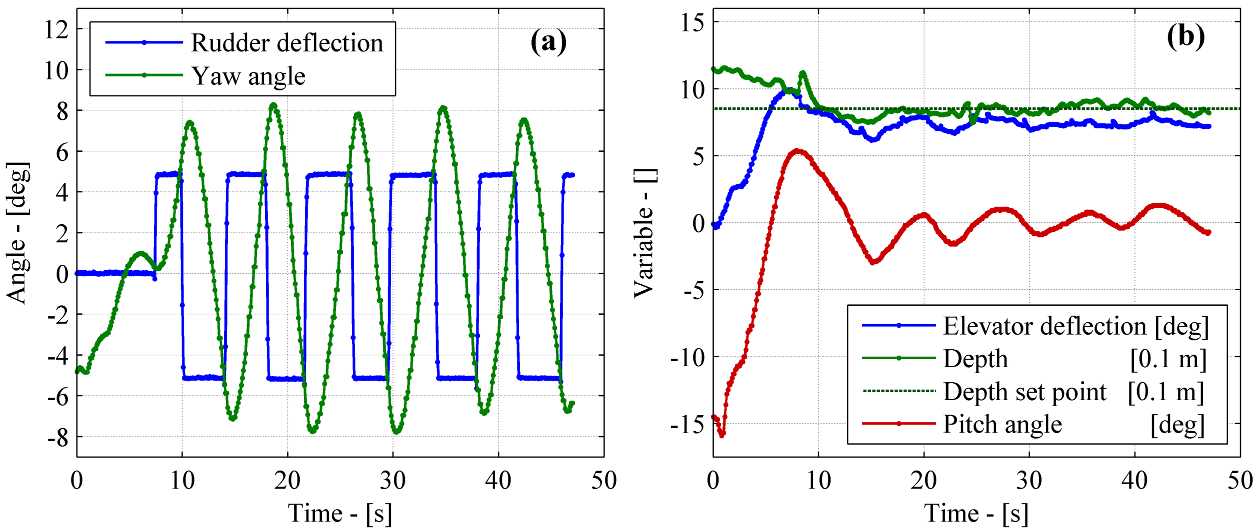

Figure 12. Results from a 5° zigzag manoeuvre: heading and rudder deflection (a), and depth control variables (b).

5 CONCLUSION

In general, the captive model tests presented good results, allowing the LVNT improve the investigations on AUVs hydrodynamics characteristics (de Barros *et al.*, 2008a) and AUV development (de Barros *et al.*, 2010, 2011; Dantas *et al.*, 2010).

Of course, further hydrodynamic aspects of AUVs need to be investigated in order to complete the study on manoeuvrability. It can be mentioned, for instance, the investigation on the hull-hydroplane combination, considering the local measurements of the plane load, the effects of the rudder based on the NACA 0015 profile, and the efforts related to rudder deflections.

The preliminary tests using the self-propelled vehicle validated the real-time implementation of pre-programmed manoeuvres. The tests pointed, however, the need for improvement on the vehicle ballast and floating systems, and better environmental conditions for producing the manoeuvres required in the identification of the AUV dynamics.

These and other problems should be overcome by the use of the university basin, and the newer version of the Pirajuba AUV.

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