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Improving parameter estimation efficiency of a non linear manoeuvring model of an underwater vehicle based on model basin data

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ABSTRACT

In this work, a methodology is proposed for the improvement of the parameter estimation efficiency of a non-linear manoeuvring model of a torpedo shaped unmanned underwater vehicle. For this purpose, data from different tests, were carried out with the aforementioned vehicle at the facilities of the CEHIPAR (Canal de Experiencias Hidrodinámicas de El Pardo), Madrid. In the proposed methodology, the following aspects are taken into account in order to improve the parameter estimation efficiency: selection of the sampling period, smoothing of the data acquired in the tests, considering a compromise between bias and variance of the smoothing filter to be applied, analysis of the classical linear regression model proposed in each trial from the statistical point of view for the estimation of the parameters. Improvements in efficiency are verified by graphical and statistical methods.

1. Introduction

The use of unmanned vehicles, in the naval field, is widely known in the scientific world [37]. The security sector is the one that is moving this technology forward in recent years. Fleet formation constitutes one of the basic requirements for the design of a new generation of underwater vehicles that will be employed in various missions such as mine clearance pathways, anti-submarine warfare, perimeter defense, surface warfare, support for special operations forces, etc. Today, the autonomous underwater vehicles or the so-called unmanned underwater vehicles AUV-UUVs are of paramount importance, for both military and civilian applications and procedures for underwater exploration and inspection. The incorporation of unmanned vehicles to the defense sector has contributed to the state of the art of unmanned systems for hazardous or high-risk missions, such as tracking, detection and neutralization of mines.

The cited underwater applications are in many cases based on a mathematical model that describes the motion of the vehicle. It is of great importance in naval construction to obtain a mathematical manoeuvring model as accurate as possible in order to meet contractual agreements. This requirement is also of high importance in motion control applications in which, if the mathematical model used for the control design is not accurate when considering the operational conditions of the vehicle, or if external disturbances exist, it is difficult to tune the controller for a good behaviour of the vehicle.

As far as the accuracy of the model is concerned, a significant number of contributions are found in the literature regarding to the fit to the data and the accuracy of the manoeuvring model when it is applied ordinary least squares (OLS) to surface vehicles [27,30,38,22,19,39,36]. In the same way, regarding to underwater vehicles, there is a variety of references [1,3,28,31,12,33,20,13,10], which also emphasizes data fit and accuracy of the model when OLS is applied. However, in the cited works there is no study related to the statistical properties of the estimated parameters. A good fit to the data does not necessarily mean that the obtained parameters are correct as it is stated by [29], who pointed out that for a function f, if more than a parameter θ corresponds to a given value of f, not an even infinite-sized sample can distinguish between them. That is why, it is very important to analyze the bias and the variance of the parameter estimates, which are respectively related to the accuracy and the efficiency of the estimated parameters [26].

For all the mentioned above, the application of OLS is widely known in the literature and can be used as an initial guess for a more sophisticated estimator in case of biased parameters. Moreover, the application of OLS is often used to compare its results with the ones of other methods, thus it is convenient to obtain an efficient parameter estimation in order to establish a reliable comparison. It is also important, when using prediction error methods, which may cause problems of

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local minima in the optimization process. This actually happens in the work published by [15], where it is indicated the importance of having adequate initial parameter estimates.

There are no references specifically related to parameter estimation efficiency of manoeuvring models with OLS. In the case of parameter estimation, based on data acquired in a model basin, object of study in this article, the efficiency is of high importance due to the high costs of these tests. The number of data that can be captured is limited and it is important to obtain efficient estimates, as far as possible. This article aims to cover this aspect of the literature, proposing a methodology to improve the parameter estimation efficiency of a non linear manoeuvring model of an underwater vehicle based on the application of an iterative procedure. This methodology combines different types of classical methods and data filtering in order to improve parameter estimation efficiency based on acquired data of model basin tests.

In the above mentioned hydrodynamic model basin tests are usually performed the so-called planar motion mechanism (PMM) tests [4,17]. In the literature, there are some articles related to PMM tests performed on underwater vehicles [24,11]. In this work, we have made some modifications in the PMM tests in order to estimate roll coefficients and other actuators parameters.

In the view of the commented above, the main contributions of this paper can be summarized as: (a) To propose a methodology for the improvement of the parameter estimation efficiency of a non-linear manoeuvring model. This methodology is applied to the data acquired in a model basin of a torpedo shaped unmanned underwater vehicle for different trials. This methodology improves efficiency by combining different types of classic methods that involves: data filtering, regression analysis and an iterative procedure. (b) To propose a modification in the PMM tests in order to estimate the roll coefficients. (c) To verify the proposed methodology by graphical and statistical methods, which show the improvement in the estimation efficiency of the hydrodynamic parameters based on model basin data. The statistical properties of the methodology are tested by a Monte Carlo study of 100 realizations.

The outline of the paper is as follows: Section 2 reviews non linear manoeuvring models for an underwater vehicle, Section 3 describes the model basin trials carried out, Section 4 discusses the aspects that have influence on the parameter estimation efficiency and provides a methodology for its improvement. Finally, Section 5 summarizes the main conclusions.

2. Manoeuvring model

Underwater vehicles move in six degrees of freedom (DOF). In order to describe the vehicle motion, three translational coordinates are needed and other three to define the orientation. Two coordinate systems are used to study the vehicle movement: one coordinate is fixed to the vehicle and is used to define its translational and rotational movements and another one is located on Earth (NED-frame) to describe its position and orientation.

The 6 DOF non linear manoeuvring model can be expressed in the following form [6]:

$$\mathbf{M}\dot{\nu} + \mathbf{C}(\nu)\nu + \mathbf{D}(\nu)\nu + \mathbf{g}(\eta) = \tau, \tag{1}$$

$$y = \nu + \omega, \quad \dot{\eta} = \mathbf{J}(\eta)\nu \tag{2}$$

where $\eta = [x, y, z, \phi, \theta, \psi]^T$ is the position and Euler angles vector, $\nu = [u, v, w, p, q, r]^T$ are the linear and angular speeds, $\tau = [X, Y, Z, K, M, N]^T$ are the forces and moments and ω is the measurement noise. $\mathbf{M}$ is the added mass matrix, $\mathbf{C}(\nu)\nu$ is the Coriolis term, $\mathbf{g}(\eta)$ is the restore matrix and $\mathbf{J}(\eta)$ is the rotation matrix and $\mathbf{D}(\nu)\nu$ represents the hydrodynamic damping forces that are a combination of lineal and non linear damping.

The kinematic relationship between the speed ν in the body-fixed coordinate system and the position η in the NED (North East Down) coordinate system is given by:

$$\mathbf{J}(\eta) = \begin{bmatrix} R(\Theta) & 0_{3x3} \\ 0_{3x3} & T_\Theta(\Theta) \end{bmatrix} \tag{3}$$

where

$$R(\Theta) = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{4}$$

$$T_\Theta(\Theta) = \begin{bmatrix} 1 & -s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & \frac{s\phi}{c\theta} & \frac{c\phi}{c\theta} \end{bmatrix}, \quad \theta \neq \frac{\pi}{2} \tag{5}$$

and $c(\cdot) = cos(\cdot)$, $s(\cdot) = sin(\cdot)$, $t(\cdot) = tan(\cdot)$ and $\Theta = [\phi\ \theta\ \psi]^T$.

The matrices of Eq. (1) are the following:

The rigid body and added mass matrices, $\mathbf{M} = M_{RB} + M_A$.

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & 0 \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & 0 & mx_G & 0 \\ 0 & -mz_G & 0 & I_x & 0 & 0 \\ mz_G & 0 & -mx_G & 0 & I_y & 0 \\ 0 & -mz_G & 0 & 0 & 0 & I_z \end{bmatrix} \tag{6}$$

where m is the mass of the vehicle, I_x, I_y, y I_z are the inertia moments, $r_G = [x_G, y_G, z_G]^T$ is the center of gravity position with respect to the body-fixed coordinate system.

$$M_A = \begin{bmatrix} -X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -Y_{\dot{v}} & 0 & 0 & 0 & -Y_{\dot{r}} \\ 0 & 0 & -Z_{\dot{w}} & 0 & -Z_{\dot{q}} & 0 \\ 0 & 0 & 0 & -K_p & 0 & 0 \\ 0 & 0 & -M_{\dot{w}} & 0 & -M_{\dot{q}} & 0 \\ 0 & -N_{\dot{v}} & 0 & 0 & 0 & -N_{\dot{r}} \end{bmatrix} \tag{7}$$

In this article, it is considered that the underwater vehicle operates at depths below the area affected by the movement induced by the waves. Therefore, it is considered that the coefficients of the added mass matrix are constant, for more details on this aspect and on operating conditions see [23,8].

The Coriolis matrix $\mathbf{C}(\nu) = C_{RB}(\nu) + C_A(\nu)$

$$C_{RB} = \begin{bmatrix} 0 & 0 & 0 & c_{41} & -c_{51} & -c_{61} \\ 0 & 0 & 0 & -c_{42} & c_{52} & -c_{62} \\ 0 & 0 & 0 & -c_{43} & -c_{53} & c_{63} \\ -c_{41} & c_{42} & c_{43} & 0 & -c_{54} & -c_{64} \\ -c_{51} & -c_{52} & -c_{53} & -c_{54} & 0 & -c_{65} \\ c_{61} & c_{62} & -c_{63} & c_{64} & c_{65} & 0 \end{bmatrix} \tag{8}$$

$$C_A(\nu) = \begin{bmatrix} 0 & 0 & 0 & 0 & -a_3 & a_2 \\ 0 & 0 & 0 & a_3 & 0 & -a_1 \\ 0 & 0 & 0 & -a_2 & a_1 & 0 \\ 0 & -a_3 & a_2 & 0 & -b_3 & b_2 \\ a_3 & 0 & -a_1 & b_3 & 0 & -b_1 \\ -a_2 & a_1 & 0 & -b_2 & b_1 & 0 \end{bmatrix} \tag{9}$$

where

$c_{41} = mz_G r$ $\quad c54_1 = -I_{\dot{z}} r$

$c_{42} = mw$ $\quad c_{61} = m(x_G r + v)$

$c_{43} = m(z_G p - v)$ $\quad c_{62} = -mu$

$c_{51} = m(x_G q - w)$ $\quad c_{63} = -mx_G p$

$c_{52} = m(z_G r + x_G p)$ $\quad c_{54} = I_y q$

$c_{53} = m(z_G q + u)$ $\quad c_{65} = -I_x p$