Sociedade Brasileira de Automática (SBA)
XXV Congresso Brasileiro de Automática - CBA 2024, 15 a 18 de outubro de 2024

Obtaining the Surge Hydrodynamic Derivatives of a Container Ship ⋆

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Abstract: Ship maneuver simulators and autonomous vessels rely substantially on the hydrodynamic coefficients identification to accurately reproduce its dynamics. Therefore, the objective of this article is to propose and execute a specific maneuver to identify the surge hydrodynamic derivatives for a container ship class. For this purpose, ship motions are generated through a maneuvering model implemented by Fossen (1994) in Matlab. Therefore, given the container ship and its sea trial data, a system identification method for nonlinear dynamics (SINDYc), adapted to identify hydrodynamic derivatives directly, and a regression method (LASSO) are applied to obtain the hydrodynamic coefficients that satisfy the tested maneuver. The maneuver is repeated with the new coefficients and the trajectories are compared. The results obtained for the ship's coefficients and trajectory show good adherence, specially for the most excited terms.

Keywords: System Identification. Nonlinear Dynamics. Container ship. Ship maneuvering. Hydrodynamic derivatives.

1. INTRODUCTION.

It is known that one of the design requirements for both merchant and warships is good maneuverability, which is evaluated shortly after launch through what is known as sea trials, Masetti (2018).

According to the ITTC (2002) conclusion, maneuverability is understood as the vessel's ability to turn, its behavior in abrupt stops, among others:

- Course-keeping ability;
- Initial turning/course-changing ability;
- Yaw checking ability;
- Turning ability and
- Stopping ability.

Mao, et al., analyze the methods used to assess ship maneuverability, from sea trials to experimental tests and those based on computational fluid dynamics (CFD), and discuss how ship dynamics have been identified, Alexandersson et al. (2022).

Experimental tests on a reduced scale with non-captive models (Free running model tests, ITTC(2008)) are commonly recognized as the most accurate, Alexandersson et al. (2022), but they can also be performed using CFD with good results, Araki et al. (2012). However, these methods are expensive, Alexandersson et al. (2022).

There is also the option to conduct experiments with captive models or using mechanical arms that restrict part of their movement (Planar motion mechanism - PMM) or virtual captive tests, (VCT) He et al. (2022), but these are also costly, Alexandersson et al. (2022).

In this context, simulation presents itself as a low-cost solution.

Identifying ship dynamics to predict its maneuverability can be done using simulation, Alexandersson et al. (2022). This corresponds to the majority of publications in this area, Alexandersson et al. (2022).

Therefore, for identification purposes, it is possible to conduct sea trials in a virtual environment, provided that the ship and its maneuver model are known. The data obtained from the trials can feed an algorithm that seeks the hydrodynamic coefficients of the ship (see Section 4.3).

Starting from a reference ship of the container class, called CONTAINER, and its maneuvering model, Fossen (1994), a method to identify nonlinear system dynamics (SINDYc) and a regression method (LASSO) were applied by this author, Strauhs (2023), to obtain the hydrodynamic coefficients that satisfy the tested maneuver. From the conclusion of the undergraduate thesis, one main future research project was highlighted and motivated this article.

Instead of selecting a traditional maneuver such as Turning Circle or Zig-Zag to identify all coefficients in a single run, the suggestion was to identify the hydrodynamic derivatives separately and to develop a specific maneuver that aims at a specific set of coefficients in order to enhance the results.

⋆ The authors acknowledge LabOceano's team.

Thus, to continue this research, one maneuver is developed to identify all the five (05) CONTAINER surge coefficients, presented in Table 5.

To achieve this goal, the system identification algorithm was updated to identify the hydrodynamic coefficients directly and to allow the substitution of the obtained results in the original plant in order to compare the trajectories obtained by both sets of coefficients.

The trajectories show very good adherence, and the hydrodynamic coefficients results are highly promising.

Section 2 describes the mathematical modeling of the problem and Section 3 presents the identification equations used in this article. Section 4 describes the proposed maneuver, the identification algorithm, the reference coefficients and the maneuver model calibration. Finally, Sections 5 and 6 present the results and conclusion.

2. MATHEMATICAL MODEL.

2.1 Modeled Ship.

The container ship has a length between perpendiculars of 175 meters and a block coefficient of 0.559, as shown in Table 1, Fossen (1994).

Table 1. Characteristics of the modeled ship, Fossen (1994).

Length between perpendiculars	(L_{pp})	175.00	m
Beam	(B)	25.40	m
Fore draft	(d_F)	8.00	m
Aft draft	(d_A)	9.00	m
Displaced volume		21.222	m^3
Block coefficient	(C_B)	0.559	
Rudder area	(A_R)	33.0376	m^2
Propeller diameter	(D)	6.533	m

The ship in maneuvering condition can also move in 6 degrees of freedom, but typically, the problem is modeled only for *surge, sway* and *yaw*.

For the container ship, particularly, the *roll* motion can also be considered given its operational characteristics.

Environmental conditions are assumed to be wave-free and wind-free, and the ship's dynamics are modeled for 4 degrees of freedom, namely *surge, sway, roll* and *yaw*, Machado (2021).

2.2 Reference System.

When modeling the ship's movements during maneuvering, it is convenient to define two coordinate systems, as shown in Figure 1.

The fixed reference O_2 moves fixed to the vessel, and the inertial reference O_1 remains stationary, fixed at a point on Earth.

The problem is discretized, and throughout the maneuver, the so-called state variables are recorded, i.e., positions and velocities for each degree of freedom. It is convenient to describe positions in the inertial reference frame and velocities in the fixed reference frame, Fossen (1994).

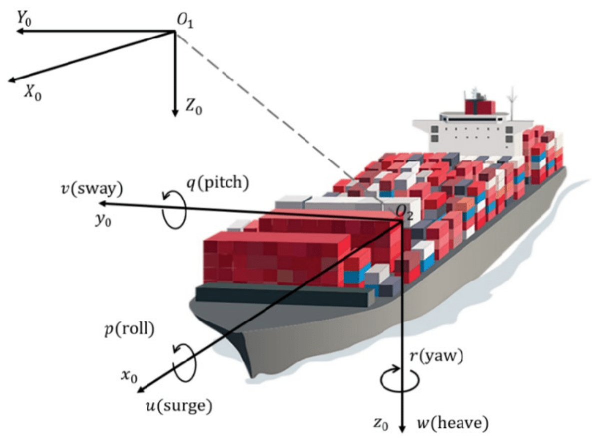

Figure 1. Fixed and inertial reference frames, CC BY 4.0.

2.3 Equations of Motion.

It is assumed that the ship is a rigid body. There are two formulations for modeling the equations of motion, Lagrangian and Newton-Euler. Despite the differences, both yield equivalent results, Machado (2021).

The Son and Nomoto (1982) structure is used, which opts for the Newton-Euler Formulation, a model that was implemented in MATLAB by Fossen (1994).

In this formulation, Euler's axioms are used to express Newton's Second Law in terms of the conservation of linear and angular momentum, Fossen (2011). The deduction was published by Abkowitz (1964).

The force is written as

$$\boldsymbol{F} = \frac{d}{dt}(m\boldsymbol{U}) = m\frac{d\boldsymbol{U}}{dt} + \boldsymbol{U}\frac{dm}{dt} = m\dot{\boldsymbol{U}} + \boldsymbol{U}\frac{dm}{dt}, \quad (1)$$

where m is the mass of displaced fluid or the displacement of the ship, and $\boldsymbol{U}$ is the linear velocity vector, whose components are u, v, and w along the x, y, and z axes, respectively,

$$\boldsymbol{U} = \hat{\imath}u + \hat{\jmath}v + \hat{k}w. \quad (2)$$

The variation of mass with time is negligible $\frac{dm}{dt} = 0$. Due to the motion of the fixed reference frame, the terms $\frac{d\hat{\imath}}{dt}$, $\frac{d\hat{\jmath}}{dt}$, and $\frac{d\hat{k}}{dt}$ are non-zero, Abkowitz (1964).

The expressions above are substituted, and the terms are grouped in their respective directions

$$X = m(\dot{u} + qw - rv), \quad (3)$$

$$Y = m(\dot{v} + ru - pw), \quad (4)$$

$$Z = m(\dot{w} + pv - qu). \quad (5)$$

Analogously for the moments K, M, and N

$$K = I_x\dot{p} + (I_z - I_y)qr, \quad (6)$$

$$M = I_y\dot{q} + (I_x - I_z)rp, \tag{7}$$

$$N = I_z\dot{r} + (I_y - I_x)pq. \tag{8}$$

Mass Matrix. From equations (3) to (8), the left-hand side of the equations is expanded to obtain their hydrodynamic forces and moments, as shown in Section 2.4. The terms multiplying the accelerations are gathered on what is called mass matrix, as in a mass-spring-damping system. Thus, given that Fossen (1994) uses prime notation for non-dimensional terms, the mass matrix for the container ship and the reference at the center of gravity is

$$\left[M^{'}\right] = \begin{bmatrix} m^{'} + m_x^{'} & 0 & 0 & 0 \\ 0 & m^{'} + m_y^{'} & -m_y^{'}l_y^{'} & m_y^{'}\alpha_y^{'} \\ 0 & -m_y^{'}l_y^{'} & I_x^{'} + J_x^{'} & 0 \\ 0 & m_y^{'}\alpha_y & 0 & I_z^{'} + J_z^{'} \end{bmatrix}, \tag{9}$$

where $m^{'}$ is the mass displaced by the vessel, $I_x^{'}$ and $I_z^{'}$ are the moments of inertia around the x and z axes, respectively, $m_x^{'}$ and $m_y^{'}$ are the additional masses in x and y. $l_y^{'}$ is the z coordinate of the center of application of the force due to the additional mass $m_y^{'}$, $\alpha_y^{'}$ is the x coordinate of the resultant force due to $m_y^{'}$, $J_x^{'}$ and $J_z^{'}$ are the additional moments of inertia in x and z, Machado (2021). Prime notation indicates non-dimensional terms.

2.4 Hydrodynamic Forces of the Hull and Actuators.

The formulation used by Fossen (1994) is shown below, where the terms $(m^{'} + m_y^{'})v^{'}r^{'}$, $-(m + m_x^{'})u^{'}r^{'}$, and $m_x^{'}l_x^{'}u^{'}r^{'}$ come from the other side of the equations of motion (3) to (8),

$$\begin{aligned} X^{'} &= X_{uu}^{'}u^{'2} + X_{vr}^{'}v^{'}r^{'} + X_{vv}^{'}v^{'2} + X_{rr}^{'}r^{'2} + X_{\phi\phi}^{'}\phi^{'2} \\ &+ (m^{'} + m_y^{'})v^{'}r^{'} + (1 - t_r)T^{'} + c_{RX}F_N^{'}\sin\delta, \end{aligned} \tag{10}$$

$$\begin{aligned} Y^{'} &= Y_v^{'}v^{'} + Y_r^{'}r^{'} + Y_p^{'}p^{'} + Y_\phi^{'}\phi^{'} + Y_{vvv}^{'}v^{'3} + Y_{rrr}^{'}r^{'3} \\ &+ Y_{vvr}^{'}v^{'2}r^{'} + Y_{vrr}^{'}v^{'}r^{'2} + Y_{vv\phi}^{'}v^{'2}\phi^{'} + Y_{v\phi\phi}^{'}v^{'}\phi^{'2} \\ &+ Y_{rr\phi}^{'}r^{'2}\phi^{'} + Y_{r\phi\phi}^{'}r^{'}\phi^{'2} - (m^{'} + m_x^{'})u^{'}r^{'} + (1 + a_H)F_N^{'}\cos\delta, \end{aligned} \tag{11}$$

$$\begin{aligned} K^{'} &= K_v^{'}v^{'} + K_r^{'}r^{'} + K_p^{'}p^{'} + K_\phi^{'}\phi^{'} + K_{vvv}^{'}v^{'3} + K_{rrr}^{'}r^{'3} \\ &+ K_{vvr}^{'}v^{'2}r^{'} + K_{vrr}^{'}v^{'}r^{'2} + K_{vv\phi}^{'}v^{'2}\phi^{'} + K_{v\phi\phi}^{'}v^{'}\phi^{'2} \\ &+ K_{rr\phi}^{'}r^{'2}\phi^{'} + K_{r\phi\phi}^{'}r^{'}\phi^{'2} + m_x^{'}l_x^{'}u^{'}r^{'} - W^{'}\phi^{'}\overline{GM}^{'} \\ &- (1 + a_H)z_R^{'}F_N^{'}\cos\delta, \end{aligned} \tag{12}$$

$$\begin{aligned} N^{'} &= N_v^{'}v^{'} + N_r^{'}r^{'} + N_p^{'}p^{'} + N_\phi^{'}\phi^{'} + N_{vvv}^{'}v^{'3} \\ &+ N_{rrr}^{'}r^{'3} + N_{vvr}^{'}v^{'2}r^{'} + N_{vrr}^{'}v^{'}r^{'2} + N_{vv\phi}^{'}v^{'2}\phi^{'} \\ &+ N_{v\phi\phi}^{'}v^{'}\phi^{'2} + N_{rr\phi}^{'}r^{'2}\phi^{'} + N_{r\phi\phi}^{'}r^{'}\phi^{'2} \\ &+ (x_R^{'} + a_H x_H^{'})F_N^{'}\cos\delta, \end{aligned} \tag{13}$$

with

$$F_N^{'} = \frac{-6.13\Lambda}{\Lambda + 2.25}\frac{A_R}{L^2}(u_R^{'2} + v_R^{'2})\sin\alpha_R, \tag{14}$$

where $X^{'}$ and $Y^{'}$ are the forces in the x and y directions, K' and N' are the moments about the x and z axes, $X_{[\,]}^{'}$, $Y_{[\,]}^{'}$, $K_{[\,]}^{'}$, and $N_{[\,]}^{'}$ are the hydrodynamic derivatives of the ship, $T^{'}$ is the thrust generated by the propeller, $F_N^{'}$ is the force generated by the rudder, δ is the rudder angle, $W^{'}$ is the weight of the ship, $\overline{GM}^{'}$ is the metacentric height, u_R and v_R are the flow incident velocities on the rudder, α_R is the flow angle of attack on the rudder, $t_r, c_{RX}, a_H, x_R^{'}$, and $x_H^{'}$ are empirical constants.

Solution Method for the Maneuvering Model. For 04 (four) degrees of freedom, the Newton-Euler formulation can be written as Fossen (1994) (see Section 2.3):

$$\left[M^{'}\right]\left[\dot{u}^{'}\ \dot{v}^{'}\ \dot{p}^{'}\ \dot{r}^{'}\right]^T = \left[X^{'}\ Y^{'}\ K^{'}\ N^{'}\right]^T. \tag{15}$$

Both sides of the equation are multiplied by $\left[M^{'}\right]^{-1}$,

$$\left[\dot{u}^{'}\ \dot{v}^{'}\ \dot{p}^{'}\ \dot{r}^{'}\right]^T = \left[M^{'}\right]^{-1}\left[X^{'}\ Y^{'}\ K^{'}\ N^{'}\right]^T. \tag{16}$$

So that to obtain the acceleration vectors over time in each degree of freedom, one must substitute equations (9) and (10)-(13) into 16.

Once the hydrodynamic derivatives and the states are known, the numerical solution of the maneuvering equations by time integration provides the ship's trajectory.

3. IDENTIFICATION EQUATIONS.

For the purpose of hull coefficient identification, it is convenient to subtract rudder and propeller forces and moments and all terms that are not hydrodynamic derivatives. Thus, equations (10)-(13) are rewritten as

$$\begin{aligned} X_f^{'} &= X_{uu}^{'}u^{'2} + X_{vr}^{'}v^{'}r^{'} + X_{vv}^{'}v^{'2} + X_{rr}^{'}r^{'2} \\ &+ X_{\phi\phi}^{'}\phi^{'2}, \end{aligned} \tag{17}$$

$$\begin{aligned} Y_f^{'} &= Y_v^{'}v^{'} + Y_r^{'}r^{'} + Y_p^{'}p^{'} + Y_\phi^{'}\phi^{'} + Y_{vvv}^{'}v^{'3} \\ &+ Y_{rrr}^{'}r^{'3} + Y_{vvr}^{'}v^{'2}r^{'} + Y_{vrr}^{'}v^{'}r^{'2} + Y_{vv\phi}^{'}v^{'2}\phi^{'} \\ &+ Y_{v\phi\phi}^{'}v^{'}\phi^{'2} + Y_{rr\phi}^{'}r^{'2}\phi^{'} + Y_{r\phi\phi}^{'}r^{'}\phi^{'2}, \end{aligned} \tag{18}$$

$$\begin{aligned} K_f^{'} &= K_v^{'}v^{'} + K_r^{'}r^{'} + K_p^{'}p^{'} + K_\phi^{'}\phi^{'} + K_{vvv}^{'}v^{'3} \\ &+ K_{rrr}^{'}r^{'3} + K_{vvr}^{'}v^{'2}r^{'} + K_{vrr}^{'}v^{'}r^{'2} + K_{vv\phi}^{'}v^{'2}\phi^{'} \\ &+ K_{v\phi\phi}^{'}v^{'}\phi^{'2} + K_{rr\phi}^{'}r^{'2}\phi^{'} + K_{r\phi\phi}^{'}r^{'}\phi^{'2}, \end{aligned} \tag{19}$$

$$N_f' = N_v'v' + N_r'r' + N_p'p' + N_\phi'\phi' + N_{vvv}'v'^3 + N_{rrr}'r'^3 + N_{vvr}'v'^2r' + N_{vrr}'v'r'^2 + N_{vv\phi}'v'^2\phi' + N_{v\phi\phi}'v'\phi'^2 + N_{rr\phi}'r'^2\phi' + N_{r\phi\phi}'r'\phi'^2, \quad (20)$$

where

$$X_f' = X' - (m' + m_y')v'r' - (1 - t_r)T' - c_{RX}F_N' \sin\delta, \quad (21)$$

$$Y_f' = Y' + (m' + m_x')u'r' - (1 + a_H)F_N' \cos\delta, \quad (22)$$

$$K_f' = K' + W'\phi'\overline{GM}' - (1 + a_H)z_R'F_N' \cos\delta, \quad (23)$$

$$N_f' = N' - (x_R' + a_H x_H')F_N' \cos\delta, \quad (24)$$

where X_f' is the force in surge direction and has components associated only with the hull;

Y_f' is the force in sway direction and has components associated only with the hull;

K_f' is the roll moment, and has components associated only with the hull and;

N_f' is the yaw moment, and has components associated only with the hull.

4. PROPOSED METHOD.

Data is generated from virtual maneuvers performed using a container ship reference model and its maneuvering model published by Fossen (1994). These data are fed into an identification algorithm to obtain the hydrodynamic derivatives, according to Section 4.2.

The Figure 2 presents a flowchart of the proposed method, where rectangles represent algorithms and respective subroutines executed in this work, and diamonds represent this article's contributions.

The proposal includes a Zig-Zag maneuver with varying propeller rotation, data processing to ensure communication between algorithms, coefficients identification and result analysis.

The proposed maneuver is implemented in the maneuvering model, composed of the subroutines container_main, container_calc_v222, container_ode, and container_posf_v2. The model exports forces, moment and states to the SINDYf_v2 algorithm. This calls subroutines lib, rgs and lasso among others, and exports the hydrodynamic coefficients, which are compared with reference values. The maneuver is repeated using the identified coefficients and the trajectories are compared.

4.1 Proposed Maneuver.

Traditional Zig-Zag. This maneuver assesses the ability of the rudder to control the ship, Lewis (1967). In this maneuver, the propeller's rpm is not varied.

The procedure is as follows:

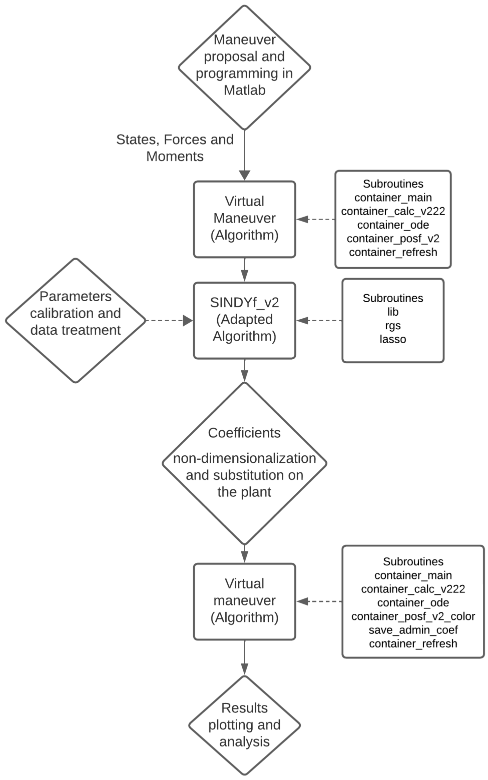

Figure 2. Flowchart of the proposed method.

(1) Ship in equilibrium condition heading straight ahead, yaw angle is zero for simplicity;
(2) Activate the rudder to a pre-selected angle, say 10 degrees to port, and maintain it until a pre-selected yaw angle is achieved, say 20 degrees, to the same side (20 deg to port);
(3) Rudder activation, 10 deg to the opposite side (10 deg to starboard), and kept still until ship's yaw angle is 20 degrees to the opposite side (20 deg to port) and;
(4) If the maneuver is complete, repeat the initial rudder activation (10 degrees to port) until 3 (three), 4 (four), or more cycles are completed, although the first cycle is the most relevant, Lewis (1967).

The notation used for this maneuver is of the Zig-Zag type $(\delta_c|\psi_c)$ where δ_c is the rudder angle command and ψ_c is the yaw angle variation mentioned in item (2). Therefore, the maneuver described above would be a Zig-Zag (10|20).

Figure 3 shows a Zig-Zag maneuver example, where execution is the rudder activation, δ is the rudder angle, and ψ is the yaw angle.

From Figure 3, the concept of overshoot in the Zig-Zag maneuver can be illustrated, which in other words consists of the variation that the yaw angle (ψ) or another parameter presents after the rudder reversal. This occurs due to the inertia of the movement and the rudder activation ramp.

Zig-Zag maneuver is proposed because it involves multiple rudder activations, implying turns to both sides, making it more appropriate to capture nonlinearities and to excite the system.

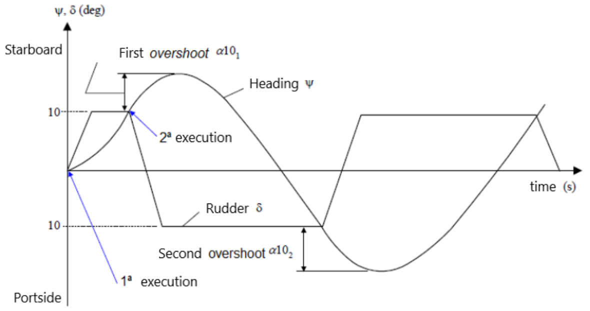

Figure 3. Description of Zig-Zag and overshoot, Masetti (2018).

To excite the system even further, the propeller rotation is also varied, which is unusual in a traditional Zig-Zag maneuver. All rules above apply for the new Zig-Zag maneuver proposed in this article, and on top of that the propeller's rpm varies in time.

One maneuver is proposed with initial forward speed, first rudder activation at time $t = 100s$ and a rudder actuation of thirty (30) degrees, where u_0 is the initial velocity in knots, n_0 is the initial propeller rotation in rpm, δ_c is the angle of the first rudder activation in degrees, and finally, we have the column with the approximate duration of the maneuver in minutes.

Table 2. Parameters of the Proposed Zig-Zag (30|30) maneuver.

u_0 [knots]	n_0 [rpm]	δ_c [deg]	ψ_c [deg]	Duration [min]
7.39	35	30	30	25

The propeller's commands are given in table 3, where t is time in seconds and n_c is the rpm command. It may be highlighted that this phenomenon is transient.

Table 3. Propeller's commands.

t [s]	t [min]	n_c [rpm]
0	0.00	35
100	1.66	70
400	6.66	50
1200	20.00	0

4.2 Identification Algorithm

Inserted in the context of automation of discovering governing equations of physical phenomena, the Sparse Identification of Nonlinear Dynamics with control (SINDYc) was proposed by Brunton and Kutz (2019).

SYNDYc takes as input the states obtained from sea trials using a maneuvering model with 04 (four) degrees of freedom and a library matrix of nonlinearities, which contains the set of variables and variable products that may appear in the governing equations.

Furthermore, the algorithm outputs the coefficients that multiply these variables. This output, in matrix form Ξ, is obtained by the Least Absolute Shrinkage and Selection Operator (LASSO) regression method. A more detailed description of the method is available in Strauhs (2023).

In this article, instead of identifying the acceleration equations coefficients, Equation 16, the so-called surge hydrodynamic derivatives were identified using surge forces equation, Equation 17. This novel approach allows the authors to refresh the plant's derivatives and compare ship's trajectories.

Nonlinearities Matrix The library of nonlinearities is a matrix $\Theta_{n \times c}$ where n is the number of time steps of the executed maneuver and c is the number of nonlinearities that may appear in the governing equations.

A total of seventeen (17) terms were provided, among them, $vr, u^2, v^2, r^2, \phi^2$. The method requires also an extra column of *ones*. Those terms are outputs of the maneuver model and inputs of the identification algorithm. As shown in Table 4, some terms not expected to be obtained in the identification were also included, such as v and p, highlighting that the equations are not known a priori and that the method may be applied to other ships with different hull geometries.

Table 4. Nonlinearities library.

v	p	r	vr	u^2	v^2	r^2	ϕ^2	
v^3	r^3	v^2r	vr^2	ϕ^2v	$v^2\phi$	$r^2\phi$	ϕ^2r	1

LASSO Regression As there is more data than predictors, i.e., $n > c$, the system is classified as overdetermined. In this type of system, generally $Ax = b$ cannot be satisfied, and therefore, the approximate solution minimizing the error is sought, Brunton and Kutz (2019).

Following the principle of parsimony, the Least Absolute Shrinkage and Selection Operator (LASSO) balances the complexity of the model with its ability to describe it. It is a method that promotes sparse solutions and works well for overdetermined systems, Brunton and Kutz (2019).

From the time series of the surge resistance X_f and the matrix Θ of nonlinearities, the identification algorithm uses LASSO regression to obtain the vector Ξ of hydrodynamic derivatives.

4.3 Reference Derivatives

In this section, reference hydrodynamic derivatives are presented for identification results evaluation, Fossen (1994).

Table 5. Reference Hydrodynamic Derivatives.

X_{vr}	X_{uu}	X_{vv}	X_{rr}	$X_{\phi\phi}$
-3.11E-03	-4.23E-04	-3.86E-03	-2.00E-04	-2.00E-04

The SNAME (1950) convention was applied to non-dimensionalize the identified hydrodynamic derivatives.

4.4 Maneuver model calibration

As expected, it is confirmed that rudder to port induces a port turn. Furthermore, for symmetric rudder activations, symmetry is observed not only in the forces and moments of the actuators but also in the ship's trajectory. Additionally, in Zig-Zag maneuvers, a small distance is covered in x for a large rudder activation angle, as predicted.

All these findings pertain to the calibration of the maneuvering model, an essential step for identification.

5. RESULTS AND DISCUSSION.

The proposed maneuver results are presented below.

Figure 4 shows the reference maneuver performed in blue and the identified trajectory in red markers.

Table 6 shows the hydrodynamic derivatives identified and the discrepancy results, calculated according to the following expression, where b is the measured value and B is the reference value of each coefficient, listed in Table 5.

$$\epsilon = \frac{b - B}{|B|} 100\%. \tag{25}$$

The other terms of the nonlinearities library were correctly identified as null values.

Table 6. Hydrodynamic Derivatives comparison.

Hyd. Der.	Ref. Value	Result	ϵ (%)
X_{vr}	-3.11E-03	-2.28E-03	27
X_{uu}	-4.23E-04	-4.28E-04	-1
X_{vv}	-3.86E-03	-2.37E-03	38
X_{rr}	-2.00E-04	3.38E-04	69
$X_{\phi\phi}$	-2.00E-04	-1.19E-03	-497

6. CONCLUSION.

These results demonstrate the potential of the adopted method to correctly identify the CONTAINER hydrodynamic derivatives, with low discrepancies overall. Also, the identified trajectory closely follows the original path throughout the maneuver.

It is known that the more the system is excited, the better the identification tends to be, which follows that the proposed maneuver, with varying propeller rpm, was a good choice to excite X_{uu}.

Despite the good results for most coefficients, the proposed method encountered difficulties in identifying the surge force due to roll displacements coefficient $X_{\phi\phi}$. It can be said that this term was not excited enough, due to the fact that there was no wind or abrupt yawing.

As a consequence of this, in an effort to fit $X_f^{'}$ curve (ship's resistance in surge direction excluding components not associated only with the hull), the algorithm might have majored the other derivatives values, namely X_{vr}, X_{vv} and X_{rr}, which means that their discrepancies could have been even smaller if $X_{\phi\phi}$ was excluded from the identification.

As an effort to enhance this particular result, it is possible to adapt the current maneuvering model to perform a captive test or a planar mechanism test designed specifically to excite roll motions.

This type of test may also be employed to aim at the sway, roll and yaw hydrodynamic derivatives.

7. ACKNOWLEDGMENT.

The authors acknowledge LabOceano's team.

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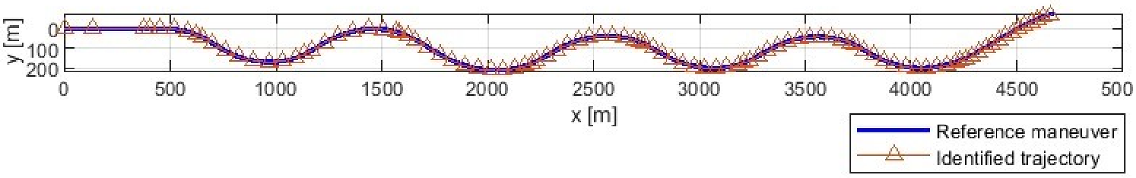

Figure 4. Ship trajectory comparison.