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Quick Identification and Dynamic Positioning Controller Design for a Small–Scale Ship Model

Viktor Vladić, Nikola Mišković and Zoran Vukić

***Abstract*— Dynamic positioning (DP) in marine robotics is a valuable feature that can significantly improve vessel performance at sea. In order to have satisfactory DP behavior, a sufficiently accurate mathematical model and parameters have to be known. Performing extensive identification trials at sea is a tedious and time consuming task. This paper demonstrates the application of a quick identification method based on self–oscillations (IS–O) applied to all controllable degrees of freedom (surge, sway and yaw) of a small–scale tanker model. In the paper we prove the consistency of the applied identification method. The identified model parameters are then used to tune DP controller parameters. The high quality of the model–based DP controller performance is demonstrated, proving the applicability of the IS–O method for DP controller tuning.**

I. INTRODUCTION

Nowadays, the marine robotics field or research has experienced rapid progress in the highest control levels such as mission planning, path following etc. However, the problem that still remains is how to tune low level controllers so that higher level control quality is ensured. Many textbooks and papers have been published on the topic of control design for marine vehicles, only some of which are referenced in this paper: [5], [3], [10]. However, the challenges that marine engineers still tackle are related to coupled dynamics, reliable model identification and rejection of environmental disturbances such as sea currents, waves and wind.

The ever–present problem that needs to be resolved is identification of marine vehicles' dynamic model parameters. Model parameters often change under different payload, and applying conventional identification techniques can be a tedious and time–consuming task. A method for quick and in–the–field applicable identification has been developed and reported in [8]. This procedure is based on self–oscillations, and will be tested in this paper on a small–scale tanker model. In addition to that, the obtained results will be used for tuning dynamic positioning (DP) controller parameters. The small–scale ship model that has been developed, was inspired by Cybership vessel developed at NTNU, Norway, [6], [4].

Two hypotheses will be proved by applying methods presented in this paper:

1) Uncoupled mathematical model parameters obtained through the identification by use of self–oscillations (IS–O) are consistent even when strong mathematical model approximations are introduced.
2) Model–based controller design based on IS–O identified parameters gives satisfactory results.

This paper is organized as follows. The introductory part is followed by Section II where a small–scale ship model used for experiments is described, and a simplified mathematical model of the ship is given. Section III gives short description of the identification method based on self–oscillations and its application to marine vehicles, while Section IV describes the dynamic positioning control design. Results of the IS–O method applied to the ship model are given in Section V. The same section includes experimental results of the DP controllers together with their comparison with the model function. The paper is concluded with Section VI.

II. DESCRIPTION OF THE SHIP MODEL

The ship model was built at the Laboratory for Underwater Systems and Technologies (LABUST), UNIZG–FER and it is shown in Fig. 1. The hull is made from fiberglass with epoxy coating. The dimensions are: length 120cm, width 27cm, and height 17cm (25 cm with cabin). Surge directed propulsion is made by main propeller, while sway propulsion is generated by bow and stern tunnel thrusters. Thrusters are powered by 12V DC motors. Each DC motor is controlled by MOSFET H-bridge with HIP4082 driver, and H-bridges are controlled by AT-Mega16 microcontroller. The rudder is controlled using a step motor with potentiometer used as angular feedback. Communication between ship model and control computer is serial, established through XbeePro communication module. The ship model is equipped with a compass (HMC6352) and GPS (LS20031) modules. Internal communication between MCU and its modules is established via I2C bus.

The experiments that will be presented here were performed at LABUST in the testing pool. A camera mounted above the pool was used to extract the positions and orientations of the ship model. Future experiments will include processing of the GPS and compass data.

A. Mathematical Model

The notation used in this section is adopted from [5]. The presented mathematical model is limited to the horizontal plane, and the assumption is that pitch and roll angles are negligible. Two coordinate frames are defined: Earth-fixed coordinate system {E} is used to define vehicle's positions

The authors are with the University of Zagreb, Faculty of Electrical Engineering and Computing, LABUST - Laboratory for Underwater Systems and Technologies Unska 3, Zagreb, Croatia

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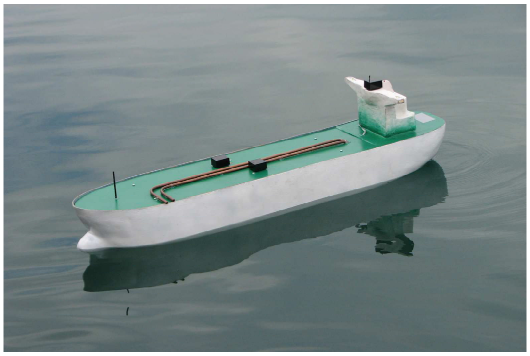

Fig. 1. Photo of the ship model (taken at the lake Jarun in Zagreb).

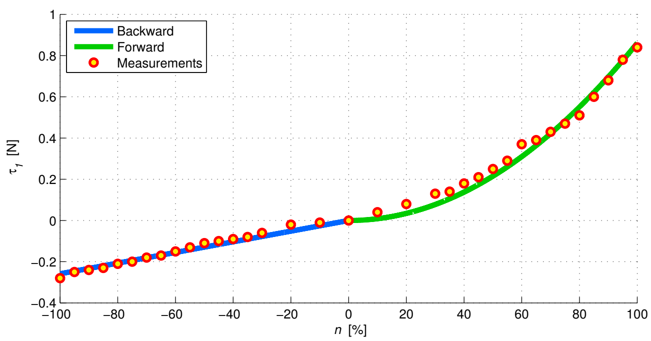

Fig. 2. Main thruster mapping ($\tau_1 = f(n_1)$).

and orientations forming a vector $\eta = \begin{bmatrix} x & y & \psi \end{bmatrix}^{\mathrm{T}}$, and body-fixed coordinate frame is used to define linear (surge, sway) and angular velocities (yaw) forming a vector $\nu = \begin{bmatrix} u & v & r \end{bmatrix}^{\mathrm{T}}$. Motion of the vehicle is achieved by applying external forces and moments, $\tau = \begin{bmatrix} X & Y & N \end{bmatrix}^{\mathrm{T}}$.

1) Actuators: The ship model is equipped with three thrusters and a rudder. The main thruster force τ_1 is in charge of surge motion both in cruising and dynamic positioning. The main thruster mapping shown in Fig. 2 resulted in the following equation describing the input n_1 and the resulting thrust: forward thrust is given with $\tau_1 = 8.603 \cdot 10^{-5} n_1^2$ and backward thrust with $\tau_1 = 2.585 \cdot 10^{-3} n_1$.

The thrust exerted by the rudder τ_2 is perpendicular to the rudder surface (see Fig. 3). Rudder is in charge of yaw motion only during the cruising maneuver while during the dynamic positioning it is held in the neutral (central) position. The force τ_2 can be described with $\tau_2 = c_F v_{av}^2 \sin\left(\frac{\pi}{2}\frac{\delta_a}{\delta_s}\right)$ if $|\delta_a| < \delta_s$, where δ_a is the relative degree between the rudder and the water flow (attack angle), δ_s is the stall angle and c_F is the rudder coefficient, [2], [11]. In the case when sway speed v is negligible and yaw rate r is small, the angle of attack can be approximated with the rudder angle δ. Parameter v_{av} is the average flow passing through the rudder and can, according to [11], be modeled with $v_{av}^2 = u_a^2 + C_T\tau_1$, where u_a is ambient water velocity and C_T is a constant parameter. If the sea current is negligible, then $u_a \approx U$, where $U = \sqrt{u^2 + v^2}$. With low sway speed, $U \approx u$, and the square of the surge speed can be approximated as proportional to the thrust exerted

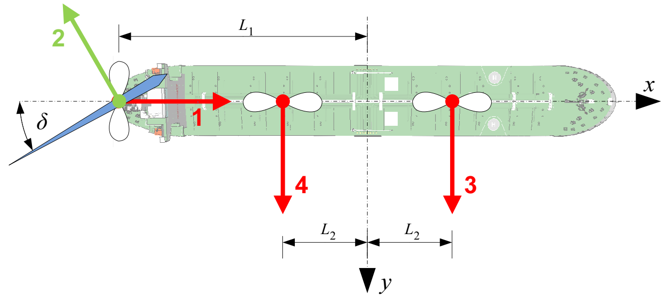

Fig. 3. Schematic representation of actuator allocation.

by the main propeller, i.e. $u^2 \sim \tau_1$. If the sea current cannot be neglected, than the term u_a can be considered as model uncertainty. In any case, the assumption is made that $v_{av}^2 \sim \tau_1$, resulting in (1) (small deflection angles and $\sin\alpha \approx \alpha$ are assumed).

$$\tau_2 = c_F v_{av}^2 \sin\left(\frac{\pi}{2\delta_s}\delta\right) \approx c_F v_{av}^2 \frac{\pi}{2\delta_s}\delta \approx k_F \tau_1 \delta \quad (1)$$

Bow and stern thruster exert thrusts τ_3 and τ_4, respectively. They are used mainly during the dynamic positioning when they are in charge of both sway and yaw motion. These thrusters have lower power than the main thruster and their mapping to the inputs n_3 and n_4 is assumed to be linear and described with $\tau_{3,4} = 10^{-3} n_{3,4}$.

2) Actuator allocation: Actuator allocation gives the relation between the forces exerted from the thrusters and the rudder angle, and the forces acting on the vessel in the body frame (X, Y and Z). From Fig. 3, the following equations can be written: $X = \tau_1 - \tau_2 \sin\delta$, $Y = -\tau_2\cos\delta + \tau_3 + \tau_4$ and $N = L_1\tau_2\cos\delta + L_2\tau_3 - L_2\tau_4$, where L_1 and L_2 are distances of appropriate actuators to the center of gravity of the ship model as shown in Fig. 3. For small rudder deflection angles approximations $\sin\delta \approx \delta$, $\cos\delta \approx 1$ and $\delta^2 \approx 0$ are introduced, what results in the following allocation model:

$$X = \tau_1 \quad (2)$$
$$Y = -k_F\delta\tau_1 + \tau_3 + \tau_4 \quad (3)$$
$$N = L_1 k_F \delta\tau_1 + L_2\tau_3 - L_2\tau_4 \quad (4)$$

During cruising, the bow and the stern thrusters are not used, i.e. $X = \tau_1$ and $N = L_1 k_F \delta \tau_1$. During dynamic positioning the rudder is kept in the neutral position resulting in allocation equation given with (5).

$$\begin{bmatrix} X \\ Y \\ N \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & L_2 & -L_2 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_3 \\ \tau_4 \end{bmatrix} \quad (5)$$

3) Dynamic model: The full dynamic model gives relation between velocities ν and accelerations $\dot{\nu}$ of the vessel and forces that act on it, and is highly nonlinear and coupled. Detailed explanations of the dynamic model parameters can be found in [5]. The simplified model which will be used in this paper assumes that vessel dynamics are uncoupled, i.e. coupled added mass terms are negligible, center of gravity CG coincides with the origin of the body-fixed coordinate frame {B}, and roll and pitch motion are negligible. These simplifications lead to one, generalized, uncoupled, nonlinear dynamic equation that describes each controllable degree of freedom separately and it is given with (6) where parameters $\nu(t)$ is u, v or r, $\tau(t)$ is X, Y or N, depending on the degree of freedom (DOF). Parameter Δ represents environmental disturbances, and α_ν and $\beta(\nu(t))$ are constant parameters of mathematical model.

$$\alpha_\nu \dot{\nu}(t) + \beta(\nu) \cdot \nu(t) = \Delta + \tau(t) \tag{6}$$

Further simplification includes the dominance of constant or linear drag only. It has been shown in literature that usually for small speed constant, drag can be approximated with a constant while at higher speeds linear drag better describes the dynamics of the vehicle, [5]. In other words, general drag $\beta(\nu)$ can obtain one of the two values:

$$\beta(\nu) = \begin{cases} \beta_\nu & \text{for constant drag} \\ \beta_{\nu\nu}|\nu| & \text{for linear drag} \end{cases} . \tag{7}$$

4) Kinematic model: The kinematic model which takes only surge, sway and yaw motion into account is given with (8).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \underbrace{\begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\mathbf{J}} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{8}$$

III. Identification by use of self–oscillations (IS–O)

The idea of using self–oscillations to determine system parameters was introduced in [1] under the name "autotuning variation" method. The proposed identification method applied to marine vehicles (with nonlinear models) has been published by the authors of this paper and described in detail in [8], [9], under the name identification by use of self–oscillations (IS–O). In this section we present only the basic principles and the final formulae.

IS–O is performed in closed loop which consists of the process itself and a relay with hysteresis (C is relay output and x_a is hysteresis width). The method is based upon forcing the system into self-oscillations. The magnitude X_m and frequency ω of the obtained self–oscillations can be used to determine process' (nonlinear) model parameters, by calculating the describing function of the nonlinear element, (see [13]). Detailed derivation of the general algorithm for determining parameters of LTI processes can be found in [7].

A summary of equations used to determine the linear or nonlinear model parameters for marine vehicles is given in Table I where x_0 is the bias in the obtained self–oscillations caused by the asymmetries in the vessel or external disturbances, and T_H and T_L are durations of high and low relay outputs during one oscillation, respectively.

In order to induce self-oscillations by using the relay with hysteresis, the process' phase characteristic has to exceed 90°. In the case of marine vehicles, this means that the procedure cannot be applied by feeding the speed measurements

TABLE I

Formulae for determining unknown parameters using IS–O method with relay with hysteresis

Linear model (constant drag)	Nonlinear model (linear drag)
$\alpha_\nu = \frac{2C}{\pi}\frac{1}{\omega^2 X_m}\left[\sqrt{1-\left(\frac{x_a-x_0}{X_m}\right)^2}+\sqrt{1-\left(\frac{x_a+x_0}{X_m}\right)^2}\right]$	
$\beta_\nu = \frac{4Cx_a}{\pi}\frac{1}{\omega X_m^2}$	$\beta_{\nu\nu} = \frac{3Cx_a}{2}\frac{1}{\omega^2 X_m^3}$
$\Delta = C\frac{T_H-T_L}{T_H+T_L}$	

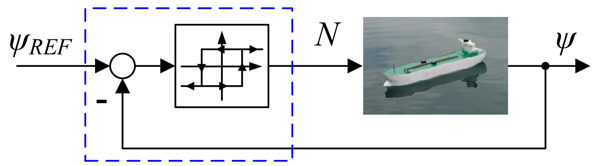

Fig. 4. IS–O method applied to the yaw DOF.

(yaw rate r, surge u or sway v speed) to the nonlinear element because the differential equations describing the relation between the speeds and the thrust that generates them are of first order. That means that the process has to be astatic (Type 1 process). Depending on the DOF that is to be identified, different approaches can be taken.

A. Identifying Yaw DOF

In the case of identifying the yaw degree of freedom, if heading measurements, i.e. $\psi_{ref}-\psi$, are fed to the nonlinear element, the process becomes inherently astatic and the IS–O method can be applied. The schematic approach to conducting the IS–O experiment for yaw degree of freedom is shown in Fig. 4.

Once the experimental data has been obtained, formulae in Table I can be applied (by substituting $\nu = r$ and $C = N_{max}$) to determine the unknown model parameters. Experimental results of the IS–O method applied on the ship model yaw DOF are described in Section V.

B. Identifying Surge/Sway DOF

Unlike in the case of yaw identification, there are no inherent measurements in the surge or sway degree of freedom that would introduce and integrator in the open loop. That is why the proposed approach is based on introducing an integrator, as it is shown in Fig. 5, in order to induce oscillations. Indeed, this approach is similar to taking position measurements (e.g. from a GPS), transferring them to the vehicle coordinate system, and differentiating them. This way, the existence of self–oscillations in identifying surge or yaw DOF is guaranteed. Once the experimental data has been obtained, formulae in Table I can be applied (by substituting $\nu = u$ and $C = X_{max}$ for the case of surge, and $\nu = v$ and $C = Y_{max}$ for the case of sway identification) to determine the unknown model parameters.

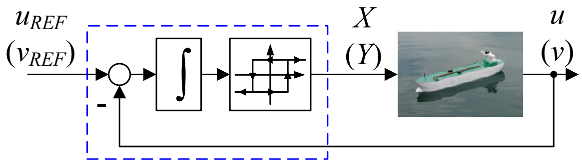

Fig. 5. IS–O method applied to the surge and sway DOF.

IV. Dynamic positioning (DP) controller design

Conventional DP controllers rely on a coupled dynamic model of the vessel. The coupled model parameters are usually difficult to obtain. Since the IS–O procedure gives only uncoupled model parameters, the DP controller design presented in this paper relies on uncoupled control of surge, sway and yaw degree of freedom and it is shown schematically in Fig. 6. One of the tasks of this paper is to demonstrate the applicability of the uncoupled model identified using the IS–O method for the purpose of DP controller tuning.

The individual DOF controller are chosen to be in the I–PD form given with (9) where $\boldsymbol{\eta_{ref}} = \begin{bmatrix} x_{ref} & y_{ref} & \psi_{ref} \end{bmatrix}^T$ and $\boldsymbol{K_I}$, $\boldsymbol{K_P}$ and $\boldsymbol{K_D}$ are row vectors with integral, proportional and derivative gains for each DOF, respectively. The symbols with asterisk ($*$) represent the parameters in the rotated coordinate system, i.e. $\boldsymbol{\eta}^* = \boldsymbol{J}^{-1}\boldsymbol{\eta}$, where $\boldsymbol{J}$ is defined in (8). The states marked with tilde sign ($\sim$) are estimated though a Kalman filter which includes the dynamic model of the vessel. The parameters of the dynamic model are tuned based on the parameters obtained from the IS–O experiment. The Kalman filter is introduced for two reasons: to smooth the measurements and estimate the velocities needed for the control algorithm. The proposed controller is suitable for marine vehicle applications since the output is always smooth, i.e. abrupt changes of the reference value are not directly passed to the actuators, [12].

$$\tau = \boldsymbol{K_I} \int_0^t \left[\boldsymbol{\eta^*_{ref}} - \tilde{\boldsymbol{\eta}}^*\right] dt - \boldsymbol{K_P}\tilde{\boldsymbol{\eta}}^* - \boldsymbol{K_D}\tilde{\boldsymbol{\nu}} \quad (9)$$

Using the proposed control algorithm, the closed loop equation for individual DOF is

$$\frac{\eta}{\eta_{ref}} = \frac{1}{\frac{\alpha_\nu}{K_{I\nu}} s^3 + \frac{\beta_\nu + K_{D\nu}}{K_{I\nu}} s^2 + \frac{K_{P\nu}}{K_{I\nu}} s + 1}. \quad (10)$$

The controller parameters are set so that the closed-loop transfer function is equal to the model function $G_m(s) = \frac{1}{a_3 s^3 + a_2 s^2 + a_1 s + 1}$ which is stable. In that case, the controller parameters will be as follows:

$$K_{I\nu} = \frac{\alpha_\nu}{a_3}, K_P = \frac{a_1}{a_3}\alpha_\nu, K_{D\nu} = \frac{a_2}{a_3}\alpha_\nu - \beta_\nu. \quad (11)$$

The antiwindup algorithm is implemented as shown in Fig. 6. The inverse allocation matrix is in charge if distributing thrusts to individual thrusters. The configuration of the inverse allocation matrix depends on the mode of operation of the vessel (cruising or dynamic positioning).

TABLE II
IS–O results for the ship model yaw DOF using the rudder.

n [%]	δ_c [deg]	N [Nm]	$\frac{\alpha_r}{k_F}$ $\left[\frac{\text{Nms}^2}{\text{deg}}\right]$	$\frac{\beta_r}{k_F}$ $\left[\frac{\text{Nms}\cdot 10^{-1}}{\text{deg}}\right]$	$\frac{\beta_{rr}}{k_F}$ $\left[\frac{\text{Nms}^2\cdot 10^{-2}}{\text{deg}^2}\right]$
60	10	3.114	4.237	2.472	5.922
	20	6.228	4.356	3.304	7.205
	25	7.785	4.834	3.529	6.889
	30	9.342	5.078	3.851	7.213
	35	10.899	4.851	3.991	6.447
	40	12.456	4.538	3.391	4.710
	45	14.013	5.253	3.715	5.194
75	15	7.298	4.476	2.973	5.698
	20	9.730	4.529	4.243	7.484
	25	12.163	4.625	4.052	5.965
	30	14.595	4.425	3.724	4.742
	35	17.028	4.681	3.845	4.473
	40	19.460	4.805	3.925	4.268
	45	21.893	5.835	3.610	3.714
90	15	10.509	4.521	3.204	4.917
	20	14.012	4.658	3.407	4.333
	25	17.515	4.442	3.638	4.021
	30	21.018	4.461	3.835	3.753
	35	24.521	4.841	3.846	3.512
	40	28.024	5.908	4.357	3.992
	45	31.527	5.696	4.429	3.715
$\frac{\sigma_x}{\bar{x}} \cdot 100\%$			10.050	12.527	25.272

V. Results

A. Identification by use of self-oscillations

The experiments that are presented in this subsection are performed on the yaw degree of freedom of the ship model by applying rudder motion. A set of 21 IS–O experiments was performed on the ship model by applying various yaw moments $N = \delta\tau_1$ as relay outputs, formed by applying different main propeller thrusts τ_1 and rudder deflections δ. The identification results are summarized in Table II. The main advantage of the IS–O method is that the mathematical model parameters can be obtained from one experiment. The results presented in Table II show that the obtained results are consistent (with a standard deviation in determined inertia of about 10% and linear drag 12.5%) and precise identification can be expected from each experiment.

In [8] it is reported that two experiments are needed to make a conclusion whether a linear or nonlinear model fits the process better. By comparing the difference in the identified parameters from the two experiments, the model with less discrepancy in the identified drag parameters should be used. In both experiments, the identified inertia should be the same since the same formula for inertia calculation is used in both cases (see Table I). The results in Table II show that the linear model fits the yaw dynamic much better.

The experiments that were obtained on Charlie autonomous catamaran and presented in [8] all relied on the fact that different model parameters are obtained for different forward speeds. The results presented here show that one, reliable model can be obtained regardless of the forward speed, if the main thruster model is mapped.

The IS–O experiments were performed also for yaw DOF

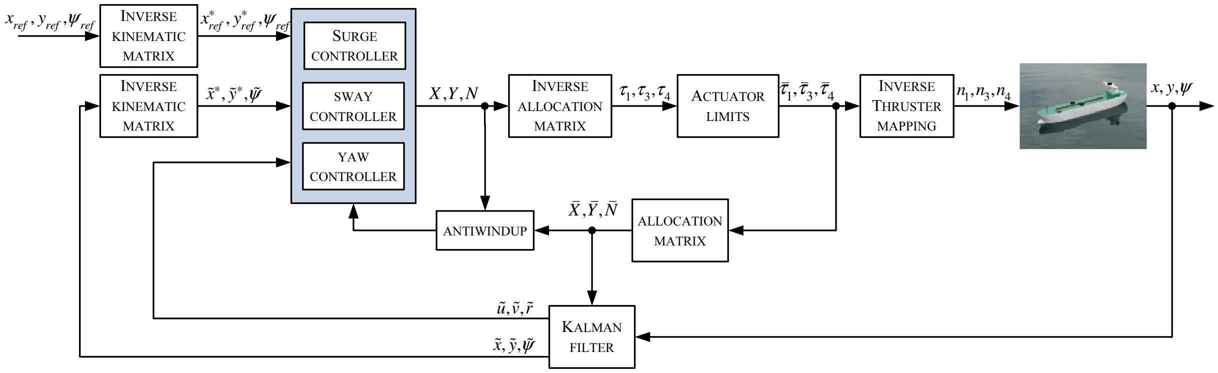

Fig. 6. DP controller diagram.

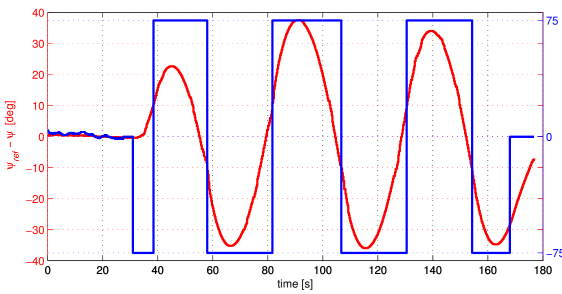

Fig. 7. An example of ship response during one IS–O experiment.

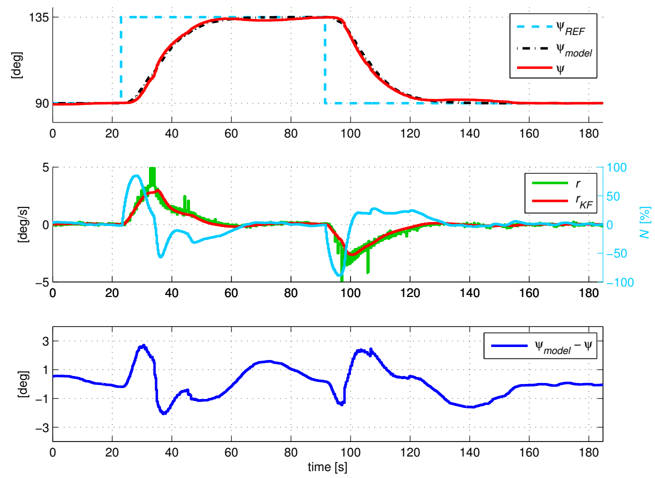

Fig. 8. Ship response while referent heading changes by $45°$.

using bow and stern thrusters (shown in Fig. 7), surge and sway DOF. The obtained results were used for tuning Kalman filter dynamic model parameters and the DP controller.

B. DP controller

The DP controller was tuned such that the heading control loop has the binomial filter dynamics with the characteristic frequency $\omega_n = 0.2\frac{rad}{s}$, while the surge and sway control loop have $\omega_n = 0.1\frac{rad}{s}$. These values were chosen such that thruster activity in steady state is reasonable. Speeding up the closed loop dynamics, increases thruster activity.

In order to test the quality of the closed loop heading system, the reference value was changed by $45°$ such that the thrusters do not saturate. The results are shown in Fig. 8 where the model function response is shown with black dotted line. The difference between the model function and the response never exceeds $3°$ (see subfigure 3 in Fig. 8). The integral of absolute error (IAE) of the response is only about 2% larger than IAE of the model function. This clearly indicates that the controller parameters tuned based on the IS–O experiment ensure desired closed loop dynamics. Subfigure 2 in Fig. 8 shows smooth yaw controller output, yaw rate calculated based on heading differentiation (green line) and Kalman filter estimate of yaw rate (red line). The quality of the Kalman filter is obvious.

Fig. 9 shows the case when the heading reference has changed by $90°$ causing the controller output to saturate. Naturally, the model response cannot be followed exactly, but the response is still satisfactory. Also, the response shows the quality of the antiwindup algorithm.

The DP controller was tested such that the ship model was commanded to move from the initial position in the vicinity of (0 pix, 0 pix) to (100 pix, 100 pix) in the camera frame. The path of the ship is shown in Fig. 10, indicating that DP was successful. It should be mentioned that the curvature at the end of the path is present since x^* and y^* are the controlled variables.

Subfigure 1 in Fig. 11 shows $|x^*|$ and $|y^*|$ (absolute values are shown for clearer presentation), i.e. the positions rotated using the inverse kinematic equation (8). These values are shown since they are in fact the controlled values (see Fig. 6). Both controlled values practically coincide with the model function. From subfigure 3 it is clear that the difference is never greater than 6 pix.

During the DP maneouvre, the reference heading was set to $90°$. The response of the heading closed loop is shown in Fig. 12, clearly demonstrating the quality of performance.

VI. CONCLUSION

This paper presented how the IS–O method for quick identification of marine vessel parameters (in surge, sway and yaw DOF) can be succesfully used to tune DP controller parameters. The consistency of the identified model for different IS–O parameters was demonstrated, even when the

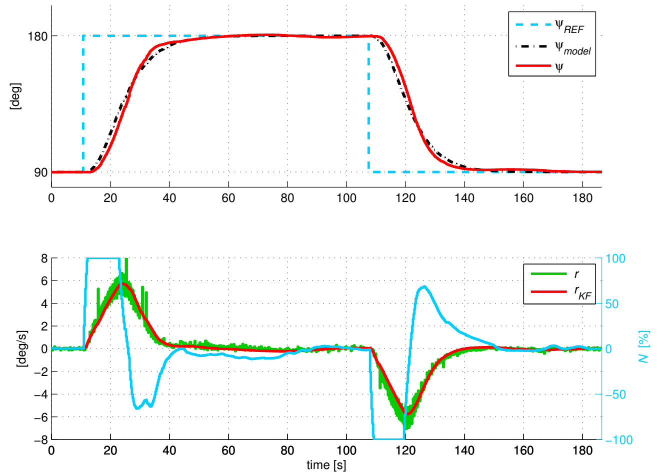

Fig. 9. Ship response while referent heading changes by 90°.

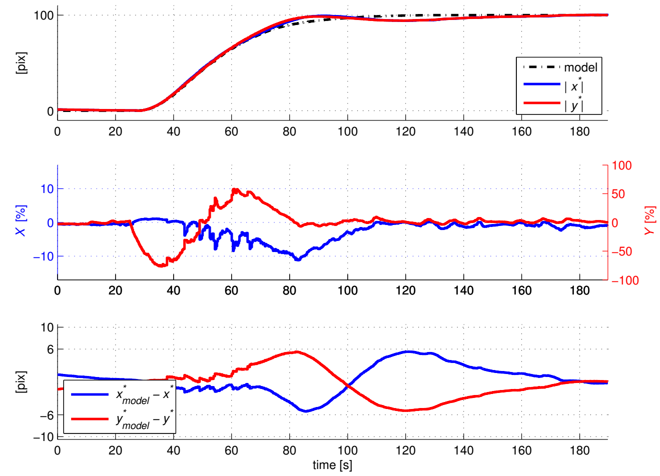

Fig. 11. Ship states during DP toward point $(x_{ref}, y_{ref}) = (100, 100)$.

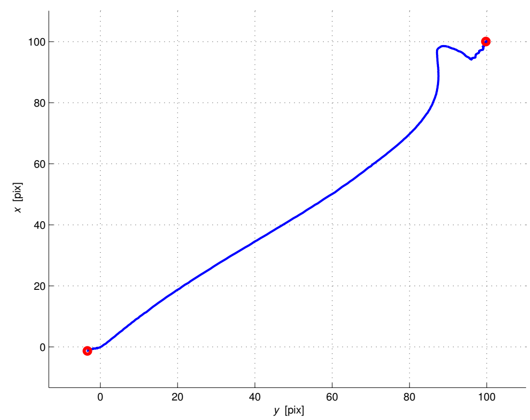

Fig. 10. Ship path during DP toward point $(x_{ref}, y_{ref}) = (100, 100)$.

Fig. 12. Ship heading during DP toward point $(x_{ref}, y_{ref}) = (100, 100)$.

model is assumed to be in the simplified form. The IS–O determined parameters were used to tune Kalman filter parameters and DP controllers. The Kalman filter was used to estimate the velocities since the measurements obtained by differentiation of the positions are noisy. The DP control system experiments showed that excellent following of the model function is achieved, and satisfactory behaviour of the Kalman filter. The experiments have proved the applicability of the IS–O method for controller design and the results are obtained from a ship model in laboratory conditions. Future work will focus on taking the ship model to the real world, i.e. applying the proposed methodology on measurements obtained via GPS and compass. Simulation results (which are not reported here) have shown that the controllers effectively compensate environmental disturbances - this will also be demonstrated on results obtained in field conditions.

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