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Identification of the nonlinear ship model parameters based on the turning test trial and the backstepping procedure

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Abstract

This work presents a novel contribution to solve the problem of identification of ship models parameters using the temporal variation data of the yaw angle achieved from a particular trial test as the turning circle. A relatively complex nonlinear model of Wagner-Smith has been chosen as basis because it represents the ship's dynamics appropriately as proved through the experimental measures obtained in a particular ship. The proposed algorithm of identification of the six ship model parameters is based on the combination of two sub-algorithms: the backstepping procedure and the tuning design method. The simulation results show the suitability of the proposed procedure.

Keywords: Nonlinear systems; Modelling; Trajectory planning; Adaptive control; Backstepping; Tuning functions design

1. Introduction

Considerable efforts have been carried out in the modelling and the identification of nonlinear systems. In the particular case of the ship manoeuvring, the presence of different kinds of uncertainty in the not precisely known ship models as well as

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the random processes' statistics, such as winds, waves, currents, and other exogenous effects, on different sailing conditions such as speed, loading conditions, trim, etc. and sailing routes in open sea (deep water), coastal (shallow waters) with a possible change in the under-keel clearance, conducts to necessary application of techniques that take into account the nonlinear equations that describe the ship's motion and the presence of unknown but constant parameters which appear linearly in these system equations. In this sense, the backstepping procedure based on an indirect MRAC procedure and the tuning functions design (Krestić et al., 1992) is a relatively novel method for solving the identification problem of ship's parameters. The procedure has been applied with considerable success in: axial compressors have been developed under backstepping designs for throttle and bleed valve (Banaszuk and Krener, 1997), and the air injection (Behnken and Murray, 1997; Protz and Paduano, 1997); in ship control: backstepping with optimality (Fossen, 1994), route planning (Casado and Velasco, 2003); electric machines (induction motor), (Marino et al., 1999). In this paper, it is shown that for identification purposes it is only necessary to know the temporal variation of the ship yaw angle during a particular trial test. This measurement is available from relatively inexpensive measurement devices based on GPS/INS, that is, the satellite based on the Global Positioning System (GPS), aided with an Inertial Navigation System (INS).

There are no definitive international standards for conducting manoeuvring trials with ships. Many shipyards have developed their own procedures driven by their experience with consideration to the efforts made by the International Towing Tank Conference (ITTC, Proceedings 1963–1975) and other organisations or institutes (Journée and Pinkster, 2001).

The Society of Naval Architects and Marine Engineers (SNAME) has produced three guidelines: 'Code on maneuvering and Special Trials and Tests' (1950), 'Code for Sea Trials' (1973) and 'Guide for Sea Trials' (1989). The Norwegian Standard Organization has produced 'Testing of New Ship, Norsk Standard' (1985). The Japan Ship Research Association (JSRA) has produced a 'Sea Trial Code for Giant Ships' (1972) for manoeuvering trial procedure and analysis of measurements.

The International Maritime Organization (IMO) has emitted the Resolutions A.601 (1987) and A.751 (1993). The last Resolution adopted by this Organization whose title is 'Standards for ship manoeuvrability' with code MSC.137 adopted on 4 December 2002, resolves that its previsions annexed supersede the previous annexed to Resolution A.751.

Between the 18 types of manoeuvering tests only the Turning Test, mainly used to calculate the ship's steady turning radius and to check how well the steering machine performs under course—changing maneuvers, Z-Manoeuvring Test, used to compare the manoeuvering properties and control characteristic of a ship with those of other ships and the Stopping Test (crash-stop and low-speed) used to determine the ship's head reach and manoeuverability during emergence situations, are recommended by all Organizations.

The remainder of this paper is organised as follows. Section 2 deals with the modelling problem, Section 3 describes the identification procedure and, finally, Section 4 discusses results, highlighting some concluding remarks.

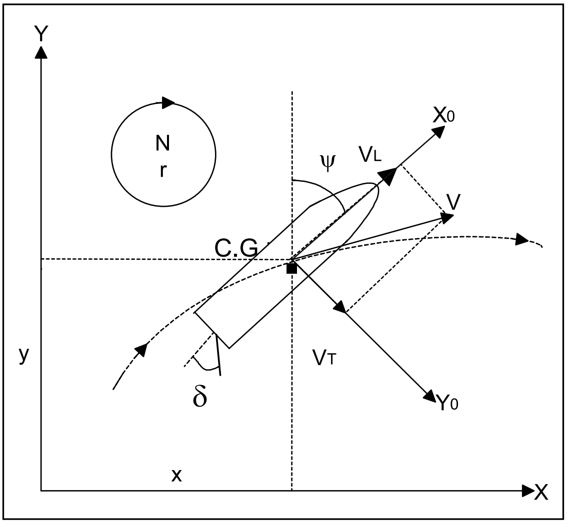

Fig. 1. Co-ordinate systems for the description of ship motion.

2. Ship model

2.1. Coordinate systems

In the process of analysing the motion of a ship in 2 degrees of freedom (DOF) it is convenient to define two co-ordinate systems as indicated in Fig. 1. The moving co-ordinate frame X_0 Y_0 is conveniently fixed to the ship and is denoted as the body-fixed frame. The origin of this body-fixed frame is usually chosen to coincide with the centre of gravity (CG) when CG is in the principal plane of symmetry. The earth-fixed co-ordinate frame is denoted as X Y. The angle Ψ is the difference between heading and track course, V_L is the forward velocity measured by the log, V_T is the velocity in starboard direction and δ the rudder angle. The co-ordinates (x,y) denotes the ship's position along the track.

2.2. Ship model structure

The high complexity of the hydrodynamic processes caused by the ship motion in deep and confined water and the wide variety of ships shapes and sizes lead to various non-stochastic ship models. These models could be divided in two groups: precise models, typical for given particular ships shapes and sizes such as the model of Van Leeuwen (1978) and Sobolev (1976), the cubic model of Abkowitz (1964), the quadratic model of Norrbin (1981) and models with greater generality but lower accuracy, Nomoto (1960) and Pershitz (1973) models.

The model of Bech and Wagner Smith (1969) is chosen as the basic model to assure a good trade-off between model complexity and model accuracy. It is obtained by means of replacing the linear term of yaw rate ($\dot{\psi}$) in the Nomoto second-order model with a nonlinear manoeuvring characteristic $H_B(\dot{\psi})$, whose coefficients are determined by Bech's spiral manoeuvre. This way allows passing from a general model to a more particular one.

The resulting model is described by the following equations

$$T_1 \cdot T_2 \cdot \dddot{\psi} + (T_1 + T_2) \cdot \ddot{\psi} + K \cdot H_B(\dot{\psi}) = K \cdot (\delta + T_3 \cdot \dot{\delta}) \quad (1a)$$

$$H_B(\dot{\psi}) = b_0 + b_1 \cdot \dot{\psi} + b_2 \cdot \dot{\psi}^2 + b_3 \cdot \dot{\psi}^3 \quad (1b)$$

where Ψ is the ship course, $r = \dot{\psi}$, the rate of turn and δ is the rudder angle.

In this paper, the turning test circle is utilised instead of the Bech's Reverse Spiral Manoeuvre, being only necessary for identification purposes to record the variation of the yaw angle vs time, where all terms of the nonlinear characteristics are considered. Nevertheless, with the purpose of simplification of the nonlinear equations the following simplifications are usually taken into account:

- hull symmetry; it implies that $b_2 = 0$,
- the dynamic stability is known. This implies that the sign of b_1 is known. For a course-stable ship $b_1 > 0$, while for a course-unstable one $b_1 < 0$,
- the bias term b_0 is frequently taken as null, being conveniently treated as an additional rudder off-set that can be made null by an adequate selection of the integral action in the autopilot design.

The procedure has been applied to a roll-on/roll-off ship (Izar, 2001) whose characteristics and picture are shown in Table 1 and Fig. 2, respectively.

2.3. Time-series response

The temporal variation (time-series response) of the yaw angle for the tested ship is represented by expression (2). This time-series function was achieved by means of a Least-Squares regression fitting procedure from experimental data points acquired from

Table 1
Main characteristics of the tested ship

Draught forward (full load condition) (m)	6
Draught aft (full load condition) (m)	6
Deadweight (metric tonnes)	7456
Maximum displacement (metric tonnes)	19,949
Length overall (m)	188.3
Breadth (moulded) (m)	28.7
Bulbous bow	Yes
Type of rudder	Becker (2 units)
Maximum angle of rudder (degrees)	65
Time of hard-over to hard over (s)	56
Propellers	2
Engine (2 per shaft), maximum power (kW)	4×6000
Speed loaded (maximum full ahead) (knots)	23.14

Fig. 2. Picture of the ship under analysis.

experimental sea trial. Data used belong to the realisation of the first three phases of the turning test. The test was carried out in the normal ballast condition, maximum ahead speed (23.14 knots) with a rudder angle of 20°

$$\psi_r(t) = -1.5191\times10^{-3} - 3.3818\times10^{-4}t + 1.1351\times10^{-3}t^2 - 2.2872 \times10^{-5}t^3 + 0.2278\times10^{-6}t^4 - 0.1125\times10^{-8}t^5 + 0.2191\times10^{-11}t^6 \quad (2)$$

where ψ_r is expressed in radians and the time in seconds.

2.4. Model parameters identification

To establish the goodness of the proposed procedure of identification it is necessary to know the true values of the parameters (supposed constants) that appear in the dynamical equations. For this purpose, the goal to be achieved is to reduce the difference between the fitting Eq. (2) and the solutions of the nonlinear differential Eq. (1a) by means of an appropriate selection of the equation's parameters. The procedure is based on the following algorithms:

- A Backward-Euler integration algorithm with a step size of 1 s.
- An optimisation algorithm of Powell (Darnell and Margolis, 1990) with an optimisation criteria ITAE (assuming the ITAE performance criterion as the product of integral of time-weighted absolute error).
- A trial and error procedure.

The resulting parameters are shown in Table 2, while in Table 3 there appears the values of the cost indexes for the yaw angle, yaw rate and angular acceleration.

In Figs. 3–5, the experimental yaw angle, yaw rate and angular acceleration are compared with the theoretical ones, showing an excellent agreement between them.

Table 2
Values obtained in the identification process

Parameter	Value	Units
T_1	112.023	s
T_2	13.5705	s
T_3	1.7	s
K	6.4917×10^{-2}	s^{-1}
b_0	1.8196×10^{-2}	rad/s
b_1	-56.1261	adim
b_2	3421.7915	s/rad
b_3	573.4967	s^2/rad^2

The purpose of this paper is to design a systematic procedure for finding an identification algorithm that does not depend, even partially, on a heuristic method such as the one used to know the true values of the ship's model parameters and thus it is possible to know the excellence of the proposed procedure. The procedure of the identification based on the tuning functions design resembles the classical procedure used in the model reference adaptive control (MRAC) (both are based in the Liapunov stability theory) but, however, it shows a considerable advantage over the traditional scheme. Both for a same control effort and initial conditions, the transient performance of tuning functions is far superior, whereas the tracking error with the tuning functions scheme is only a fraction of the indirect method. This is a consequence of incorporating the parameter update law into the controller (Kanellakopoulos et al., 1991). Other two most important factors which contribute to the superior performance of the tuning functions scheme are nonlinear damping and reference model initialisation.

The procedure described in this paper can be used as a new and alternative estimation method on the traditional ones, Continuous Least-Squares, Recursive Least-Squares, Recursive Maximum Likelihood, State Augmented Kalman Filter (Fossen, 1994).

2.5. Statement of the problem under a state space description

In order to carry out the system description by the nonlinear state equations it is preferable to define the following state variables. $x_1=\Psi$ (yaw angle), $x_0=\dot{\psi}=r$ (yaw rate), $x_3=\ddot{\psi}=\dot{r}$ (angular acceleration), being the output $y=x_1$. The kinematic equations of ship dynamics are

$$\dot{x}_1 = x_2 \tag{3a}$$

$$\dot{x}_2 = x_3 \tag{3b}$$

Table 3
Values of the cost indexes obtained

Variable	ITAE	Units
ψ	72.3803	rad s^2
$\dot{\psi}$	0.8711	rad s
$\ddot{\psi}$	0.1199	rad

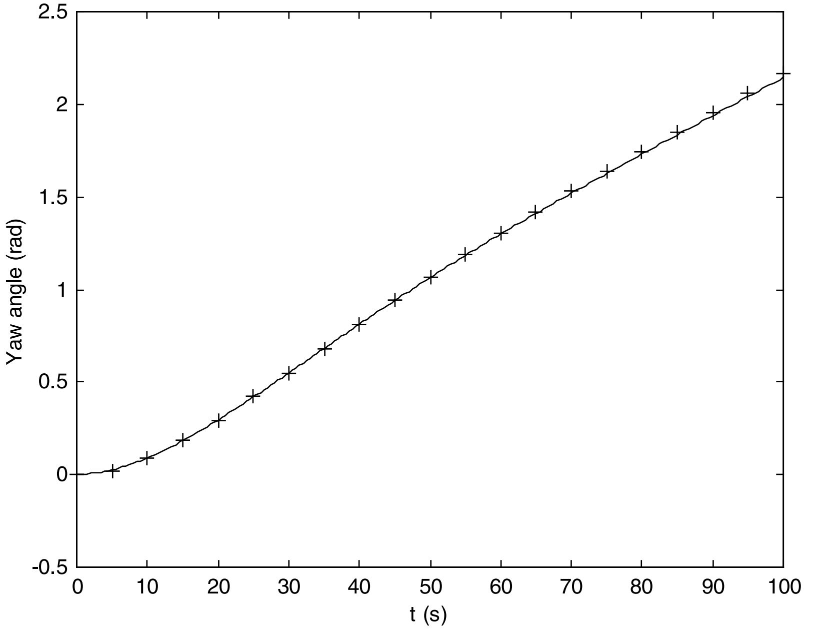

Fig. 3. Time response of the yaw angle. Sign + line: experimental values. Continuous line: polynomial fit.

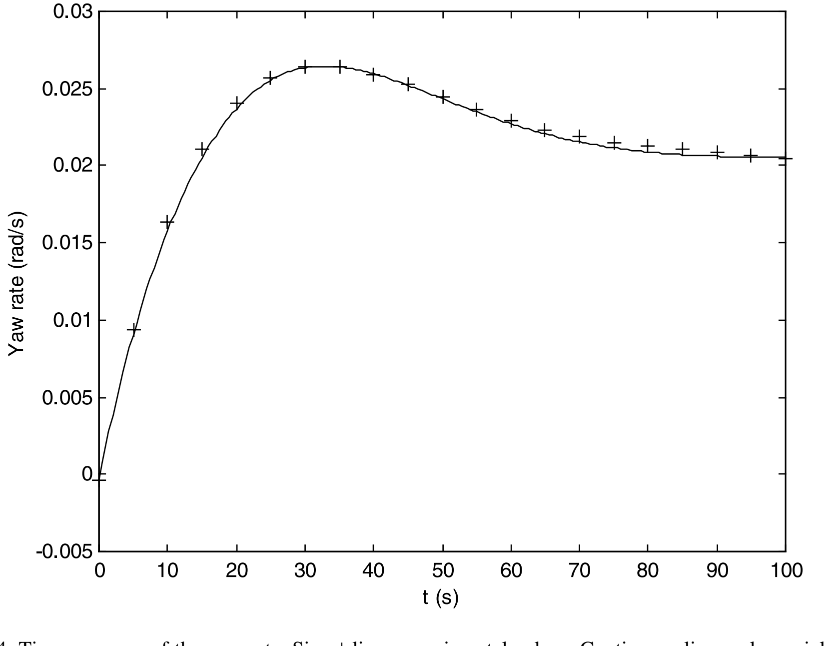

Fig. 4. Time response of the yaw rate. Sign + line: experimental values. Continuous line: polynomial fit.

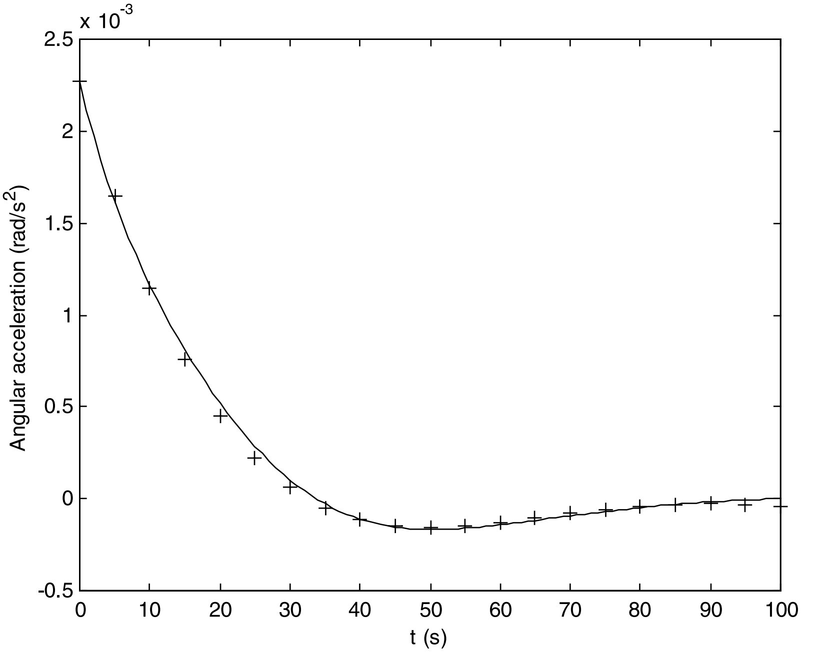

Fig. 5. Time response of the angular acceleration. Sign + line: experimental values. Continuous line: polynomial fit.

$$\dot{x}_3 = d \cdot U + a \cdot x_3 + c_3 \cdot x_2^3 + c_2 \cdot x_2^2 + c_1 \cdot x_2 + c_0 = d \cdot U + \varphi^{\mathrm{T}} \cdot \theta \tag{3c}$$

$$y = x_1 \tag{3d}$$

being the coefficient's values:

$$a = -\frac{T_1 + T_2}{T_1 \cdot T_2} \tag{4a}$$

$$c_3 = -\frac{K \cdot b_3}{T_1 \cdot T_2} \tag{4b}$$

$$c_2 = -\frac{K \cdot b_2}{T_1 \cdot T_2} \tag{4c}$$

$$c_1 = -\frac{K \cdot b_1}{T_1 \cdot T_2} \tag{4d}$$

$$c_0 = -\frac{K \cdot b_0}{T_1 \cdot T_2} \tag{4e}$$

$$d = \frac{K}{T_1 \cdot T_2} \tag{4f}$$

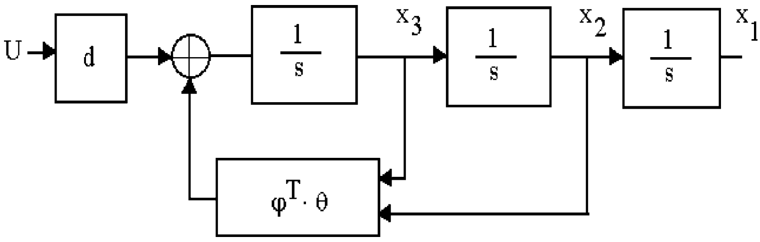

Fig. 6. Block diagram of a third-order parametric strict—feedback analysed system.

The rudder angle δ is governed by a control signal U with a first-order dynamics

$$U = \delta + T_3 \cdot \dot{\delta} \tag{4g}$$

and

$$\varphi^{\mathrm{T}} = [1\ x_2\ x_2^2\ x_2^3\ x_3] \tag{4h}$$

$$\theta^{\mathrm{T}} = [c_0\ c_1\ c_2\ c_3\ a] \tag{4i}$$

where $\theta \in R^4$ is a vector of unknown parameters.

The rudder angle is computed by numerical integration of:

$$\dot{\delta} = -\frac{1}{T_3} \cdot (\delta - U) \tag{5}$$

The control objectives are:

(1) to force the output $y = x_1 = \psi$ of the system (3a)–(3c) whose block diagram is presented in Fig. 6 to asymptotically track the reference output $y_r(t) = \psi_r(t)$.
(2) to carry out the identification task of the unknown parameters, a, c_i $(i = 0, \ldots, 3)$ and d.
(3) to keep the rudder angle in the selected value chosen for the sea trial test.

3. Adaptive backstepping procedure and identification

3.1. Adaptive backstepping procedure

The new recursive design known as the adaptive backstepping (Krestić et al., 1992) is based on three techniques which differ in the construction of adaptation law:

(i) Adaptive backstepping with overparametrisation, when at each design step a new vector of adjustable parameters and the corresponding adaptation law are introduced (Kanellakopoulos et al., 1991).
(ii) Adaptive backstepping with modular identifiers, when a slight modification of the adaptive control allows independently the construction of estimation-based identifiers of unknown parameters (Krestić et al., 1992).

(iii) Adaptive backstepping with tuning functions, when at each design step a virtual adaptation law known as tuning function is introduced, while the actual adaptation algorithm is defined at the final step in terms of all the previous tuning functions (Krestić et al., 1995).

Fig. 6 shows the block diagram of the third-order parametric strict feedback system under analysis. Initially on the recursive procedure, the state x_2 is treated as a virtual control for Eq. (3a). At each subsequent step, it will be increased the designed subsystem by one equation. At the i-step, the ith-order subsystem is stabilised with respect to a Liapunov function V_i by the design of a stabilising function α_i and a tuning function τ_i. The updating law of the adaptive control system that allows us to know the true values of the dynamic model and the control signal is designed at the final step. To implement the identification procedure by combining backstepping with tuning functions design, following steps are to be performed:

STEP1

Introducing the variable z_1 representing the tracking error, and z_2 which means the error variable that expresses the fact by which x_2 is not the true control, both are defined by:

$$z_1 = x_1 - y_r \tag{6a}$$

$$z_2 = x_2 - \dot{y}_r - \alpha_1 \tag{6b}$$

Eq. (3a) yields

$$\dot{z}_1 = z_2 + \alpha_1 \tag{7}$$

the stabilising function α_1, is designed to stabilise Eq. (7) with respect to the Liapunov function:

$$V_1 = \frac{1}{2} \cdot z_1^2 \tag{8}$$

The simple linear feedback law has been chosen

$$\alpha_1 = -K_1 \cdot z_1, \quad K_1 > 0 \tag{9}$$

then

$$\dot{V}_1 = -K_1 \cdot z_1^2 + z_1 \cdot z_2 \tag{10}$$

the second term $z_1 \cdot z_2$ in (10) will be cancelled at the next step.

STEP 2

It is necessary to consider that state x_3 is the control variable in the second Eq. (3b). The third backstepping variable z_3 is defined by the equation

$$z_3 = x_3 - \alpha_2 - \ddot{y}_r \tag{11}$$

where $\hat{\rho}$ is the estimation of coefficient $d = 1/\rho$ in (3c) equation. This change has been done to avoid an indetermination when in the identification process this variable can take occasionally the null value. The expression (3b) is transformed by Eqs. (6b) and (11) in

$$\dot{z}_2 = z_3 + \alpha_2 - \dot{\alpha}_1 \tag{12}$$

where α_2 is the second stabilising function. It is important to observe that the time derivative $\dot{\alpha}_1$ can be implemented analytically without a differentiator in the following manner:

$$\dot{\alpha}_1 = \frac{\partial \alpha_1}{\partial x_1} \cdot x_2 + \frac{\partial \alpha_1}{\partial y_r} \cdot \dot{y}_r = -K_1 \cdot x_2 + K_1 \cdot \dot{y}_\mathrm{r} \tag{13}$$

The second Liapunov function is defined in the form

$$V_2 = V_1 + \frac{1}{2} \cdot z_2^2 \tag{14}$$

yielding its derivative as

$$\dot{V}_2 = -K_1 \cdot z_1^2 + z_1 \cdot z_2 + z_2 \cdot \left[z_3 + \alpha_2 - \frac{\partial \alpha_1}{\partial x_1} \cdot x_2 - \frac{\partial \alpha_1}{\partial y_\mathrm{r}} \cdot \dot{y}_\mathrm{r} \right] \tag{15}$$

If the second stabilising function α_2 is chosen in the form

$$\alpha_2 = -z_1 - K_2 \cdot z_2 + \frac{\partial \alpha_1}{\partial x_1} \cdot x_2 + \frac{\partial \alpha_1}{\partial y_\mathrm{r}} \cdot \dot{y}_\mathrm{r} = -z_1 - K_2 \cdot z_2 - K_1 \cdot x_2 + K_1 \cdot \dot{y}_\mathrm{r} \tag{16}$$

then

$$\dot{V}_2 = -K_1 \cdot z_1^2 - K_2 \cdot z_2^2 + z_2 \cdot z_3 \tag{17}$$

To depart of (12) with (13) and (16) it is possible to represent the second state equation in z_i co-ordinates as:

$$\dot{z}_2 = -z_1 - K_2 \cdot z_2 + z_3 \tag{18}$$

In matrix form, Eq. (7) with the stabilising functions (9) and (18) can be expressed as:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} -K_1 & 1 \\ -1 & -K_2 \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ z_3 \end{bmatrix} \tag{19}$$

STEP 3

By means of transformation (11), the last equation of the state space representation (3c) can be transformed in

$$\dot{z}_3 = d \cdot U + \varphi^\mathrm{T} \cdot \theta - \dot{\alpha}_2 - \ddot{y}_\mathrm{r} \tag{20}$$

The second stabilising function (16) can be written into x_i co-ordinates by the transformations (6a) and (6b), with the aid of (9), yielding:

$$\alpha_2 = -(1 + K_1 \cdot K_2) \cdot x_1 - (K_1 + K_2) \cdot x_2 + (1 + K_1 \cdot K_2) \cdot y_\mathrm{r} + (K_1 + K_2) \cdot \dot{y}_\mathrm{r} \tag{21}$$

Consequently, its derivative is computed, being implemented in (20) as

$$\begin{aligned}\dot{\alpha}_2 &= \frac{\partial \alpha_2}{\partial x_1}\cdot x_2 + \frac{\partial \alpha_2}{\partial x_2}\cdot x_3 + \frac{\partial \alpha_2}{\partial y_r}\cdot \dot{y}_\mathrm{r} + \frac{\partial \alpha_2}{\partial \dot{y}_r}\cdot \ddot{y}_\mathrm{r} \\ &= -(1+K_1\cdot K_2)\cdot x_2 - (K_1+K_2)\cdot x_3 + (1+K_1\cdot K_2)\cdot \dot{y}_\mathrm{r} + (K_1+K_2)\cdot \ddot{y}_\mathrm{r}\end{aligned} \tag{22}$$

Let $\hat{\theta}$ and $\hat{d}$ be an estimations of the unknown vector parameter θ and d in the system (3c). The Liapunov's function of the entire system is

$$V_3 = V_2 + \frac{1}{2}\cdot z_3^2 + \frac{1}{2}\cdot \tilde{\theta}^\mathrm{T}\cdot \Gamma^{-1}\cdot \tilde{\theta} + \frac{|d|}{2\cdot \gamma_\rho}\cdot \tilde{\rho}^2 \tag{23}$$

where Γ is a positive definite matrix referred to as the adaptation gain. Furthermore, its derivative is:

$$\begin{aligned}\dot{V}_3 = &-\sum_{i=1}^{2} K_i\cdot z_i^2 + z_3\left[z_2 + d\cdot U + \varphi^\mathrm{T}\cdot\hat{\theta} - \frac{\partial \alpha_2}{\partial x_1}\cdot x_2 - \frac{\partial \alpha_2}{\partial x_2}\cdot x_3\right. \\ &\left. - \frac{\partial \alpha_2}{\partial y_\mathrm{r}}\cdot \dot{y}_\mathrm{r} - \frac{\partial \alpha_2}{\partial \dot{y}_\mathrm{r}}\cdot \ddot{y}_\mathrm{r} - \dddot{y}_\mathrm{r} - \frac{\partial \alpha_2}{\partial \hat{\theta}}\cdot \dot{\hat{\theta}}\right] + \tilde{\theta}^\mathrm{T}\cdot[z_3\cdot\varphi^\mathrm{T} - \Gamma^{-1}\cdot\dot{\hat{\theta}}] + \frac{|d|}{\gamma_\rho}\cdot\tilde{\rho}\cdot\dot{\tilde{\rho}}\end{aligned} \tag{24}$$

In order to eliminate the error in the vector parameter θ, the following updating law is chosen:

$$\dot{\hat{\theta}} = \Gamma\cdot\varphi^\mathrm{T}\cdot z_3 = \Gamma\cdot\tau \tag{25}$$

where $\tau = \varphi^\mathrm{T} z_3$ represents a tuning function and Γ a diagonal matrix whose coefficients are the gains ($\gamma_i,\ i=0,\ldots,3,\ \gamma_a$). The block diagram of the adaptive system designed for the vector parameter θ is shown in Fig. 7.

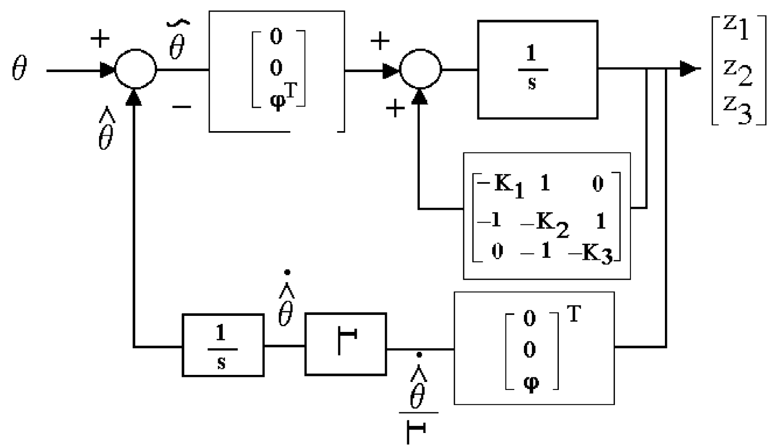

Fig. 7. Block diagram for vector of parameters updating.

If the estimation values of the parameters were correct, then the parameter errors must satisfy, $\tilde{\theta}=\theta-\hat{\theta}=0$, $\tilde{d}=d-\hat{d}=0$, $\hat{\theta}=\theta$, $d=\hat{d}$. The control law could adopt the following form

$$U=-\frac{1}{\hat{d}}\cdot(-K_3\cdot x_3-\varphi^{\mathrm{T}}\cdot\hat{\theta}) \tag{26}$$

it would achieve the global asymptotic tracking of y_{r}. Since this is not the case, the parameter estimation errors, $\tilde{\theta}$, $\tilde{d}$ continues to act as a disturbance which may carry the system to an unstable region. Our objective task is to find an updating law for $\hat{\theta}(t)$ and $\hat{d}(t)$ which preserves the convergence of $x(t)=[x_1(t)\ x_2(t)\ x_3(t)]^{\mathrm{T}}$ and achieves the tracking of the output to $y_{\mathrm{r}}(t)$. It is necessary to introduce a third stabilising function α_3 and modify the control (26) in the following manner

$$U=\frac{1}{\hat{d}}\cdot(\alpha_3+\ddot{y}_{\mathrm{r}})=\hat{\rho}\cdot(\alpha_3+\ddot{y}_{\mathrm{r}}) \tag{27}$$

with this control, the temporal variation of the third Liapunov function (24), considering that d is time invariant ($\dot{\tilde{\rho}}=-\dot{\hat{\rho}}$), results in:

$$\begin{aligned}\dot{V}_3=&-\sum_{i=1}^{2}K_i\cdot z_i^2\\&+z_3\cdot\left[z_2+\alpha_3+\varphi^{\mathrm{T}}\cdot\hat{\theta}-\frac{\partial\alpha_2}{\partial x_2}\cdot x_2-\frac{\partial\alpha_2}{\partial x_2}\cdot x_3-\frac{\partial\alpha_2}{\partial y_{\mathrm{r}}}\cdot\dot{y}_{\mathrm{r}}-\frac{\partial\alpha_2}{\partial\dot{y}_{\mathrm{r}}}\cdot\ddot{y}_{\mathrm{r}}-\frac{\partial\alpha_2}{\partial\hat{\theta}}\cdot\dot{\hat{\theta}}\right]\\&-d\cdot\tilde{\rho}\cdot(\alpha_3+\ddot{y}_{\mathrm{r}})-\frac{|d|}{\gamma_\rho}\cdot\tilde{\rho}\cdot\dot{\hat{\rho}}\end{aligned} \tag{28}$$

The estimation of the parameter $d=1/\rho$ can be found from (28) in the way

$$\dot{\hat{\rho}}=-\frac{d}{|d|}\cdot\gamma_\rho(\alpha_3+\ddot{y}_r)=-\mathrm{sgn}(d)\cdot\gamma_\rho\cdot(\alpha_3+\ddot{y}_{\mathrm{r}}) \tag{29}$$

for which, the parameter sign must be known.

The stabilising function α_3 is chosen so that the total Liapunov function be semidefinite negative:

$$\begin{aligned}\alpha_3=&-z_2-K_3\cdot z_3-\varphi^{\mathrm{T}}\cdot\hat{\theta}+\frac{\partial\alpha_2}{\partial x_1}\cdot x_2+\frac{\partial\alpha_2}{\partial x_2}\cdot x_3+\frac{\partial\alpha_2}{\partial y_{\mathrm{r}}}\cdot\dot{y}_{\mathrm{r}}+\frac{\partial\alpha_2}{\partial\dot{y}_{\mathrm{r}}}\cdot\ddot{y}_{\mathrm{r}}+\frac{\partial\alpha_2}{\partial\hat{\theta}}\cdot\dot{\hat{\theta}}\\=&-z_2-K_3\cdot z_3-\varphi^{\mathrm{T}}\cdot\hat{\theta}-(1+K_1\cdot K_2)\cdot x_2-(K_1+K_2)\cdot x_3+(1+K_1\cdot K_2)\cdot\dot{y}_{\mathrm{r}}\\&+(K_1+K_2)\cdot\ddot{y}_{\mathrm{r}}\end{aligned} \tag{30}$$

Previous described laws guarantee that:

$$\dot{V}_3=-\sum_{i=1}^{3}K_i\cdot z_i^2\le 0 \tag{31}$$

This choice by means of LaSalle's invariance theorem or Barbalat lemma (Khalil, 1996), lets us obtain the global stability of the equilibrium defined as $z_1 = 0$, that is to say, $y = y_r$, $\hat{\theta} = \theta$, and $\hat{\rho} = \rho$.

The third state equation into the error variables, can be obtained starting from (20) with the control (27) and the stabilising function α_3 (30):

$$\dot{z}_3 = -z_2 - K_3 \cdot z_3 + \varphi^{\mathrm{T}} \cdot \tilde{\theta} - d \cdot (\alpha_3 + \ddot{y}_r) \cdot \tilde{\rho} \tag{32}$$

Finally, the resulting error dynamics obtained from Eqs. (19) and (32) is written as:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} -K_1 & 1 & 0 \\ -1 & -K_2 & 1 \\ 0 & -1 & -K_3 \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \varphi^{\mathrm{T}} \end{bmatrix} \cdot \tilde{\theta} - d \cdot \begin{bmatrix} 0 \\ 0 \\ \alpha_3 + \ddot{y}_r \end{bmatrix} \cdot \tilde{\rho} \tag{33}$$

3.2. Identification procedure

The control objective is to carry out the ship's manoeuvring of change of yaw angle from the initial value to the final one, in such a way that indicates the reference $y_r = \Psi_r$ given by expression (2). The restriction imposed on the rudder angle (whose dynamics is also taken into account) is the value that takes during the realisation of the turn until the third (steady phase) is reached. This value is $20° = 0.3491$ rad. The identification process has been carried out by the use of the Backward–Euler algorithm with a step size of 1 s. The initial estimations were the same for all model parameters (25% of its true values).

The procedure start from Eq. (33), straight on by its integration with the updating laws (25) and (29) with some optimisation criteria on the errors between the estimation of the parameters and its true values. The final step consists in the change between the states z_i and the x_i ones by the application of the equations of change of coordinates. These equations can be easily obtained from expressions (6a), (6b) and (11). The results are:

$$z_1 = x_1 - y_r \tag{34a}$$

$$z_2 = K_1 \cdot x_1 + x_2 - K_1 \cdot y_r - \dot{y}_r \tag{34b}$$

$$z_3 = (1 + K_1 \cdot K_2) \cdot x_1 + (K_1 - K_2) \cdot x_2 + x_3 - (1 + K_1 \cdot K_2) \cdot y_r + (K_2 - K_1) \cdot \dot{y}_r - \ddot{y}_r \tag{34c}$$

Table 4
True parameters of the ship model

Parameter	True value	Estimate value	Units
A	-8.26149×10^{-2}	-8.26235×10^{-2}	s^{-1}
C_3	-2.44894×10^{-2}	-2.4546×10^{-2}	rad^{-2}/s
C_2	-0.146117	-0.144152	rad^{-1}/s
C_1	$2.39669.10^{-3}$	$2.39703.10^{-3}$	s^{-1}
C_0	$-7.77.10^{-7}$	$-7.93144.10^{-6}$	rad
D	4.27019×10^{-5}	4.27019×10^{-5}	s^{-3}

Table 5
Values of the gains utilised in the identification process

Gain	Value (p.u)
K_1	23.8227
K_2	28.4585
K_3	25
γ_0	2000
γ_1	$-5.63348.10^{-4}$
γ_2	-2.08884
γ_3	$-5.63348.10^{-4}$
γ_a	1.85566×10^{-2}
γ_ρ	0.547183

In Table 4, the true parameters of the ship model (3c) obtained from Table 2 are shown, and the corresponding ones that were obtained by the identification procedure, while in Table 5 appear the values of the used gains.

The identification algorithm and the optimisation one fails in the determination of the coefficient c_0. There is an alternative form of computing this coefficient. The procedure starts from the steady value in the yaw rate temporal variation shown in Fig. 4. Under this condition, from Eq. (3c) yields

$$c_0 = -(c_3 \cdot \bar{x}_2^3 + c_2 \cdot \bar{x}_2^2 + c_1 \cdot \bar{x}_2 + d \cdot U) \tag{35}$$

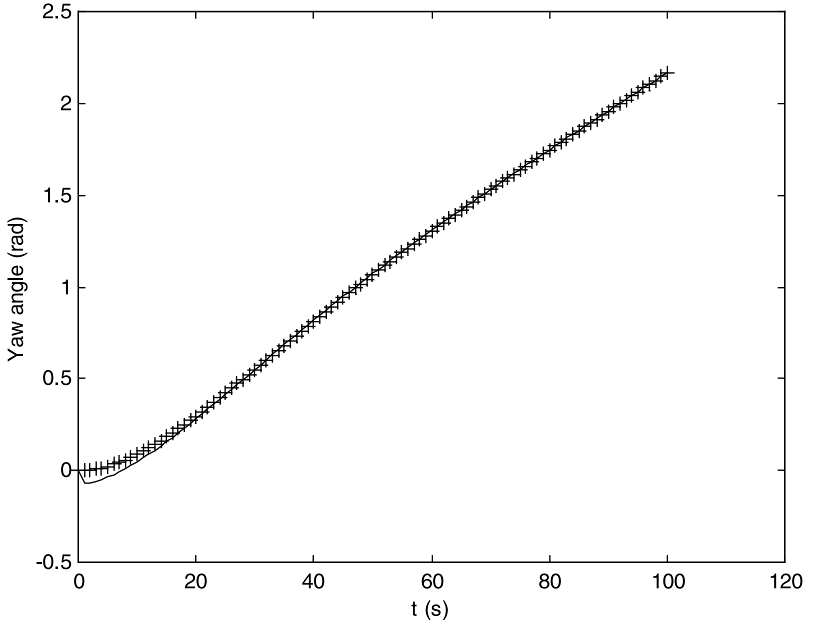

Fig. 8. Variation of the yaw angle. Continuous line: fitted curve to experimental. Data using the least square method. Sign plus: using the parameters identified.

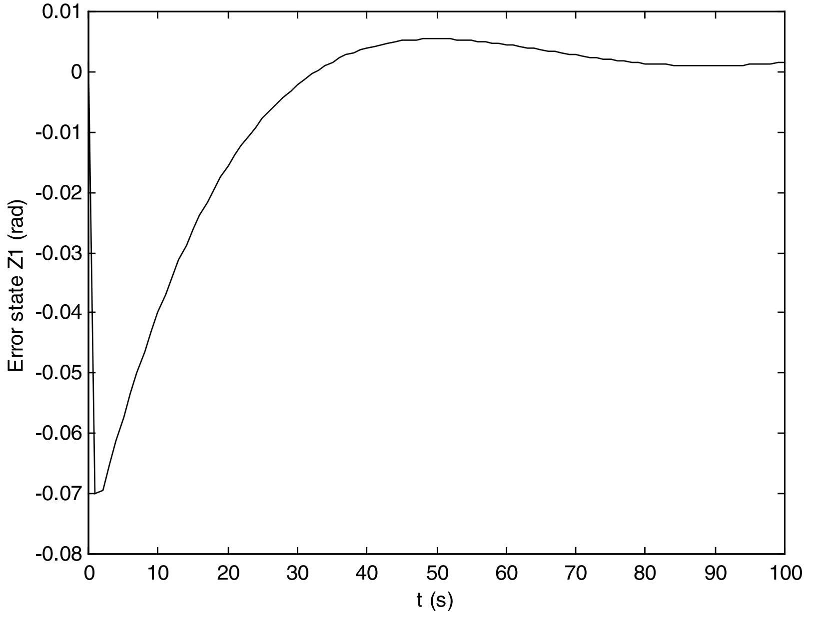

Fig. 9. Variation of the error state z_1.

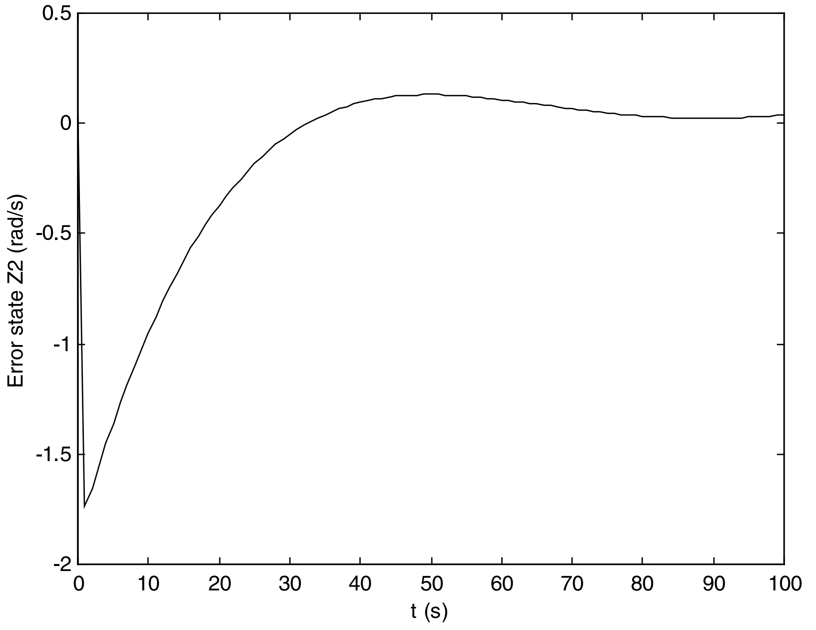

Fig. 10. Variation of the error state z_2.

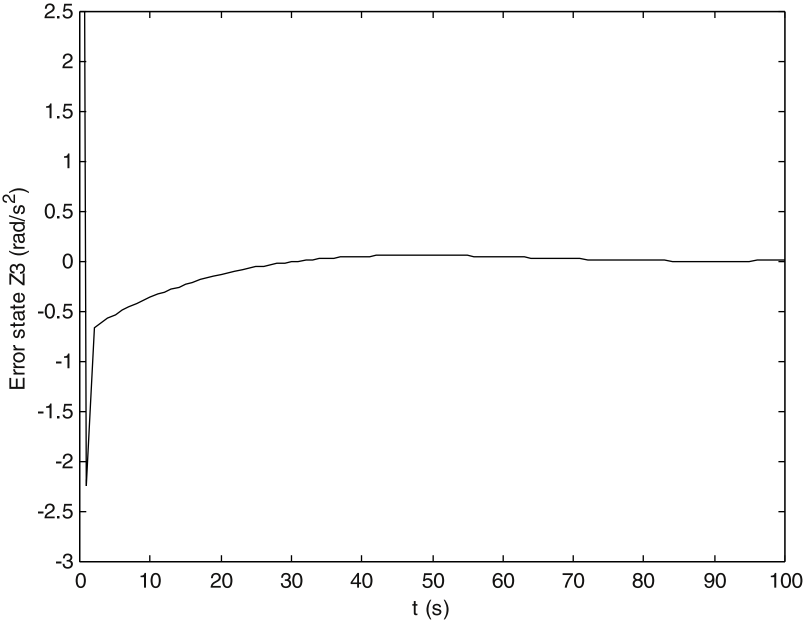

Fig. 11. Variation of the error state z_3.

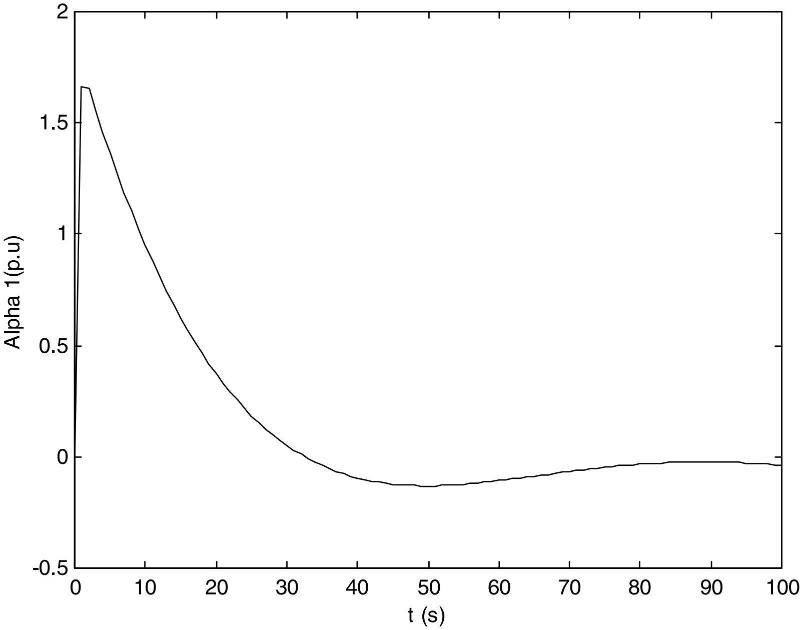

Fig. 12. Variation of the stabilising function α_1.

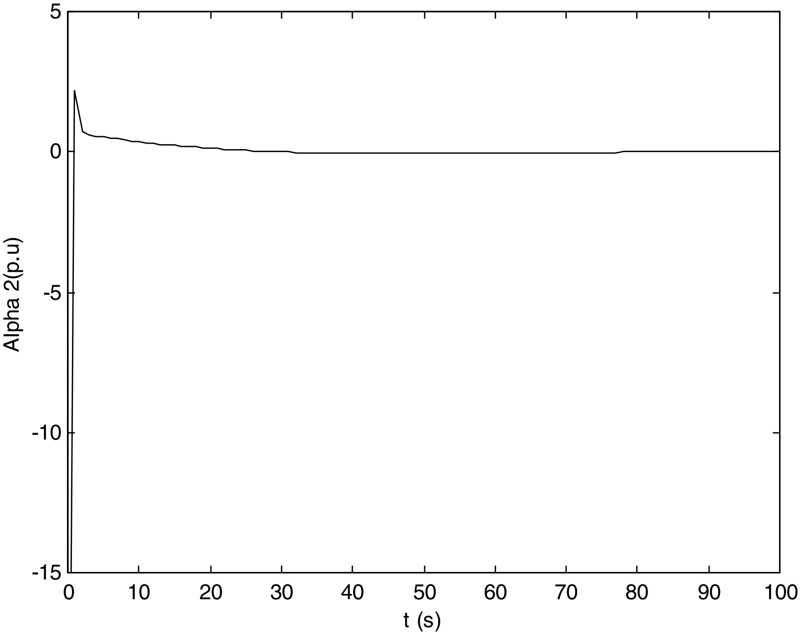

Fig. 13. Variation of the stabilising function α_2.

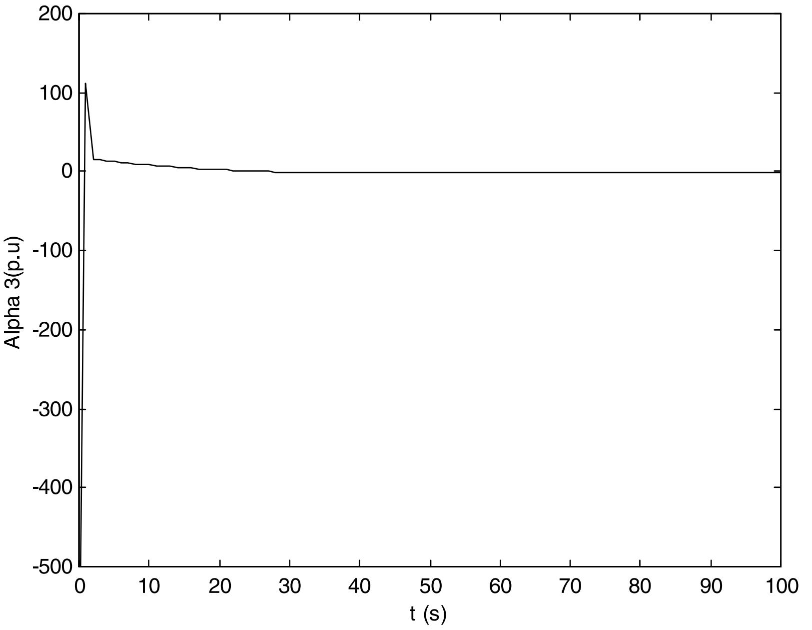

Fig. 14. Variation of the stabilising function α_3.

where $\bar{x}_2 = 2.04618 \times 10^{-2}$ rad/s, $U = 0.3491$ rad and c_i ($i = 1,\ldots,3$), d are the true values shown in Table 4.

Fig. 8 shows the variation of the yaw angle. There is an excellent agreement between the experimental values and the corresponding ones obtained by the simulation-optimisation processes. Figs. 9–11 show that state error variables z_1, z_2 and z_3, used in expressions (34a)–(34c), converge quickly towards the null values for the gain values K_1, K_2, K_3, γ_i ($i = 0,\ldots,3$), γ_a, γ_ρ shown in Table 5. Furthermore, stabilising functions α_1, α_2, and α_3, shown in Figs. 12–14, converge also according to imposed requirements.

4. Conclusion

The adaptive, identification and tracking processes have been carried out. The procedure based on the backstepping procedure by the tuning functions design is capable of realising this task starting from initial estimations values in a nonlinear ship characterised by a relatively complex nonlinear model capable of adjusting the ship's dynamics. The identification procedure only needs the values of the temporal variation of the yaw angle in a traditional turning test. The fail in the determination of the independent term c_0 can be due to the optimisation algorithm used for this purpose. This inconvenient can be overcome by the use of more complete algorithms, such as the Fletcher–Reeves or the Polak–Ribiere ones.

References

Abkowitz, M., 1964. Lectures on Ship Hydrodynamics. Steering and Manoeuvrability. HyA, Rep. 5.

Banaszuk, A., Krener, A., 1997. Design of controllers for MG3 compressor models with general characteristics using graph backstepping, Proceedings of the 1997 American Control Conference, Albuquerque, NM 1997, pp. 977–981.

Bech, M.I., Wagner Smith, L., 1969. Analogue simulation of ship maneuvers. Technical Report Hy-14, Hydro- and Aerodynamics Laboratory, Lynby, Denmark.

Behnken, B., Murray, R., 1997. Combined air injection control of rotating stall and bleed valve control of surge. Proceedings of the 1997 American Control Conference, Albuquerque, NM 1997, pp. 987–992.

Casado, M.H., Velasco, F., 2003. Surface ship trajectory control using non-linear backstepping design. Journal of Marine Engineering and Technology, Part A3.

Darnell, P.A., Margolis, P.E., 1990. C: A Software Engineering Approach. Springer, Berlin.

Fossen, T.I., 1994. Guidance and Control of Ocean Vehicles. Wiley, Chicester.

Izar., 2001. State Shipyard Localised in Cádiz Bay, Spain. Construction code H81.

Journée, J.M.J., Pinkster, J.A., 2001. Ship Hydromechanics. Delft University of Technology, p. 70.

Kanellakopoulos, I., Kokotović, P., Morse, S., 1991. Systematic design of adaptive controllers for feedback linearizable systems. IEEE Transactions in Automatic Control 36 (11), 1241–1253.

Khalil, H.K., 1996. Nonlinear Systems. Prentice Hall, Englewood Cliffs, New Jersey.

Krestić, M., Kanellakopoulos, I., Kokotović, P.V., 1992. Adaptive nonlinear control without overparametrization. Systems Control Letters 19, 177–185.

Krestić, M., Kanellakopoulos, I., Kokotović, P., 1995. Nonlinear and Adaptive Control Design. Wiley, New York.

Marino, R., Peresada, S., Tomei, P., 1999. Output feedback control of induction motors with uncertain rotor resistence. IEEE Transactions on Automatic Control 44, 967–983.

Nomoto, K., 1960. Directional Steerability and Automatically Steered Ship with Particular Reference to their Bad Perfomance in Rough Sea. DTMB Rep. 461, First Symposium on Ship Maneuverability.
Norrbin, N., 1981. Theory and Observations on the Use of ARPA Mathematical Model for Ship Maneuvering in Deep and Confined Waters. SSPA. N68.
Pershitz, R., 1973. Ship's Manoeuvrability and Control. Sudostroenie, Leningrad in Russian.
Protz, J., Paduano, P., 1997. Rotating Stall and Surge: Alternate Modeling and Control Concepts, Proceedings of the IEEE International Conference on Control Applications, Hartford 1997, pp. 866–873.
Sobolev, G., 1976. Ship Manoeuvrability and Ship's Control Automatization. Sudostronie, Leningrad in Russian.
Van Leeuwen, G., 1978. A simplified nonlinear model of a manoeuvring Ship, Report N.262. Naval Architecture Dept., Delf University of Technology.