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A NEW RECURSIVE IDENTIFICATION PROCEDURE OF THE NONLINEAR MODEL SHIP BASED ON THE TURNING TEST MANOEUVRING AND THE NORRBIN EQUATION

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ABSTRACT

In this paper has been carried out an identification procedure based on the adaptive backstepping design. The process depart of the experimental results obtained for a particular ship in the turning circle test. The ship's dynamics has been adjusted according to the Norrbin model being the coefficients of the nonlinear manoeuvring characteristics determined by the described procedure.

Key words: Modelling, nonlinear systems, ship's dynamics, adaptive backstepping.

1. INTRODUCTION

Several trial test for marine vehicles has been proposed, namely, the Turning, the Z-Manoeuvre (Kempf), Modified Z-Maneuver, Direct Spiral (Dieudonné), Reverse Spiral (Bech), Pull-Out, Stopping, Stopping Inertia, New Course Keeping, Man-Overboard, Parallel Course Manoeuver, Inertial Turning, Z-Maneuver Test at Low Speed, Accelerating Turning, Acceleration /Deceleration, Thruster, Minimum Revolution, Crash Ahead Test, though there are no definitive international standards for conducting manoeuvring trials with ships. Many shipyards have developed their own procedures driven by their experience and with consideration to the efforts made by the International Towing Tank Conference (ITTC, Proceedings 1963-1975) and other organizations or institutes, Journée and Pinkster (2001). The society of Naval Architects and Marine Engineers (SNAME) has produced three guidelines: "Code on manoeuvring 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). IMO Resolution A.601 (1987) and IMO Resolution A.751 (1993), were adopted by the IMO Assemblies to address ship manoeuvrability. The last Resolution adopted by this organization was the MSC 137(76) on 4 December 2002. The Z - Maneuver Test (Kemf) jointly with the Spiral Manoeuvre give some indication of control effectiveness (yaw- angle rate versus rudder angle) are recommended for all organisations and let us to carry out a compare the manoeuvring properties and control characteristic of a ship with those of other ships.

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Experimental results of trial tests can be to meet in the references showed in Principles of Manoeuvring and Control (Crane, 1999).

The backstepping designs (Krstić, et al., 1995) has been applied with considerable success in: Throttle valve and bleed valve, Banaszuk and Krener (1997) and the air injection, Behnken and Murray (1997), Protz and Paduano (1997), aeronautic systems, Monahemi and Krstić (1996), electric machines (Marino, et al., 1999), ship control, route planning, Haro and Velasco (2003), and in optimality problems (Fossen, 1994), electric generator systems based on the wind energy (Haro, et al.,2003).

The purpose of this paper is to carry out the identification process of the nonlinear dynamics of a ship supposing that its dynamics verify the Norrbin model (1963). El procedure based on the adaptive backstepping theory and the Turning Test manoeuvre let us the calculus of the coefficients that defines the nonlinear equation of the ship steering dynamics. A only measurement, the temporal variation of the yaw rate, it is necessary for this purpose. 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). The four phases of the turning test, Fig.1, are distinguishable by the conditions shown in Table 1, where v, r , represents the sway velocity of the ship and the angular one about the a perpendicular axis, while $\dot{v}$, $\dot{r} = \alpha$ are the corresponding linear and angular accelerations, respectively.

2. SHIP MODEL

The ship movement is described in the Norrbin's model by the following equation,

Figure 1. Turning path of a ship.

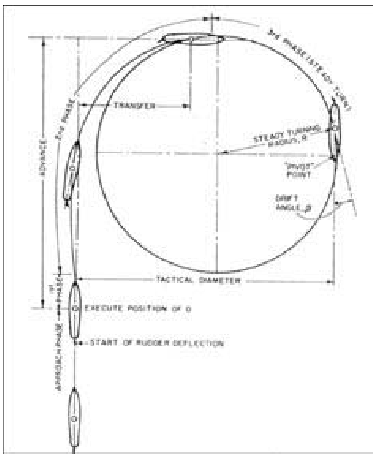


Table 1. Characteristics of the transient phases of a turn.

Phase	$\dot{v}$	$\dot{r}$	v	r
Approach	0	0	0	0
First	≠ 0	≠0	0	0
Second	≠ 0	≠ 0	≠ 0	≠ 0
Third	=0	=0	≠ 0	≠ 0

$$T \cdot \ddot{\o} + H_N(\dot{\o}) = K \cdot \ddot{a} \qquad \textbf{(1)}$$

where ψ is the course, $r=\dot{\psi}$ the yaw rate, δ the rudder angle, governed by a linear first order dynamics with a time constant τ, K the Nomoto gain constant, and T an equivalent time constant

$$\frac{\delta(s)}{U(s)} = \frac{1}{1 + s \cdot \tau} \quad (2)$$

U represents to the control and $H_N(\dot{\psi})$ the nonlinear manoeuvring characteristic usually represented by a third order polynomial as

$$H_N(\dot{\psi}) = n_3 \cdot \dot{\psi}^3 + n_2 \cdot \dot{\psi}^2 + n_1 \cdot \dot{\psi} + n_0 \quad (3)$$

The steering dynamic with the equations (1) and (3) can be expressed as

$$\ddot{\psi} = a_3 \cdot \dot{\psi}^3 + a_2 \cdot \dot{\psi}^2 + a_1 \cdot \dot{\psi} + a_0 + b \cdot \delta \quad (4)$$

being

$$a_i = -\frac{n_i}{T} \qquad (i = 0 \cdots 3) \quad (5.a)$$

$$b = \frac{K}{T} \quad (5.b)$$

The state equations with the state variables r and $\alpha = \dot{r}$ (angular acceleration) are,

$$\dot{r} = \alpha \quad (6.a)$$

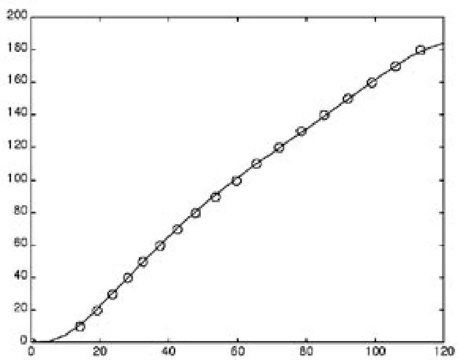
$$\dot{\alpha} = a_3 \cdot r^3 + a_2 \cdot r^2 + a_1 \cdot r + a_0 + b \cdot \delta \quad (6.b)$$

In the former equation an asymmetry in the hull is considered ($a_2 \uparrow 0$), also the procedure let us compute the term (a_0) due to environmental disturbances (wind, waves and currents) that they can act on the ship.

The roll-on/roll-off ship (Figure 2), whose characteristics are shown in the Table 2, has the following variation of the yaw angle with the time (Figure 3, equation 7) obtained

Figure 2. Ship whose characteristics has been tested in this paper.

Figure 3. Variation of the yaw angle vs time. Continuous line (fit obtained), circles (experimental points).



by means of fitting by least squares procedure of the experimental points of the yaw angle obtained by the realisation of the first three phases of the turning test to a polynomial of fourth order. The test was carried out in normal ballast condition, maximum ahead speed with a rudder angle of the 35 degrees. The turn causes a reduction in the speed of the ship like it is indicated in Table 3.

$$r_d = -0.22815\cdot 10^{-6}\cdot t^4 + 7.433\cdot 10^{-5}\cdot t^3 - 6.7401\cdot 10^{-3}\cdot t^2 + 0.2319\cdot t - 0.4611 \quad (7)$$

Figure 4. Variation of the yaw rate vs time.

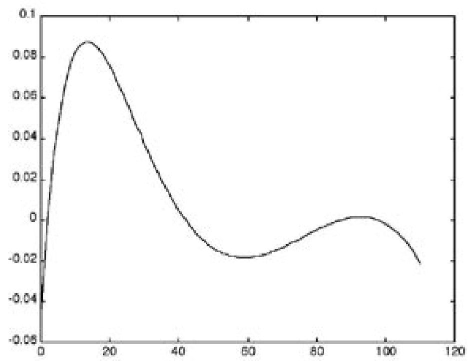
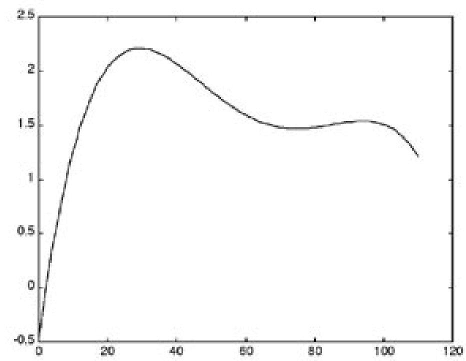


Figure 5. Variation of angular acceleration.



where r_d is the desired temporal variation of yaw rate in deg.s^{-1}.

Table 2. Main characteristics of the ship tested (Izar, 2001).

Draught forward (full load condition)	6m
Deadweight	7456 metric tonnes
Max. displacement	19949 metric tonnes
Length overall	188.3 m
Breadth (moulded)	28.7 m
Bulbous bow	Yes
Type of rudder	Becker
Number of units	2
Maximum angle of rudder	65 degrees
Time of hard–over to hard over	56 s
Propellers	2
Type	Controllable pitch
Engine (2 per shaft) Maximum power	4 x 6000 kW
Speed loaded (maximum full ahead)	22.68 knots
Speed ballast (maximum full ahead)	23.14 knots

Table 3. Reduction on the ship's speed from the initial value (22.68 knots) during the test.

Change of heading (deg)	Ship's speed (knots)	Change of heading (deg)	Ship's speed (knots)
10	19.24	100	9.07
20	18.27	110	8.18
30	17.22	120	7.37
40	16.08	130	6.69
50	14.89	140	6.15
60	13.64	150	5.69
70	12.41	160	5.30
80	11.22	170	5.00
90	10.09	180	4.74

3. ADAPTIVE BACKSTEPPING PROCEDURE

In order to get the identification of the parameters a_i (i=0...3) in equation (6.b) by the adaptive backstepping procedure it is convenient to define the new state variables,

$$z_1 = r - r_d \quad (8.a)$$

$$z_2 = \alpha - \beta(z_1) \quad (8.b)$$

where $\beta(z_1)$ represents a stabilizing function.

In the first step of the backstepping it is necessary to derive the equation (8.a) and with the aid of the (8.b) to obtain

$$\dot{z}_1 = z_2 + \beta(z_1) - \dot{r}_d \tag{9}$$

and choosing the stabilizing function as

$$\beta(z_1) = \dot{r}_d - K_1 \cdot z_1 - \beta_1(z_1) \cdot z_1 \tag{10}$$

being $K_1>0$, $\beta(z_1) \geq 0$, $\forall z_1$. In this step a Liapunov's function candidate is,

$$V_1 = \frac{1}{2} \cdot z_1^2 \tag{11}$$

whose derivative is

$$\dot{V}_1 = -[K_1 + \beta_1(z_1)] \cdot z_1^2 + z_1 \cdot z_2 \tag{12}$$

The second step of the backstepping depart of the equation (8.b) where the variation of the second backstepping state is,

$$\dot{z}_2 = \dot{\alpha} - \dot{\beta}(z_1) = \sum_{i=0}^{3} a_i + b \cdot \delta - \dot{\beta}(z_1) \tag{13}$$

As consequence of the uncertainties in the parameters a_i (i=0..3) it cannot be cancelled by the control. For the principle of certain equivalence, each one of the parameters are substituted for its estimate $\hat{a}_i$(i=0..3) , the made error is $\tilde{a}_i$(i=0..3)

$$\tilde{a}_i = a_i - \hat{a}_i \qquad (i = 0..3) \tag{14}$$

The second Liapunov function proposed is,

$$V_2 = V_1 + \frac{1}{2} \cdot z_2^2 + \frac{1}{2} \cdot \left[\sum_{i=0}^{3} \frac{1}{\gamma_i} \cdot \tilde{a}_i^2 \right] \tag{15}$$

its derivative is

$$\dot{V}_2 = \dot{V}_1 + z_2 \cdot \dot{z}_2 + \sum_{i=0}^{3} \frac{1}{\gamma_i} \cdot \tilde{a}_i \cdot \dot{\tilde{a}}_i \tag{16}$$

after of considering (12,13,14) the equation (16) can be transformed in

$$\dot{V}_2 = -[K_1 + \beta_1(z_1)] \cdot z_1^2 + z_1 \cdot z_2 + z_2 \cdot \left[\sum_{i=0}^{3} \hat{a}_i \cdot r^i + b \cdot \delta - \dot{\beta} \right] + \sum_{i=0}^{3} \tilde{a}_i \cdot \left[r^i \cdot z_2 + \frac{1}{\gamma_i} \cdot \dot{\tilde{a}}_i \right] \tag{17}$$

in a real situation it is predictable that $\sum_{i=0}^{3} \tilde{a}_i \neq 0$, that it to say, always there is an error in the parameter estimations, in consequence to eliminate the last term in (17), two solutions can be adopted,

- solution less restrictive

$$\sum_{i=0}^{3} r^i \cdot z_2 = -\sum_{i=0}^{3} \frac{1}{\gamma_i} \cdot \dot{\tilde{a}}_i \qquad \textbf{(18.a)}$$

- solution more restrictive,

$$r^i \cdot z_2 = -\frac{1}{\gamma_i} \cdot \dot{\tilde{a}}_i \qquad (i = 0 \cdots 3) \qquad \textbf{(18.b)}$$

If someone of the conditions (18.a) or (18.b) are match, then of the (17)

$$\dot{V}_2 = -[K_1 + \beta_1(z_1)] \cdot \sum_{i=0}^{3} \hat{a}_i \cdot r^i + b \cdot \delta - \dot{\beta} \,]z_1^2 + z_1 \cdot z_2 + z_2 \cdot \left[\sum_{i=0}^{3} \hat{a}_i \cdot r^i + b \cdot \delta - \dot{\beta} \right] \qquad \textbf{(19)}$$

If the rudder angle is chosen as,

$$\delta = \frac{1}{b} \left\{ -z_1 - \sum_{i=0}^{3} \hat{a}_i \cdot r^i + \dot{\beta} - [K_2 + \beta_2(z_2)] \cdot z_2 \right\} \qquad \textbf{(20)}$$

the derivative of the Liapunov function (19) is now

$$\dot{V}_2 = -[K_1 + \beta_1(z_1)] \cdot z_1^2 - [K_2 + \beta_2(z_2)] \cdot z_2^2 \qquad \textbf{(21)}$$

if $\beta_1(z_1) \geq 0, \beta_2(z_2) \geq 0, K_1 > 0, K_2 > 0$, by direct method of the Liapunov or by the theorem of LaSalle (Khalil, 1996) the system is global asymptotically stable.

The dynamics of the first error state can be obtained from (9) and considering (10). The result is

$$\dot{z}_1 = -[K_1 + \beta_1(z_1)] \cdot z_1 + z_2 \qquad \textbf{(22)}$$

the corresponding variation of the state z_2, is obtained to depart of (8.b) and considering (6.b) with the rudder value chosen (20)

$$\dot{z}_2 = -z_1 - [K_2 + \beta_2(z_2)] \cdot z_2 + \sum_{i=0}^{3} \tilde{a}_i \cdot r^i \qquad \textbf{(23)}$$

in matrix form after of taking into account (8.a)

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix}=\begin{bmatrix}-[K_1+\beta_1(z_1)] & 1\\ -1 & -[K_2+\beta_2(z_2)]\end{bmatrix}\cdot\begin{bmatrix}z_1\\ z_2\end{bmatrix}+\begin{bmatrix}0\\ \sum_{i=0}^{3}\tilde{a}_i\cdot\left(z_1+r^d\right)^i\end{bmatrix} \quad \textbf{(24)}$$

the block diagram is show in Figure 6.

For the implementation of the control rudder angle (20) it is necessary to express the derivative of the β function in terms of the variables. It is easy to show that this is defined by the equation,

$$\dot{\beta}=\ddot{r}_d-\left[K_1+\frac{\partial\,[\beta_1(z_1)\cdot z_1]}{\partial\, z_1}\right]\cdot\dot{z}_1 \quad \textbf{(25)}$$

the simplest form for the β_i(i = 12) that verifies the imposed conditions are

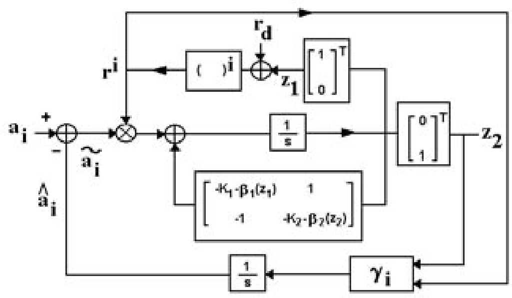
$$\beta_1(z_1)=z_1^2 \quad \textbf{(26.a)}$$

$$\beta_2(z_2)=z_2^2 \quad \textbf{(26.b)}$$

with this choice,

$$\dot{\beta}=\ddot{r}_d-\left[K_1+3\cdot z_1^2\right]\dot{z}_1=\ddot{r}_d-\left[K_1+3\cdot z_1^2\right]\left[-\left(K_1+z_1^2\right)z_1+z_2\right] \quad \textbf{(27)}$$

Figure 6. Implementation of the identification algorithm designed.



4. SIMULATION OF THE SYSTEM

According to block diagram showed in Figure 6, the simulation of the system has been carried out. By means of the algorithm of integration of Backward- Euler with a step-size of 0.1 s. The optimisation one that allows the reduction of the error between the parameters estimates and its true values was of the Fletcher Reeves, that requires few iterations to convergence (Flannery, et al., 1989). For this purpose the experimental results of the yaw rate variation versus time obtained in the turning test manoeuvring for the ship (K=1,T=97 s) whose characteristics are shown in Table 4.

Table 4. Coefficients of the nonlinear manoeuvring characteristics when the procedure of identification more restrictive (18.b) is adopted.

Coefficient	Estimated value (p.u)
a_0	$1.155.10^{-2}$
a_1	$-2.673.10^{-2}$
a_2	$2.648.10^{-2}$
a_3	$-3.719.10^{-2}$

Table 5. Values of the different gains in the analysed system.

Constant	Value (p.u)
γ_0	$-5.199.10^{-3}$
γ_1	$-5.440.10^{-4}$
γ_2	$-9.986.10^{-5}$
γ_3	$-8.830.10^{-5}$
K_1	57.09
K_2	50.00

Figure 7. Variation of the heading angle vs time. Continuous line (values obtained from of the identified model), circles (adjust show in Figure 3).

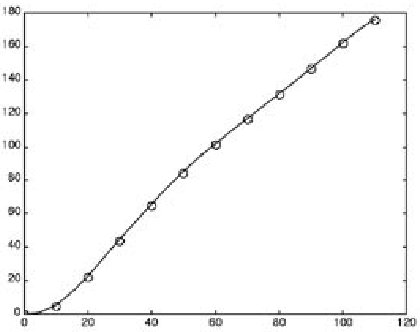


Figure 8. Variation of the error state variable (z_1).

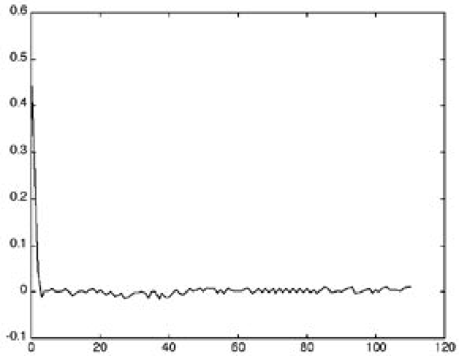


Figure 9. Variation of the error state (z_2).

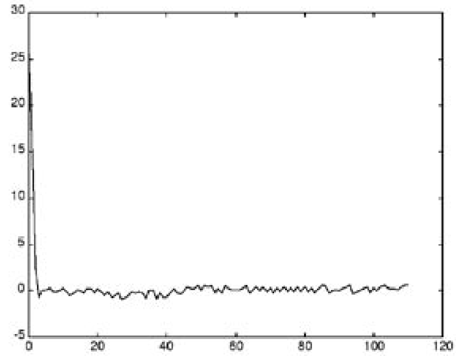


Figure 10. Variation of the yaw angle vs time. Continuous line (values obtained from the identified model), circles (adjust show in Figure 3).

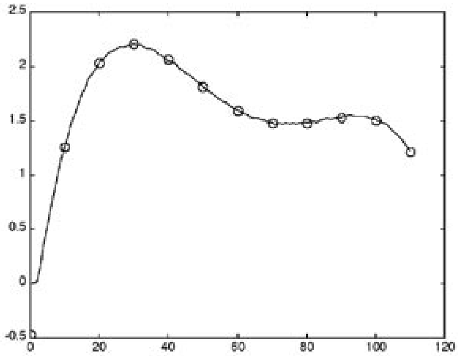
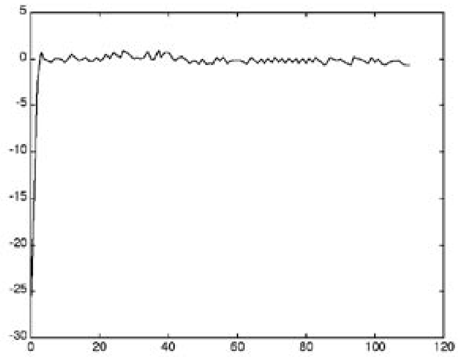


Figure 11. Variation of the stabilizing function.



4. CONCLUSIONS

A identification procedure based on the recursive backstepping procedure and the tuning functions design has been developed with the purpose of determining the coefficients of the polynomial that defines the manoeuvring characteristics. The procedure only takes into account the experimental results of the yaw variation in the particular test of the turning circle. The procedure overcomes the difficulty of the meet a solution of the a nonlinear differential equation of second order that should be necessary to resolve with the purpose of matching the experimental results of the yaw angle with the dynamics equation that represents the Norrbin model. The results show a fast convergence of the initial estimates of the parameters of the model toward their true values (Figs.8,9), in addition an excellent agreement between the experimental values and the theoretical ones (Figs.7,10).

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APENDICE:UN NOVEDOSO PROCEDIMIENTO DE IDENTIFICACIÓN DEL MODELO NO LINEAL DE UN BUQUE BASADO EN LA PRUEBA DEL CÍRCULO Y EN LA ECUACIÓN DE NORRBIN.

RESUMEN

En este artículo se ha implementado un procedimiento de identificación de la dinámica de un buque basado en el diseño del backstepping adaptativo. El procedimiento parte de los resultados experimentales obtenidos en un buque determinado durante la realización del test del círculo. La dinámica del buque ha sido ajustada a un modelo de Norrbin en donde los coeficientes de la ecuación no lineal que describen sus características de maniobra han podido ser determinados mediante el procedimiento descrito.

Palabras Clave: Modelado, sistemas no lineales, dinámica del buque, backstepping adaptativo.

INTRODUCCIÓN

En el trabajo se ha realizado un diseño de un procedimiento recursivo de identificación de la dinámica no lineal de un buque basado en la teoría del backstepping.

El procedimiento parte de los resultados de las pruebas de mar obtenidos en la realización del test del círculo de un buque roll-on/roll-off construido en el año 2001 en la factoría de IZAR de Puerto Real (Cádiz). La dinámica del buque ha sido ajustada según el modelo no lineal de Norrbin de tercer orden en donde los coeficientes de esta dinámica se han determinado mediante el procedimiento descrito. Asimismo se ha considerado la dinámica del timón representada por un sistema de primer orden. Para la realización del procedimiento de identificación solamente es necesario conocer la variación temporal del ángulo de rumbo.

METOLOGÍA

El procedimiento de identificación está basado en la teoría del backstepping introducida en el año 1995 por Krestić, Kanellakopulos y Kokotovic.

Fundamentalmente consiste en escribir la dinámica no lineal del sistema como una cadena de integradores en donde en las realimentaciones de cada uno de los subsistemas aparecen los términos de incertidumbre cuyos términos se pueden determinar a partir de las leyes de actualización de parámetros y las funciones sintonizadoras. En cada uno de los subsistemas los estados se consideran como entradas ficticias, lográndose la estabilización asintótica de los errores cometidos mediante la introducción de las funciones estabilizadoras y una elección adecuada de las funciones de Liapunov.

CONCLUSIONES

En el artículo se ha desarrollado un procedimiento de identificación recursivo basado en la teoría del backstepping y en las funciones sintonizadoras con el propósito de determinar los coeficientes del polinomio que definen la dinámica de un buque según el modelo de Norrbin. El procedimiento únicamente considera los resultados experimentales de la variación temporal del ángulo de rumbo obtenidos durante las pruebas del mar del buque durante la realización de la prueba del círculo. La sistemática desarrollada permite soslayar la dificultad de resolver una ecuación diferencial no lineal de segundo orden que sería necesario resolver si se desea ajustar los resultados experimentales a los previstos según el modelo de Norrbin. El procedimiento revela una rápida convergencia de los valores estimados de los parámetros hacia sus verdaderos valores así como la excelente concordancia entre los resultados experimentales obtenidos con los previstos por la teoría.