Simulations of an Autonomous In-scale Fast-ferry Model

Francisco Jesús Velasco, Elías Revestido, Eloy López, Emiliano Moyano and M. Haro Casado

***Abstract*—**In this paper several simulations are presented of an autonomous in-scale fast-ferry model TF-120 using data from a remote Web-Wi-Fi platform for marine vehicles. The physical model is developed to be autonomous and is controlled remotely from a PC using Wi-Fi communications. An identification and validation of a heading model is obtained with turning circle maneuverings on the coastline of the Bay of Santander. Simulations of standard maneuvering tests show the behavior of the identified model and the kinematics. The parametric model identified is used to design different classical control structures for heading autopilot. A 2-dimensional track-keeping system is developed based on line of sight guidance scheme using the identified model of the autonomous in-scale fast-ferry. The results of simulation are presented showing the good performance of the guidance and control design.

***Keywords*—** Line of sight, parametric identification, heading identification, heading control, simulation.

I. INTRODUCTION

A physical in-scale model of the TF-120 turboferry (Fig. 2) has been designed to be autonomous and is controlled remotely from a Laptop in order to perform sea vessel trials [13] with research purposes. This is part of a marine vehicle Web-Wi-Fi platform [2], [11], [12] to carry out tests in open waters that can not be made in a model basin and for at-scale experimentation of coordination between sea vessels. Autonomous guidance and control technologies are required to perform these purposes. The present paper examines the conventional line of sight (LOS) autopilot [14]. This kind of autopilot directs the physical model along a course made up of way points.

To be able to use LOS algorithm, it is necessary to develop suitable heading controllers, meaning that the corresponding parametric models are required.

In this work is developed a mathematical maneuvering model, which includes the dynamics and kinematics, by means of system identification techniques [6] using the data obtained from turning circle maneuvers with a marine vehicle Web-Wi-Fi platform for remote experimentation in the coastline of the Bay of Santander.

Moreover, classical controllers are obtained for the mathematical ship heading model which have been tested in simulation. Genetic algorithm techniques have been used to tune the controllers.

In this article simulations are presented in order to demonstrate the performance of the guidance and control design for TF-120 turboferry model. In subsequent research, a track-keeping controller will be developed to be evaluated on the coastline of the bay of Santander. Furthermore, the possibilities of the platform for experimentation of marine vehicles with research and educational purposes are discussed.

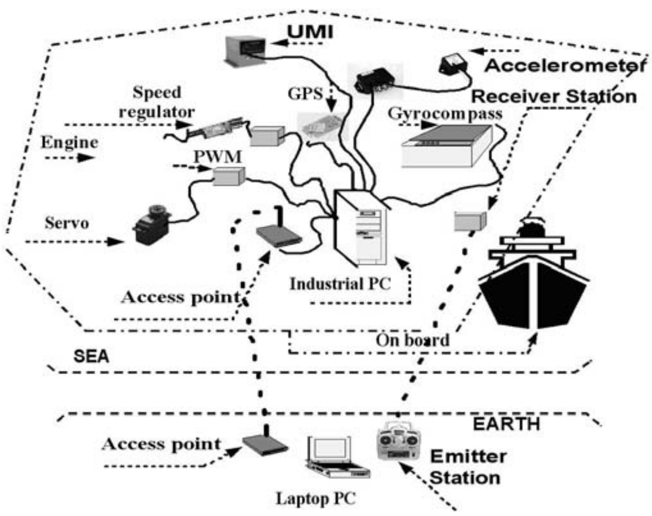

Fig. 1 Elements which make up the platform.

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II. Platform Elements

Fig. 1 shows a schema of the on-board and on-land elements which make up marine vehicle Web-Wi-Fi platform.

On-board Elements:

Components for the propulsion and steering of the vessel (motors, servos, speed controller, turbojets).

Components of the control circuitry: PWM = Pulse Width Modulation and receiver station.

Sensors (GPS, electronic gyrocompass, UMI and accelerometers).

Communication components: industrial PC and access point.

On-land Communication Elements:

One laptop with an access point.

One radio control station which takes over the steering of the vessel in case of failure of the Wi-Fi network.

III. Identification

The variables that describe the movement of the physical model on the horizontal plane (Fig. 2) are:

ψ: Heading.

v: Sway velocity.

u: Surge velocity.

U: Ship velocity.

δ: Turbojets angle.

The platform measures and stores in a file the heading data obtained by the electronic gyrocompass which is used for the identification.

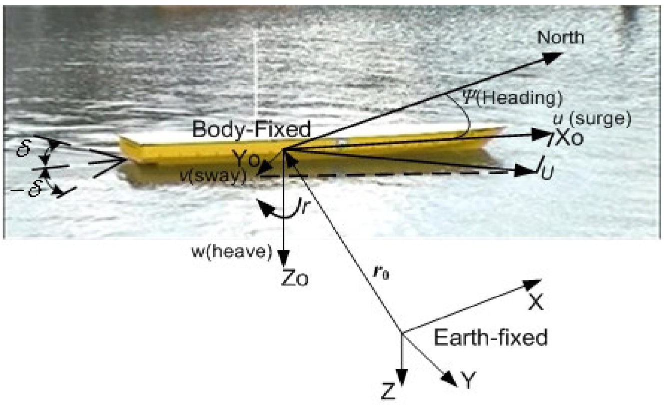

Fig. 2 Variables that describe the movement of the physical model TF-120 on the horizontal plane.

A. Maneuver for Identification

For the identification of the heading, the turning circle maneuver towards port is used (see Fig. 3). This maneuver consists of two stages. In the first, the turbojet angle is at zero and the physical model follows a constant heading. In the second, the platform rotates the turbojet to +30° in one single movement; then, the physical model begins to change its

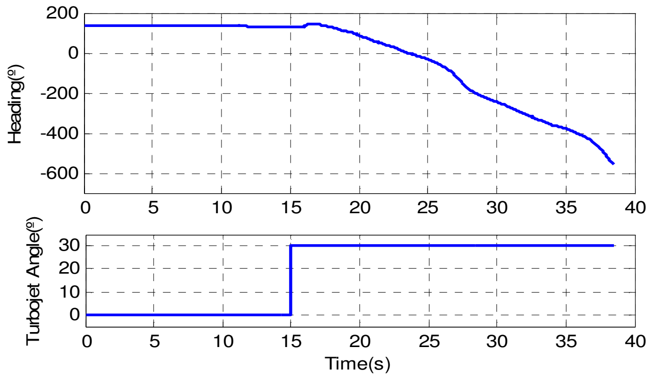

Fig. 3 Turning circle maneuver towards port.

heading towards port until it passes 540º. The platform maintains a constant speed throughout the whole maneuver (u_0 = 0,4m/s). The wind speed is less than 0.5 m/s and the current less than 2.5 m/s.

For the validation of the model, a turning circle maneuver towards starboard is performed Fig. 4.

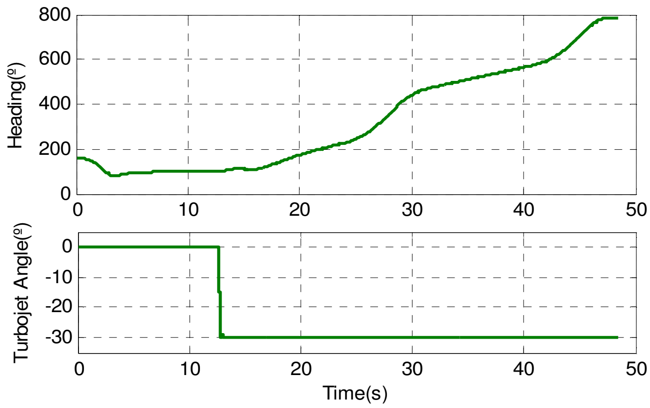

Fig.4 Turning circle maneuver towards starboard.

B. Identification of Heading Models

With the toolbox of Matlab ident [8], it is possible to identify a model with different types of structures, including continuous process models and first and second order Nomoto models [4]. Nomoto models fit the following equations:

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{1}$$

whose transfer function is:

$$\frac{\psi}{\delta}(s) = \frac{K}{s(1+Ts)} \tag{2}$$

Second order Nomoto:

$$T_1 T_2 \dddot{\psi} + (T_1 + T_2)\ddot{\psi} + \dot{\psi} = K(\delta + T_3 \dot{\delta}) \quad (3)$$

and whose transfer function is:

$$\frac{\psi}{\delta}(s) = \frac{K(1+T_3 s)}{s(1+T_1 s)(1+T_2 s)} \quad (4)$$

Table I shows all the prediction-error model structures used in the system identification process. There is also a continuous process model structure.

TABLE I
MODEL STRUCTURES

Method	Structures
Armax	$A(q)y(t) = B(q)u(t) + C(q)e(t)$
Output error	$y(t) = [B(q)/F(q)]u(t) + e(t)$
Box jenkins	$y(t) = [B(q)/F(q)]u(t) + [C(q)/D(q)]e(t)$
Continuous Model	$\Psi(s) = G(s)\delta(s)$

Table II summarizes the results given by several model structures. In all the cases, the percentage of output variations reproduced by the model is calculated. A higher number means a better model. The precise definition of the fit is:

$$\text{Fit} = [1 - \text{norm}(y - y_{\text{hat}}) / \text{norm}(y - \text{mean}(y)] * 100 \quad (5)$$

where y is the measured output and y_{hat} is the simulated/predicted model output.

The best model is the continuous model, which has a fit value of 88.59%. Other structures were tested such as arx and state space, but are not included in Table II as they have a small value of fit.

TABLE II
RESULTS FROM THE IDENTIFICATION PROCESS

Type of model	Coefficients	Fit (%)
Continuous Model	K = -0.94828, T_1 = 2.3551, T_2 = 0.5712 T_3 = -1.3234	88,59
Armax8221	$A(q)$ = 1 - 0.5803 q^-1 - 1.051 q^-2 + 0.4935 q^-3 + 0.001876 q^-4 - 0.06359 q^-5 + 0.008615 q^-6 + 0.1124 q^-7 + 0.07884 q^-8	83,27
	$B(q)$ = 0.002071 q^-1 - 0.002289 q^-2	
	$C(q)$ = 1 - 0.009262 q^-1 - 0.8128 q^-2	
Output Error 221	$B(q)$ = 0.005656 q^-1 - 0.00568 q^-2	81,93
	$F(q)$ = 1 - 1.998 q^-1 + 0.9983 q^-2	
Box Jenkins 22221	$B(q)$ = 0.005391 q^-1 - 0.005411 q^-2	61,66
	$C(q)$ = 1 + 0.7528 q^-1 - 0.09449 q^-2	
	$D(q)$ = 1 - 0.05471 q^-1 - 0.9505 q^-2	
	$F(q)$ = 1 - 1.999 q^-1 + 0.9986 q^-2	

The process of identification provides the following coefficients for second order Nomoto:

$$K = -0.94828, T_1 = 2.3551, T_2 = 0.5712, T_3 = -1.3234 \quad (6)$$

A 1st-order approximation is obtained by letting the effective time constant be equal to:

$$K = -0.94828, T = T_1 + T_2 + T_3 = 4.2497 \quad (7)$$

C. Validation of Heading Models

Fig. 5 shows how well the second order Nomoto model, equation (4), fits the heading measured in the maneuver to starboard.

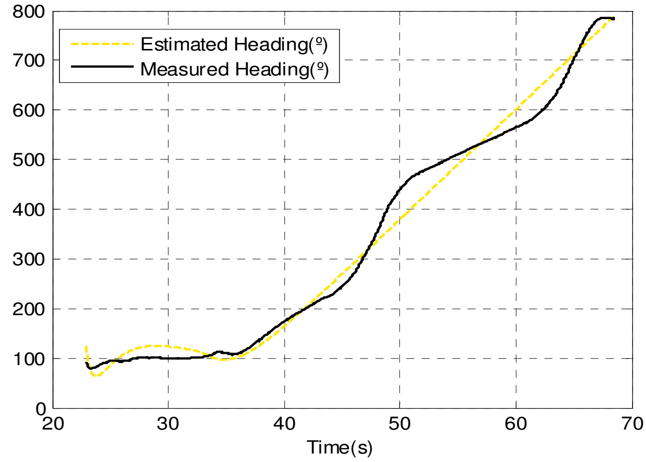

Fig.5 Simulation of identified model with measured heading.

A correlation analysis has been made on the prediction errors. If there isn't autocorrelation of residuals for the output heading, this means that the noise model structure is correct. In the same way, if Cross correlation doesn't exist between the residuals for the output (heading) and the input (turbojet angle) confirms that the input/output model is correct.

Crosscorrelation between the residuals and the input values appear adequate based on this validation (see Fig. 6).

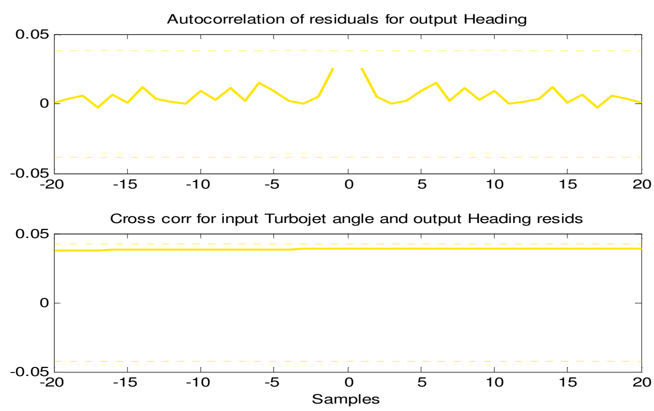

Fig. 6 Prediction-error correlation analysis.

IV. Kinematics of the In-Scale Model

In order to design a Track-keeping system, it is necessary to calculate the actual position of the model TF-120. To define the position of the vehicle, the following definitions are required:

The vehicle's flight path relative to the earth-fixed coordinate system is given by a velocity transformation according to Fig. 2:

$$\dot{\eta}_1 = J_1(\eta_2)v_1 \tag{8}$$

where,

$$\eta_1 = [x, y, z]^T, \eta_2 = [\phi, \theta, \psi]^T, v_1 = [u, v, w]^T \tag{9}$$

$$J_1(\eta_2) = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{10}$$

Assuming that in absence of the roll and pitch modes ($\theta = \phi = 0$), the following equations are obtained:

$$\dot{x} = u\cos\psi + v\sin\psi \tag{11}$$

$$\dot{y} = u\sin\psi - v\cos\psi \tag{12}$$

$$\dot{\psi} = r \tag{13}$$

V. Heading Control

A. Control Problem

An automatic pilot must fulfill two functions: course-keeping and change of course. In the first case, the objective is to maintain the trajectory of the vessel following the desired heading ($\psi(t)$ = constant). In the second case, the objective is to perform the change of heading without excessive oscillations and in the minimum time possible. In both situations, the correct functioning of the system must be independent from the disturbances produced by the wind, the waves and the currents.

The trajectory followed by a vessel can be specified by means of a second order reference model:

$$\ddot{\psi}(t) + 2\zeta\omega_n\dot{\psi}(t) + \omega_n^2\psi(t) = \omega_n^2\psi_r \tag{14}$$

where ω_n is the natural frequency and ζ ($0.8 \le \zeta \le 1$), the desired dampening coefficient system in a closed loop.

B. PID Controller Loop

With the first order Nomoto parameters obtained in (7), a PID controller has been tuned to maintain the constant heading ψ_d.

For the correct functioning of the system, a dampening coefficient in the range $0.8 \le \zeta \le 1$ is selected. ω_n is selected as the rotation angle of the turbojets ω_δ (rad./s) and the dynamics of the physical model as $1/T$ (rad./s) according to the equation:

$$\frac{1}{T} < \omega_n\sqrt{1 - 2\zeta^2 + \sqrt{4\zeta^4 - 4\zeta^2 + 2}} < \omega_\delta \tag{15}$$

Next, a dampening value of $\zeta = 0.9$ is selected and the following range of values fitted to ω_n is obtained:

$$0.1128\frac{rad.}{s} < \omega_n < 4.55\frac{rad.}{s} \tag{16}$$

In keeping with equation (16), a value of $\omega_n = 0.6$ rad./s. can be selected.

The schema of a conventional PID does not work very well when the derivate mode amplifies the noise. To avoid this problem, the following PID control schema is used [10]:

$$\frac{\delta}{E}(s) = K_c\left[1 + \frac{1}{T_i s} + \frac{T_d s}{\alpha T_d s + 1}\right] \tag{17}$$

Equation (17) shows that the derivate action is multiplied by the term $1/(\alpha T_d s + 1)$, which corresponds to a first order system where αT_d is the time constant. The manufacturers give as typical values of α the range of 0.05 to 0.2, so $\alpha = 0.1$ is selected.

Developing a procedure proposed in [4], the parameters for the PID controller are obtained:

$$K_p = 1.6133,\ T_i = 16.666,\ T_d = 1.3463 \tag{18}$$

Since the results from the tuning, given in the following sections, indicate that the integral action time is too high, a first order network (19) has also been used in which the integral action does not appear.

$$\frac{\delta}{E}(s) = K\left[\frac{s+z}{s+p}\right] \tag{19}$$

C. Tuning with Genetic Algorithms

A PID controller has been tuned by means of genetic algorithms (Gas) [7]. The aim of the design is that the ship should make a fast course change following, without oscillations, the course determined by the values $\zeta = 0.9$ and $\omega_n = 0.6$ rad/sec in equation (14). The cost function selected was:

$$J(\theta) = \sum_{i=1}^{n}\left|\Delta\psi_i + \lambda\delta_i\right| \tag{20}$$

Where θ is the vector of the controller parameters, n is the total number of iterations in the control system simulations, $\Delta\psi_i$ the *ith* heading angle error between the desired and obtained heading, λ is a scaling factor ($\lambda = 0.2$ in this case) and δ_i. the *ith* rudder angle deflection. The term δ_i has been included in order to take into account also the minimization of the control effort. A simulation time of 60 sec. has been used.

Each individual is represented by a parameter vector $\theta = [K_p\ T_i\ T_d]$ of the PID controller and $\theta = [k\ z\ p]$ for the first order network. The chromosomes are of the binary type. The selection of the range of values of the parameters was performed with a view to avoiding an excessive saturation of the actuators and to ensuring stable controllers.

The ranges of values of the parameters S selected were:

$$S = \{0.1 \le K_p \le 10,\ 1 \le T_i \le 5000,\ 0.1 \le T_d \le 10\} \tag{21}$$

for the PID controller and

$$S = \{0.1 \le k \le 100,\ 0.01 \le z \le 10,\ 0.1 \le p \le 20\} \tag{22}$$

for the first order network.

For the optimization, a population of 30 individuals over 500 generations is used with a probability of crossover of 50% and mutation of 5%. The Ga evaluates the cost function in each iteration, after running the Simulink model, with the controller. A roulette wheel was used in the selection, and the principle of elitism was also used, keeping for the next generation the best two individuals of the previous population, and selecting them for the crossover and mutation.

The resulting parameters of the PID controller (17) are:

$$K_p = 1{,}21172,\ T_i = 4951.352255,\ T_d = 2.300027 \tag{23}$$

And the resulting parameters the first order network in (19) are:

$$k = 32.603814,\ z = 0.42214,\ p = 8.696483 \tag{24}$$

VI. 2-Dimensional LOS Guidance System

Systems for guidance are systems consisting of a waypoint generator with human interface. One solution to design this system is to store the selected way points in a way-point database and use them to generate a trajectory (path) for the ship Fig. 7. Other systems can be linked to this waypoint guidance system as the case of weather routing, collision and obstacle avoidance, mission planning, etc.

LOS schemes have been applied to surface ships by [9] and [5]. In this methodology it is computed a LOS vector as the vector from the body-fixed origin (x, y) to the next way-point (x_k, y_k). This suggests that the set-point for the heading autopilot should be chosen as:

$$\psi_d(t) = \tan^{-1}\left(\frac{y_k - y(t)}{x_k - x(t)}\right) \tag{25}$$

Where (x, y) is the vessel position usually measured with a GPS. In this article, the position of the TF-120 model is calculated with the kinematical equations (11) and (12) for constant speed, so $u = u_0 = 0.4$m/s. Equation (25) requires a sign test to ensure that $\psi_d(t)$ is in the proper quadrant. The autopilot follows the heading by guiding the TF-120 model from way-point to way-point.

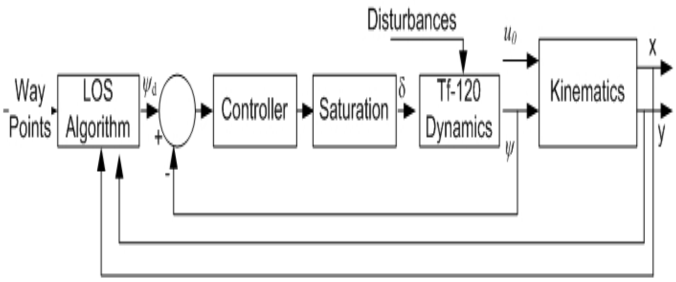

Fig. 7 Conventional LOS Guidance system.

When moving along the path a switching mechanism for selecting the next way point is needed. The way-point (x_{k+1}, y_{k+1}) can be selected on a basis of whether the ship lies within a circle of acceptance with radius R_0 around the way point (x_k, y_k). Moreover if the vehicle positions $(x(t), y(t))$ at time t satisfy:

$$[x_k - x(t)]^2 + [y_k - y(t)]^2 \le R_0^2 \tag{26}$$

A guideline could be to choose R_0 equal to two ship lengths (L_{pp}), in the case of the in-scale physical model TF-120 model $L_{pp} = 4.4$m.

VII. Computer Simulations

In the section below three types of simulations, made in Simulink [3], are presented: maneuvering simulations, close loop simulations and track-keeping simulations. The first ones show the good performance of the model identified and the kinematics (see section IV) for two typical maneuvers performed on full-scale vessels. Close loop simulations point out that the PID controller tuned in previous sections is correct. The good result of these two kinds of simulations is very important in order to obtain a good guidance system as reflected by the last simulations.

A. Standard Maneuvers

The two figures below show simulations of turning circles towards starboard for a rudder deflection of -30º. The evolution of the heading for a first order Nomoto model (2) with the parameters in (7) is presented in Fig. 8. The trajectory of the ship in Fig. 9 for a non-linear kinematical model

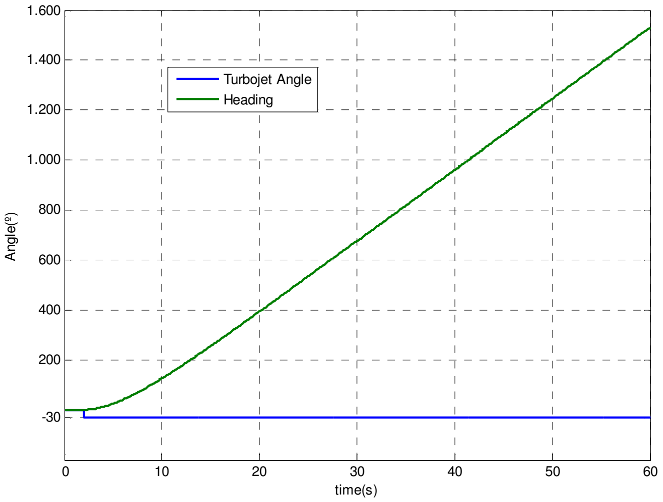

Fig. 8 Simulation of the Heading, with the Nomoto model (2) and the parameters in (7) for a turning circle maneuver.

calculated in (11) and (12), with the only assumption that $v \approx 0$, describes a circumference which is typical of the turning circle maneuver. This simulation verifies the suitability of the model identified and the kinematical equations.

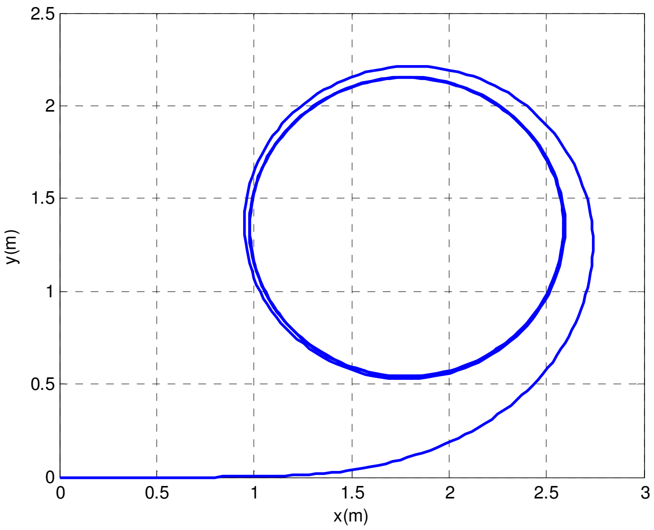

Fig. 9 Trajectory of the ship with the model formed by the equations (2) and non-linear equations (11) and (12) for a turning circle manoeuver.

The zig-zag maneuver is performed in Fig. 10 as follows: assuming that the simulation starts from an initial heading of 0º, the simulation makes a change in the turbojet angle of 0º to 10º. Thus, until the heading exceeds -10º, the simulation does not surpass from 10º to -10º of angle of the turbojet. In the same way, until the platform exceeds 10º of heading, the simulation does not change from -10º to 10º of angle of the turbojet. A minimum of five cycles are required to perform the full maneuver. Fig. 11 shows the trajectory of the ship for the zig-zag maneuver

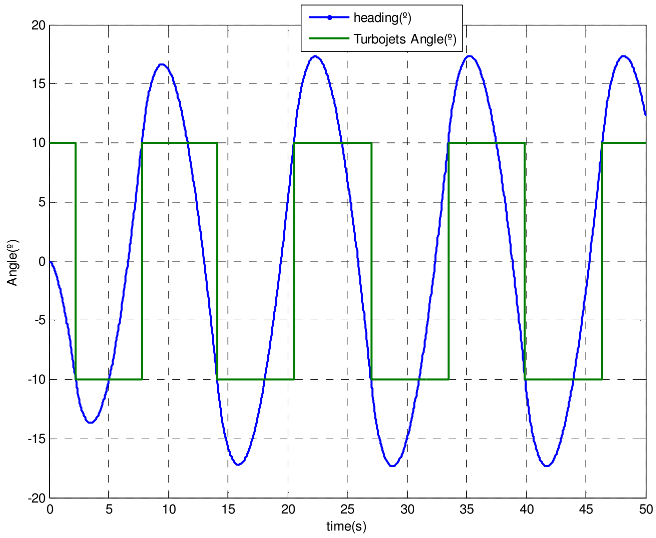

Fig. 10 Simulation of the heading for a 10º Zig-Zag maneuver.

This maneuver establishes several important characteristics of the yaw response. These are: the response time (time to reach a given heading), the yaw overshoot (amount the vessel exceeds ±10º when the rudder has turned the other way), and the total period for the 10º oscillations.

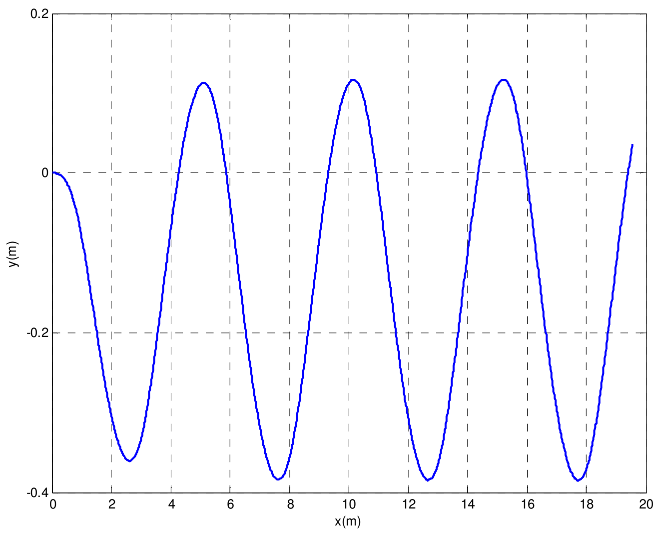

Fig. 11 Simulation of the position for a 10º zig-zag maneuver.

B. Close Loop Simulation

According to the heading control loop in Fig. 12, different simulations are performed for the controllers tuned in previous sections. In this block diagram characteristics of the servo as an actuator are included, which are very important since they can impose constrains on the control action (see Fig. 14). The transfer function δ/δ_d is the simplified model presented by [1]

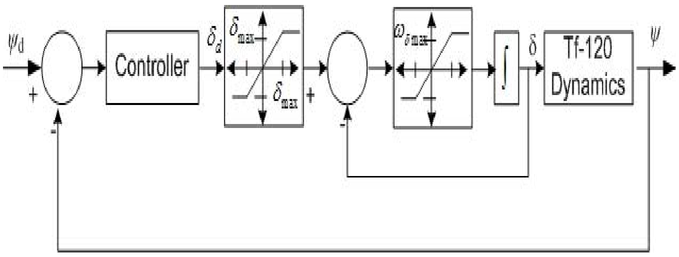

Fig. 12 Heading autopilot block diagram including actuator saturations.

and is the most commonly used in marine vehicles. This model present two kinds of saturations:

Magnitude saturation: the turbojet motion is constrained to move within a certain maximum angles. $-\delta_{max} < \delta < \delta_{max}$, $\delta_{max} = 30º$.

Slew rate saturation: the rate of turbojets is limited by a maximum valued $\omega_{\delta max}$ as it was defined in equation (16).

A comparative study is made in Fig. 13 with different types of controllers and tuning methods. PID Controllers are represented with the parameters obtained in (18) and (23), and also a first order network controller with the parameters in (24). The graphical results given by the network controller tuned with genetic algorithms are significantly much better than with a PID controller tuned with classical methods (see section V B).

The PID controller tuned with genetic algorithms gives a

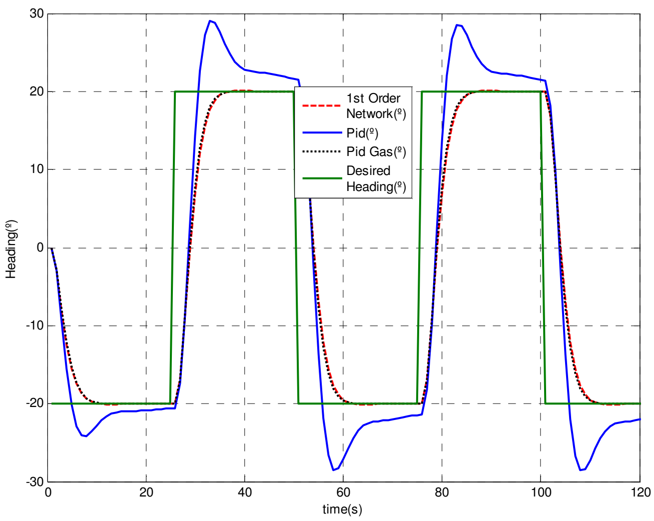

Fig. 13 Heading autopilot for different control structures and tuning methods.

response very close to the response given by the network controller. This is because the integral action time is too high in (23).

The control effort and the desired heading are plotted in Fig. 14 for different control structures and tuning methods. The control effort signal presents saturation at -30º or 30 due to the limitations of the turbojet angle.

In Fig. 15 the trajectory of the ship is plotted for a first order network controller which gives the best results.

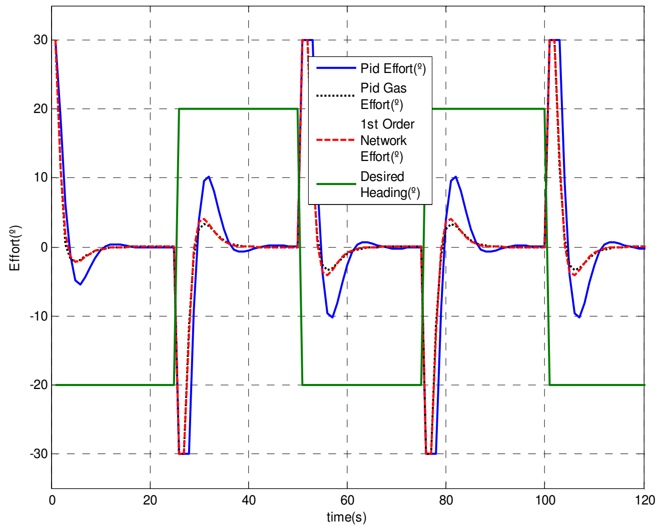

Fig. 14 Control efforts for different control structures and tuning methods.

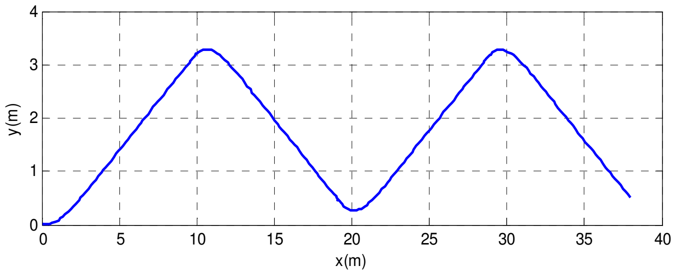

Fig. 15 Trajectory of the ship for a first order network controller tuned with genetic algorithms

C. *Track-keeping Simulation*

In this section is presented a conventional LOS guidance system simulation. It has been used a first order network as a heading controller with the parameters calculated in previous sections. Fig. 17 shows the good performance of the LOS algorithm and the heading controller (see Fig. 16) for a model identified with the platform of marine vehicles and the kinematical equations calculated in section IV.

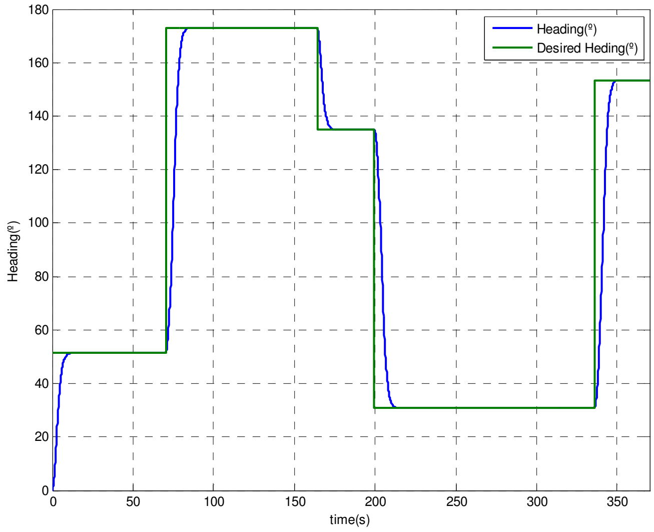

Fig. 16 Heading control of the track-keeping system using equation (26) as a switching mechanism.

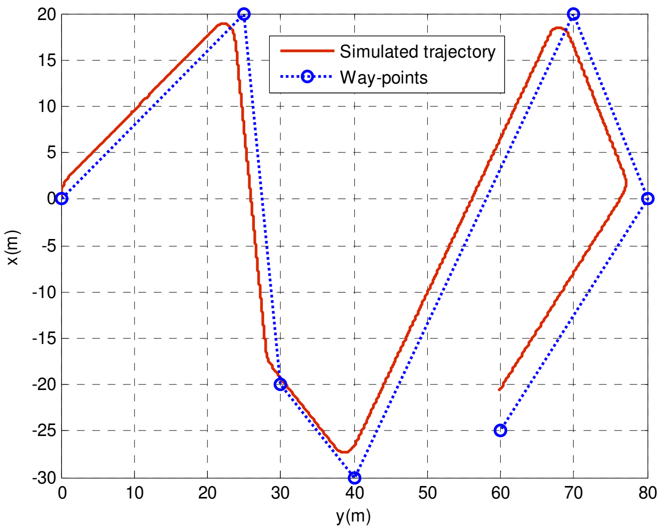

Fig. 17 *xy* plot of the simulated trajectory of the TF-120 model and desired geometrical path made up of way-points.

VIII. Conclusions

Identification has been made of the heading model of the in-scale TF-120 turboferry. With the tests carried out on the coastline of the Bay of Santander, several prediction-error model structures and continuous structures have been identified with different orders. The best model has been validated with a simulation on a data set different from the one used for parameter estimation and with a correlation analysis on the prediction errors. Simulations of standard maneuvers show the response of the identified model and the kinematics.

The results from the tuning of the controllers by means of Gas indicate that the integral action is too high, meaning that it is advisable to use a first order network for the heading controller.

The simulation has been carried out to verify the suitability of the LOS algorithm, the heading controller and also the identified model. An evaluation of a track-keeping controller will be made on the coastline of the bay of Santander in further research. Moreover, the possibilities of the platform for experimentation of marine vehicles with research and educational purposes are presented.

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