Journal of Maritime Research, Vol. I. No. 3, pp. 37-50, 2004

ISSN: 1697-4840

FULL-SCALE MANOEUVERING TRIALS SIMULATION

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ABSTRACT

This paper describes the simulation of the behaviour of a ship in some of the most widely used sea trials: turning circle, pull-out, zig-zag, and direct and inverse spiral test. For the simulation, a full non-linear mathematical model with three degrees of freedom is used. The hydrodynamics coefficients used in the mathematical model were obtained from a physical scale model with a planar motion mechanism in a towing tank. The results obtained are satisfactory, supporting the proposal that these sea trial simulation tools should be used as an important part of the design stage in the building of a ship.

Key Words: Mathematical model. Ship movement. Manoeuvring. Simulation.

INTRODUCTION

Sea vessels must be able to maintain their course in the open sea, to manoeuvre safely in ports and restricted channels and to stop within a reasonable distance. These minimum capacities are required under any load condition, both at high speeds and at more moderate speeds associated with restricted waters and in both calm conditions and in windy or rough conditions.

This paper describes the sea trials widely used to determine a ship's manoeuvring characteristics. With these tests, it is possible to measure the ship's dynamic behaviour characteristics, to obtain an indication of its straight-line stability, to evaluate the robustness and the limitations of the control system and to assess the ship's behaviour in emergency situations.

Although these tests were carried out on a ship actually built and at sea, the ship's behaviour can be simulated in the design stage by means of simulation programmes using mathematical models. This paper presents the results of the sea trials of a ship. The simulation is performed with Matlab's Simulink simulation programme.

FULL-SCALE MANEUVERING TRIALS

Many of the sea maneuvering trials performed on most merchant ships before they are formally delivered to the ship owner are based on the verification of the maximum speed of the ship,

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on the functioning of the steering and radio communications systems, on the main engine and the ship steering equipment. In order to verify the ship's maneuvering characteristics, other standard ship manoeuvres can be performed allowing the ship's dynamic behaviour characteristics to be measured and the robustness and the limitations of the ship control system to be evaluated. The manoeuvring characteristics can be obtained by holding or changing a predetermined course and speed in a systematic way.

In accordance with the recommendations of the 14th "International Towing Tank Conference" (14th ITTC, 1975), Tests have to provide owners and builders with information on the operating characteristics of the ship. These must address the course-keeping, course changing and emergency manoeuvre characteristics. In order to determine the efficiency of the vessel in course-keeping, the tests methods proposed are: the direct or reverse spiral test and the zigzag manoeuvre test with small rudder angle. To determine the quality in the course changing behaviour, the zigzag manoeuvre test and the 15 degrees helm turning test and change of heading test are recommended. To determine the ship's capacity in the face of emergency manoeuvres, the most appropriate test methods proposed are the maximum helm turning test and the crash-stop astern test.

Vessels must have manoeuvring capacities which allow them to hold course, turn, test the turns, operate at an acceptably low speed and stop in a satisfactory way. Sea maneuvering trials are intended to provide a measurement of the following characteristics (Lewis, 1989):

- *Turning circle characteristics*: These can be determined by means of turning circle tests using a rudder angle of 35º.
- *Yaw checking ability*: This can be measured by obtaining the first overshoot angle and time to check the yaw in a zig-zag manoeuvre.
- *Initial turning ability*: This can be determined at the initial stage of the zig-zag manoeuvre with the ship's change of heading angle per unit of rudder angle, and the forward distances covered after executing a rudder command.
- *Coursekeeping ability*: No single measurement of coursekeeping ability has yet been developed. However, in the case of vessels whose type, size and speeds are comparable, this capacity can be evaluated through a comparison of the zig-zag direct or reverse spiral and pull-out tests.
- *Slow steaming ability*: The capacity to proceed at a steady slow speed is a desirable characteristic. It is generally determined using only the ship's speed associated with the lowest possible engine RPM.
- *Stopping ability*: This can be calculated using the distance that the ship travels along its track, once the crash-astern command has been given.

A description is given below of some of the standard ship maneuvers: turning circle, pull-out, zig-zag and direct and reverse spiral tests.

TURNING CIRCLE

This is the manoeuvre which has received the most attention from professionals in the field. It is used to determine the ship's steady turning radius and to verify the behaviour of the steering machine and rudder control during course-changing manoeuvres. Figure 1 shows a turning circle, indicating its characteristic stages and parameters. It should be performed to both port and starboard at maximum speed, with a maximum rudder angle and with a rudder angle of 15 degrees. It is necessary to do a turning circle of 540º at least to determine the main parameters of this trial.

This manoeuvre is also used to determine other characteristic parameters such as: the tactical diameter, advance, transfer, loss of speed on steady turn, and times to change heading 90º and 180º respectively, as can be seen in Figure 1. The maximum advance and maximum transfer can also be measured.

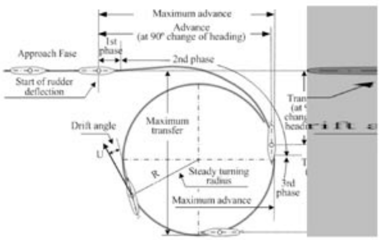

Figure 1: Terms used in turning circle.

As can be observed in Figures 1 and 2, the turning circle test is devised in the following phases:

- *Approach phase*: The ship sails in advance, in a straight line at a constant speed U and with the rudder in neutral position ($\delta = 0$). The linear and angular velocities and accelerations are: $v = \dot{v} = r = \dot{r} = 0$
- *Manoeuvre phase*: This begins when the constant rudder angle δ is applied at any of the sides. It is divided into three phases:

<u>First phase:</u> Starts at the instant the rudder begins to deflect from the neutral position and finishes when it reaches the desired δ value. During this stage, the speeds are practically null ($v \approx r \approx 0$). However, the accelerations have a value of $\dot{v} = 0$ and $\dot{r} = 0$ from the first moment.

<u>Second phase:</u> Here, the accelerations coexist with the speeds, that is, $v \neq \dot{v} \neq r \neq \dot{r} \neq 0$. In the last part of this stage, equilibrium is obtained between the forces intervening in the ship's turning circle and the accelerations tend to reduce to zero.

<u>Third phase:</u> When this equilibrium is reached, the ship begins to perform a turn of constant radius R, as shown in Figure 1. In this phase, $v \neq r \neq \dot{v} = \dot{r} = 0$ and the ship's speed is reduced by 60% from the speed it had when the turning circle was initiated (Bonilla, 1979).

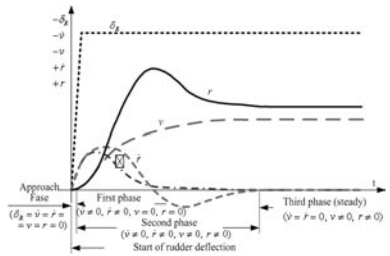

Figure 2: Characteristics of phases of a turning circle.

PULL-OUT MANOEUVRE

The pull-out manouevre is a simple test used to obtain a rapid indication of the stability of a straight-line course held by a ship.

A rudder angle of approximately 20º is applied and time is allowed to pass until the ship reaches a constant change of heading rate $r = \dot{\psi}$; at that instant, the rudder is returned to midships (neutral position). If the ship is stable, the speed will drop to zero both for port and starboard rudder changes. If the ship is unstable, the change of heading rate will drop to some residual speed rate.

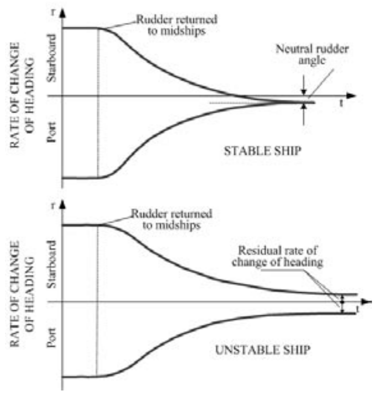

Figure 3: Presentation of results of the Pull-out manouevre.

This manoeuvre must be performed in both directions, port and starboard, to show any possible asymmetry. Figure 3 shows the results of a pull-out manoeuvre for a stable ship sailing in a straight line and for another unstable one.

KEMPF'S ZIG-ZAG MANOEUVRE

The zig-zag manoeuvre is obtained by inverting the rudder alternatively by δº to both sides, with a shift ofψ from the initial course. The typical procedure is as follows (Lewis, 1989):

Make the ship sail in advance and in a straight line at a predetermined speed for a certain time.
Place the rudder to the starboard side at the maximum speed for a predetermined quantity of δ, for example 10º, and maintain this value until the preselected (10º) course changing ψ occurs (10º) (first operation).
Place the rudder at the maximum speed on the opposite side (port) at the same angle (10º) (second operation). Maintain the rudder position and the ship continues to rotate in the original direction, at a rotation speed which drops gradually until the movement stops. Then, in response to the rudder, the ship turns to port. The rudder position is held until the preestablished course changing ψº is obtained on the opposite side (port). This completes the overshoot test.
To complete the zig-zag test, the rudder is again set at the maximum speed at the same angle (10º) on the initial side (starboard) (third execution). Continue until a total of 5 executions of the rudder are completed.
The normal course changing value ψ is 10º. A modified trial can also be taken into account with a course changing of 20º. The 14th ITTC conference recommends executing the manoeuvres at maximum approach speed and, if possible, also at medium speed.

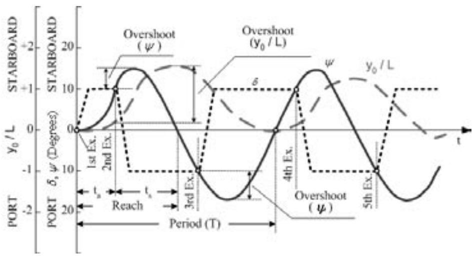

Figure 4: Zig-zag manoeuvre graph: rudder angle δ , ψ ship's course, yo/L normal distance to the initial trajectory divided by the ship's length.

The results of this manoeuvre are indicators of the capacity of the rudder to control the ship's heading. They can also be used to compare different ship manoeuvring capacities. It should be noted that, from the point of view of the interpretation of the international rules of sea sailing, the use of rudder angles δ to starboard to verify the turning capacity and heading control of a ship are recommended, since, in case of emergency, changes in heading must be made to starboard. For this reason, the normal zig-zag manoeuvre begins with the application of the rudder angle to starboard.

For a simple, initial analysis of the results, the characteristic heading values defined in Figure 3 can be used. The values are given as a function of rudder angle δ.

The main measurements obtained are:
- The time t_a it takes to reach the second execution of the heading, which indicates the capacity of the ship to change heading course or the efficiency of the rudder.
- The angle of overshoot in the heading.
- The overshoot of the trajectory obtained when performing the trial.

These latter two measurements are indicative of the amount of anticipation required by the helmsman to sail in restricted waters. In (Arentzen y Mandel, 1960), it is shown that the magnitude of the overshoot in the heading drops when the stability increases but increases when rudder efficiency increases. Also, the overshoot in the trajectory drops when either the dynamic stability or rudder efficiency.

The results of the zig-zag test depend on the ship's speed, since the time it takes to reach a given heading falls when this increases.

Direct and reverse spiral tests

These manoeuvres provide a qualitative measure of the directional stability of the ship in a straight line. For ships which show stable characteristics, the Dieudonné direct or Bech inverse spiral tests can be used to obtain the response to small rudder angles. For unstable ships, the 14th ITTC recommends the Bech inverse spiral test within the limits indicated by the results of the pull-out manoeuvres.

Dieudonné Direct Spiral Manoeuvre

The direct spiral manoeuvre is used to determine the directional stability characteristics of the vessel, and also provides information on the degree of stability and range of validity of the linear theory.

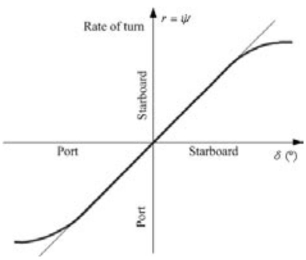

Figure 5: Graph of direct spiral manouevre of a stable, symmetrical vessel.

The procedure for performing the is as follows:

- Make the ship sail in advance with an initial straight course at constant speed.
- Set the rudder at an angle δ, of 25° to starboard and keep it there until the rate of change of heading is constant $r = \dot{\psi}$.
- Once a constant value is reached, the rudder angle δ is reduced by 5° and again held until steady conditions of turning have been obtained.
- This procedure is repeated until the rudder has run through all of the rudder angles from 25° to starboard to 25° to port and again to starboard.
- In the range of rudder angles from 5° on either side of zero or neutral rudder angle, the intervals must be reduced.

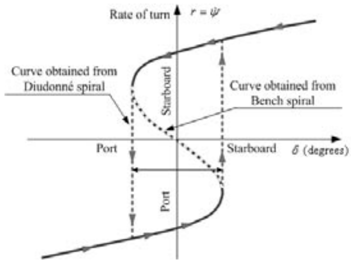

Figure 6: Graphs of the Diudonne and Bench spiral manouevres for an instable ship with a hysteresis cycle.

With this procedure, the ship performs a spiral movement. The graph shows the ship's yaw rate $r = \dot{\psi}$ as a function of each angle δ of the rudder, such as those shown in Figures 5 and 6. This manoeuvre should be carried out in still air and calm water conditions.

In carrying out the manoeuvre, it is essential to leave sufficient time to reach the stationary state at each angle the rudder is seta t. In (Lewis, 1989) the results of three tests performed with different time intervals between consecutive angles of rudder setting are presented (Strom-Tejsen, 1965). It is shown that to perform an exact study of the stability of a ship, it is essential not to limit the experimental time between the rudder angles.

An indication of the stability of the ship can be obtained from this graph. For example, if it is a single line that goes from starboard to port and is inverse, as shown in Figure 5, then the ship is stable (has stability in a straight course). However, if the graph presents two branches formed by a hysteresis cycle, the ship is unstable. The height and width of the cycle measure the degree of instability, so that the wider the hysteresis cycle, the more unstable the vessel.

Reverse spiral manoeuvre

Bech's reverse spiral manoeuvre is an alternative to the direct spiral manoeuvre (Bech, 1968). In this manoeuvre, the ship's course is set at a constant change of heading speed and the rudder angle δ required to produce this speed of change of heading $r = \dot{\psi}$ is also set. In this trial, the values of the points of the change of heading speed curve with respect to the rudder angle can be taken in any order.

The equipment required is a rate-gyro (alternatively, the heading ψ given by the gyrocompass can be differentiated to provide $r = \dot{\psi}$), and an exact indicator of the rudder angle δ. The accuracy of the trial can be improved if the information on the change of heading speed and the rudder angle are available continuously. If manual control is used, the helmsman can visualise the instantaneous change of heading speed in a register or indicator. The procedure originally proposed by Bech for obtaining a point in the curve is recommended and is outlined below.

The ship is made to approach the desired change of heading speed or "rate of turn", $r_0 = \dot{\psi}_0$, applying a moderate rudder angle. Once the desired change of heading rate is obtained, the rudder is activated to maintain this desired rate of change of heading as accurately as possible. The helmsman must attempt to maintain the desired change of heading rate using shorter and shorter rudder movements until constant values of the ship's speed and rate of change of heading are obtained. Normally, a stable change of heading rate is obtained quite fast, so that it is easier to perform the test using a rate-gyro than with a normal gyrocompass.

MANOEUVRE MODEL USED

For the simulation of the sea trials, the model of a "Mariner" class ship, widely used in the literature, has been selected. Data from the ship 'USS Compass Island' (Chiselett y Strom-Tejsen, 1965) have been used. The main characteristics of the ship are shown in Table 1.

Description	Symbol	Value	Units
Length overall	L	171,80	m
Length between perpendiculars	L_{pp}	160,93	m
Maximun beam	B	23,17	m
Design draft	D	8,23	m
Design displacement	∇	18541	m3
Design speed	U_0	20	knots
Max. design rudder angle	δ	40	deg
Max. design rudder rate	$\dot{\delta}_{max}$	2,5 – 3,7	deg/sec

Table 1: Main dimensions of the "Mariner" class ship

The mathematical model used for the simulation with three degrees of freedom is:

$$\begin{bmatrix} m' - X'_{\dot{x}} & 0 & 0 \\ 0 & m' - Y'_{\dot{v}} & m'x'_G - Y'_{\dot{r}} \\ 0 & m'x'_G - N'_{\dot{v}} & I'_z - N'_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{u}' \\ \dot{v}' \\ \dot{r}' \end{bmatrix} = \begin{bmatrix} X' \\ Y' \\ N' \end{bmatrix} \quad (1)$$

The non-linear forces X and Y and the hydrodynamic moment N are developed using the Abkowitz (1964) model.

To develop the simulation model, the cinematic equations must be added, giving:

$$\mathbf{M}\,\dot{\mathbf{v}}' = \boldsymbol{\tau}' \quad (2)$$

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v}' \quad (3)$$

To include the model of the rudder action, the simplified model suggested by Van Amerongen (1982) has been used, as indicated in Figure 7 where δ_c is the rudder angle demanded by the controller and δ is the real rudder angle. The typical saturation values of the rudder angle and turning speed are in the following value ranges: $\delta_{max} = 35^o$ y $2.5^o/seg \leq \dot{\delta}_{max} < 7^o/seg$.

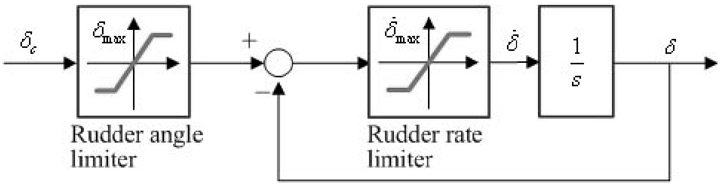

Figure: 7: Simplified Diagram of the rudder control loop.

In the development of this model, in accordance with the characteristics of the Mariner-type vessel, the rudder angle and rudder rate limits have been set at 30º and 4,6 /s respectively.

Description of the Simulink Model

The mathematical model has been developed in the Matlab-Simulink environment. Figure 8 shows the block diagram used. The main block receives as input the desired rudder angle δ_c and generates as output the ship's heading angle ψ. The model of the ship has been separated into two blocks. The first contains the rudder behaviour model and the second the ship dynamics model.

The ship dynamics model has been developed using an s function of Matlab which receives as input the rudder value δ and generates as output: the longitudinal advance speed u, the transversal speed v, the turning speed r, the heading ψ, the ship's position x, y, the rudder angle δ and the ship's speed U.

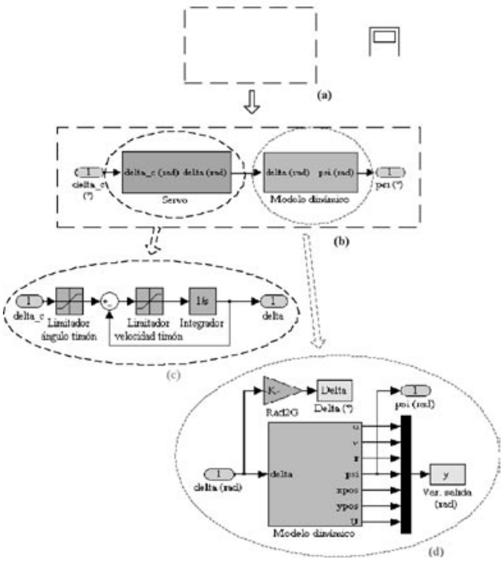

Figure 8: Simulink block diagrams used in simulation: (a) Main block of ship (b) Separation into two servo blocks and dynamic model. (c) Diagram of model used in rudder servo. (d) Block diagrams of dynamics model indicating output variables.

Sea trials simulation

Firstly, Figure 9 shows a graph of the rudder dynamics. It can be observed that a time of approximately 10 s is required to go from the neutral position of 0º to the maximum angle allowed (± 30º) and 19 s to make the maximum change from -30º to 30º which is a normal result in this type of vessels.

The turning circle, zig-zag and spiral tests have also been simulated. The results of the simulations can be used to obtain an initial estimate of the dynamics behaviour and the stability and manoeuvrability characteristics of the ship.

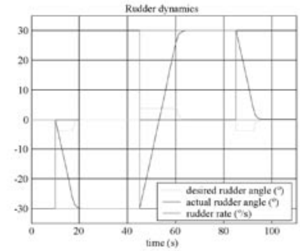

Figure.9: Rudder dynamics behaviour.

Figure 10 shows the turning circle for the rudder angles 5º, 10º, 15º, 20º and 25º. It can be observed that the gyro radius drops as the rudder angle δ increases.

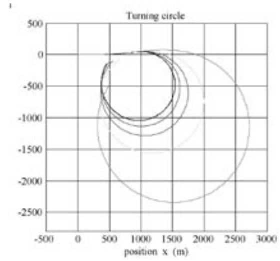

Figure 10: Turning circle for various rudder angles δ.

Figure. 11 shows the results of a zig-zag manoeuvre 20º/20º. The results of this trial are indicative of the manoeuvring capacity of the ship for a specified rudder angle.

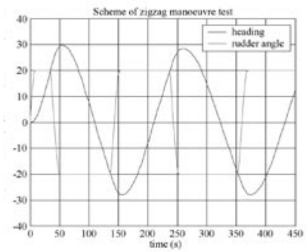

Figure 11: Zig-zag test 20º-20º.

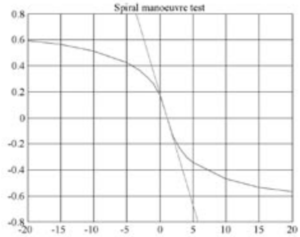

Figure 12: Graph with results of spiral test 20º/20º.

The simulation of t' l manoeuvre is shown in Figure 12, representing the reduction speed of the ship as a function of each angle δ set at the rudder. The graph obtained indicates that the ship has a stable behaviour on a straight course. The slope of the line tangent to the curve allows us to determine the gain in the linear approach over the Nomoto model. A stable behaviour of the ship is also observed in the results of the pull-out manoeuvre as can be seen in Figure 13.

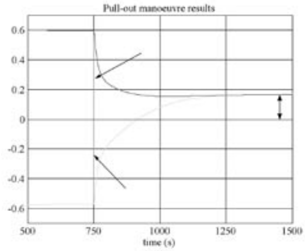

Figure 13: Pull-out manoeuvre

CONCLUSIONS

Although sea trials are carried out with the ship already built and at sea, it is useful to simulate the dynamic behaviour of the ship in the design stage using mathematical models.

Some of the most widely used sea trials have been simulated using a full, non-linear mathematical model with three degrees of freedom. The simulation results allow the ship's dynamic behaviour characteristics to be measured, an indication of its stability on a straight course to be obtained, its robustness and the limitations of the control system to be evaluated and its behaviour in emergency situations to be assessed.

The results obtained in the sea trial simulations indicate that sea trial simulation tools form an important part of the design stage in the building of a ship.

ACKNOWLEDGEMENTS

This work has been partially financed by the MCYT through project DPI2003-09745-C04-03.

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SIMULACIÓN DE PRUEBAS DE MAR

RESUMEN

En éste artículo, se simula el comportamiento de un buque en algunas de las pruebas de mar habituales, curva de evolución, pull-out, zig-zag, y prueba de espiral directa e inversa. Para la simulación se utiliza un modelo matemático no lineal completo con tres grados de libertad. Los coeficientes hidrodinámicos utilizados en el modelo matemático se habían obtenido a partir de un modelo físico a escala en el canal hidrodinámico. Los resultados obtenidos son satisfactorios, permitiendo proponer las herramientas de simulación de pruebas de mar como una parte importante del proceso de diseño previo a la construcción de un buque.

INTRODUCCIÓN

En este artículo se describen las pruebas de mar que se utilizan habitualmente para determinar las características de maniobra del buque. Estas pruebas permiten medir las características del comportamiento dinámico del buque, obtener una indicación de su estabilidad en línea recta, valorar la robustez y las limitaciones del sistema de control, y evaluar el comportamiento del buque en situaciones de emergencia.

Aunque las pruebas se desarrollan con el buque ya construido y en la mar, en el proceso de diseño se puede simular el comportamiento del buque mediante programas de simulación utilizando modelos matemáticos. En este artículo se presentan los resultados de la simulación de las pruebas de mar de un buque.

De acuerdo con las recomendaciones de la 14th ITTC (1975), las pruebas tienen que proporcionar a los armadores y a los astilleros información sobre las características de funcionamiento del buque. Estas deben abarcar las características de mantenimiento y cambio de rumbo y las maniobras de emergencia. Para determinar la eficacia del comportamiento del buque para el mantenimiento de rumbo las pruebas apropiadas propuestas son: prueba en espiral directa e inversa y maniobra de zig-zag con ángulos del timón pequeños. Para determinar la calidad del comportamiento en la maniobra de cambio de rumbo se recomiendan la maniobra de zig-zag, la prueba de evolución de 15º de timón y la maniobra de cambio del rumbo. Para determinar la capacidad del buque ante situaciones de emergencia, las pruebas de mar más convenientes propuestas son: prueba de evolución con el máximo timón y maniobra de parada de emergencia o "crash-stop".

La duración total de las pruebas de mar debe ser aceptable para los armadores y los astilleros.

METODOLOGÍA

Se simulan las pruebas de mar de un buque de la clase "Mariner", ampliamente utilizado en la literatura (Chiselett y Strom-Tejsen, 1965) utilizando el modelo matemático no lineal con 3 GDL:

$$\begin{bmatrix} m' - X'_{\dot{u}} & 0 & 0 \\ 0 & m' - Y'_{\dot{v}} & m'x'_G - Y'_{\dot{r}} \\ 0 & m'x'_G - N'_{\dot{v}} & I'_z - N'_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{u}' \\ \dot{v}' \\ \dot{r}' \end{bmatrix} = \begin{bmatrix} X' \\ Y' \\ N' \end{bmatrix} \quad \textbf{(1)}$$

Las fuerzas X e Y y el momento hidrodinámico N se desarrollan utilizando el modelo de Abkowitz. (1964).

En el modelo de simulación, se incluyen las ecuaciones cinemáticas, resultando:

$$\mathbf{M}\,\dot{\mathbf{v}}' = \boldsymbol{\tau}' \quad \textbf{(2)}$$

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v}' \quad \textbf{(3)}$$

Como modelo del comportamiento del timón se utiliza el modelo simplificado sugerido por Van Amerongen (1982).

En primer lugar, se simula el comportamiento dinámico del timón. Se puede apreciar que necesita aproximadamente un tiempo de 10 s para pasar de la posición neutral de 0º al valor máximo (± 30º) y de 19 s para realizar el cambio máximo de -30º a 30º que es un resultado normal en este tipo de buques.

Se obtienen las curvas de evolución para distintos ángulos del timón, y se puede observar que el radio de giro disminuye a medida que aumenta el ángulo δ del timón.

Los resultados de la prueba de Zig-Zag 20º/20º son indicativos de la capacidad de maniobra del buque para el ángulo de timón especificado.

La prueba en espiral obtenida indica que el buque tiene un comportamiento estable en línea recta. La pendiente de la recta tangente a la curva nos permite determinar la ganancia de la aproximación lineal del modelo de Nomoto. El comportamiento estable del buque se observa también de los resultados de la maniobra de Pull-Out.

CONCLUSIONES

Aunque las pruebas de mar se desarrollan con el buque ya construido y en la mar, resulta conveniente simular el comportamiento dinámico del buque en la fase previa de diseño utilizando modelos matemáticos.

Se han simulado algunas de las pruebas de mar habituales utilizando un modelo matemático no lineal completo con tres grados de libertad. Los resultados de la simulación permiten medir las características del comportamiento dinámico del buque, obtener una indicación de su estabilidad en línea recta, valorar la robustez y las limitaciones del sistema de control, y evaluar el comportamiento del buque en situaciones de emergencia.

Los resultados obtenidos en la simulación de las pruebas de mar indican que las herramientas de simulación de pruebas de mar representan una parte importante del proceso de diseño previo a la construcción de un buque.