Journal of Maritime Research, Vol. I. No. 1, pp. 23-34, 2004
Copyright © 2004. SEECMAR

Printted in Santander (Spain). All rights reserved
ISSN: 1697-4840

THE INFLUENCE OF SOME SHIP PARAMETERS ON MANOEUVRABILITY

F. Pérez Arribas[1] and J. A. Clemente Fernandez[2]

ABSTRACT

Although there are advances in safety devices for ships every year, the risks of collision or grounding are still significant. Shipping accidents can have numerous negative effects involving not only damage to the cargo or delays due to ship repair but even loss of the ship, which may result in ecological disasters, in the case of oil or chemical tankers, as well as significant risks for both humans and wildlife.

Collision and grounding are the most common accidents in ship operation. Some accidents are due to human error, but several research projects have shown that a high percentage of these accidents could have been avoided izf the ship had had better manoeuvrability characteristics.

In this paper, numerical methods will be used to study the influence of some ship parameters on the manoeuvrability a model ship. This kind of analysis can help the naval architect to improve the manoeuvrability characteristics during the early stages of ship design.

Key words: manoeuvrability, hydrodynamics, numerical models

1. MANOEUVRABILITY EQUATIONS

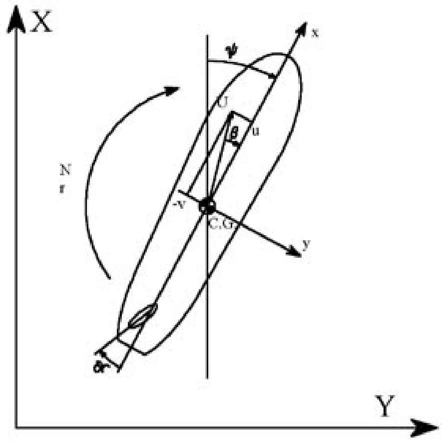
In this paper, manoeuvrability will be approached as a bidimensional phenomenon. Two reference systems will be used, one of them fixed (X,Y) and the other moving with the ship, with its origin at the centre of gravity of the vessel. Yaw motion is assumed to occur around this point. In the moving reference system, the x axis is positive forward and y is positive starboard. For both systems, moving and fixed, angles are positive in the clockwise sense.

In Fig. 1 U is the ship's velocity, which can be decomposed into an advance velocity u and a transversal velocity v. The ship has also a rotation velocity with respect to the z-axis. This axis is normal to the XY plane and passes through the ship centre of gravity. β is the angle between U and the x axis and it is called the *drift angle*. ψ is the ship heading angle and dr is the rudder angle.

[1]Doctor Profesor Asociado. Escuela Técnica Superior de Ingenieros Navales, fperez@etsin.upm.es. Avda. Arco de la Victoria s/n. Madrid. 28040 España.

[2] Oficina Técnica. IZAR San Fernando, jaclemente@izar.es. Carretera de la Carraca. San Fernando. 11080 España

Figure 1: Reference axis



Once the reference systems have been defined, the ship is considered as a solid with three degrees of freedom: surge, sway and yaw. Roll, pitch and heave are not considered in this case. Roll begins to be important at high Froude numbers when the roll angle is large and this affects manoeuvrability. This case is not considered in the present paper.

Taking into account these three degrees of freedom, Newton's equation is applied to the moving reference system of Fig. 1 for each motion (1):

$$\begin{aligned} &Surge: \quad m\cdot(\overset{*}{u}-v\cdot r)=X_H+X_P+X_R \\ &Sway: \quad m\cdot(\overset{*}{v}+u\cdot r)=Y_H+Y_P+Y_R \\ &Yaw: \quad I_Z\cdot\overset{*}{r}=N_H+N_P+N_R \end{aligned} \qquad \textbf{(1)}$$

The subindexes H, P and R stand for hull, propeller and rudder. X, Y and N are the forces (X, Y) and moments (N) acting on the ship with respect to the moving reference system *x*, *y*. A short review of the force terms in equation (1) follows:

-X_H is the force acting on the hull in the *x* direction or the advance resistance at speed u.
-X_P is the propeller force in the *x* direction or propeller thrust corrected with speed r, which will affect the flow entering the propeller. This effect will be included in the wake fraction.
-X_R will be the rudder drag, which can be obtained by using the *x* component of the rudder force.
-Y_H will be the *y* component of hull damping.
-Y_P will be the transversal propeller force.
-Y_R will be *y* component of the rudder force.
-N_H is the moment of Y_H with respect to the ship's centre of gravity.
-N_P is the moment of Y_P with respect to the ship's centre of gravity.
-N_R is the moment of Y_R with respect to the ship's centre of gravity.

The effect of waves, sea currents and wind forces are not included in (1). On the left side of (1), v·r and u·r represent the centrifugal component of the acceleration. The coefficient m is ship displacement and I_z is the ship inertia moment with respect to the *z* axis.

2. NUMERICAL MODEL USED FOR SHIP MANOEUVRABILITY

A non-linear numerical model that predicts ship manoeuvres from a small set of parameters will be described in this section, Pérez (2000). This method gives the different components of (1)

2.1 Surge equation

$$(m + m_x) \cdot \overset{*}{u} - (m + m_{vr}) \cdot vr = X(H) + X(P) + X(R) \qquad \textbf{(2)}$$

-$X(H) = -\frac{1}{2} \cdot \rho \cdot S \cdot C_T \cdot u^2$ (Advance resistance at speed u).
-ρ: density
-S: wetted surface
-C_T: total resistance coefficient. This is considered as constant during the manoeuvres. In this paper it is calculated using the Holtrop method.
-$X(P) = (1-t) \cdot \rho \cdot n^2 \cdot D_p{}^4 \cdot K_T$ (Propeller thrust)
-n: propeller rate
-t: suction coefficient
-D_p: propeller diameter
-K_T: propeller thrust coefficient, which can be expressed as a function of the propeller advance coefficient ($J = \dfrac{(1-w_P).u}{n.D_P}$) using a second order polynomial that is calculated using a least squares fitting: $K_T = C_1 + C_2 \cdot J + C_3 \cdot J^2$; K_T is based on Wageningen B systematic series.
-w_P = wake fraction, modified with the turning effects as will be seen later.
-$X(R) = -(1 - t_R) \cdot F_N \cdot \mathrm{Sin}(\delta)$ (Rudder drag)
-t_R: rudder drag coefficient. This coefficient is obtained by using the expression of Kijima & Tanaka (1993)
-F_N: normal force acting on rudder face
-δ: rudder angle

The coefficients m_x and m_{vr} are called added masses for surge and crossed for sway and yaw respectively. These added masses are calculated using Lewis (1989).

2.2 Sway equation

$$(m + m_y) \cdot \overset{*}{u} + (m + m_{ur}) \cdot ur = Y(H) + Y(R) \qquad \textbf{(3)}$$

The coefficient m_y is the sway added mass and is calculated using Ankudinov (1987).

$$-Y(H) = Y_B \cdot \beta + Y_r \cdot r' + Y_{BB} \cdot \beta \cdot |\beta| + Y_{rr} \cdot r' \cdot |r'| + Y_{Brr} \cdot \beta \cdot r' \cdot r' + Y_{BBr} \cdot \beta \cdot \beta \cdot r'$$

represents the hull effects according to Kijima et al. (1990). All the coefficients of the equation are non-dimensioned by $½ \cdot \rho \cdot T \cdot L_{pp} \cdot U^2$. β is the drift angle of Fig. 1 and $r' = r \cdot L_{pp} / U$ where U is the ship speed.

$$-Y(R) = -(1+a_h) \cdot F_N \cdot \text{Cos}(\delta) \quad \text{(Rudder effects)}$$

In this formula, F_N is the normal force acting on the rudder face and a_h represents the interaction between rudder and hull forces. It is calculated using Kijima & Tanaka (1993).

2.3 Yaw equation

$$(I_{zz} + i_z) \cdot \overset{*}{r} = N(H) + N(R) \qquad \textbf{(4)}$$

i_z is the added inertia moment, Ankudinov (1987).

$$N(H) = N_B \cdot \beta + N_r \cdot r' + N_{BB} \cdot \beta \cdot |\beta| + N_{rr} \cdot r' \cdot |r'| + N_{Brr} \cdot \beta \cdot r' \cdot r' + N_{BBr} \cdot \beta \cdot \beta \cdot r'$$

represents the hull effect on yaw, Kijima et al. (1990). As in the sway equation, all the coefficients are non-dimensioned by $½ \cdot \rho \cdot T \cdot L_{pp}^2 \cdot U^2$.

$$N(R) = -(1+a_h) \cdot X_{rg} \cdot F_N \cdot \text{Cos}(\delta) \quad \textit{(Rudder effects)}$$

F_N is the normal force acting on the rudder face and X_{rg} is the distance between the rudder axis and the ship centre of gravity. So, N(R) is the moment of Y(R) with respect to the ship centre of gravity. The interaction between rudder and hull is supposed to be positioned at the rudder axis in this formula.

2.4 Normal force acting on rudder face

The normal force is usually presented as:

$$F_N = ½ \cdot \rho \cdot C_L \cdot A_R \cdot V_R^2 \cdot \text{Sin}(\alpha_R) \qquad \textbf{(5)}$$

-C_L: rudder lift coefficient, which depends on the rudder mean line, generally a NACA profile.
-A_R : effective rudder area.
-V_R : speed at the rudder leading edge. It can be calculated using Kijima et al. (1990) or in towing tank tests. This speed depends on the hull, rudder and propeller interaction and is a function of propeller and rudder characteristics and wake coefficient.

-α_R : effective rudder angle. Due to the variation in the flow entrance angle to the rudder during the manoeuvres, the rudder angle δ is corrected and transformed into α_R, Kijima et al. (1990).

3. THE INFLUENCE OF SOME MAIN PARAMETERS OF THE SHIP ON ITS MANOEUVRABILITY

The previously described method is now applied to a Fast Ferry to see how the variation in some of its main parameters affects its manoeuvrability. The ship stations can be seen in Fig. 2 and its main characteristics are:

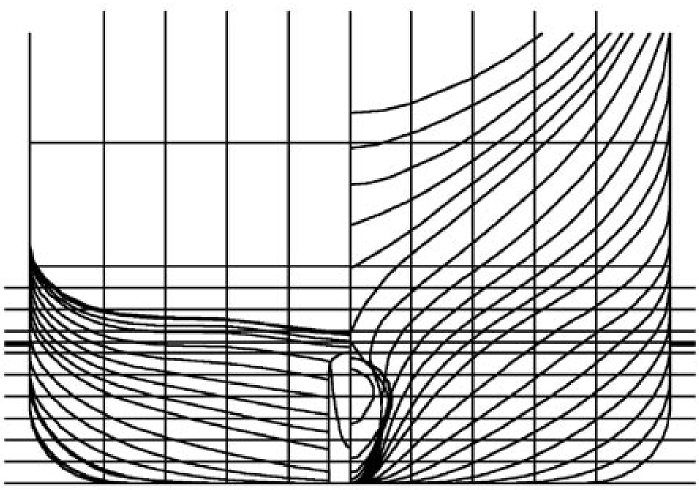
Table 1: Ship main parameters

Lpp =	173 m	Speed =	29 knots
Lwl =	174.8 m	kW =	4 x 12000 kW
B =	23 m	P.M. =	4800 Tm
T =	5.5 m	PAX =	1500 Pax.
CB =	0.53	CM =	0.97

This ship has two 5 m diameter propellers and two rudders with an area of 18.9 m^2 and a height of 5.2 m each.

Displacement and block coefficient are constant for all the calculated variations. Affine transformations have been applied to make these variations and for every one of these, a turning manoeuvre with a rudder angle of 35º and a Zigzag manoeuvre of 20º have been studied. All the transformations are assumed to be without trim. For every variation, propulsion and resistance have to be recalculated and this was carried out using the Holtrop method for the resistance prediction and the Wageningen BB propeller series for the propulsion. Once the new variation is completely defined, manoeuvres can be calculated.

Figure 2: Stations of the example ship



The variations subject to analysis have been:

Original ship without changes
– 5% Beam, + 5% Draft
– 5% LCB (Afterward)
– 5% Rudder area
– 5% Lpp, + 5% Beam
– 5% Lpp, + 5% Draft
+ 5% Beam, – 5% Draft
+ 5% LCB (Forward)
+ 5% Rudder area
+ 5% Lpp, – 5% Beam
+ 5% Lpp, – 5% Draft

In the plots of the turning manoeuvres, abscissa and ordinates are adimensionalised with ship length.

Figure 3: Beam and Draft effects on 35º Turning manoeuvre

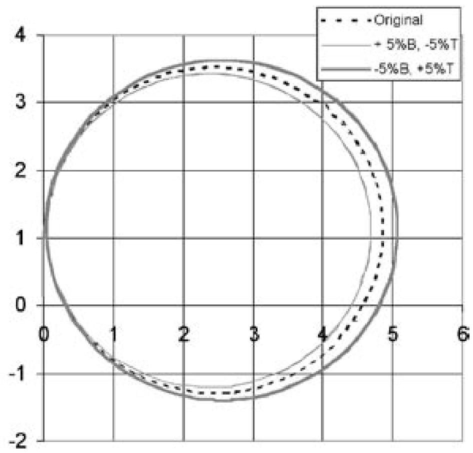


Figure 4: Beam and Draft effects on 20º Zigzag manoeuvre

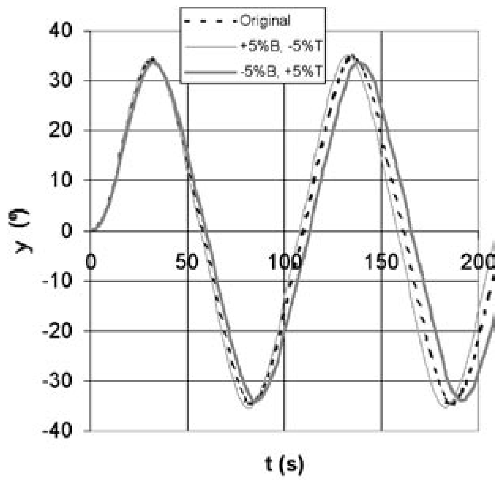


Figure 5: LCB effects on 35º Turning manoeuvre

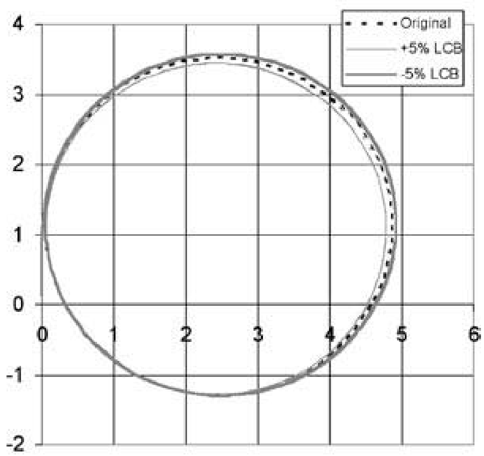
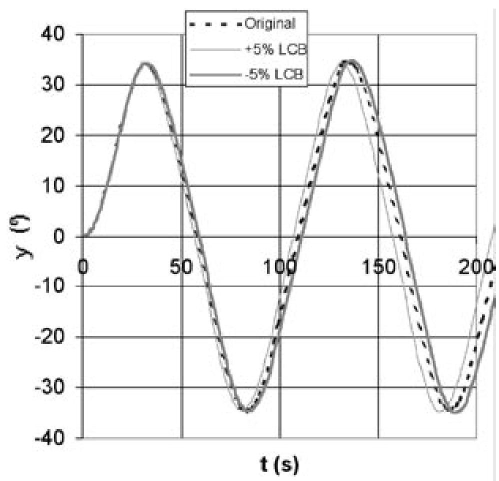


Figure 6: LCB effects on 20º Zigzag manoeuvre



3.1 BEAM AND DRAFT EFFECTS

From Fig. 3 and 4, it can be seen that increasing beam and decreasing draft have a positive effect on the turning manoeuvre. Turning diameter and advance diminish as beam increases (Fig. 3). The effects on the Zigzag manoeuvre (Fig. 4) are of minor importance.

3.2 LCB position effects

Displacing the position of the LCB forward has a positive effect on the turning manoeuvre as can be seen in Fig. 5. As in 3.3 the effects of this transformation on the Zigzag manoeuvre are of minor importance (Fig. 6).

3.3 Rudder area effects

Fig. 7 shows that increasing rudder area results in a clear improvement in the turning manoeuvre. Decreasing this area will have quite a negative effect. As in the previous variations, the effect on the Zigzag manoeuvre is negligible (Fig. 8).

Figure 7: Rudder area effects on 35º Turning manoeuvre

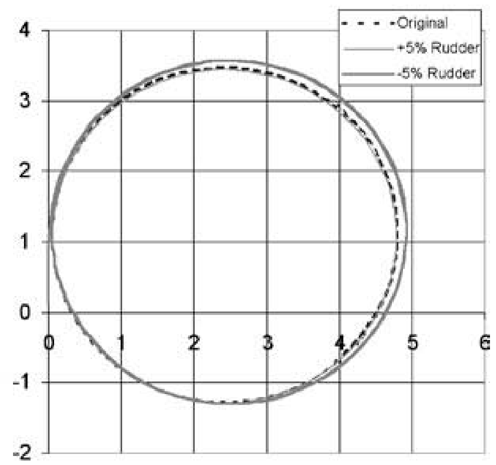


Figure 8: Rudder area effects on 20º Zigzag manoeuvre

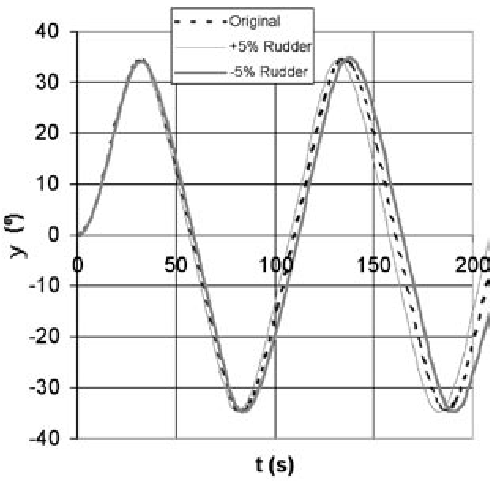


Figure 9: Ship length and beam effects on 35º Turning manoeuvre

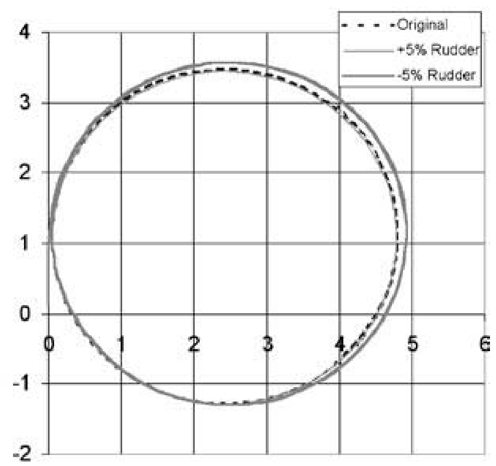
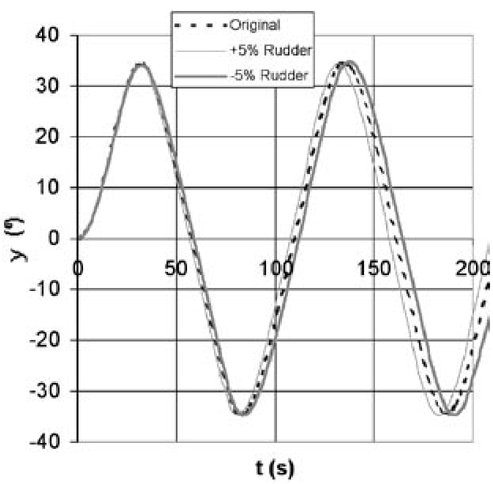


Figure 10: Ship length and beam effects on 20º Zigzag manoeuvre



3.4 Ship length and Beam effects

As can be seen in Fig. 9, a large effect on the turning manoeuvre is produced by lowering Lpp and increasing beam. Variation in ship length affects the Zigzag manoeuvre more than variations in other parameters. The positive effects on the turning manoeuvre have negative effects on the Zigzag manoeuvre (Fig. 10).

3.5 Ship length and draft effects

The positive effect of a smaller Lpp and a greater draft on the turning manoeuvre can be seen in Fig. 11. Ship length and draft affects the Zigzag manoeuvre less than variation in the length and beam. The positive effects on the turning manoeuvre have negative effects on the Zigzag manoeuvre (Fig. 12).

Figure 11: Ship length and draft effects on 35º turning manoeuvre

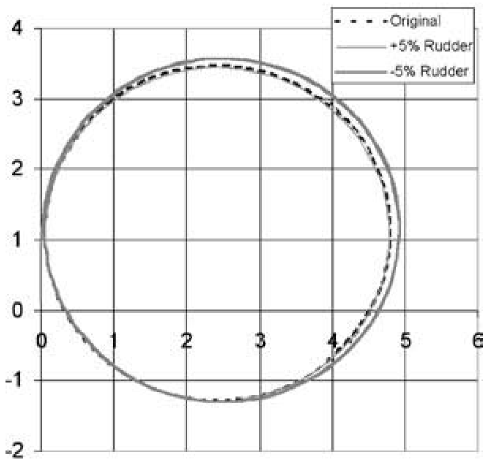
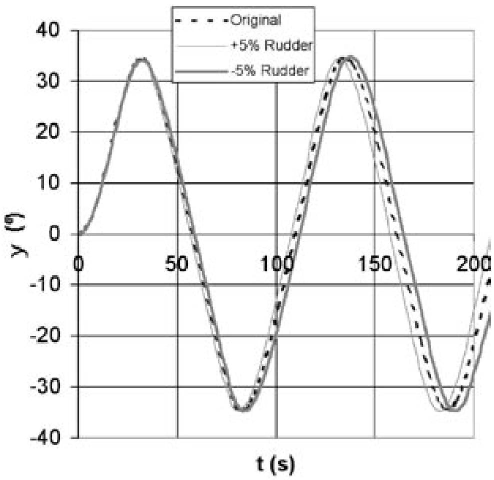


Figure 12: Ship length and draft effects on 20º Zigzag manoeuvre



3.6 Global effects of the variations

The effect of the variations on some global parameters of the manoeuvres is shown in Table 1. This table presents the advance and tactical diameter of the turning manoeuvre (divided by ship length) and the overshoot angle of the Zigzag manoeuvre.

Table 1: global parameters of the manoeuvres

	Original	+5%B, -5%T	+5%T, -5%B	+5% LCB	-5% LCB	+5% Rudder	-5% Rudder
Advance	3.44	3.35	3.56	3.37	3.50	3.39	3.49
Tactical D.	4.80	4.61	5.01	4.71	4.85	4.73	4.86
Overshoot	14.10	14.80	13.50	14.20	14.20	14.20	14.00

	Original	+5% L, -5% B	-5% L, +5% B	+5% L, -5% T	-5% L, +5% T
Advance	3.44	3.57	3.29	3.50	3.38
Tactical D.	4.80	5.13	4.43	4.97	4.61
Overshoot	14.10	12.56	16.12	13.17	15.16

The effects on the Zigzag manoeuvre are small except for variations in ship length. The variations in ship length have the most important effects on the manoeuvres but these effects are negative for the Zigzag manoeuvre. Increasing the beam and decreasing the length reduce the advance and the tactical diameter but increase the overshoot angle. The effect of draft is not clear and depends on the other dimension that is varied. Displacing the LCB position forward is positive for the turning manoeuvre and has little effect on the Zigzag manoeuvre. It is obvious that increasing the rudder area is positive for manoeuvrability, but the negative aspect is the increase in power required to move the rudder. The effect on the Zigzag manoeuvre is small.

3.7 Combined variations

Increasing ship length is positive for the turning manoeuvre but negative for the zigzag manoeuvre, so it is better not to modify length if a global optimisation of ship manoeuvrability is desired. The option of choice is: + 5% Beam, – 5% Draft (displacement has to be constant) and +5% LCB. Rudder area and ship length are not varied due to the aforementioned disadvantages. The parameters improved by means of these variations are the Advance (3.29 L, – 4.4%) and the Tactical diameter (4.54 L, – 5.4%).

4. CONCLUSIONS

Manoeuvrability is an important issue in ship design due to its influence on ship safety, operability and petrol costs. Manoeuvrability can be studied numerically during the early stages of ship design to ensure that the ship can manoeuvre as required.

The manoeuvres we have studied are a turning manoeuvre with a 35º rudder angle and a Zigzag manoeuvre with a 20º rudder angle. IMO requirements are related to these manoeuvres. Turning manoeuvres are used to check the effectiveness of the rudder in making large heading changes. The Zigzag manoeuvre reflects the inherent effectiveness of the rudder in making changes in heading.

The effects of the parameter variations on the Zigzag manoeuvre are small except for variations in ship length. Diminishing length has a strong positive effect on turning manoeuvres but affects the Zigzag manoeuvre negatively. Ship length is also the most expensive dimension to change.

The increase of beam and the reduction of ship length reduce the advance and the tactical diameter but increase the overshoot angle. The effect of draft on its own is not clear and depends on the variation of other dimensions.

Displacing the LCB position forward is positive for the turning manoeuvre and has little effect on the Zigzag manoeuvre.

It is obvious that increasing the rudder area is positive for the manoeuvrability, but its drawback is the increase in power required for moving the rudder. This variation has little effect on the Zigzag manoeuvre.

Combined variation of several ship parameters can give better results than the individual variation of each parameter.

REFERENCES:

Ankudinov V. (1987): *Design workbook on ship manoeuvrability*. SNAME

Kijima K., Yasuaki N., Masaki T. (1990): *Prediction method of ship manoeuvrability in deep water*. Marsim & ISCM 90, Tokio.

Kijima K., Tanaka S. (1993): *On the prediction of ship manoeuvrability characteristics.* Intl. Conf. of Ship Simulation and Ship manoeuvrability. London

Lewis E.V. (1989): *Principles of Naval Architecture. Vol. 3* SNAME.

Perez F.L. (2000): *Resolución de las ecuaciones no lineales de la maniobrabilidad*. Internal researching report. ETSI Navales.

APÉNDICE: INFLUENCIA DE ALGUNOS PARÁMETROS SOBRE LA MANIOBRALIDAD DEL BUQUE

RESUMEN

A pesar de los cada vez más sofisticados medios de ayuda a la navegación y de detección de otros buques o elementos extraños dentro de su trayectoria, es evidente que los riesgos de colisión o varada no son en absoluto despreciables. Un accidente de cualquier tipo puede redundar no sólo en el daño sufrido por la carga o en el tiempo perdido en reparaciones del buque en dique, sino que puede llevar a la pérdida del mismo y hasta consecuencias más graves, y por desgracia más frecuentes en nuestros días, como es el grave desastre ecológico en la zona en que se produce el accidente, caso del transporte de crudos, derivados del petróleo o productos químicos. En resumen, elevadas cifras monetarias, y riesgo para las vidas humanas.

Entre las causas de accidentes figuran en primer lugar los choques (colisiones, varadas...). Como es lógico, un cierto número de los accidentes son debidos a errores humanos o a causas inevitables, pero según distintos estudios, un alto porcentaje de ellos podrían haberse evitado si el buque hubiera estado dotado de unas mejores cualidades de maniobrabilidad.

METODOLOGÍA

En este artículo se ha visto como afectan a las cualidades de maniobrabilidad distintos parámetros fundamentales del buque, en este caso aplicado a un Ferry, analizando la maniobrabilidad a partir de métodos numéricos desarrollados en la Escuela Técnica Superior de Ingenieros Navales, y que pueden ayudar al ingeniero naval en las primeras etapas de proyecto en un campo como es el de la maniobrabilidad, poco tratado en las etapas de diseño.

A pesar de los cada vez más sofisticados medios de ayuda a la navegación y de detección de otros buques o elementos extraños dentro de su trayectoria, los riesgos de colisión o varada de los buques aún existen. Un accidente de cualquier tipo puede producir no sólo daño para la carga o tiempo perdido en reparar el buque en dique, sino que puede llevar a la pérdida del mismo y hasta tener consecuencias igual de graves, y por desgracia más frecuentes en nuestros días, como es el desastre ecológico en la zona en que se produce el accidente, como es el caso del transporte de crudos, derivados del petróleo o productos químicos.

Todo esto se traduce en elevadas cifras monetarias a tener en cuenta a la hora de considerar la explotación del buque en un determinado tráfico y la aparición del riesgo para las vidas humanas, tanto la tripulación del propio buque como para personas externas a éste, y el medio marino.

Entre las causas de accidentes figuran en primer lugar los choques (colisiones con otros buques, varadas...) con un 40% del total de buques accidentados. Como es lógico, un cierto número de los accidentes son debidos a errores humanos o a causas inevitables, pero según un estudio realizado por encargo de la U.S. Coast Guard sobre los accidente producidos en la década de los 70, más de 800 casos, alrededor del 35%, podrían haberse evitado si el buque hubiera maniobrado de forma más adecuada a las circunstancias.

Sin llegar a las dramáticas consecuencias antes expresadas, existe otro problema de gran importancia relacionado con la explotación del buque, y en concreto con la rentabilidad del mismo. Generalmente el buque está destinado a moverse la mayor parte de su vida en línea recta, y por eso es lógico elegir las dimensiones principales en el anteproyecto de forma que se optimice la propulsión y a la resistencia al avance.

Ciertos buques poseen una gran tendencia a abandonar la trayectoria rectilínea ante una pequeña perturbación. Se dice que presentan inestabilidad de ruta. Con objeto de que el rumbo sea el deseado, es preciso actuar entonces sobre el timón frecuentemente y con ángulos de timón excesivamente grandes. El buque avanzará entonces con una trayectoria de tipo sinusoidal o zig-zag, más o menos acusada en función de la tendencia que tenga a perder el rumbo.

El tener el timón metido unos grados a una banda causa un aumento de la resistencia al avance del buque y si este realiza guiñadas apreciables, el efecto se hace de mayor importancia. Lógicamente el camino recorrido es más largo debido al abandono de la trayectoria rectilínea.

La consecuencia final es que aparte del excesivo desgaste al que se puede someter al sistema de gobierno con el consiguiente aumento de consumo por parte del mismo, la velocidad media de servicio es menor pudiéndose llegar a contrarrestar las pequeñas mejoras alcanzadas en la velocidad por un estudio cuidadoso del bulbo de proa, una mejora en la estela, o un sofisticado estudio de la hélice. En definitiva, el consumo de combustible aumenta y la rentabilidad disminuye si la maniobrabilidad es mala.

El buque considerado como elemento de transporte de mercancías o pasajeros debe cumplir unos requisitos operacionales, es decir, desarrollar una determinada misión en unas determinadas condiciones ambientales. Si no cumple adecuadamente estos requerimientos se tendrá una baja calidad del buque en cuanto a la misión que tiene que cumplir, y se puede llegar en algunos casos a la incapacidad para realizar dicha misión. Una patrullera por ejemplo debe ser capaz de maniobrar con agilidad a alta velocidad, un pesquero debe ser capaz de faenar en un caladero y un remolcador de desenvolverse con soltura cerca de los buques sobre los que actuará.

Todas las consideraciones anteriores sobre la capacidad para maniobrar de un buque, no son nuevas ni desconocidas. Sin embargo, no suelen ser tomadas en cuenta en la elección de las dimensiones principales que influyen poderosamente en la maniobrabilidad y en la facilidad de gobierno. Ciertos organismos internacionales han puesto requisitos sobre maniobrabilidad para evitar accidentes.

Así por ejemplo la U.S. Coast Guard exige desde los finales de los 70 a los buques que van a atracar en puertos norteamericanos unos gráficos en el puente con las características de maniobrabilidad del mismo. La I.M.O. impone unos límites para ciertos parámetros de las maniobras, como puede ser el avance y el diámetro táctico en la maniobra de giro, o el ángulo de rebasamiento en la maniobra de zig-zag.

CONCLUSIONES

La maniobrabilidad es un factor a tener en cuenta en la explotación del buque debido a la mejora de la seguridad de operación, operatividad y ahorro de combustible que se consiguen con una adecuada maniobrabilidad.

La maniobrabilidad puede estudiarse en etapas de anteproyecto del buque y ver si el buque cumplirá con los requerimientos de maniobrabilidad impuestos. Esto puede hacerse numéricamente o bien a partir de ensayos.

Pequeñas variaciones de algunos parámetros globales del buque conllevan mejoras en la maniobrabilidad. Así por ejemplo favorece la maniobrabilidad manteniendo el desplazamiento del buque un aumento de la manga, una disminución del calado, desplazar el centro de carena a proa y lógicamente aumentar el área del timón.

Se puede mejorar la maniobrabilidad jugando con múltiples parámetros al mismo tiempo, lográndose un mayor efecto que al variar los parámetros individualmente.