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COURSE-KEEPING AND TURNING CIRCLE ANALYSIS IN EARLY SHIP DESIGN STAGE

Dan Obreja
"Dunarea de Jos" University of Galati,
Faculty of Naval Architecture, Galati, Domneasca Street, No. 47, 800008, Romania,
E-mail:dan.obreja@ugal.ro

Mirela-Roxana Chicăroşă
"Dunarea de Jos" University of Galati,
Faculty of Naval Architecture, Galati, Domneasca Street, No. 47, 800008, Romania,
E-mail: roxanachicarosa@yahoo.com

ABSTRACT

The course-keeping is an important ship's quality. Starting with the initial ship design process, the knowledge of the stability on route represents a main component of the manoeuvring performance. Also, the turning circle characteristics must be estimated in order to analyse the manoeuvring performance. Preliminary theoretical methods may be used to study the course-keeping quality and turning circle characteristics. For that purpose, the numerical solution of the Nomoto equation based on the Runge-Kutta method can be applied in order to compute the turning rate of the ship and to analyse the spiral manoeuvre. A new computer code, in Java language, was developed in the Research Centre of the Naval Architecture Faculty from "Dunarea de Jos" University of Galati in order to analyse the ship's stability on route. Also, the turning circle characteristics are estimated on the basis of statistical relations. Practical evaluations based on the computer code were presented in this paper. The conclusions reveal the possibility to use the new computer code for the course-keeping and turning circle analyse in the preliminary design stage.

Keywords: ship, course-keeping, Nomoto equation, turning circle, computer code

1. INTRODUCTION

Starting with the preliminary ship design stage it's necessary to estimate the manoeuvring performance, with a satisfactory accuracy level. The ship manoeuvrability concept includes the problem of the stability on route. In the case of a stable route, the ship is moving straight ahead in the absence of external disturbances (wind, waves, currents) at a given speed and neutral rudder position, keeping a constant heading angle.

One of the most important methods used to study the mentioned problem is the Dieudonne's spiral manoeuvre analysis ([1], [5]). In this case, is possible to obtain the diagram of the constant value of the rate of turn at preselected rudder deflection angles. If the ship is stable on route, there is a unique rate of change of heading for each rudder angle (Figure 1). In the case of an unstable ship, a form of hysteresis loop can be observed (Figure 2). The slope of the rate of turn, the height and the width of the loop are numerical measures of the degree of instability.

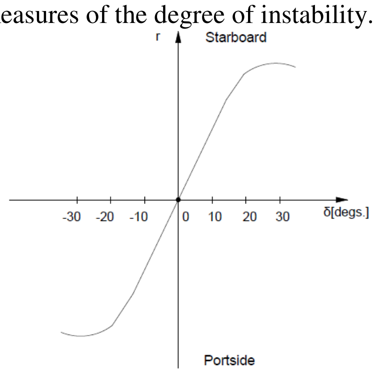

Fig. 1. Spiral manoeuvre. Ship stable on route

In order to determine the rate of turn at a preselected rudder angle, a simple mathematical model of the yaw motion, given by Nomoto ([4], [5]) can be applied

$$T\frac{dr}{dt}+\left(r+\alpha\cdot r^3\right)=K\delta \tag{1}$$

where, T is the course stability index, K is the turning ability index, r is the rate of turn, δ is the rudder deflection angle and α is a nonlinear response coefficient.

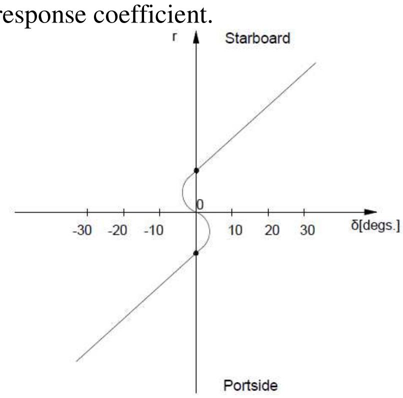

Fig. 2. Spiral manoeuvre. Ship unstable on route

The nondimensional values of the coefficients T and K can be estimated by using the following expressions [5], in function of the nondimensional yaw inertia moment I_z and the nondimensional hydrodynamic derivatives N_r, $N_{\dot{r}}$, N_δ

$$T=\frac{I_z-N_{\dot{r}}}{N_r} \tag{2}$$

$$K=\frac{N_\delta}{N_r} \tag{3}$$

The nondimensional values of the hydrodynamic derivatives can be estimated depending by the length of waterline L, the mean draught T_m, the beam of waterline B and the block coefficient C_B, by using the following relations [6]

$$N_r=-\pi\cdot\left(\frac{T_m}{L}\right)^2\cdot\left(0.25+\frac{0.039\cdot B}{T_m}-\frac{0.56\cdot B}{L}\right) \tag{4}$$

$$N_{\dot{r}}=-\pi\cdot\left(\frac{T_m}{L}\right)^2\cdot\left(0.083+\frac{0.017\cdot C_B\cdot B}{T_m}-\frac{0.33\cdot B}{L}\right) \tag{5}$$

$$N_\delta=-1.5\cdot\frac{A_R}{L^2} \tag{6}$$

Also, the nondimensional values of the Nomoto coefficients (T and K) can be calculated in function of the length of waterline L, mean draught T_m, volumetric displacement ∇ and the rudder area A_R, on the basis of the following relations [6]

$$T=1{,}1845+0{,}00007\cdot K\cdot\frac{\nabla}{L\cdot A_R} \tag{7}$$

$$K=-1{,}9545+42{,}0221\cdot\frac{\nabla}{L^2\cdot T_m}-16{,}6975\cdot\frac{A_R}{L\cdot T_m} \tag{8}$$

It can be seen that the course-keeping of the ship may be analysed on the basis of the preliminary ship design data.

Also, the nondimensional value of the steady turning diameter (*STD/L*) can be determined, depending by the turning ability index K, by using the following preliminary relation [5]

$$\frac{STD}{L}=\frac{2}{K\cdot\delta} \tag{9}$$

In the same time, *STD/L* can be estimated in function of the length of waterline L, the beam of waterline B, the block coefficient C_B, the rudder area A_R and the rudder deflection angle δ, on the basis of the following relation [6]

$$\frac{STD}{L}=12{,}11-1.788\cdot\frac{C_B}{\delta}-38.47\cdot\frac{B}{L}+\frac{0.855}{\delta}-\frac{65.9}{A_R} \tag{10}$$

By using the steady turning diameter, the manoeuvring quality of the ship can be analysed in the early design stage.

2. TIME DOMAIN SIMULATION

Applying the equation of Nomoto (1), the rate of turn can be obtained on the basis of Runge-Kutta method of fourth order.

The equation (1) can be written under the following equivalent form

$$\frac{dr}{dt}=\frac{1}{T}\cdot\left[K\cdot\delta-\left(r+\alpha\cdot r^3\right)\right] \tag{11}$$

If the right part of the equation (11) is noted with *f(r,t)*, where t is the time, is obtained the general form

$$\frac{dr}{dt}=f(r,t) \tag{12}$$

having the solution [3]

$$r_{i+1} = r_i + \frac{h}{6} \cdot (k_1 + 2 \cdot k_2 + 2 \cdot k_3 + k_4) \qquad (13)$$

for i=1 … n, where,

$$\begin{aligned} h &= t_{i+1} - t_i \\ k_1 &= f(r_i, t_i) \\ k_2 &= f(r_i + \frac{h}{2} \cdot k_1, t_i + \frac{h}{2}) \\ k_3 &= f(r_i + \frac{h}{2} \cdot k_2, t_i + \frac{h}{2}) \\ k_4 &= f(r_i + h \cdot k_3, t_i + h) \end{aligned} \qquad (14)$$

The rudder deflection angle is considered as a variable function in time (Figure 3).

The initial condition is given by the relation

$$r_1 = 0 \text{, for } t_1 = 0 \qquad (15)$$

A computer code was developed in Java language, in the Research Centre of the Naval Architecture Faculty from "Dunarea de Jos" University of Galati, in order to obtain the numerical solution of the Nomoto equation.

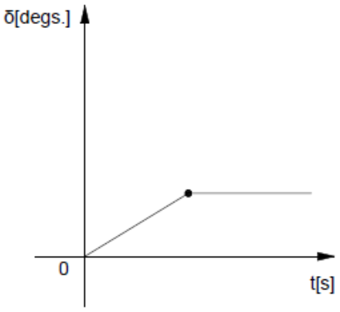

Fig. 3. Rudder deflection angle in time domain

On the basis of this computer code, practical applications were performed for different types of ships, in order to evaluate the course-keeping and manoeuvring performance. The most important results are presented in the next chapters.

3. PRACTICAL EVALUATION OF THE COURSE-KEEPING

A practical evaluation was developed by using the following benchmark ships: MARINER cargo ship, KCS container ship, KVLCC2 tanker and DTMB surface combatant. The value α=1 was adopted as input data for the nonlinear response coefficient, in all cases.

The input data for MARINER cargo ship are presented in Table 1. The characteristic diagrams of the spiral manoeuvre are depicted in Figure 4. The blue curve was obtained by using the relations (2) and (3) and the red curve on the basis of the expressions (7) and (8).

Table 1. MARINER cargo ship. Input data

Main characteristics	Full scale
Volumetric displacement, ∇ [m^3]	16622.0
Length between perpendiculars, L_{BP} [m]	160.930
Beam, *B* [m]	23.170
Draft, *T* [m]	8.230
Plan form area of the rudder, A_R [m^2]	30.012
Ship speed, *v* [Knots]	15.0
Froude number, *Fn*	0.194
Water density, ρ [t/m^3]	1.025

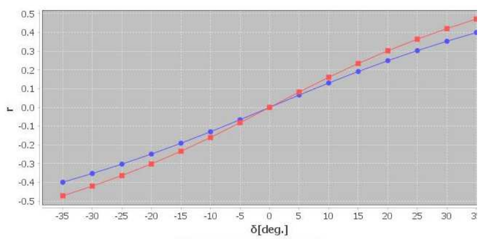

Fig. 4. MARINER cargo ship. Spiral diagram

The maximum difference of 12,3% between the spiral diagrams was established for the rudder angle equal with 35 deg.

Taking into consideration the curves form, without hysteresis loop, the stable on route of the MARINER cargo was demonstrated.

The input data for the case of KCS container ship are presented in Table 2.

The spiral diagrams are presented in Figure 5. The maximum difference of 28,7% between the spiral diagrams was registered for the rudder angle equal with 35 deg. Also, the KCS container ship is stable on route.

The input data for the case of KVLCC2 tanker are presented in Table 3. The spiral diagrams are presented in Figure 6.

Table 2. KCS container ship. Input data

Main characteristics	Full scale
Volumetric displacement, ∇ [m^3]	52030.0
Length between perpendiculars, L_{BP} [m]	230.0
Beam, *B* [m]	32.20
Draft, *T* [m]	10.80
Plan form area of the rudder, A_R [m^2]	54.50
Ship speed, *v* [Knots]	24.0
Froude number, *Fn*	0.260
Water density, ρ [t/m^3]	1.025

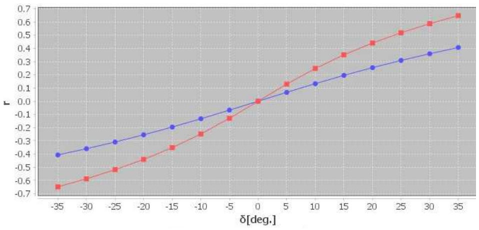

Fig. 5. KCS container ship. Spiral diagram

Table 3. KVLCC2 tanker. Input data

Main characteristics	Full scale
Volumetric displacement, ∇ [m^3]	320438.0
Length between perpendiculars, L_{BP} [m]	320.0
Beam, *B* [m]	58.0
Draft, *T* [m]	20.80
Planform area of the rudder, A_R [m^2]	136.70
Ship speed, *v* [Knots]	15.5
Froude number, *Fn*	0.142
Water density, ρ [t/m^3]	1.025

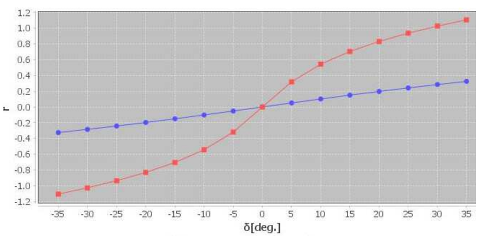

Fig. 6. KVLCC2 tanker. Spiral diagram

A maximum difference of 47,9% between the spiral diagrams was determined for the rudder angle equal with 35 deg. The KVLCC2 tanker is stable on route.

The input data for the case of DTMB surface combatant are presented in Table 4 and the spiral diagrams are depicted in Figure 7.

The maximum difference of 6,8% between the spiral diagrams was determined for the rudder angle equal with 35 deg. Also, the DTMB surface combatant is stable on route.

Table 4. DTMB combatant. Input data

Main characteristics	Full scale
Volumetric displacement, ∇ [m^3]	8355.350
Length between perpendiculars, L_{BP} [m]	142.0
Beam, *B* [m]	19.10
Draft, *T* [m]	6.110
Plan form area of the rudder, A_R [m^2]	15.40
Ship speed, *v* [Knots]	30.0
Froude number, *Fn*	0.413
Water density, ρ [t/m^3]	1.025

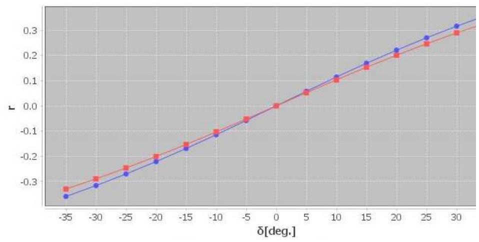

Fig. 7. DTMB surface combatant. Spiral diagram

The influence of the nonlinear response coefficient α was analysed in the case of KVLCC2 tanker, for rudder angle δ=35 deg. The results are presented in Table 5.

Table 5. The influence of the nonlinear response coefficient α

Nonlinear response coefficient α	Nondimensional rate of turn for δ=35 deg. r	
	Blue curve	Red curve
0.	0.738	2.458
0.01	0.735	2.332
0.10	0.707	1.838
0.50	0.630	1.317
1.0	0.576	1.106
1.5	0.540	0.992
2.0	0.514	0.917
5.0	0.428	0.705
10.0	0.366	0.573
100.0	0.209	0.279

The reduction of the difference between the nondimensional values of the rate of turn for δ=35 deg., specific to the red and blue curves can be noticed, when the nonlinear response coefficient increases.

In all cases, KVLCC2 tanker is stable on route.

4. ESTIMATION OF THE STEADY TURNING DIAMETER

The nondimensional values of the course stability index *T*, turning ability index *K* and steady turning diameter *STD/L* calculated on the basis of the manoeuvring derivatives by using the relations (2), (3) and (9) are presented in Table 6.

The small values of the T index and large values of the K index are recommended in order to obtain good course-keeping and respectively manoeuvring performances.

Table 6. Manoeuvring characteristics by using hydrodynamics derivatives

Ship	K	T	STD/L
MARINER	0.758	0.439	4.320
KCS	0.775	0.512	4.225
KVLCC2	0.586	0.602	5.583
DTMB	0.664	0.433	4.930

Referring to the MARINER cargo ship, the estimated value of the *STD/L* is close to the experimental values situated in the domain 3.8 … 4.2 [2].

In the case of KVLCC2 tanker, the minimum value of the K index was obtained. As a consequence, a large value of the nondimensional steady turning diameter was estimated.

At the same time, the T index of KVLCC2 has the maximum value compared with other ships.

The nondimensional values of the course stability index *T*, turning ability index *K* and steady turning diameter *STD/L* calculated on the basis of the main dimensions of the ship by using the relations (7), (8) and (10) are presented in Table 7.

In order to apply these relations, the following restrictions must be considered:

$$\begin{aligned} C_B &= 0.6 \ldots 0.83 \\ L/B &= 6 \ldots 8 \\ L/T_m &= 14.25 \ldots 23 \\ B/T_m &= 2.15 \ldots 4.7 \end{aligned} \tag{16}$$

The restriction of the block coefficient is not fulfilled for MARINER and DTMB, while the restriction related to the ratio *L/B* is not accomplished for the case of KVLCC2. Also, the L/T_m restriction is not fulfilled for DTMB.

Table 7. Manoeuvring characteristics by using main dimensions of the ship

Ship	K	T	STD/L
MARINER	0.944	1.185	4.190
KCS	1.506	1.185	5.011
KVLCC2	4.025	1.187	3.625
DTMB	0.599	1.185	2.580

It can be seen from Table 7 that the values of the course stability index *T* are very closed.

The estimated value of the *STD/L* in the case of MARINER cargo ship is situated in the domain of the experimental values (3.8 … 4.2) and is very close to the similar result from the Table 6.

In the case of KVLCC2 tanker, the maximum value of the K index was obtained. As a consequence, a relative small value of the nondimensional steady turning diameter was estimated. This conclusion is opposite to the similar results presented in Table 6.

Also, large differences related to the nondimensional values of the steady turning diameter STD/L can be observed in the case of DTMB surface combatant.

As a consequence, in order to use the results obtained by using statistical relations in the initial design stage, maximum circumspection must be necessary.

4. CONCLUDING REMARKS

The estimation of the manoeuvring performances of the ship represents an important objective, starting with the early design stage. Two main aspects of the manoeuvring qualities were analysed in this paper: the course-keeping and the turning circle characteristics.

The course-keeping problem was studied on the basis of the Dieudonne's spiral manoeuvre. The mathematical model of the yaw motion due to the Nomoto was applied, in order to estimate the ship's rate of turn, for preestablished rudder angle.

The Nomoto equation was solved by using the Runge-Kutta method, of fourth order.

The spiral diagram can be analysed in order to decide if the ship is stable on route.

Also, by means of statistical relations the steady turning diameter can be estimated.

The Nomoto coefficients and the steady turning diameter were estimated by means of two methods: one of them is based on the hydrodynamics derivatives and other on the main dimensions of the ship.

A computer code in Java language was developed in the Research Centre of the Naval Architecture Faculty from "Dunarea de Jos" University of Galati, in order to obtain the numerical solution of the Nomoto equation and to solve both the course-keeping and turning circle problems.

The practical evaluations were developed by using benchmark ships: MARINER cargo ship, KCS container ship, KVLCC2 tanker and DTMB surface combatant.

The spiral diagrams and the nondimensional values of the steady turning diameter were analysed. All the ships are stable on route.

Some important differences and contradictory results were obtained, depending by the specific relations, for the steady turning diameter.

As a consequence, circumspection must be necessary in the initial ship design stage, related to the estimation of the steady turning diameter with statistical relations.

Acknowledgements

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