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A COMPARATIVE ANALYSIS OF COURSE KEEPING AND TURNING CIRCLE FOR A 37000 TDW CHEMICAL TANKER

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ABSTRACT

The manoeuvring characteristics of the ships represent a complex phenomenon, which includes their capacity for both maintaining a steady course and turning ability. There are no simple methods for evaluating a ship's performance in these aspects. Furthermore, the flow patterns connected to these phenomena are complex and frequently coupled with other factors. The purpose of this study is to evaluate the course keeping and turning performance for a 37000 tdw chemical tanker. Course-keeping is evaluated based on stability criteria, while empirical relations and numerical simulations using hydrodynamic derivatives from both empirical and computational fluid dynamics (CFD) methods are employed to analyse the turning circle and then compared with data from actual sea trials.

Keywords: manoeuvrability, course keeping, turning circle, sea trials

1. Introduction

In the field of ship hydrodynamics, predicting a ship's manoeuvrability has been a constant challenge. Traditionally, forecasting a ship's manoeuvrability heavily relied on empirical methods or physical model tests because analytical methods were lacking.

The advent of high-speed computers has revolutionized the way we approach the prediction of complex systems and phenomena. This new approach involves determining a system's behaviour through numerical integration of equations of motion. In the shipbuilding industry, time-domain simulation has become a widely adopted method, particularly for predicting ship movements, evaluating their performance in different sea conditions, and assessing their manoeuvring capabilities. These simulations rely on hydrodynamic derivatives, derived from computational fluid dynamics (CFD) or data obtained from model tests conducted in towing tanks and manoeuvrability tanks.

The main goal of this research is to examine the course-keeping and turning capabilities of a 37000 tdw chemical tanker. The assessment of course-keeping relies on stability criteria, while an analysis of the turning circle is conducted using Lyster and Knights [1] relations, alongside numerical simulations that use hydrodynamic derivatives obtained from both empirical and computational fluid dynamics (CFD) methods. The results of these analyses are then compared with the data obtained from the real sea trials.

2. Ship description

The study was conducted on a 37000 tdw chemical tanker, which was one of a series of

21 ships built by Constanta Shipyard in Romania. Chemical tankers are specialized vessels designed for the safe transport of dangerous goods such as petroleum or chemical products.

In Table 1 are presented the main characteristics of the ship.

Table 1 Main characteristics of the ship

L_{PP} [m]	172
L_{WL} [m]	175
B [m]	32.2
D [m]	16.5
T [m]	10.5
Deadweight (t)	37000
∇ (m^3)	46318.5
v [Kn]	15
C_B	0.78
Rudder type	Horn
Rudder profile type	NACA0019
H_R (m)	8.6
A_R (m^2)	34.52

Figure 1 Chemical tanker

3. Mathematical model

3.1 Coordinate systems

The coordinate systems used in ship manoeuvrability are shown in Figure 2: the earth-fixed coordinate system $O_0\ x_0y_0z_0$ and the body-fixed coordinate system $O\ xyz$, which moves together with the ship. The heading angle ψ is defined as the angle between the direction of the x_0 axis and the x axis and drift angle β is defined as the angle between x axis and U. In the earth-fixed coordinate system, the ship's centre of gravity is designated as the ship's position x_{0G} and y_{0G}, and the heading angle ψ signifies the ship's orientation. The rudder angle δ is considered positive when it rotates to the starboard side, u and v represents velocity components in the x and y directions, while r is the yaw rate. The ship's speed $U = \sqrt{u^2 + v^2}$.

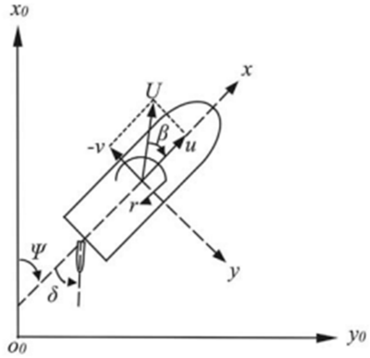

Figure 2 Coordinate systems

3.2 Equations of motion

A simplified form of equations of motion in horizontal plane is used [2].

$$\begin{aligned} X + X_{Rd} &= m\dot{u} \\ Y + Y_{Rd} &= m(\dot{v} + ur + x_G r) \\ N + N_{Rd} &= I_{zz}\dot{r} + mx_G(\dot{v} + ru) \end{aligned} \qquad (1)$$

where X, Y, and N are the total forces and moments experienced by the ship and X_{Rd}, Y_{Rd} and N_{Rd} are the corresponding rudder forces and moments. Utilizing the Taylor series expansion to derive hydrodynamic derivatives, the total external forces and moments can be calculated. In the context of a linear hydrodynamic model, the ship's equations of motion can be expressed in the following form which can be solved numerically:

$$\begin{gathered} X_u\Delta u + X_{\dot{u}}\dot{u} = m\dot{u} \\ Y_v v + Y_r r + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_\delta\delta = \\ m(\dot{v} + ur + x_G\dot{r}) \\ N_v v + N_r r + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_\delta\delta = \\ I_{zz}\dot{r} + mx_G(\dot{v} + ru) \end{gathered} \qquad (2)$$

Hydrodynamic derivatives correspond to the gradients of the force or moment curve versus the components of velocity or acceleration at origin.

Examining a ship's course-keeping stability can be carried out by assessing the stability solutions provided by the system of linear equations of motion. When external perturbations are not taken into account, this analysis leads to the establishment of the stability criterion [3]:

$$C = Yv'^{(Nr'-m'x_{G}')} + Nv'^{(m'-Yr')} > 0 \qquad (3)$$

3.3 Hydrodynamic derivatives

The nondimensional values of the hydrodynamic derivatives can be estimated using empirical formulas proposed by Clarke et al [4]. Also the rudder derivatives can be estimated using the following relations [3]:

$$Y_{\delta}' = 3\frac{A_R}{L^2} \qquad (4)$$

$$N_{\delta}' = -0.5Y_{\delta}' \qquad (5)$$

In Table 2 are presented hydrodynamic derivatives used in the simulations. An approximate relation for *Xu̇* derivative may be used [3].

$$X\dot{u}' \approx -0.05m' \qquad (6)$$

where *m'* is the dimensionless mass of the ship.

Table 2 Hull hydrodynamic derivatives

	Value x 10^{-5}	
	Clarke et al	CFD
Yv'	-2213.09	-1281.67
$Y\dot{v}'$	-1368.5	-
Yr'	385.134	433.397
$Y\dot{r}'$	-104.3	-
Nv'	-728.347	-710.908
$N\dot{v}'$	-867	-
Nr'	-301.472	-268.740
$N\dot{r}'$	-716	-

In table 3 are presented the rudder derivatives:

Table 3 Rudder derivatives

	Value x 10^{-5}
Yδ'	338.151
Nδ'	-169.077

4 Results and discussion

The ship's dynamic stability criterion calculated based on relation (3) with empirically and numerically estimated derivatives which is negative in both and, therefore, the vessel is unstable from the course keeping point of view. The values of stability criterion *C* are presented in Table 4.

Table 4 Stability criterion C values

	Value x 10^{-5}	
	Clarke et al	CFD
C	-2.63	-5.46

Turning circle simulations was conducted for a 37000 tdw chemical tanker. The simulations involved using empirical estimated derivatives and CFD obtained linear static hydrodynamic derivatives. Additionally, turning circle characteristics were obtained using Lyster and Knights [1] statistical formulas. The obtained results were then compared with data from the actual sea trials. According to ITTC, sea states of 3 or less and a true wind speed below Beaufort 6 (20 Kn) are the desired conditions for the sea trials. The conditions for the sea trials are presented in Table 5.

Table 5 Sea trials conditions

Wind	[°B]	2-3
Sea state	[°D]	1-2
Water temperature	[°C]	6
Stream flow	(N-S)	1.5
Depth	[m]	69
Shaft power	[kW]	8667
Draft	[m]	10.5
Speed	[m/s]	7.96

A set of two simulations were performed. In the first simulation, derivatives used were all determined by empirical formulas [4] and in second simulation the velocity dependent derivatives were replaced with velocity derivatives obtained with CFD techniques.

In Table 6 are presented the coefficients for dimensionless values of mass, centre of gravity and yaw moment of inertia used in simulations. Values for *m'*, x_G*'* and *Izz'* were determined with equations (7), (8) and (9) while the value of yaw moment of inertia *Izz* is calculated with equation (10).

$$m' = \frac{m}{0.5\rho {L_{PP}}^2} \quad (7)$$

$$x'_G = \frac{x_G}{L_{PP}} \quad (8)$$

$$Izz' = \frac{Izz}{0.5\rho {L_{PP}}^5} \quad (9)$$

$$Izz = {K_{zz}}^2 m \quad (10)$$

where K_{ZZ} is the yaw radius of turning circle and can be approximated as $0.25L_{PP}$ [5].

Table 6 Coefficients used in simulations

	Value x 10^{-5}
m'	1722.24
x_G'	1149.14
Izz'	103.981

According to ABS (American Bureau of Shipping), all the manoeuvres, except stopping, are to be executed on both port and starboard and averaged values are to be used for rated and non-rated criteria. A comparison of turning circle trajectories is shown in Figure 3. Numerical simulations don't consider the direction of rotation of the propeller and the environmental conditions, so that the ship's trajectory is symmetrical on both sides.

An error comparison between the sea trials and simulations results is presented in Table 8. The CFD obtained derivatives give the best results with the minimum error of 4% at the transfer value and maximum error of -10% at the advance value. Tactical diameter gives a 7% error and steady turning diameter gives a 9% error. At the opposite pole are the results obtained with the help of hydrodynamic derivatives empirically determined with a minimum error of 13% at the transfer value and maximum error of 93% at the steady turning diameter value. Advance gives a -26% error and tactical diameter gives a 30% error. Lyster and Knights relations have a good approximation of turning circle characteristics with a minimum error of just 2% at transfer value and a maximum error of 26% at steady turning diameter value. Advance gives an error of -9% and tactical diameter gives an error of 13%. It can be observed that advance value is underestimated in all determinations and the rest of values are overestimated.

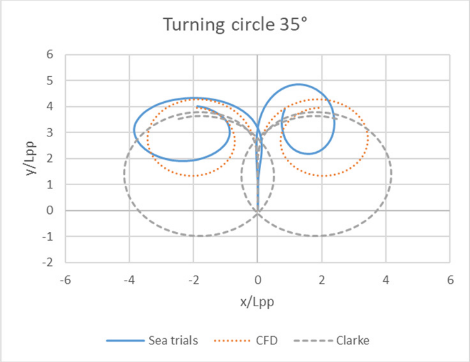

Figure 3 Comparison of turning circle trajectory

Table 7 Turning circle characteristics

	Sea trials	CFD	Clarke et al	Lyster and Knights
AD/L	3.42	3.08	2.54	3.12
TR/L	1.68	1.75	1.90	1.72
TD/L	3.19	3.42	4.16	3.6
STD/L	2.31	2.52	4.47	2.92

Table 8 Error comparison

	Error [%]		
	CFD	Clarke et al	Lyster and Knights
AD/L	-10	-26	-9
TR/L	4	13	2

TD/L	7	30	13
STD/L	9	93	26

To have a better view of the results, in Figure 4 can be observed a comparative diagram of turning circle characteristics.

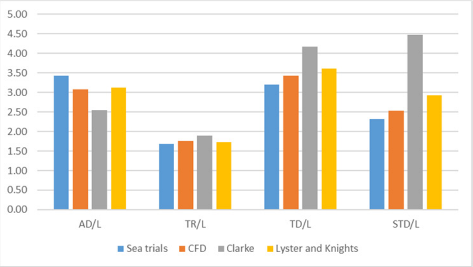

Figure 4 Comparative diagram of turning circle characteristics

5 Concluding remarks

Course-keeping and turning circle results refer to a 37000 tdw chemical tanker. Course-keeping has been determined based on stability criterion *C*. In both cases results that ship is unstable on route.

Turning circle analysis based on Lyster and Knights formulas and numerical simulations that use hydrodynamic derivatives obtained from both empirical and computational fluid dynamics (CFD) methods. The results have been compared with the actual sea trials data, obtained from turning circle manoeuvre. The results show good agreement between simulation with CFD obtained derivatives and sea trials data. All characteristics meet the IMO criteria of manoeuvrability.

Although the mathematical model selected uses only linear hydrodynamic derivatives, it has provided satisfactory results. Even so, it is necessary to determine and implement nonlinear hydrodynamic derivatives in the mathematical model in order to benefit from a high degree of confidence.

Future research will focus on estimating nonlinear hydrodynamic derivatives that are needed to solve the nonlinear mathematical model.

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