THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE XI – SHIPBUILDING. ISSN 1221-4620, e-ISSN 2668-3156
DOI: https://doi.org/10.35219/AnnUgalShipBuilding/2023.46.02
2023

ESTIMATION OF LINEAR HYDRODYNAMIC DERIVATIVES OF A 37000 TDW CHEMICAL TANKER USING VIRTUAL CAPTIVE MODEL TESTS

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ABSTRACT

Forecasting the hydrodynamic properties of a ship is crucial for assessing its maneuvering capabilities. This study presents the results of static drift and circular motion simulations conducted on a 37000 tdw chemical tanker. The calculations were carried out using the ISIS-CFD solver, accessible through the Fine^{TM}/Marine academic license provided by NUMECA. The flow solution was obtained by numerically solving the Reynolds-Averaged Navier Stokes equations, employing the k-ω Shear Stress Transport (SST) model to represent turbulence. The simulation results were used to determine the linear hydrodynamic derivatives, which were then compared with hydrodynamic derivatives estimated with empirical formulas proposed by Clarke et. al. [1] and Tribon Initial Design module in the absence of experimental results.

Keywords: manoeuvrability, hydrodynamic derivatives, CFD

1. Introduction

The ship hydrodynamics has faced significant challenges in predicting a ship's maneuvering abilities.

Throughout history, efforts to forecast ship maneuverability have heavily relied on empirical approaches or experimental model tests due to the absence of the analytical methods. Nevertheless, advancements in Computational Fluid Dynamics (CFD) capabilities and enhanced computational power have sparked significant interest among researchers in investigating maneuverability-related issues using CFD.

There are two primary Computational Fluid Dynamics (CFD) approaches commonly utilized for forecasting ship maneuverability. The first approach involves a comprehensive CFD-based simulation that replicates typical maneuvers using a steering rudder and a rotating propeller. Although direct CFD simulation holds promise for providing precise predictions, it is not yet sufficiently developed for practical applications due to its significant computational demands and the complex numerical techniques required to handle the coupled motions of the hull, rudder, and propeller.

An alternative approach, recognized for its practicality, involves employing a system-based method. This technique conducts maneuver simulations by solving mathematical models such as the Abkowitz model [2] and the MMG model [3]. In these models, hydrodynamic derivatives relevant to maneuvering

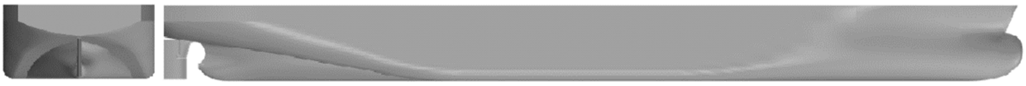

Figure 1 Ship geometry

are derived by virtually conducting captive tests using CFD techniques. The utilization of CFD methods to predict hydrodynamic derivatives has gained increasing attention within the domain of maneuverability studies in the recent years.

The numerical simulations performed in this study are carried out using the ISIS-CFD solver of the software FINE^{TM}/Marine provided by NUMECA. The solver is based on the finite volume method to build the spatial mesh of the transport equation to solve the Reynolds-Averaged Navier Stokes Equations (RANSE). Closure to turbulence is achieved through the two-equation Shear Stress Transport k-ω SST Menter model.

The curent study presents static drift and circular motion tests simulations for a 37000 tdw chemical tanker. The simulation results were used to predict the linear sway and yaw dependent hydrodynamic derivatives, which were then compared with linear hydrodynamic derivatives estimated with the empirical formulas proposed by Clarke et al [1], and the theoretical ones provided by the ''Manoeuvring'' code which is part of the module ''Calc & Hydro/Initial Design'' of the commercial software Tribon.

2. Geometry and analysis conditions

2.1. Ship geometry

The study was performed for a 37000 tdw chemical tanker which was built in a series of 21 ships by Constanta Shipyard Romania. Ship geometry is presented in Figure 1 and main characteristics of the ship are presented in Table 1.

Table 1 Main particulars

L_{PP} [m]	172
L_{WL} [m]	175
B [m]	32.2
T [m]	10.5
∇ [m$^{3]}$	46318.5
v [Kn]	15

Also, the characteristics of the rudder are presented in Table 2.

Table 2 Rudder characteristics

Rudder type	Horn
Rudder profile type	NACA0019
H_R (m)	8.6
A_R (m^2)	34.52

2.2. Computational domain and mesh

The domain consists of a rectangular prism (Figure 2) with the following dimensions:

- In the x direction - 6L_{WL};
- In the y direction - 4L_{WL};
- In the z direction - 3L_{WL} ;

The upstream limit is located at 1.5L_{WL} from the fore perpendicular; the downstream limit is located 3.5L_{WL} from the aft perpendicular; the lateral limits are located at 2L_{WL} from the ship centerline; the upper and lower limits are located at 0.5L_{WL} and 1.5L_{WL} above and below the free surface. The free surface is located at the design draft of the ship.

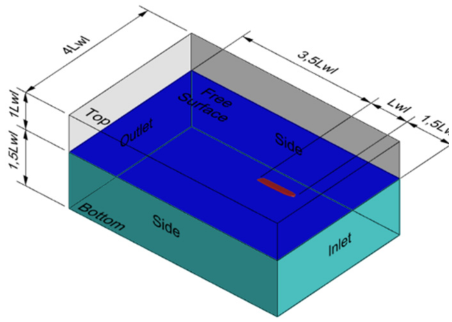

Figure 2 Computational domain

The mesh grids are generated using the HEXPRESS^{TM} grid generator integrated into the Fine^{TM}/Marine software package. This tool produces nonconformal, body-fitted, hexahedral unstructured meshes for intricate and irregular geometries suchs as hulls. Refinement of the grid near the bow, stern and rudder are shown in Figure 3.

A simplified rudder model was utilized to generate a smaller number of cells. Then, the high curvature surfaces were refined to preserve as much as possible, the geometry of the ship, resulting in a final number of approximately 2.5 million cells.

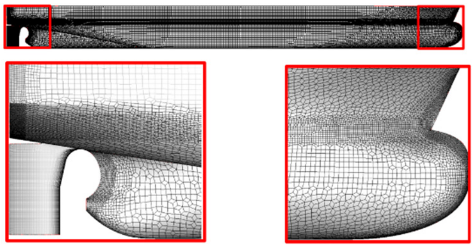

Figure 3 Mesh distribution on hull form and rudder

2.3. Computational cases

In order to obtain the linear hydrodynamic derivatives, simulations of an oblique towing tests and circular motion tests are carried out for the chemical tanker. Table 3 presents a summary of the computational conditions. All computations are performed under static conditions in which all ship motions are restricted.

Table 3 Computational conditions

Test	r'	β (°)
OTT	0	-0.5, -1, -2, -3, -6, -9
CMT	0.2, 0.4, 0.5	0

The simulations were performed in a single node Intel® Core i5 CPU with 4 cores, clock speed 1.8 GHz and 16 GB of physical memory. The time step used was calculated with (1) where Δt is the time step used, L_{WL} is the waterline length, v is the ship simulation speed and for simulating each case with stable output, the required physical time was about 24h per case.

$$\Delta t = 0.01\frac{L_{WL}}{v} \quad (1)$$

The ship speed U corresponds to $Fr = 0.186$. The Froude number is defined as $Fr = U / (gL_{WL})^{1/2}$ where g is the gravitational acceleration.

Computational forces and moments are non-dimensional in the following way:

$$Y' = \frac{Y}{0{,}5\rho {L_{WL}}^2 U^2} \quad (2)$$

$$N' = \frac{N}{0{,}5\rho {L_{WL}}^3 U^2} \quad (3)$$

where ρ represents the sea water density [1.025 t/m^3].

3. Results and discussion

3.1. Static drift

Static drift test is the towing of the ship in a tank in oblique condition, as show in Figure 4, where β represent the drift angle, X represents the force in x direction, Y represents the force in y direction and N represents the yaw moment.

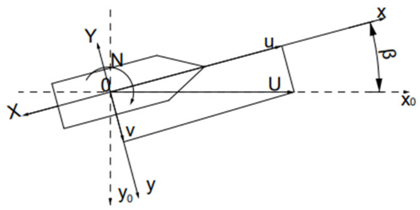

Figure 4 Static drift

For simulations, the same conditions were reproduced in CFD environment. The non-dimensional hydrodynamic forces and moments have been expressed as a function of the non-dimensional lateral component of current speed ($v' = -sin\beta$) as shown in Figure 5 and Figure 6. Using curve fitting, the variation of the non-dimensional lateral force and the non-dimensional rotation moment in the horizontal plane was approximated with a linear function depending on the non-dimensional lateral component of the velocity ($v' = v / U$).

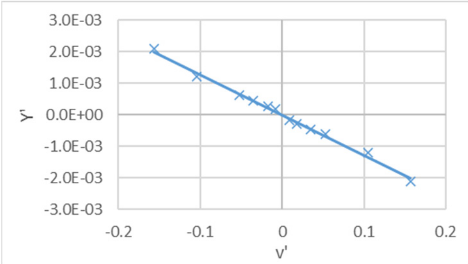

Figure 5 Representation of dimensionless lateral force vs dimensionless lateral velocity

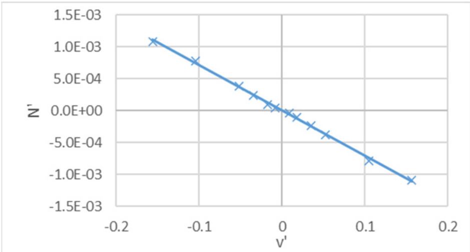

Figure 6 Representation of dimensionless yaw moment vs dimensionless lateral velocity

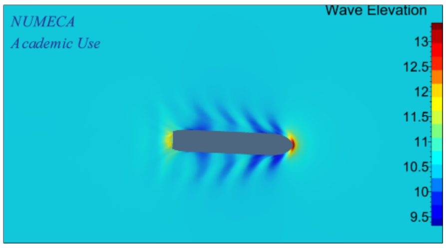

Figure 7 Free surface – β = -3°

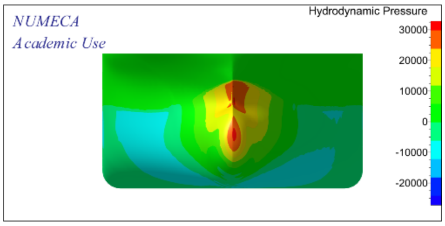

Figure 8 Hydrodynamic pressure – front view - β = -3°

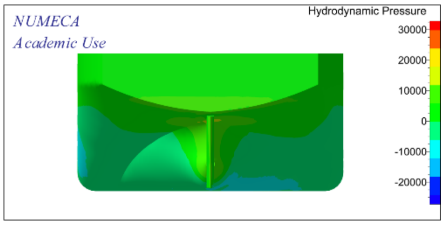

Figure 9 Hydrodynamic pressure – aft view - β = -3°

In Figure 7 is presented the free surface at drift angle $\beta = -3°$ and in Figures 8 and 9 is presented the hydrodynamic pressure on hull surface, views from front and from aft of the ship.

The non-dimensional hydrodynamic derivatives obtained from the static drift tests are presented in table 3.

Table 4 Static drift derivatives

	Value x 10^{-5}
Yv'	-1281.67
Nv'	-710.908

3.2. Rotating arm technique

An angular velocity is imposed to the model by securing it at the tip of a radial arm and rotating it around a vertical axis fixed within the tank. The model is positioned such that its x-axis and z-axis align perpendicular to the radial arm, and it's ideally attached to the arm at its centre of gravity. Due to this specific orientation, while the model revolves around the tank axis, it rotates at the rate denoted by r with its lateral velocity component v consistently being zero ($\beta = 0$). Simultaneously, its axial velocity component u remains equal to its linear speed ($u = U$).

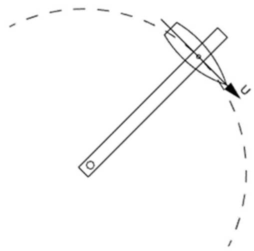

Figure 10 Rotating arm device

In order to determine hydrodynamic derivatives specific to circular motion tests, the model is rotated at different angular velocities. Angular velocity r changes with the variation of the radius of the circular trajectory R, according to (4). The same conditions were reproduced in CFD environment.

$$r = \frac{u}{R} \tag{4}$$

The dimensionless hydrodynamic forces and moments have been expressed as a function of the dimensionless angular velocity ($r' = rL/U$) as shown in Figures 8 and 9. Using curve fitting, the variation of the dimensionless lateral force and the dimensionless rotation moment in the horizontal plane was approximated with a linear function depending on the dimensionless angular velocity.

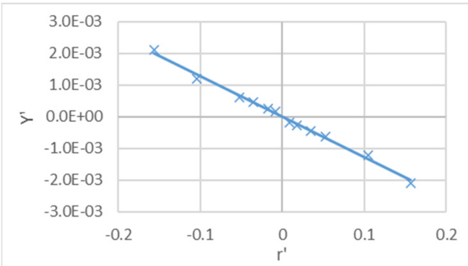

Figure 11 Representation of dimensionless lateral force vs dimensionless angular velocity

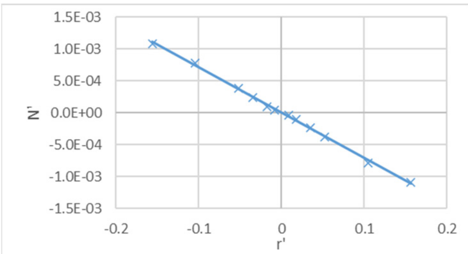

Figure 12 Representation of dimensionless yaw moment vs dimensionless angular velocity

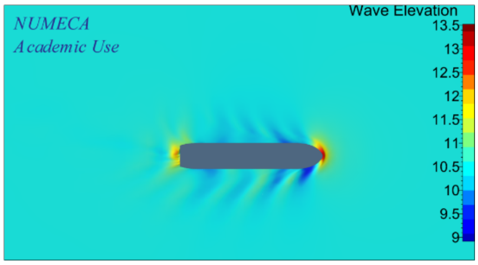

Figure 13 Free surface – r'= 0.4

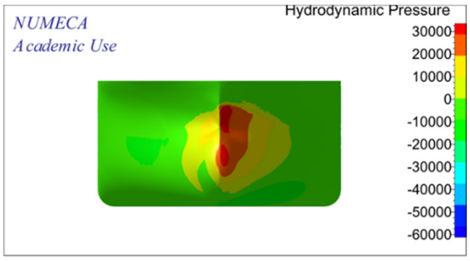

Figure 14 Hydrodynamic pressure – front view – r'= 0.4

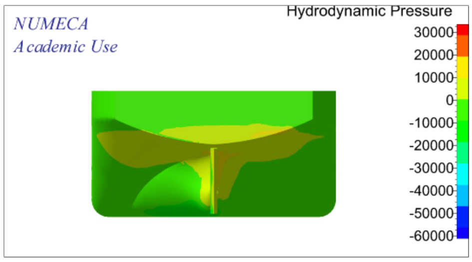

Figure 15 Hydrodynamic pressure – aft view – r'= 0.4

In Figure 13 is presented the free surface at dimensioless angular velocity *r'= 0.4* and in Figures 14 and 15 is presented the hydrodynamic pressure on hull surface, front and aft views.

The non-dimensional hydrodynamic derivatives obtained from circular motion tests are shown in Table 4.

Table 5 Rotating arm derivatives

	Value x 10^{-5}
Yr'	433.397
Nr'	-268.740

3.3. Theoretical determination of hydrodynamic derivatives

The non-dimensional linear hydrodynamic derivatives can be estimated using empirical formulas proposed by Clarke et al [1], and the ''Manoeuvring'' code which is part of the module ''Calc & Hydro/Initial Design'' of the commercial software Tribon. A comparison between the ones obtained with empirical formulas and with Tribon code are shown in Table 6.

Table 6 Comparison of dimensionless hydrodynamic derivatives

	Value x 10^{-5}	
	Clarke et al	Tribon code
Yv'	-2213.09	-2265.96
Yr'	385.134	486.947
Nv'	-728.347	-770.489
Nr'	-301.472	-312.298

The derivatives *Yv'*, *Nv'* and *Nr'* are in close agreement and the derivative *Yr'* show a good agreement.

3.4. Discussion

Linear hydrodynamic derivatives are predicted from lateral forces and yaw moments encountered by the ship model at different drift conditions and angular velocities. By using curve fitting to the data for dimensionless forces and moments as a function of dimensionless lateral component of velocity *v'* and dimensionless angular velocity, *r'*; the linear hydrodynamic derivatives, *Yv*, *Yr*, *Nv* and *Nr* can be predicted. A comparison between the derivatives obtained with CFD techniques and derivatives obtained theoretically is shown in fig. 12.

The derivatives *Yr'*, *Nv'* and *Nr'* are in close agreement while the derivative *Yv'* have significant a difference of 76.8% with Tribon code and 72.7% with Clarke et al [1]. In Table 7 is presented a comparison of differences between the derivatives.

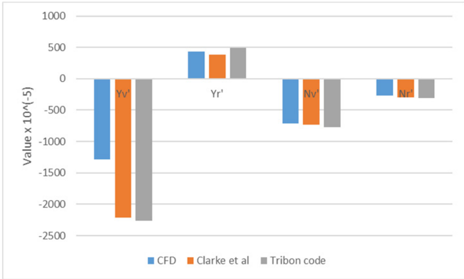

Figure 16 Comparison of hydrodynamic derivatives

Table 7 Difference comparison

Derivative	Diff [%]		
	Clarke et al – Tribon	CFD - Tribon	CFD - Clarke et al
Yv'	2.4	76.8	72.7
Yr'	26.4	12.4	-11.1
Nv'	5.8	8.4	2.5
Nr'	3.6	16.2	12.2

4. Concluding remarks

Prediction of ship hydrodynamic derivatives is an essential part of ship design to ensure that the design meets required maneuverability characteristics. In this study, linear hydrodynamic derivatives were determined using theoretical and CFD approaches.

Static drift and circular motion tests were carried out using ISIS-CFD solver disponible in Fine^{TM}/Marine software provided by Numeca. The simulation results are fitted to linear curves. As the results, the velocity-dependent derivatives and rotary-dependent derivatives are estimated. Resulting derivatives were compared with theoretical ones determined using empirical formulas proposed by Clarke et al [1], and the ''Manoeuvring'' code which is part of the module ''Calc & Hydro/Initial Design'' of the commercial software Tribon.

Linear derivatives *Yr'*, *Nv*' and *Nr'* shows a good agreement while the derivative *Yv'* have a significant difference. Further investigations are needed to validate the results. In conclusion, CFD and theoretical approaches can be used to determine the hydrodynamic derivatives but it must be taken into account that the latter have a fairly high degree of error and must be doubled by tests on an experimental model in a maneuvering basin.

Acknowledgements

The authors would like express their gratitude for all the support offered by Constanta Shipyard Romania, Diagnose and Measurements Group Ltd and NUMECA Academic Group.

The study was supported by the Research Centre of the Faculty of Naval Architecture of "Dunarea de Jos" University of Galati.

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Paper received on October 26th, 2023

