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ELIGMOS: Time domain simulation of the manoeuvring of ships in deep and shallow waters

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ABSTRACT: Calm water manoeuvring simulations are commonly used at the initial design stage as they provide useful an practical insight concerning ship's manoeuvrability and compliance with the relevant IMO criteria. In this paper the authors present ELIGMOS; a time-domain numerical code utilizing a 3-DOF manoeuvring model based on the MMG method. For the validation of the code's predictions, a comparison with the experimental results on the turning ability of S-175 has been conducted. The paper presents also the investigation performed regarding the accuracy of certain empirical formulas for the derivation of the manoeuvring derivatives is also investigated, especially for the case of shallow water where experimental data and results remain scarce. The code is written in C++ programming language, adopting a modular approach for the calculation of external forces and moment (i.e. hydrodynamic hull, rudder and propeller) which allows future enhancements with the introduction of additional terms.

KEYWORDS: manoeuvring; time domain simulations; S-175; shallow water performance; turning circle

1. INTRODUCTION

The manoeuvring behavior of a ship is usually assessed by sea trials or model tests in calm water. However, due to the high cost of such experiments and full scale sea trials, numerical methods have been developed for the fast and accurate calculation of ship's trajectories based on CFD techniques or time-domain simulation tools. One of the most well-known method, is the one proposed by the Japanese Manoeuvring Modelling Group (Inoue et al., 1981a). This method consists of empirical and semi-empirical formulas for rudder, propeller and hydrodynamic/hull forces and moments' approximations. Since the first publication of the MMG report, several other versions of this method have been published. For instance, Sano and Yasukawa (2008) proposed third-order polynomials for the estimation of the horizontal sway force and yaw moment. Furthernore, corrected formulas for rudder inflow angle and rudder inflow velocity are proposed.

When shallow water (h/d=1.2÷1.5) manoeuvring is considered, the manoeuvring properties of the ship change. Due to the increasing resistance in such seas, ships usually sail in lower speed to avoid possible risks arisen by other ships sailing nearby. In shallow water the flow due to drifting passes around the ship rather than under the keel resulting in changes of the lateral forces (Hooft, 1973). Prediction of ship's manoeuvrability in such areas is usually difficult to be assessed due to the lack of experimental data. The only ship that was tested in both deep and shallow water is the legendary Esso Osaka (Crane, 1979). For that reason, approximate expressions for deriving both the linear and the nonlinear manoeuvring derivatives have been developed by the Japanese MMG (23rd ITTC, The Manoeuvring Committee) and by Ankudinov et al., (1990). Ankudinov's formulas cover a greater range of under keel clearance (1.085<h/d<5). In the context of the present work, Ankudinov's practical formulas were used, which allowed for a qualitative assessment of S-175 manoeuvring behavior in shallow water to be conducted. Finally, corrections for the added inertia terms in shallow water obtained using Li and Wu's (1990) approximate formulas.

2. MATHEMATICAL MODEL

For the needs of the analysis conducted two coordinate systems were used. The first one is the inertial system which is fixed at O and XY plane remains always parallel to the mean free surface. The second one, M-xyz is fixed on the ship, with M locate at her midpoint and on the undisturbed free surface.

The nonlinear system of surge, sway and yaw equations of motion are shown below.

$$(m' + m'_x)\dot{u}' - (m' + m'_y)v'r' - m'x'_G r'^2 = X' \quad (1)$$

$$(m' + m'_x)u'r' + (m' + m'_y)\dot{v}' + m'x'_G\dot{r}' = Y' \quad (2)$$

$$(I'_N + J'_N)\dot{r}' + m'^{x'_G}(\dot{v}' + u'r') = N' \quad (3)$$

where u΄=u/Uo, v΄=v/Uo, r΄=rL/Uo (Uo is the speed at the beginning of the turning circle) are the dimensionless surge, sway and yaw velocities, m'_x, m'_y and J'_z the dimensionless surge and sway added masses and yaw added moment of inertia, respectively. In addition, m΄ and x'_G are the dimensionless mass of the ship and longitudinal position of the centre of gravity with respect to the body fixed coordinate system. Finally, X΄, Y΄ are the dimensionless external surge and sway forces whereas N΄ the dimensionless external yaw moment.

Ship's mass and added masses are getting dimensionless using the expressions shown below.

$$m', m'_x, m'_y = {m, m_x, m_y}/{0.5\rho L^2 d} \quad (4)$$

$$I'_N, J'_N = {I_N, J_N}/{0.5\rho L^4 d} \quad (5)$$

where L is ship's length between perpendiculars, d is the draught of the ship while ρ is the density of the water.

Surge and sway forces as well as yaw moment have been dimensionless by using the following expressions in order to comply with the experimental input values provided.

$$X' \;, Y' = {X \;, Y}/{0.5pLdU_o^2} \quad (6)$$

$$N' = {N}/{0.5pL^2dU_o^2} \quad (7)$$

Expressions for the external forces and moment are depicted below.

$$X' = X'_o + X'_H + X'_R + (1 - t_p)X'_P (6)$$

$$Y' = Y_H + Y'_R \quad (8)$$

$$N' = N'_H + N'_R \quad (9)$$

where subscripts H, R, P denote hull/hydrodynamic forces and moment, rudder and propeller forces and moment.

1.1 Wave resistance

Wave resistance is calculated by using the simple expression

$$X'_o = a_0 u'u' \quad (10)$$

where α_o is obtained by regression analysis on experimental data. In the present work α_o obtained from Son and Nomoto's (1982) study on S-175.

1.2 Hull/hydrodynamic forces and moment

For the calculation of hull/hydrodynamic forces and moment third-order polynomials are used.

$$X'_H = X'_{vv}v'v' + X_{vr}v'r' + X_{rr}r'r' \quad (11)$$

$$Y'_H = Y'_v v' + Y'_r r' + Y'_{vvv}v'v'v' + Y'_{vvr}v'v'r' + Y'_{vrr}v'r'r' + Y'_{rrr}r'r'r' \quad (12)$$

$$N'_H = N'_v v' + N'_r r' + N'_{vvv}v'v'v' + N'_{vvr}v'v'r' + N'_{vrr}v'r'r' + N'_{rrr}r'r'r' \quad (13)$$

X'_{vv}, X'_{vr}, X'_{rr} etc are the manoeuvring derivatives obtained from model tests. Later on, we will also use practical formulas provided by the Japanese MMG for the calculation of these coefficients in order to investigate their applicability.

2.2 Propeller forces

Propeller's thrust according to Sano and Yasukawa (2008) is modeled using expression (14).

$$T = \rho\, rps^2 D^4\, K_T(J_P) \quad (14)$$

where rps is propeller's revolutions per second, D the diameter of the propeller and K_T is the thrust coefficient which is a function of the advance ratio J.

When the propeller operates at the wake of the ship, the axial velocity at this region decreases by a wake fraction (1-w_p). The effect of the manoeuvring motion on w_p is taken into account by implementing the empirical equation (Inoue et al., 1981b)

$$w_p = w_{po} e^{(C_1 \beta_p^2)} \quad (15)$$

where C_1=-8.0 and β_p is the inflow angle at propeller position derived by the expression $\beta_P = \beta - x'_P r'$. β is the drift angle of the ship due to the turning motion and x'_P is the dimensionless longitudinal position of the propeller. Propeller's revolutions per second for a service speed of U_o=0.879m/s which corresponds to a Froude number of Fn=0.15, has a value of rps=10.05.

2.3 Rudder forces and moment

Surge and sway rudder forces as well as yaw rudder moment are calculated using the following formulas.

$$X_R = -(1 - t_R) FN sin\delta \quad (16)$$

$$Y_R = -(1 + aH) FN cos\delta \quad (17)$$

$$N'_R = -(x'_R + aHx'_H) FN cos\delta \quad (18)$$

In equations (16) to (18) FN stands for the normal force on the rudder which can be found using expression (19) according to the MMG method (Inoue, 1981b)

$$FN = 0.5\rho A_R f_a U_R^2 sina_R \quad (19)$$

In expression (18) A_r is rudder's area whilst f_α is the gradient of the lift coefficient which can be calculated using expression (20)

$$f_a = {}^{6.13\Lambda}/_{(2,25 + \Lambda)} \quad (20)$$

where Λ is the aspect ratio of the rudder.

Finally, $U_R = \sqrt{(u_R^2 + v_R^2)}$ and $\alpha_R = \delta - \left(\frac{v_{RP}}{u_R}\right) - \gamma_R(\beta - l'_R r')$ are the inflow velocity and angle at the region of the rudder.

The components of the rudder's inflow velocity in our study are defined using the expressions found in Sano and Yasukawa (2008). The difference between starboard and port turning due to propeller's action, is modeled by incorporating different values for the coefficient γ_R which also accounts for the reduction of the lateral inflow velocity along the hull of the ship.

3. RESULTS

In the context of the present work, the S-175 container ship in model scale is used in our calculations. Both starboard and port turning circles after setting the rudder at ±35° are modeled and the accuracy of certain approximate formulas is examined both for both deep and shallow water cases. The principal particulars of S-175 in full and model scale are given in Table 1.

Table 1. S-175 main particulars

Scale	1:1	1:50
L_{bp}	175.0 m	3.500 m
B	25.40 m	0.508 m
d	9.50 m	0.190 m
x_G	-2.5445 m	-0.05089 m
Cb	0.572	0.572

3.1 Experimental input

Experimental data concerning the non-dimensional manoeuvring derivatives and other interaction coefficients are included in Table 2.

Table 2. Input data for S-175 Container Ship

m'_x	0,0044	N'_r	-0.0409
m'_y	0,1299	N'_{vvv}	0.0275
J'_N	0.0077	N'_{vvr}	-0.7811
X'_{vv}	-0.0711	N'_{vrr}	0.0287
X'_{vr}	-0.0573	N'_{rrr}	-0.4220
X'_{rr}	0.0037	α_o	-0.0078
Y'_v	-0.2137	ε	0,9210
Y'_r	0.0446	κ	0,6310
Y'_{vvv}	-2.0080	wpo	0.1684
Y'_{vvr}	0.3942	t_R	0.2900
Y'_{vrr}	-0.7461	αH	0,2370
Y'_{rrr}	0.0326	$\gamma_{R\,(+)}$	0,1930
N'_v	-0.0710	$\gamma_{R\,(-)}$	0,0880

Figures of starboard and port turning circles compared against experimental results can be seen in Figure 1.

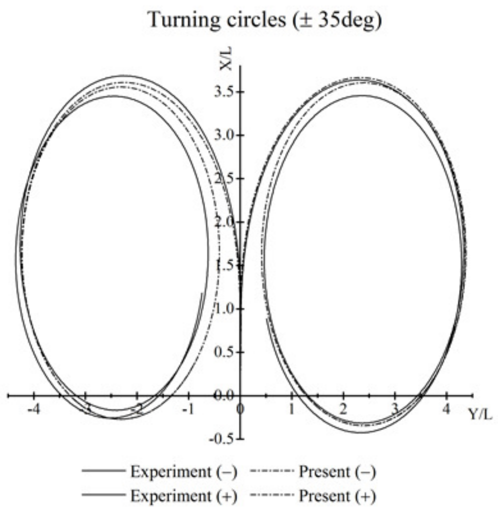

Figure 1. Starboard and port turning circles compared against experimental results

The accuracy succeeded by our numerical simulations versus the experimental results with regards to manoeuvring characteristics is depicted at Table 3.

Table 3. Error between numerical and experimental results (starboard turn)

	AD/L	TR/L	DT/L
Num	3.664	2.330	4.374
Exp	3.639	2.296	4.332
% error	0.710	1.492	0.953

Table 4. Error between numerical and experimental results (port turn)

	AD/L	TR/L	DT/L
Num	3.610	-2.260	-4.236
Exp	3.686	-2.261	-4.351
% error	-2.07	-0.067	-2.638

Figures that show the comparison of forward speed and yaw rate between numerical and experimental results are also added below.

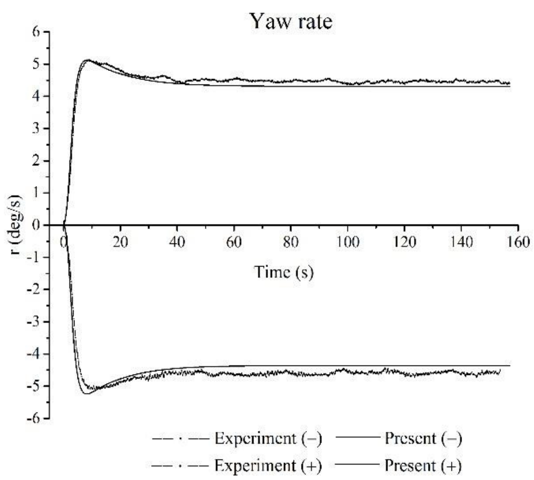

Figure 2. Yaw rate during starboard and port turns

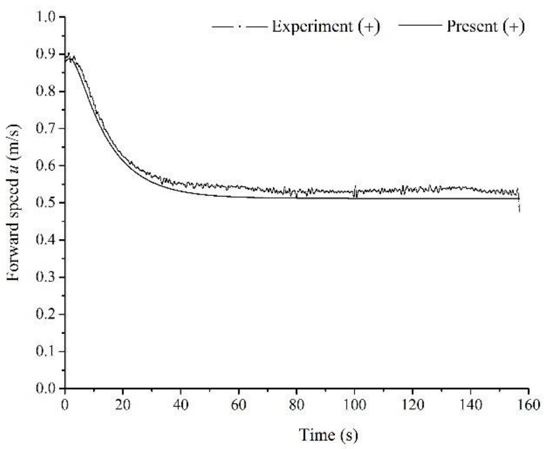

Figure 3. Forward speed during starboard turn

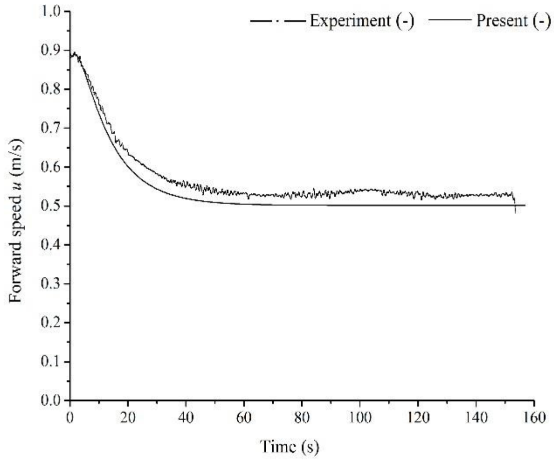

Figure 4. Forward speed during port turn

3.2 Empirical formulas

Studies have been conducted in order to examine the validity of empirical formulas for the derivation of the linear as well as nonlinear manoeuvring derivatives. For this purpose, MMG formulas are implemented (Inoue et al, 1981a). Furthermore, shallow water effect is investigated by implementing Ankudinov's formulas

For a sea depth to ship's draught ratio of 1.2. the estimated values of manoeuvring derivatives for both cases can be found in Table 5.

Table 5. Estimated values for manoeuvring derivatives and added masses and yaw added moment of inertia for deep and shallow water

	Deep water (MMG)	Shallow water (Ankudinov)
m'_x	0.00440	0.02451
m'_y	0.12990	0.41710
J'_N	0.00770	0.02222
Y_v	-0.28677	-0.92741
Y_r	0.08527	0.17828
N_v	-0.10857	-0.27027
N_r	-0.04684	-0.10393
$Y_{v\|v\|}$	0.90020	3.91669
$Y_{r\|r\|}$	0.00338	0.00750
Y_{vvr}	-0.12790	-0.41364
Y_{vrr}	-0.95247	-3.08024
$N_{v\|v\|}$	-0.00924	-0.40214
$N_{r\|r\|}$	-0.04973	-0.12225
N_{vvr}	-0.62309	-1.41720
N_{vrr}	0.05697	0.12957

*m'_x, m'_y, J'_N for deep water are the same as the experimental values

Surge and sway added masses as well as yaw added moment of inertia terms were corrected implementing Li and Wu (1990) expressions.

Fig. 5 depicts the comparison of starboard and port turning circles between the experimental results and the results derived after the aforementioned empirical methods were used. The curves for shallow water are also plotted in order to show qualitatively the way that the under keel clearance affects ship's manoeuvring characteristics.

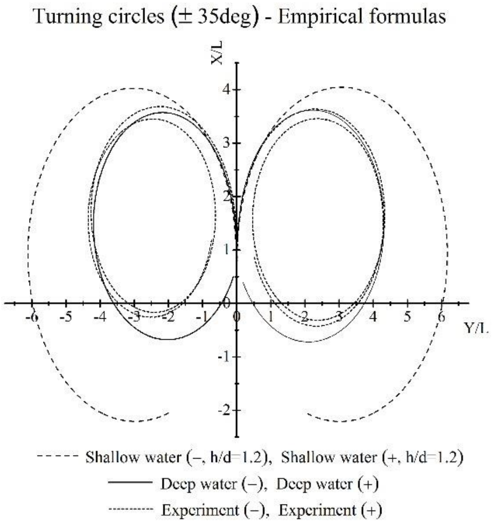

Figure 5. Turning trajectories using empirical formulas to derive the manoeuvring coefficients including shallow water simulations

Comparison of the manoeuvring characteristics between experimental and numerical results based on approximate expressions is illustrated in Tables 6 and 7.

Table 6. Error between experimental and numerical results using empirical methods (starboard turn)

	AD/L	TR/L	DT/L
Num	3.618	2.238	4.315
Exp	3.639	2.296	4.332
% error	-0.572	-2.521	-0.411

Table 7. Error between experimental and numerical results using empirical methods (port turn)

	AD/L	TR/L	DT/L
Num	3.573	-2.166	-4.195
Exp	3.686	-2.261	-4.351
% error	-3.071	-4.243	-3.594

4. DISCUSSION

Turning circle manoeuvring behavior of S-175 container ship in 3-DOF was investigated using time-domain numerical simulations. Fig. 1 shows that numerical results compare satisfactorily with experimental results. The analysis depicts that manoeuvring characteristics such as advance, transfer and tactical diameter coincide well with the relevant experimental elements. In several cases, especially for the starboard turn, the difference is negligible (below 1%). Furthermore, satisfactory agreement can be noted for the time histories of forward speed and yaw rate during the turning motion. Acceptable agreement was found when manoeuvring derivatives were calculated using approximate formulas for the first 180^o of the turning motion. This is very useful when experimental data are not available. Although agreement seems to be acceptable, additional research is needed in order to gain more confidence regarding the validity and applicability of the aforementioned formulas.

Results when studying the effect of shallow water on manoeuvring characteristics show that when h/d=1.2, the trajectory of the ship becomes larger. From the results presented in Fig. 5 we see that advance and transfer characteristics of shallow water trajectories are approximately 11% and 34% larger compared against the experimental values for starboard turn while in case of port turn they are 9% and 34% larger respectively. Furthermore, the tactical diameter is around 42% larger than the experimental value in starboard turn while it is 41% larger in port turn. For fine ship hulls there is such a tendency whilst, full form ships usually tend to have shorter trajectories. However, the attained accuracy that the presented results have, must be validated by relevant experimental results. In the present study, it is also assumed that only the manoeuvring derivatives, the surge and sway added masses and the yaw added moment of inertia change due to the effect of shallow water. However, previous studies have shown that interaction coefficients between rudder-propeller and the hull itself are also affected by shallow water, parameters that are not considered here. For that reason, future research is needed in order to establish accurate models for simulating the manoeuvring behavior of ships in shallow water.

5. CONCLUSION

In the present paper, the numerical tool ELIGMOS, developed in-house, capable of simulating in time domain the manoeuvring behavior of a ship has been presented. Its predictions have been verified using the well-known S-175 container ship both in deep and shallow water. The results suggest that the proposed MMG method from Sano and Yasukawa

(2008) seems to be quite reliable for the investigation of 3-DOF manoeuvring in calm water. In case of lack of experimental data, practical formulas can be used to study the manoeuvring behavior. The 3-DOF mathematical model presented herein together with all the data provided can be used for validation purposes of numerical tools which are under development and simulate ship manoeuvring behavior in calm water.

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REFERENCES

Ankudinov, V.K., Miller, E.R., Jakobsen, B.K., and Daggett, L.L., 1990, "Manoeuvring performance of tug/barge assemblies in restricted waterways",. MARSIM & ICMS Proceedings, pp. 515-525. Tokyo

Hooft, J.P., 1973, "Manoeuvring Large Ships in Shallow Water-I", Journal of Navigation, Vol.26, Issue 2

Inoue, S., Hirano, M., and Kijima, K., 1981a, "Hydrodynamic derivatives on ship manoeuvring", International Shipbuilding Progress, Vol. 28, No. 321.

Inoue, S., Hirano, M., Kijima, K., and Takashina, J., 1981b, "A practical calculation method of ship maneuvering motion", International Shipbuilding Progress, Vol. 28 No. 325

Li, M., and Wu, X., 1990, "Simulation calculation and comprehensive assessment on ship manoeuvrabilities in wind, wave, current and shallow water", Proceedings of MARSIM & ICMS, pp. 403-411, 459-465. Tokyo.

Proceedings of the 23rd ITTC, "Report of the Manoeuvring Committee", Vol. I, pp. 153-200

Sano, M., and Yasukawa, H., 2008, "Manoeuvring Motions of KVLCC1 and KVLCC2 using MMG model", SIMMAN Proceedings, Volume E, pp. 51-55. Copenhagen.

Son, K., and Nomoto, K., 1981, "On the coupled motion of steering and rolling of a high speed container ship", Journal of the Society of Naval Architects of Japan, 180, pp. 311-319

Vantorre, M., 2001, "Manoeuvring coefficients for a container carrier in shallow water: an evaluation of semi-empirical formulae", Mini Symposium on Prediction of Ship Manoeuvring Performance, pp. 71-81, Tokyo