Numerical analysis of the container vessel's self-propulsion at different rudder deflection angles

Michał Wawrzusiszyn[a], Radosław Kołodziej[a, b], Sebastian Bielicki[a]

[a] *Ship Design & Research Centre, CTO S.A, 80-392 Gdańsk, Szczecińska 65, Poland*
[b] *Gdansk University of Technology, 80-233 Gdańsk, Narutowicza 11/12, Poland*
Michal.Wawrzusiszyn@cto.gda.pl, Radoslaw.Kolodziej@cto.gda.pl, Sebastian.Bielicki@cto.gda.pl

1. Introduction

Nowadays, CFD becomes one of the most commonly used research method in ship hydrodynamics, limited to the analyses of hull resistance in calm water. With continuously improving computing power and increasingly more accurate numerical methods it is possible to simulate more complex cases. State of the art CFD tools also enable development of new ways of assessing ship maneuvering performance. This paper presents an attempt on using CFD for evaluation of the coefficients used in the formulation of rudder forces applied in the ship manoeuvring model. These coefficient are normally evaluated in captive tests of the hull with working propeller and rudder deflected at different angles; the paper presents the results of CFD simulation of this kind of experiment. The test case used in the analyses is the well known the KRISO Container Ship (KCS). The computations were carried out at model scale 1:50, for which the reference model test results are available. Comparison of CFD and experimental results is presented.

2. Mathematical model

There are many approaches to decomposition of forces acting on the ship during manoeuvring described in literature. According to MMG standard method [1] they can be presented as sum of following components:

$$X = X_H + X_P + X_R \quad (1)$$
$$Y = Y_H + Y_R \quad (2)$$
$$N = N_H + N_R \quad (3)$$

where:
X, Y, N - Surge force, lateral force, yaw moment
X_H, Y_H, N_H - Surge force, lateral force, yaw moment acting on the hull
X_R, Y_R, N_R - Surge force, lateral force, yaw moment acting on rudder
X_P - Surge force generated by the propeller

Effective rudder forces and moment are expressed as:

$$X_R = -(1 - t_R)F_N \sin\delta \quad (4)$$
$$Y_R = -(1 + a_H)F_N \cos\delta \quad (5)$$
$$N_R = -(x_R + a_H x_H)F_N \cos\delta \quad (6)$$

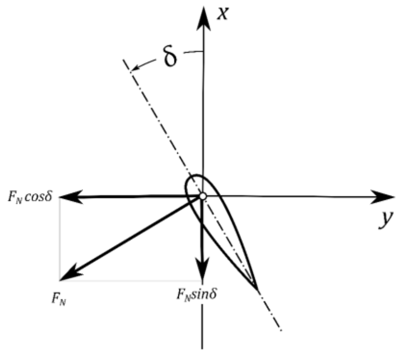

Fig. 1: Coordinate system

where:
F_N - Rudder normal force
t_R - Steering resistance deduction factor
a_H - Rudder force increase factor
x_H - Longitudinal coordinate of point of application
x_R - Longitudinal coordinate of rudder position (~$0.5L_{PP}$)

Mathematical model of maneuvering ship includes certain parameters that are unknown at initial design stage (a_H, x_H and t_R) thus they can be evaluated only by the means of model tests or numerical analyses. The evaluation consists in analysis of forces acting on hull and rudder in vessel moving straight ahead with rudder deflected at certain angles and constant speed, when forces Y_H and N_H on right hand sides of equations (2) and (3) are equal to zero. Forces X_H+X_P are assumed to be constant for considered propeller rate of revolution and vessel speed (constant propeller advance ratio).

3. CFD Simulation

The computations were carried out at model scale 1:50 using the Reynolds Averaged Navier-Stokes Equations (RANSE) method. The CFD method applied is based on previous publications for NuTTS conferences [2][3]. Meshing and flow simulations were conducted with use of Star CCM+ 2019.1. Analyses were done with the use of the Estimating Hull Performance (EHP) module.
As turbulence model the Realizable K-Epsilon (two-layer all-y+ wall treatment) was used. The mean value of y+ on the hull was about 3.2 and below 1.0 in rudder/propeller region. Main particulars of the hull and propeller are presented below.

Fig. 3: Propeller CP572

Propeller CP572	**Value**
Diameter [m]	0.160
Pitch ratio [-]	1.240
Hub ratio [-]	0.333
Expanded area ratio [-]	0.640
Direction of rotation	Left

Main hull particulars	**Unit**	**Value**
Model scale	[-]	1:50
Length b.p.	m	4.600
Length of waterline	m	4.649
Breadth	m	0.644
Draught	m	0.216
Displacement volume	m^3	0.416
Surface wetted area	m^2	3.781
Block coefficient	[-]	0.651
Midship section coefficient	[-]	0.985

Configuration for propulsion analyses is presented in Fig. 4. The flow was computed in the rectangular domain of the following dimensions: [6L; 5L; 2.5L], where L is the hull length. Analyses were divided into three parts:
- Mesh sensitivity study;
- Bare hull computations;
- Appended hull computations with working propeller.

Mesh sensitivity study with bare hull (half domain) was done. The size of mesh was analysed against influence on resistance value. Taking into account almost constant value of resistance for meshes 3, 4 and 5, mesh No. 3 was used for further computations as the optimal compromise providing the mesh-independend solution (see the table below).

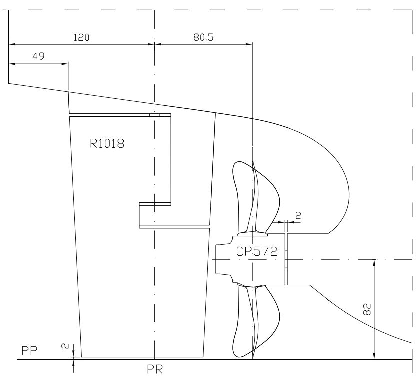

Fig. 4: Propulsion arrangement

No.	**Mesh size [Num. of cells]**	**y+**	**Size of base element [m]**	**Resistance [N]**	**Relative resistance [%]**
1	1 840 000	9.65	1.000	11.226	94.45
2	2 410 000	5.64	0.095	11.310	94.57
3	**3 330 000**	**3.27**	**0.085**	**11.996**	**100.30**
4	4 510 000	3.25	0.750	11.992	100.27
5	7 960 000	2.82	0.600	11.960	100.00

During analyses with propeller the hull was fixed to reduce computation time. The free surface was modelled. Values of hull trim (0.078^{o}) and sinkage (-0.0046m) for propulsion analyses were determined from resistance computations.

Total mesh size for analyses with working propeller was about 8 000 000 cells (see Fig. 5). Seven rudder angels were analysed: 0^0; $\pm10^0$; $\pm20^0$; $\pm35^0$.
For resistance and propulsion computations a constant inlet velocity was set to 1.31m/s. Water density was set to 998.540kg/m^3 and dynamic viscosity was set to 1.0122×10^{-3} Pa-s.

The time step value was changed during computations:
t_s=0.030s – for development of a free surface and resistance stabilisation
t_s=0.001s – when propeller was rotated by 2.94^0 per one time step.

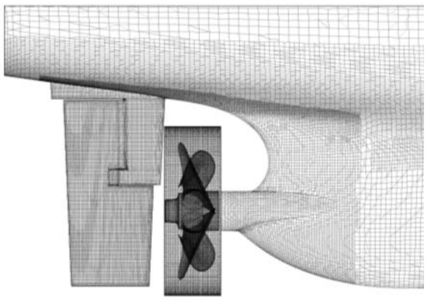

Fig. 5: Mesh presentation

Designed pitch ratio set on propeller geometry was $P/D_{0.7}$=1.24 while in experiment $P/D_{0.7}$=0.80. The constant propeller revolutions n=8.165 [RPS] were set according to propeller thrust value T_P=13.0[N] from model test results, where rudder was not deflected. Simulation of propeller rotation in the domain was solved by using sliding mesh.
Global forces in *i* and *j* direction on rudder and hull were monitored. Moment acting on the entire ship model (rudder, propeller and hull) was measured relative to z-axis located in hull LCB (x=2.23m).

4. Results of CFD analyses

Detailed results of computations are presented in below table and in Figs. 6-7.

Rudder angle δ [deg]	Propeller thrust T_P [N]	Hull resistance R_H [N]	Force X_{FN} [N]	Force Y_{FN} [N]	Force F_N [N]	Force X [N]	Force Y [N]	Moment N [Nm]	U_{Rmean} In front of rudder [m/s]
-35.0	14.54	24.60	-9.62	13.24	-16.36	-10.40	15.85	-34.35	1.289
-20.0	13.37	19.22	-3.95	13.45	-13.99	-6.16	16.15	-35.15	1.336
-10.0	13.05	16.81	-1.47	7.27	-7.41	-4.08	9.20	-19.64	1.351
0.0	13.17	16.12	-0.59	-0.19	0.19	-3.29	0.09	-0.26	1.362
10.0	13.13	16.75	-1.17	-7.59	7.68	-3.96	-9.17	19.48	1.357
20.0	13.55	19.08	-3.50	-13.26	13.66	-5.85	-15.75	33.70	1.344
35.0	14.48	24.06	-8.77	-18.37	20.08	-9.88	-21.68	46.58	1.306

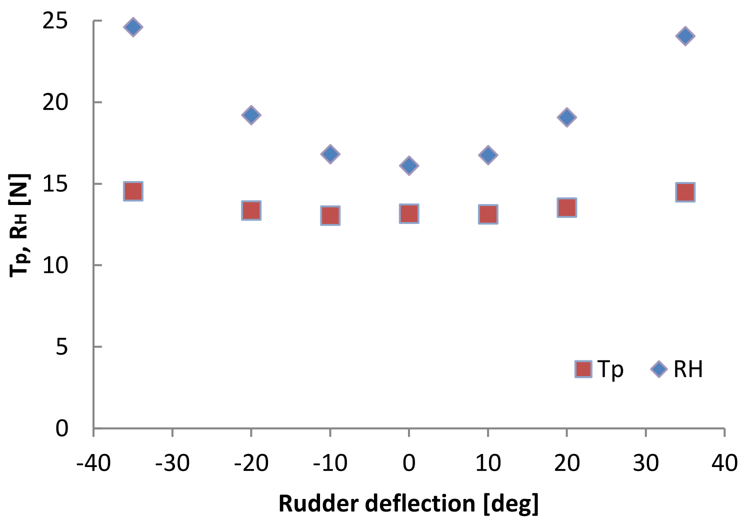

Fig. 6: Thrust and hull resistance comparison for different rudder angles

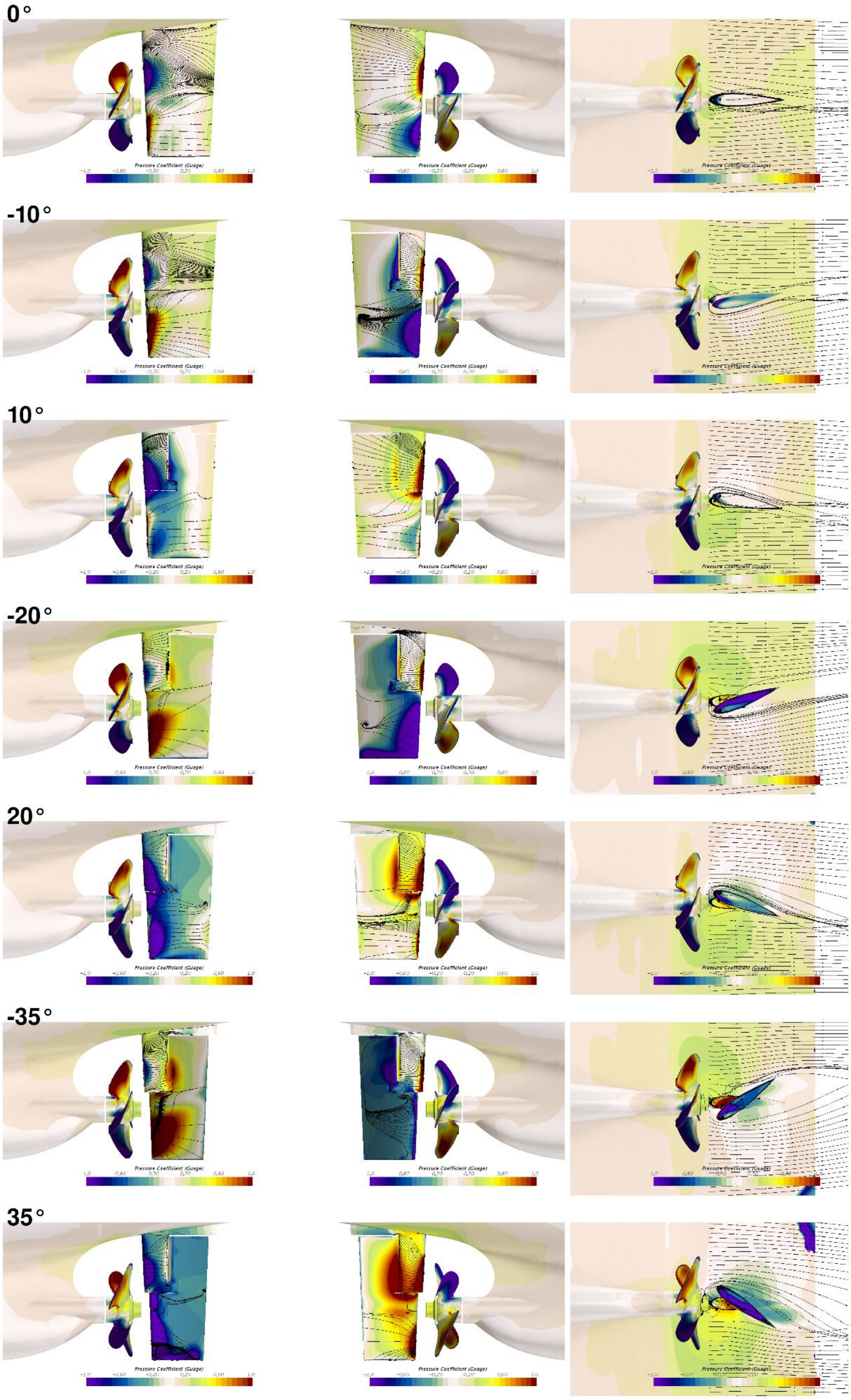

Fig. 7: Comparison of flow and pressure distribution for different rudder angles (left column port side, middle – starboard, right – top view)

During the resistance computations of bare hull the water velocity at propeller disc and rudder position was measured. The mean values were then used to calculate the wake fraction coefficients of propeller w_{P0} and rudder w_{R0} as presented below.

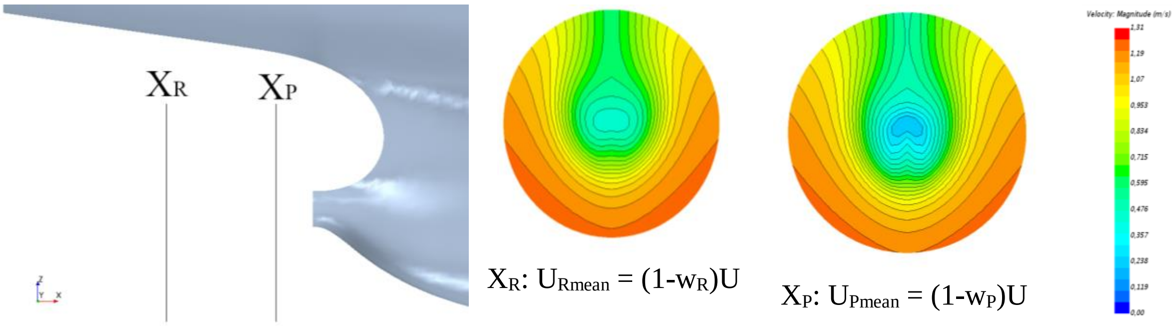

Fig. 8: Wake fraction coefficients

U_{Pmean} in propeller disc [m/s]	U_{Rmean} in front of rudder [m/s]	U [m/s]	w_{P0} propeller wake fraction coeff. [m/s]	w_{R0} rudder wake fraction coeff. [m/s]
0.893	0.954	1.309	0.271	0.319

In order to determine the hydrodynamic coefficients of rudder (t_R, a_H and x_H), forces acting on a hull X_H+X_P, Y_H and moment N_H can be expressed as a function of $F_N\sin\delta$ and $F_N\cos\delta$ [4]. It turns out that their relationship is almost linear for given propeller load, therefore derivatives can be approximated as a constant value (Fig. 8).

The results for -35° rudder deflection were substantially different from other results. It seems it is the consequence of the flow separation. Therefore the data for this particular rudder angle, were not taken into consideration during rudder coefficients calculation.

t_R	a_H	x_H	x_R
0.426	0.262	-0.346	-0.500

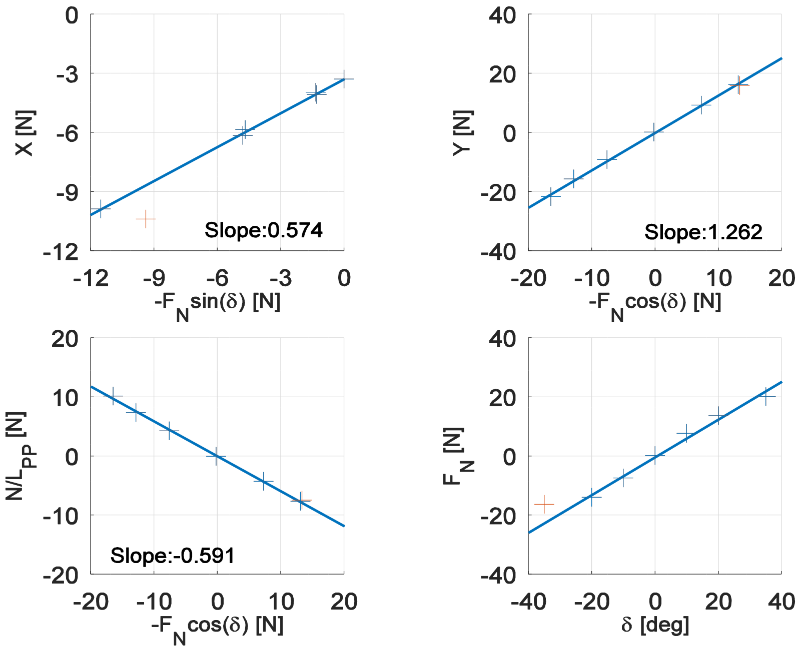

Fig. 8: Rudder coefficients approximation (red cross – points excluded from analyses)

5. Conclusions

- Considerable difference between water flow in rudder section for portside and starboard can be noticed.
- The coefficients resulting from CFD vary substantially from the experimental values. The difference may arise from neglecting in the experiment the force component generated on the rudder horn. Despite the simulations of turning test based on CFD and experimental coefficients show that the sensitivity of the model to the values of these coefficients is rather small the influence of rudder horn forces will be analysed to enhance the approach.

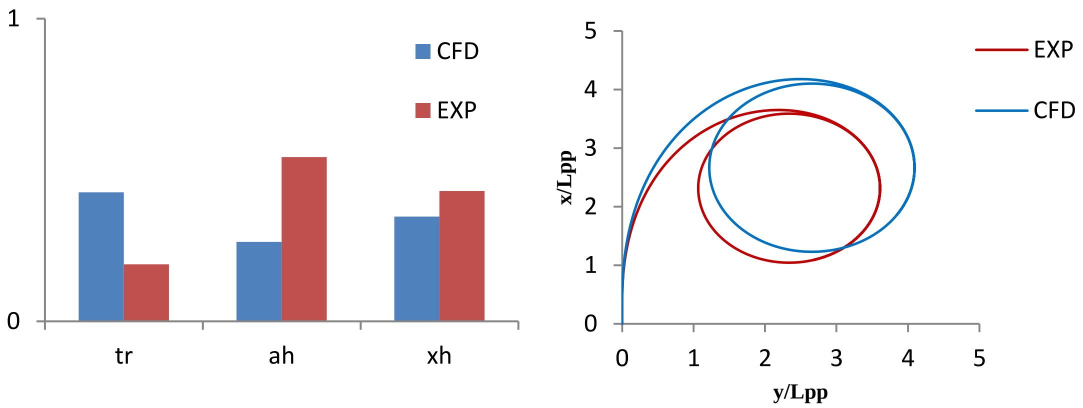

Fig. 9: Comparison of CFD and experimental results (left) and the results of turning simulation based on CFD and experimental input.

6. References

1. Yasukawa Y.Y.H., "*Introduction of MMG standard method for ship maneuvering*", Technol, 2015
2. Wawrzusiszyn M., Kraskowski M., Król P., Bugalski T., (2018). "Experimental and numerical hydrodynamic analysis of propulsion factors on R/V Nawigator XXI with pre-swirl stator device", 21st Numerical Towing Tank Symposium
3. Wawrzusiszyn M., Bugalski T., Hoffmann P., (2015). "Numerical simulations of ship hull-propeller interaction phenomena", 18th Numerical Towing Tank Symposium
4. Bielicki S.: Opracowanie matematycznego manewrowania statku na fali. Część1: identyfikacja charakterystyk kadłuba i opracowanie modelu matematycznego ruchu statku na wodzie spokojnej, Technical Report No. RH-2018/T-104, Gdańsk, December 2018