Simulations of Resistance, Sinkage and Trim of KCS in Calm Water Condition Using OpenFOAM

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SUBMISSION EXPLANATION

Test cases: Case 2.1
Name of the code: foam–extend 3.1, Naval Hydro pack, navalFoam solver
Institution: FMENA, University of Zagreb, Croatia

MATHEMATICAL MODEL

Two–phase model is based on a single set of mixture equations taking into account jump conditions at the free surface implicitly [1]. Volume of Fluid (VOF) method will be used for interface capturing [4].
Governing equations are the continuity equation:

$$\nabla\cdot\mathbf{u} = 0,$$

and the momentum equation:

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla\cdot(\mathbf{u}\mathbf{u}) - \nabla\cdot(\nu_e \nabla \mathbf{u}) = -\frac{1}{\rho}\nabla p_d.$$

Dynamic pressure jump conditions on the free surface:

$$p_d^- - p_d^+ = -(\rho^- + \rho^+)\mathbf{g}\cdot\mathbf{x},$$
$$\frac{1}{\rho^-}\nabla p_d^- - \frac{1}{\rho^+}\nabla p_d^+ = 0.$$

NUMERICAL MODEL

OpenFOAM uses Second–order accurate polyhedral FV method for spatial discretization. Rigid body motion is solved using quaternion based six degrees of freedom (6DOF) equations. Mesh motion is modelled as a rigid body motion with special boundary conditions accounting for the relative flux. Coupling of pressure, velocity, free surface and 6DOF equations is performed in a segregated manner using PIMPLE algorithm. Turbulence is modelled using k–ω SST model in all simulations.

SIMULATION SET–UP

Domain is approximately 4.5 times longer than model length, and 11 times broader. Only half of the ship is simulated due to the symmetry of the phenomenon. Ship advancement is modelled using constant current, while the ship itself has zero velocity in respect to the global coordinate system. Wave relaxation zone [2] is placed in the outlet region of the domain, where calm water surface is enforce to prevent wave reflection. Maximum Courant–Friedrichs–Lewy (CFL) number occurring in the simulations ranges from 10 to 50, allowing large time steps. Smaller Froude numbers demanded lower Froude numbers to converge to acceptable results. Four grids that are used have approximately $600\,000$, $950\,000$, $2\,600\,000$ and $4\,600\,000$ cells. Constant grid refinement ratio is hard to achieve for unstructured grids, thus an average refinement ratio is calculated, $r_G = 1.28$. Maximum non–orthogonality is approximately 80^o, while the maximum aspect ratio is 760.

VALIDATION AND VERIFICATION

Grid refinement study is performed for total resistance, sinkage and trim for six Froude numbers. Grid uncertainty U_G and iterative uncertainty U_I are determined following [3]. Below are the comparison graphs with error bars. Total resistance shows very good agreement. Generally, the numerical uncertainty reduces for larger Froude numbers. Exception is the design Froude number $F_r = 0.26$, for which the uncertainty is inconsistently high. Trend of sinkage depending on the F_r is well described. Relative errors are larger for smaller Froude numbers. Trim results also show good agreement, and the general trend is well captured. In the tables below relative error of resistance, sinkage and trim obtained on the finest grid is presented. Order of accuracy p_G, iterative uncertainty U_I and grid convergence uncertainty U_G are also shown. It can be observed that resistance and sinkage relative error reduces for larger Froude numbers. However, trim does not show such consistency. Order of accuracy is often not available due to oscilatory convergence or divergence.

Figure 1: Comparison of total resistance coefficient with error bars.

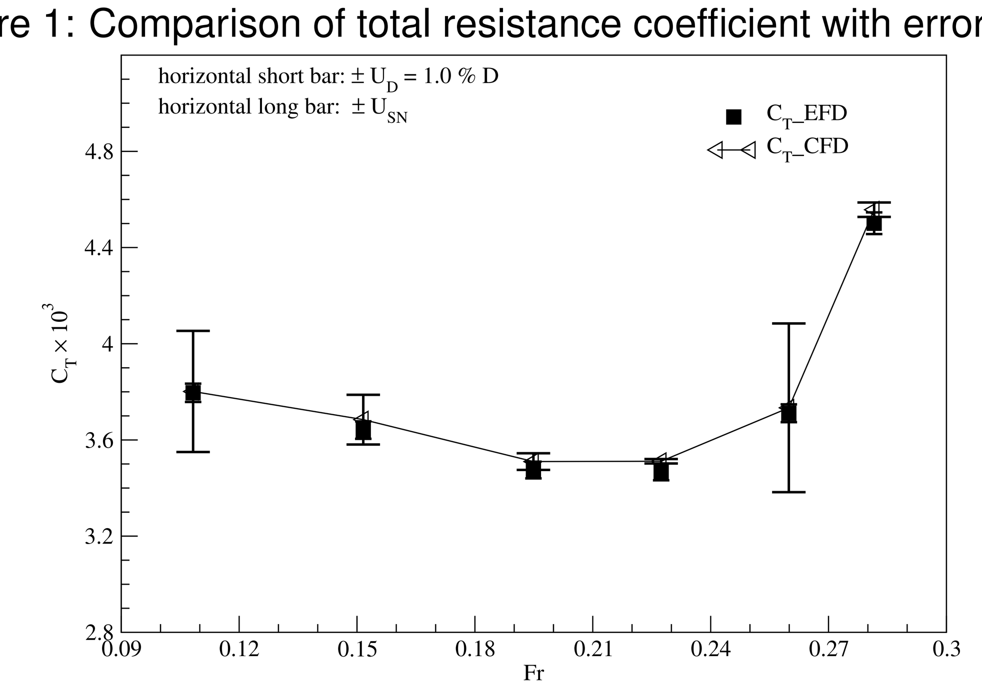

Table 1: C_t validation and verification results.

F_r	p_G	$\epsilon_{C_t}, \%$	$U_I/\epsilon_{k_{21}}$	$U_G/S_1, \%$	U_V
0.108	N/A	-4.62	$-9.36\cdot10^{-3}$	N/A	N/A
0.152	1.85	-4.88	$-5.82\cdot10^{-2}$	2.7	0.1096
0.195	N/A	-1.472	$-5.18\cdot10^{-2}$	N/A	N/A
0.227	16.0	-2.00	-5.09	0.0	0.0359
0.256	0.86	-0.39	$-3.15\cdot10^{-1}$	9.4	0.3528
0.282	3.98	-1.313	$-1.79\cdot10^{-1}$	0.6	0.0541

Figure 2: Comparison of dynamic sinkage with error bars.

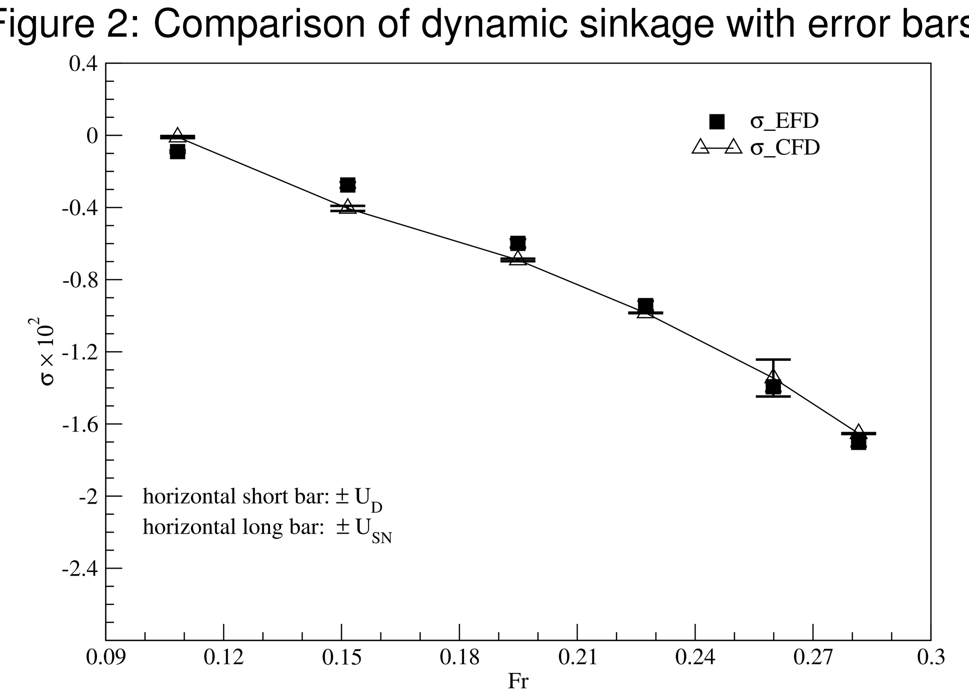

Table 2: Sinkage validation and verification results.

F_r	p_G	$\epsilon_\sigma, \%$	$U_I/\epsilon_{k_{21}}$	$U_G/S_1, \%$	U_V
0.108	N/A	-109	$1.98\cdot10^{-5}$	N/A	N/A
0.152	N/A	-40.74	$1.05\cdot10^{-5}$	N/A	N/A
0.195	2.57	-15.28	$3.29\cdot10^{-5}$	1.1	0.0245
0.227	3.7	-4.29	$7.64\cdot10^{-4}$	0.2	0.0263
0.256	0.13	3.48	$4.00\cdot10^{-3}$	7.6	0.1056
0.282	N/A	2.87	$2.59\cdot10^{-4}$	0.2	0.0233

Figure 3: Comparison of dynamic trim with error bars.

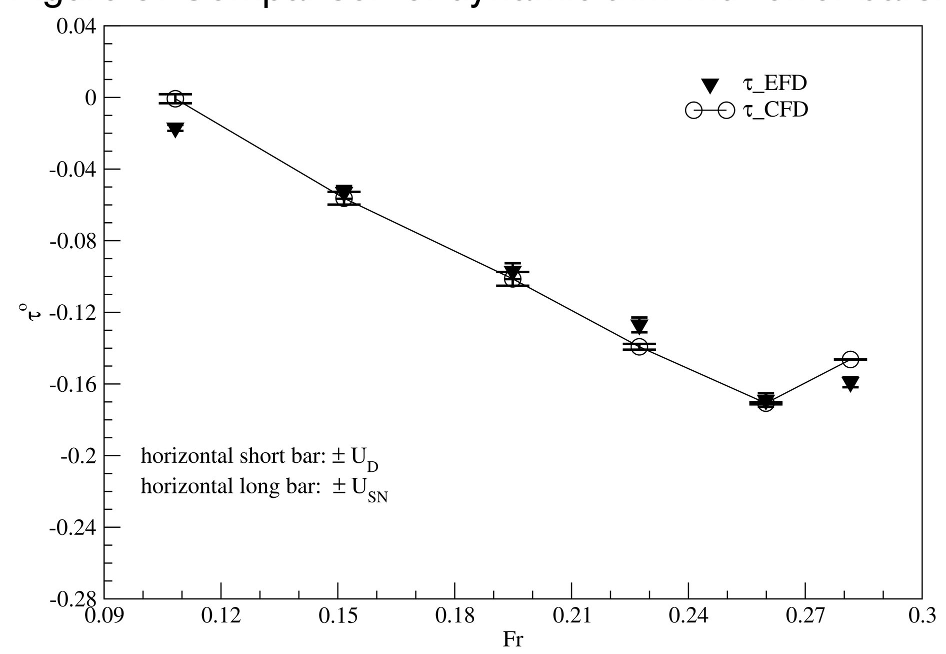

Table 3: Trim validation and verification results..

F_r	p_G	$\epsilon_\tau, \%$	$U_I/\epsilon_{k_{21}}$	$U_G/S_1, \%$	U_V
0.108	N/A	-74.75	$4.62\cdot10^{-6}$	N/A	N/A
0.152	N/A	-7.47	$1.05\cdot10^{-5}$	N/A	N/A
0.195	N/A	-5.14	$-1.69\cdot10^{-4}$	3.8	0.006
0.227	N/A	-9.63	$-5.04\cdot10^{-4}$	1.2	0.004
0.256	N/A	-1.03	$-7.65\cdot10^{-3}$	0.4	0.0039
0.282	6.21	7.97	$2.57\cdot10^{-3}$	0.04	0.0028

References

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