DEVELOPMENTS THE ‘ESPER’ FOR ESTIMATING SHIP PERFORMANCE

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Keywords: *OpenFOAM, KCS, JBC, KP505, MP687, propeller open-water test, ship resistance, ship self-propulsion, virtual propeller*

The methods for estimating the ship performance are mainly the model test in the towing tank and the method using CFD. Using CFD to estimate the ship performance has recently been actively pursued because it has advantages over the model test not only reduction of the cost but also duration of the estimation of ship performance. Many articles such as [1], [2] and [3] shows that numerical methods are effective and accurate by comparing the calculation results to experimental data of towing tank.

The estimation of ship performance using CFD was conducted with commercial CFD programs such as ‘Fluent’ and ‘starCCM+’ that are mainly used in the shipyard. The versatile commercial programs are developed for various kinds of fluid flow simulation like compressible flow, heat transfer, chemical reaction, non-Newtonian fluids, therefore it is too expensive to calculate ship resistance and population calculation. Many Korean ship building companies are examining OpenFOAM to replace the commercial CFD programs with OpenFOAM solvers.

'ESPER' is an OpenFOAM package including libraries and solvers for Propeller Open-Water (POW), ship resistance and self-propulsion analysis developed by NEXTfoam. ‘ESPER’ puts emphasis on the development of unique analysis technique and numerical model to stabilize the solution and reduce calculation time. 'ESPER' uses the RANS equation as the governing equations and can optionally use the turbulence model provided by OpenFOAM. ‘ESPER’ computes the pressure Poisson equation using Rhie-Chow interpolation and linearizes source term in k-omegaSST turbulence model for stability of the solution.

In this paper, the numerical methods of ESPER are introduced briefly and verified by comparing the results with other experimental data. Validation cases consist of ship resistance case, POW case and self-propulsion case. Target hulls are KRISO Container Ship(KCS) and Japan Bulk Carrier(JBC) and target propellers for POW Test are KP505 and MP687. ESPER’s calculation results were compared to the Towing tank experiment data.

Numerical Method

ESPER is developed by improving simpleFoam for POW and interDyMFoam for resistance and self-propulsion. OpenFOAM standard solver simpleFoam and interDyMFoam is not as stable as commercial code. To increase the stability, Rhie-Chow interpolation is employed to calculation of the flux of Poisson equation source term.

	original	modified
1. solve momentum equation and get $\vec{U}^*$	$a_P\vec{U}_P = H(\vec{U}) - V_P(\nabla p)_P$	$a_P\vec{U}_P = H(\vec{U}) - V_P(\nabla p)_P$
2. interpolate pseudo-velocity to get mass flow rate	$F^* = \left\{\frac{H(\vec{U}^*)}{a}\right\}_f \cdot \vec{S}_f$	$F^* = \left\{\vec{U}^* + \frac{V_P}{a_P}(\nabla p)_P\right\}_f \cdot \vec{S}_f$
3. solve pressure equation and get p^*	$\nabla \cdot \left(\frac{V}{a}\nabla p\right) = \sum_f F^*$	$\nabla \cdot \left(\frac{V}{a}\nabla p\right) = \sum_f F^*$
4. correct mass flow rate	$F^{new} = F^* - \left(\frac{V}{a}\right)_f \lvert\vec{S}_f\rvert \vec{n} \cdot (\nabla p^*)_f$	$F^{new} = F^* - \left(\frac{V}{a}\right)_f \lvert\vec{S}_f\rvert \vec{n} \cdot (\nabla p^*)_f$
5. original: under-relax pressure modified: correct velocity	$p^{new} = p^{old} + \alpha_p(p^* - p^{old})$	$\vec{U}_P^{new} = \vec{U}_P^* - \frac{V_P}{a_P}(\nabla p')_P$
6. original: correct velocity modified: under-relax pressure	$\vec{U}_P^{new} = \frac{H(\vec{U}^*)}{a_P} - \frac{V_P}{a_P}(\nabla p^{new})_P$	$p^{new} = p^{old} + \alpha_p(p^* - p^{old})$

Figure 1 comparison of solution procedure between standard OpenFOAM and ESPER

The pseudo velocity $\vec{U}^*$ is calculated with pressure gradient of old time step. And the mass flow rate of grid face is calculated by interpolating the pseudo velocity subtracting pressure gradient. The pressure Poisson equation is composed with the mass flow rate of grid face. The mass flow rate is corrected with the unrelaxed pressure gradient ∇p^* from the Poisson equation. The new velocity is obtained by correcting the pseudo velocity with unrelaxed pressure correction $p' = p^* - p^{old}$. The new pressure is calculated by adding the relaxed pressure correction to old pressure. The solution procedures are compared in Figure 1. The Single Rotational Frame model is employed to POW cases for propeller rotation for steady calculation. In the resistance and self-propulsion calculations, the ship speed is increased gradually to avoid spurious free-surface disturbance in initial stage. The acceleration and the derivative of the acceleration are set zero at the end of the acceleration to remove the abrupt pressure change in time. The running attitude is also controlled for smooth variation. The acceleration of the ship motion is damped. The damping coefficient is set one in initial stage and the coefficient is decreased to zero as time goes on.

POW cases

The POW test of KP505 of KCS and MP687 of JBC has calculated. The thickness of the first prism layer of a propeller is set Y^+=50 at 0.7R. The total number of the grid is about 2.0million. The results of the calculations are in good agreement with the results of the experiments, especially the error of η_0 is about 1% and error of K_T and K_Q is smaller than 3% at advance ratio 0.6 or less. The comparison results are shown in the Figure 1.

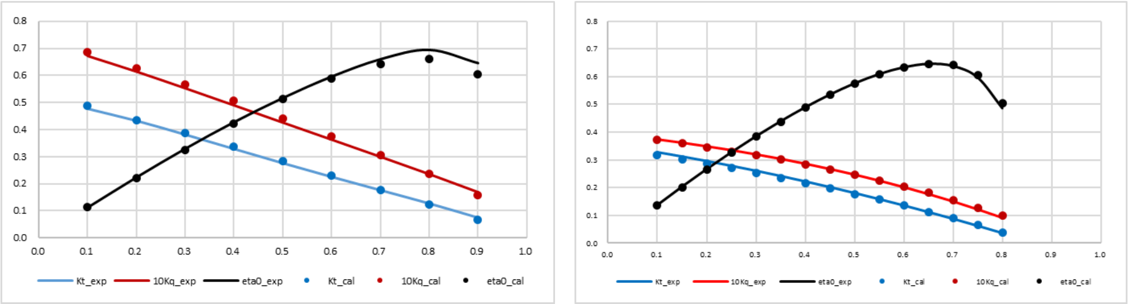

Figure 1 Comparison of thrust, torque and efficiency coefficients of KP505(left) propeller and MP687(right)

Resistance

To verify the performance of ESPER, the resistance results of KCS and JBC were compared with the experimental result [3] and [5]. The simulation conditions of the calculations are the same with experiment conditions, Froude number and Reynolds number of KCS are 0.260 and 1.40 X 10^7, respectively. In JBC case, Froude number and Reynolds number are 0.142 and 7.46 X 10^6.

The thickness of the first prism layer of KCS and JBC hull are set Y^+=30. The number of prism layers is 6 and the total number of the grid is about 1 million in KCS case and 2 million in JBC case. The calculations progressed 0s to 80s and took about 4.5 hours in KCS case and 18 hours in JBC case using 64 cores that is 2.3Ghz clock individually.

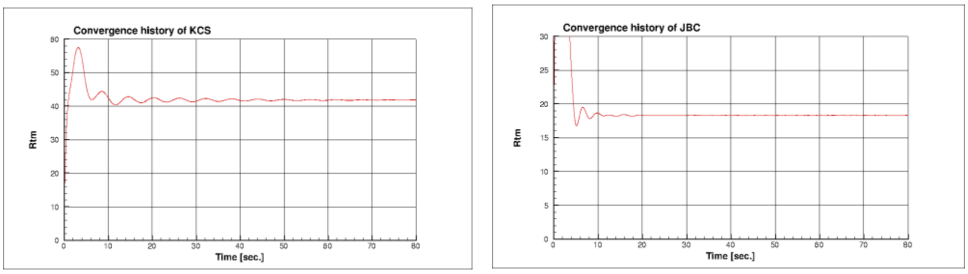

Figure 2: Convergence history of KCS(left) and JBC(right)

Table 1 shows the comparison results between the present calculation results and experimental data. The differences in total resistance between present calculations and experimental data is smaller than 2%. Wake fractions from the present calculations are also acceptable.

The wave height contours of KCS and JBC are compared in Figure 3. Divergence and transverse waves of KCS are well simulated and the agreement with experimental date is good. In JBC case, the wave height is too small to simulate the wave patterns by calculation. To observe the wave pattern of such a slow full ship, more small grids are arranged around the hull. The waves around the stem and stern are similar to experimental data due to enough wave height. Figure 4 shows the wave profiles along the KCS and JBC. The black line or dots of Figure 4 is experiment data and the red line is a wave profile of the present calculation. Figure 4 also shows good agreement. The wake distributions on the propeller planes of

KCS and JBC are shown in Figure 5. Qualitative and quantative agreements of wake distributions are enough to apply to hull form design.

Table 1: Comparison of computed resistance of the model ship of the KCS & JBC

	KCS			**JBC**		
	Exp.[3]	**Present**	**Error**	**Exp.[5]**	**Present**	**Error**
Total resistance (N)	41.170	41.847	1.64%	18.206	18.500	1.62%
Frictional resistance (N)	32.777	33.346	1.74%	13.409	13.691	2.10%
Pressure resistance (N)	8.393	8.501	1.28%	4.797	4.809	0.26%
Wake fraction	0.208	0.224	7.80%	0.61	0.59	-2.81%

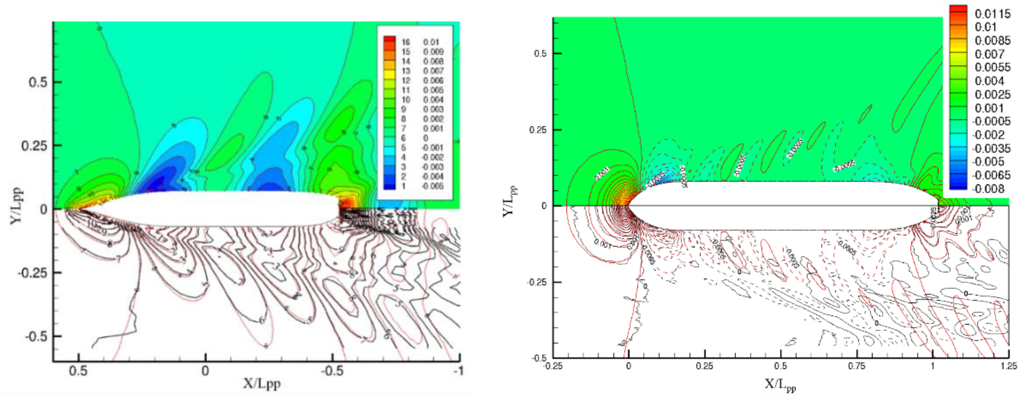

Figure 3 Wave pattern of KCS(left) and JBC(right)

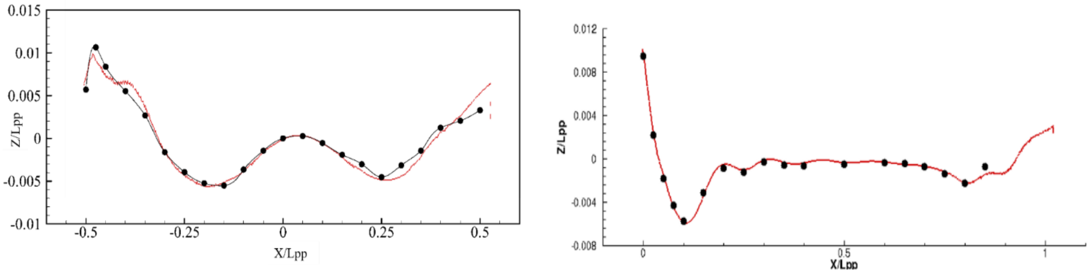

Figure 4 Wave profile along the KCS(left) and JBC(right)

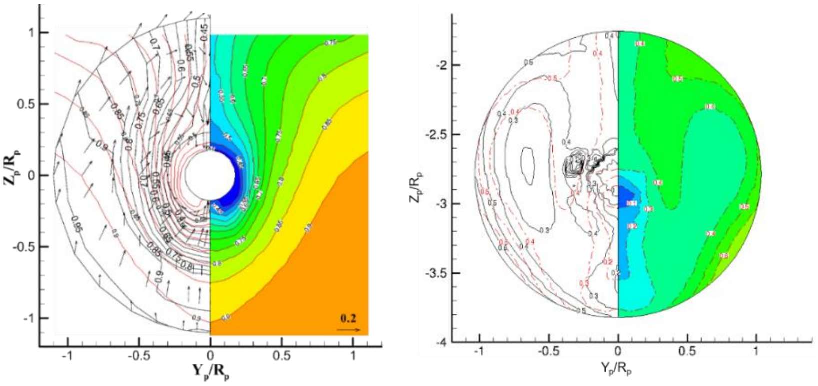

Figure 5 Wake distribution on propeller plane [KCS, X/L$_{pp}$ =-0.4825] (left), [JBC, X/L$_{pp}$ = -0.4843](right)

Self propulsion – JBC case

The self-propulsion performance of JBC is calculated with present numerical method. In this case, the propeller rotation speed is 7.8 RPS. The propulsive force is imposed as body force instead of propeller rotation to reduce the calculation time. The axial and circumferential forces are calculated with POW data. The inflow velocity of the propeller is obtained by averaging the velocity on the 2.857%LBP ahead of propeller plane. It is assumed that the propeller force is distributed following [10]. The grid for the self-propulsion simulation was generated by mirroring the grid for the resistance calculation with ‘mirrorMesh’ utility.

The Froude number of the calculation is the same with resistance case 0.142. The calculation results, K_T, K_Q and SFC are shown in Table 2. The errors of total resistance, thrust coefficient, torque coefficient and SFC are about 1.22%, -0.24%, 1.23% and 4.24%, respectively. The velocity contour at the stern of JBC has shown in Figure 6. The velocity increment due to the body forces around propeller plane is observed. The JBC hull surface has represents the pressure distribution and the free surface has represents the Z coordinate value. The contour lines around the stern represent the dimensionless velocity it is the velocity of x-axis divided by the reference velocity.

Table 2: Comparison of calculation data of the model ship of the JBC

	Exp.[5]	**Present**	**Error**
Total resistance (N)	40.844	41.344	1.22%
Frictional resistance (N)	26.818	26.783	-0.13%
Pressure resistance (N)	14.025	14.561	3.82%
Thrust Coefficient, K_T	0.217	0.216	-0.24%
Torque Coefficient, K_Q	0.0279	0.0282	1.23%
Skin Friction Correction (N)	18.2	19.0	4.24%

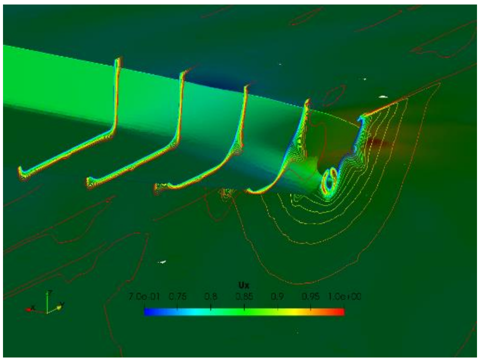

Figure 6 Velocity contour at the stern of JBC

Acknowledgements

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (No. NRF-2017M1A3A3A04016580).

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