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Comparison of Free Surface Capturing Approaches in OpenFOAM for Ship Resistance Prediction

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1 Introduction

The prediction of calm water ship resistance by computational fluid dynamics (CFD) has matured considerably in recent years. For displacement ships, accurate prediction of the free-surface is normally reasonably robust, provided the mesh resolution is sufficient. For more complex situations, such as for high speed vessels where spray becomes important or when in situations where the transom is only partially dry on medium speed ships, the numerical schemes to be used are still in development; even more so perhaps if ship motions and ocean waves are considered. Thus, in the open source package OpenFOAM, there are a wide range of options to choose from when setting up the free-surface simulation, all with different impact on performance. Thus, in the present study, free-surface prediction by different interface capturing are presented for the KCS (KRISO Container Ship) hull resistance simulation. Focus is on some of the options available in OpenFOAM, but also the commercial package Star-CCM+ has been investigated. All simulations have been performed by considering incompressible RANS and the $k-\omega SST$ turbulence model.

All tested methods are based on the Volume of Fluid (VoF) approach, where an indicator function α is used, and its evolution is modeled by a transport equation. In Star-CCM+, a HRIC (High Resolution Interface Capturing) discretization scheme is the default option available. In OpenFOAM, the FCT (Flux Corrected Transport) method based solver MULES has been developed and has been tested together with several higher order discretization schemes; also a special compressive treatment is available in OpenFOAM. Further, the NVD based high resolution schemes CICSAM and HRIC was also used to solve the α equation directly. A newly published method, isoAdvector, where geometrical interface reconstruction is performed with the potential to be able to predict a sharper and more accurate free surface interface, was also tested. Besides, development performed at the University of Applied Sciences in Kiel within the framework of OpenFOAM, a modified solver with reconstruction of pressure field at the interface where discontinuity exits was also compared.

2 Approaches

In VoF, the transport equation of α is a hyperbolic equation,

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot \alpha \mathbf{u} = 0. \tag{1}$$

In OpenFOAM, a FCT (Flux Corrected Transport) based method was used to solve this equation to guarantee boundedness and accuracy, MULES (MUlti-dimensional Limiter for Explicit Solution). A later version, CMULES, is a semi-implicit approach, which firstly solve Eq. (2) using a diffusive implicit approach (implicit Euler time stepping and upwind convection) and then solve Eq. (3) explicitly with higher order schemes.

$$\frac{\alpha_{i(upwind)}^{n+1} - \alpha_i^n}{\Delta t} V + tF_{upwind}^n = 0, \tag{2}$$

$$\frac{\alpha_i^{n+1} - \alpha_{i(upwind)}^{n+1}}{\Delta t} V + \lambda(tF_{highOrder}^n - tF_{upwind}^n) = 0, \tag{3}$$

where tF^n represent the summation of the face normal flux of α in a cell transported by the velocity. The CMULES maintains boundedness and stability at large Courant number. In the present study, van Leer, SuperBee, HRIC and CICSAM were used to calculate the high order flux in the framework of CMULES.

The High Resolution Schemes (HRS), such as HRIC and CICSAM, can be used outside of the framework of FCT. These two HRS were designed based on Normalised Variable Diagram (NVD), which can switch between high order schemes and inherent bounded schemes. This switch makes the capture of sudden gradient change possible, thus the sharp interface would be captured. For these high resolution schemes, since they already fulfil the boundedness, Eq. (1) could be solved directly. In practice, however, the CICSAM show some unstable behaviours including unboundedness, and is thus here only used with FCT. For the HRIC scheme though, the MULES in *interFoam* was replaced with equation below and discretized using the HRIC scheme,

```
fvScalarMatrix alpha1Eqn
(
    fvm::ddt(alpha1)
  + fvm::div(phi, alpha1, alphaScheme)
  + fvm::div(phirb, alpha1, alpharScheme)
)
```

In OpenFOAM, a compression term $\nabla \cdot (\alpha(1-\alpha)\mathbf{u}_r)$ is added into the α transport equation. For all the simulations in present study, the *interfaceCompression* scheme was used to calculate $\mathbf{u}_{rf}$.

The isoAdvector by Roenby et al. (2016) is a newly developed solver for complex free surface flows, which can also be used for ship resistance prediction. It is also based on the VoF method, but the transportation is treated differently. In isoAdvector, first a geometric surface inside a cell based on node α values is reconstructed, and secondly the motion of the face-interface intersection line is modelled to obtain the time evolution of the submerged face area. This makes isoAdvector able to give a sharper and more accurate interface capture. A drawback for the ship resistance simulation is the requirement that interface Courant number should below 1 in order to avoid that the interface "advect" across many cells in a time step; this makes the approach computational expensive for the steady state simulations considered here.

Another approach considered in the present study is the development of *interFoam* by the Yacht Research Unit Kiel Janek et al. (2016). This solver deals with the multi-phase problem by improved reconstruction of the pressure field when discontinuity exists based on Queutey and Visonneau (2007). Mainly, the approach establishes a way to calculate two terms used in the momentum equation, $(\nabla p)_f$ in the Laplacian term and p_f in the velocity correction source term, when a sudden change of pressure exists, and avoids the numerical smearing of $(\nabla p)_f$ as well as velocity over-prediction in the air phase in the following velocity correction step.

Finally, Star-CCM+ is a widely used commercial package. Here, a hybrid scheme of upwind differencing and a HRIC is default for the discretization of the α transport equation; in the present study, the switch criteria of Courant number between UD and HRIC was modified to use purely HRIC.

3 Settings

The KCS, Kriso Container Ship, is a widely used validation case for the free surface prediction of merchant vessels. The KCS hull in model scale was used in the present simulations (Fr = 0.26) with Lpp of 7.2786 m. The simulation domain extends about 1.5 Lpp upstream, 2 Lpp downstream, 2.5 Lpp on the portside direction, 1.25 Lpp to the upper boundary and 2.5 Lpp to the bottom. Half of the hull was simulated with symmetry condition on the center line. The mesh was generated using Star-CCM+ with trimmer and prism layer insertion with y^+ value in the range of 30-50. 40 cells near the free-surface on the vertical direction were applied to capture the induced waves. The mesh contains 1.56 million cells in total, which is a little bit on the low side but then also challenges the free surface schemes more. The $k-\omega SST$ turbulence model with wall functions was used for all the simulations. First order accurate time schemes (Euler and Local Euler) and PIMPLE algorithm were used for all the simulations as steady state solution will be expected. Second order schemes were used for velocity and turbulence terms.

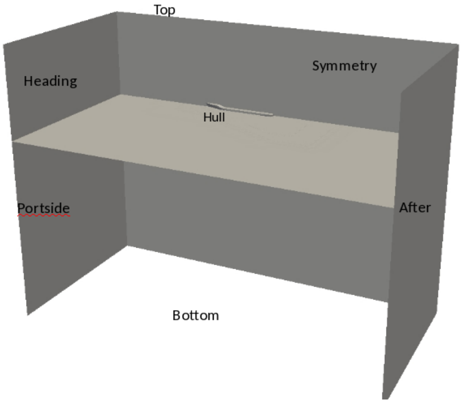


Fig. 1: Simulation domain

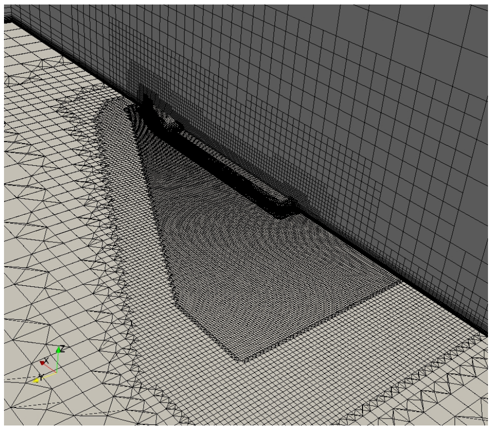


Fig. 2: Refinement near the freesurface

4 Results

The predicted wave patterns are displayed in figures 3 to 10 and compared to experimental data from Kim et al. (2001). Star-CCM+ and CMULES with SuperBee predicted sharpest wave patterns, even overly-sharp compared to the experimental measurements. CMULES with vanLeer and CICSAM, isoAdvector, and Kiel interFOAM predicted similar and reasonable results. For the HRIC related approaches in OpenFOAM, the predicted wave patterns are quite diffusive, no matter using CMULES or solving the alpha equation directly, with high Courant number or low Courant number. The secondary wave generated from the ship shoulder was predicted by all the approaches.

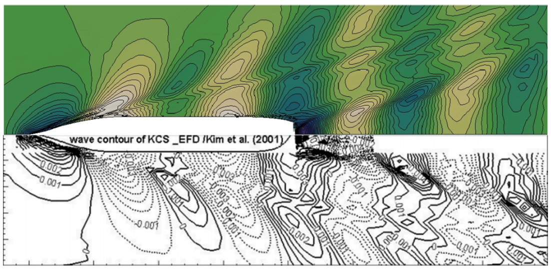


Fig. 3: Star-CCM+

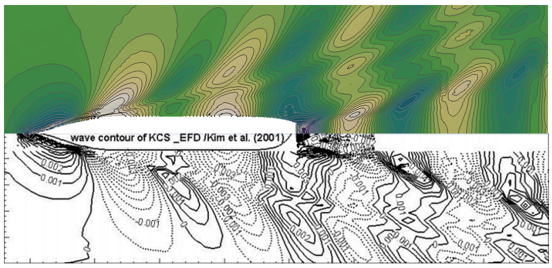


Fig. 4: CMULES with SuperBee

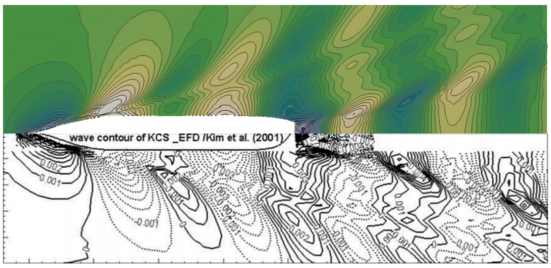


Fig. 5: CMULES with vanLeer, LTS

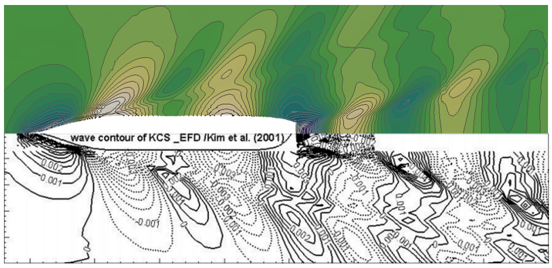


Fig. 6: CMULES with HRIC, Low Co

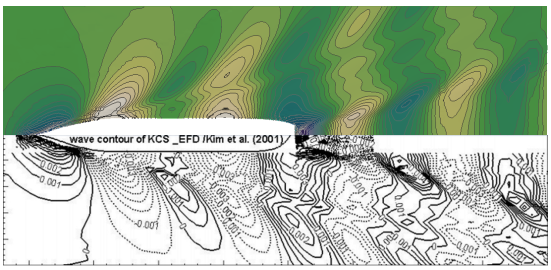


Fig. 7: CMULES with CICSAM, Large Co

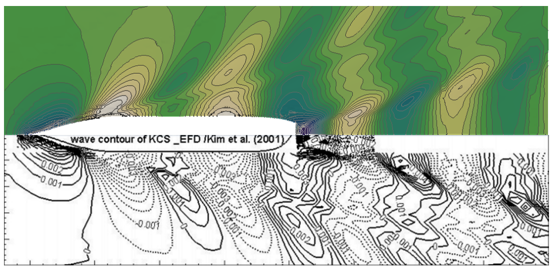


Fig. 8: CMULES with CICSAM, Low Co

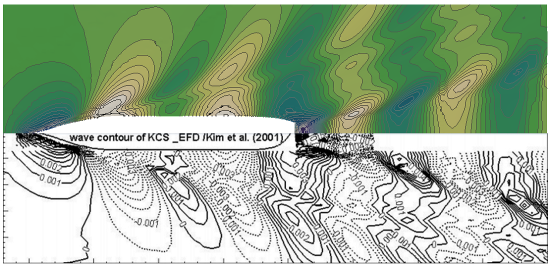


Fig. 9: IsoAdvector, max Co = 0.5

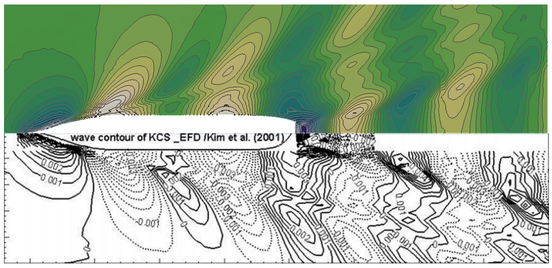


Fig. 10: Kiel interFoam

The predicted water lines on the hull and wave cuts (y/Lpp =0.0741, 0.1509, 0.424) are displayed in figures 11 to 14. Generally all the approaches predicted quite reasonable results compared to the experimental data, except the approaches using HRIC scheme, which are displayed as green lines. In the framework of CMULES, the HRIC related results show no significant difference between high Courant number ($\sim$ 40) and low Courant number ($\sim$ 0.5); and without CMULES the HRIC scheme with low Courant number predicted almost the same results. These HRIC related approaches predicted almost the same water line on the ship hull compared to other approaches, but with increasing distance away from the hull, the wave pattern show a very diffusive behaviour, as displayed in Figures 12, 13, and 14. The two HRS related approaches also show wavy predictions close to the ship hull, as displayed in Figures 11 and 12.

The differences between isoAdvector, Kiel interFoam, CMULES with Van-leer and SuperBee are quite small. The SuperBee predicted slightly overly sharp wave profile at $y/Lpp = 0.4224$. As displayed in Figure 15, the isoAdvector and Kiel interFoam predicted a more compact interface (3 cells from $\alpha \sim 0$ to $\alpha \sim 1$) than other schemes (5 cells from $\alpha \sim 0$ to $\alpha \sim 1$) which would be more realistic, but the improvement is limited on the overall wave pattern in this application.

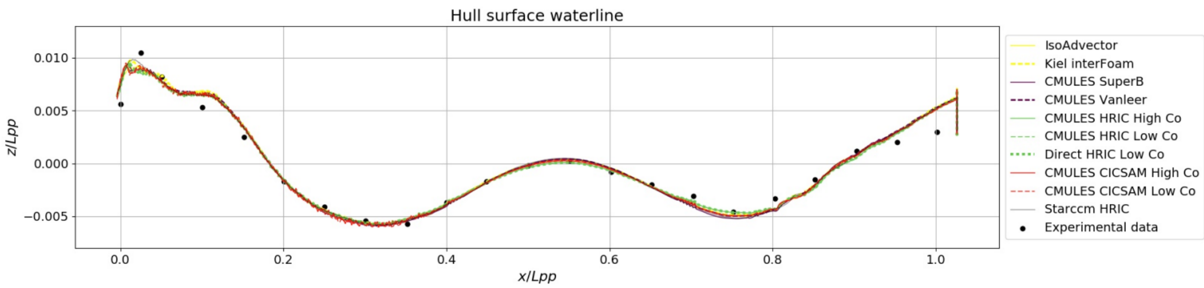


Fig. 11: Waterlines on the ship hull

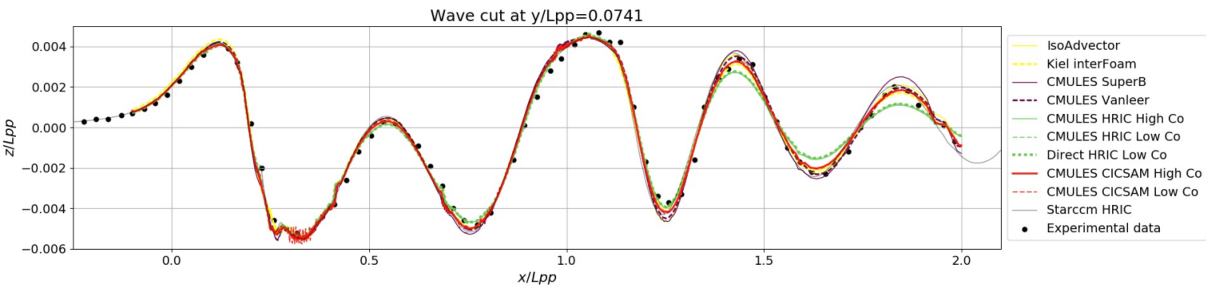


Fig. 12: Wave cuts at y/Lpp = 0.0741

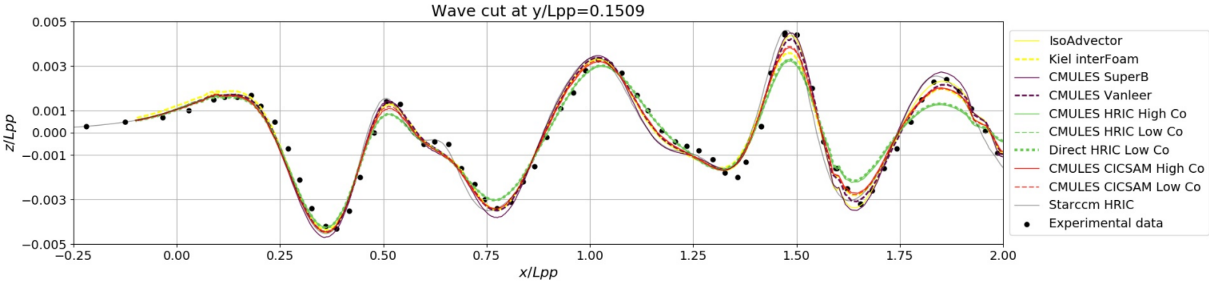


Fig. 13: Wave cuts at $y/Lpp = 0.1509$

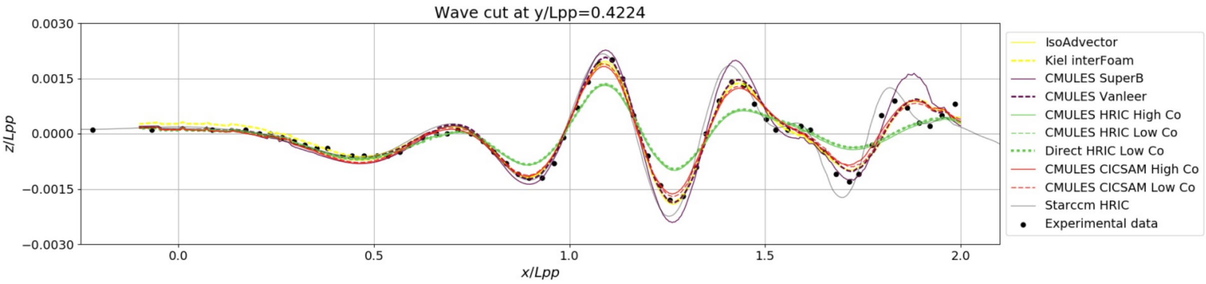
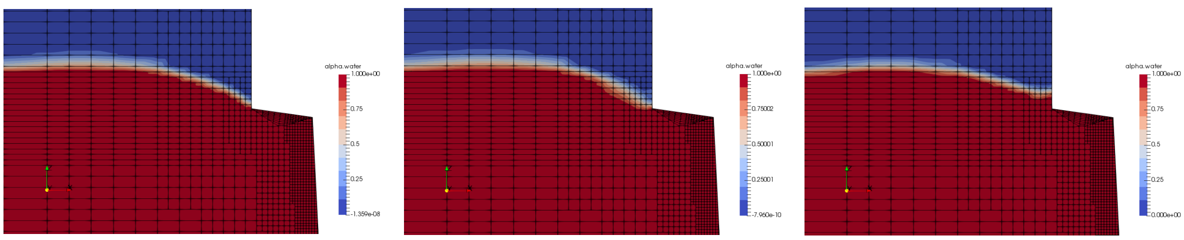


Fig. 14: Wave cuts at $y/Lpp = 0.4224$



IsoAdvector CMULES vanLeer Kiel interFoam

Fig. 15: α field near the ship stern

The summary of predicted force coefficients are listed in Table 1. All the approaches under predicted the total forces acting on the ship hull with relative difference ranging from −3% to −5.5%. Star-CCM+ and OpenFOAM predicted friction resistance coefficient (Cf) with relative difference of about 3% but quite different predictions of residual resistance coefficients (Cr) could be found between the different approaches. The differences between residual resistance coefficients show clearly a trend that depends on the discretization scheme.

Case	Cr $\times 10^3$	Cf $\times 10^3$	Ct $\times 10^3$	Relative Difference(%)
Exp.	-	-	3.577	-
Star-CCM+ HRIC	0.705	2.76	3.46	-3.3
CMULES vanLeer	0.740	2.67	3.41	-4.7
CMULES SuperBee	0.728	2.66	3.38	-5.5
CMULES HRIC	0.790	2.66	3.45	-3.6
CMULES HRIC(Low Co)	0.795	2.67	3.46	-3.3
HRIC direct(Low Co)	0.801	2.67	3.47	-3.0
CMULES CICSAM	0.755	2.66	3.42	-4.4
CMULES CICSAM(Low Co)	0.755	2.67	3.42	-4.4
isoAdvector	0.745	2.66	3.41	-4.7
Kiel interFoam	0.759	2.70	3.45	-3.6

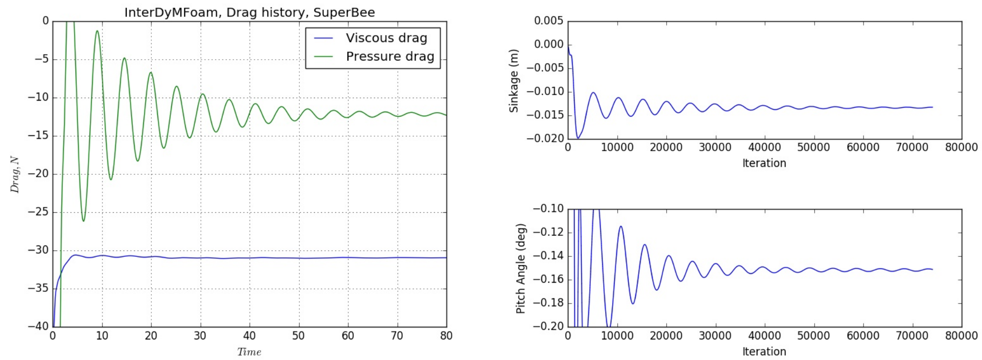
Table 1: Summary of force coefficients with different settings

For the prediction of trim and sinkage, the 6Dof motion solver was used together with SuperBee and Van

Leer in the framework of CMULES. The predicted trim and sinkage are listed in Table 2. As displayed in Figure 16, the trim and sinkage became less oscillating after about 60s simulation.

Case	Trim(deg) [rd%]	Sinkage(cm) [rd%]	Drag(N)	Ct [rd%]
Exp.	-0.169 [-]	-1.394 [-]	-	0.003711 [-]
vanLeer	-0.161 [-4.7]	-1.378 [-1.1]	82.46	0.003583 [-3.5]
SuperBee	-0.152 [-10]	-1.340 [-3.9]	86.19	0.003745 [0.9]

Table 2: Predicted ship motions and force coefficients with different settings



Drag history, SuperBee

Motion history, SuperBee

Fig. 16: Predicted forces and motions with SuperBee scheme in OpenFOAM

5 Conclusion

In the present study, several different approaches regarding ship resistance simulation were applied and tested. Some high order scheme, like van Leer and SuperBee, and two high-resolution schemes, CICSAM and HRIC, were employed for the discretization of the convective term in the phase equation under the framework of CMULES; the HRIC was also tested with a modified *interFoam* in which the CMULES was removed to solve the phase equation directly; a newly developed method IsoAdvector and the modified solver from Yacht Research Unit Kiel were also tested.

The predicted wave patterns and wave cuts were compared to the experimental data. Even though the mesh is on the coarse side, most of the approaches show good agreements with the measurement, although Star-CCM+ (HRIC) and SuperBee with CMULES predicted somewhat overly sharp wave patterns and the HRIC related approaches in OpenFOAM predicted diffusive wave patterns. The isoAdvector and Kiel interFoam predicted sharper α field but the computation cost significantly increased using isoAdvector because of the restriction of interface Courant number.

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