

Level-Set Simulation of Viscous Free Surface Flow around a Commercial Hull Form

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Abstract

The viscous free surface flow around a 3600 TEU KRISO Container Ship is computed using the finite volume based multi-block RANS code, **WAVIS** developed at KRISO. The free surface is captured with the Level-set method and the realizable k- ϵ model is employed for turbulence closure. The computations are carried out at model scale. In order to obtain an accurate free surface solution and stable convergence, the computations are performed with a proper fine grid refinement around the free surface and with an adoption of implicit discretization scheme for the Level-Set formulation. In all computational cases, the present results show a good agreement with experimental measurements.

Keyword: *RANS simulation, Level-Set method, Free surface flow, Commercial hull form*

1. Introduction

In marine hydrodynamics nonlinear ship wave problem has been regarded as a difficult and challengeable subject to obtain a reasonably accurate result for it. The approach to this ship wave-making problem may be divided into the inviscid flow method and viscous flow method. Though the inviscid flow methods [1, 2] have not consideration to the interaction between the viscous and the wave-making components, they are commonly used in marine hydrodynamics because of their robustness and computational efficiency.

The viscous flow methods can be divided into two categories: interface-tracking methods and interface-capturing methods. The interface-tracking method, also called moving grid approach [3, 4], makes use of a non-inertial coordinate system and the free surface coincides with a grid surface exactly throughout the computations. Thus, imposing the boundary conditions on the free surface as well as tracking the free surface in time is straightforward. However, these approaches involve grid regeneration, a trivial process, at every iteration step, which may not be possible for all cases. If the breaking and overturning waves, which can not be modelled in the inviscid methods either, are of no primary interest, the interface-tracking methods can be useful for predicting the ship-generated moderate wave patterns.

The interface-capturing methods such as a VOF (Volume Of Fluid) [5, 6] and Level-Set method [7, 8, 9, 10, 11] use a fixed grid in time and the free surface is allowed to move through grid points. In these approaches tracking the free surface and imposing the boundary conditions on it are not trivial. This numerical feature makes it possible to solve the strongly nonlinear wave problems, the breaking and overturning waves included using the interface-capturing methods. In the present work a Level-Set method, one of the interface-capturing methods in a two-phase formulation is therefore adopted to compute the strongly nonlinear viscous flows around a commercial ship hull forms.

The computations are done for a 3600 TEU container ship of Korea Research Institute of Ships & Ocean Engineering, KORDI (hereafter, KRISO) selected as the test cases at a *Workshop on Numerical Ship Hydrodynamics, Gothenburg 2000*. The finite volume based on multi-block grid RANS code, **WAVIS** (**W**Ave & **V**IScous flow analysis system for hull form development) [12] developed and has been extended for the viscous free surface flows at KRISO is used for the present work. In general cases the quality of ship wave solutions depends on the grid resolution, and so a proper grid refinement around the free surface region is done using a commercial code, GRIDGEN. The computed

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results are compared to the towing tank measured data of KRISO and the nonlinear potential flow solutions computed using WAVIS potential flow code.

2. Numerical Methods

The governing equations for turbulent flow in the present study are RANS equations for momentum transport and the continuity equation for mass conservation. For turbulence closure, the realizable k- ϵ model [13] is employed. It is advisory to use a near-wall turbulence model to resolve boundary layer up to the wall; however, the number of grid should be almost doubled. For the present study the so-called Launder and Spalding's wall function is utilized to bridge fully turbulent region and wall. The first grid point in the wall function approach is approximately 100 times off the wall compared to that in the near wall turbulence model. It provides the economy and robustness to a viscous flow calculation method as a design tool.

WAVIS utilizes a cell-centered finite-volume method to discretize governing equations. Convection terms are discretized using QUICK scheme of the third order. Central difference scheme is utilized for diffusion terms. Linear equations are solved using strongly implicit procedure.

If the pressure field is known a priori, momentum equations will give correct velocity field. However, those velocity components will not satisfy the continuity equation. To ensure divergence-free velocity field, the SIMPLEC method is employed. Since the collocated grid arrangement is chosen, the artificial dissipation term is added in pressure correction equation, as discussed in Rhie and Chow [14]. The description of turbulence model and numerical method is given in Kim et al [15].

In order to compute the free surface flow, a Level-Set scheme in a two-phase formulation is employed and its formulation is discretized using an implicit scheme. The deformation and movement of the free surface can be captured using the continuous smooth Level-Set function ϕ which has a feature of signed distance function and zero Level-Set ($\phi = 0$) coinciding with the free surface. At one phase of flow domain the Level-Set function has positive distance from the free surface and at the other phase negative distance. Since the fluid density and viscosity sharply change across the interface of two-phase flows, it is necessary that the free surface should have a finite thin thickness for making fluid quantity variation smooth and for giving consequent stability to the computational procedure. The fluid quantity can be described as the function of the Level-Set distribution, and so the governing equations are solved throughout the computational domain. A detailed description and application of the Level-Set scheme can be seen in Sussman et al [7], Vogt [8], Park/Chun [9] and Park [10].

3. Numerical Results

The viscous free surface flow around a 3600 TEU KRISO Container Ship (KCS) hull form moving steadily straight ahead at fixed condition is simulated using WAVIS RANS code. The wave pattern and resistance of KCS hull form measured at towing tank are utilized to validate the present numerical results. When the computed and measured wave patterns are compared with each other, the nonlinear potential flow solutions, which are obtained using WAVIS Potential flow code, are also employed. In the numerical results all the coordinates and wave height (h) are non-dimensionalized by the length of KCS and the mean velocity components by KCS speed.

The main dimensions of the KCS are L (length) = 230m, B (breadth) = 32.2m, D (draft) = 10.8m, C_B (block coefficient) = 0.6505 and the ship speed, $V = 24$ knots. The computational condition is at model scale ($\lambda=31.5994$) yielding a Reynolds number $Re = 1.4 \times 10^7$ and Froude number $Fn = 0.26$. The details of the body plan and the side profile for KCS are displayed in Fig. 1.

Fig. 2 shows the partial views of the grid configuration on the hull surface, on the symmetry plane, on the top plane of flow domain, around the transom part and above and below the free surface. Since the quality of grid system strongly influences on viscous free surface flow solutions, fine regular grid system beside and behind the hull surface and the free surface are equipped in order to keep the high resolution for the present RANS computation. H-O type grid topology is used, consisting of 3-blocks.

In Table 1, for both of the medium and the fine grid the number of grid points used on the hull surface and on the free surface and the total volume cell number are shown. In the present work the

grid dependency on the free surface solution is preferred to investigate above that on the hull surface. In the fine grid the main increase in the number of grid points against the medium grid is done behind the hull form on the free surface region. The computational domain for KCS is as following; $-1.3 \leq X(x/L) \leq 1.35$, $0.0 \leq Y(y/L) \leq 0.8$, $-0.85 \leq Z(z/L) \leq 0.215$.

The computation time required for the fine grid in a Pentium III (1GHz) PC was 168 hours when the iteration step had reached the last number 7000 with the time segment $\Delta t = 0.0004s$. The usual oscillations occur in the predicted forces because of the numeric waves of various frequencies which commonly interference after the initial computational stage and the physical unsteady wave phenomenon. Due to this computational condition the average of the last 2000 iterations in which its amplitudes are sufficiently reduced is utilized.

Fig. 3 compares the simulated global wave patterns with the measurement (EFD, Experimental Fluid Dynamics). As expected, the nonlinear potential solution comparatively shows a good agreement with EFD result, but behind the transom, in which the nonlinearity of the free surface is strong, the wave pattern is overdraw because of utilizing dry transom flow model [1, 2]. The wave pattern on the medium grid shows the much the same feature of the EFD result, but is smooth in the wake region of the hull form. The fine grid Level-Set result shows an excellent agreement with the KRISO EFD wave pattern in the local region near the hull surface and the wake region including the far downstream region, except for a small lateral far downstream region, in which the divergent waves are slightly damped.

Fig. 4 shows the magnified views of the wave pattern in the bow and stern region of KCS hull. In these local regions the interface-tracking methods including the potential flow method have restrictions on obtaining the well described sharp wave features due to the strongly disturbed free surface flows in interaction with the hull surface. The present Level-Set method gives very satisfactory solutions compared with EFD results in wave heights and its distributions.

Fig. 5 shows the wave profile along the hull surface compared with the EFD data for the present Level-Set and the potential flow result. Both computed results agree well with the EFD wave profile. Especially, the Level-Set result shows better agreement with the EFD in the bow and the shoulder of KCS hull. The deviation of the potential flow may be due to spray. This strong nonlinear flow feature, which is natural for the Level-Set method, is difficult for the potential flow method to capture.

In order to make a closer examination in the wave pattern the longitudinal wave cuts parallel to the centerplane at $Y = 0.1024, 0.1509, 0.3, 0.4$ displayed in Fig. 6. The medium grid and the potential solution show a little departure from the EFD wave cuts in the wake region. In the viscous and the free surface nonlinear effect dominant region the potential solutions show deviation from the EFD results. Unlike other published numerical results, the present Level-Set solutions well capture the irregular wave form (small hump) and the lateral far field waves.

Fig. 7 displays the transverse wave cuts at $X = -0.5, -0.1, 0.3, 0.6, 0.8$. These comparisons of the transverse wave cuts clearly tell how much the numerical dissipation exists in the viscous flow solution. However, the present viscous solutions are not affected seriously by this numerical dissipation, which could be accomplished by using a proper grid refinement around the free-surface. From Fig. 6 and 7 it can be seen that the Level-Set method is superior to the potential method in prediction of the wave pattern around a real commercial hull form in the highly viscous region and also the outer inviscid region.

Fig. 8 compares the computed and measured axial(x) velocity distributions at the propeller plane. In the numerical result it can be seen that the wake flow structure is reasonably simulated. If the propeller hub is correctly modelled and whole flow domain containing the starboard and the port side of a ship is considered, the numerical result will show closer agreement with the EFD result.

Table 2 displays the predicted and measured resistance coefficients. The coefficients are non-dimensionalized by $0.5\rho V^2 S$, where ρ is the water density, V is the model speed and S is the wetted hull surface area. The friction and the pressure resistance components C_F , C_P are analysed separately. C_F for the medium grid is 0.25% larger than that for the EFD and C_F for the fine grid is 0.46% smaller. Total resistance C_T for the medium grid is 3.43% larger than that for the EFD and C_T for the fine grid is 0.48% larger. It is observed that the present viscous free surface solutions simulated using the RANS and Level-Set method show well predicted values in the resistance coefficients.

4. Concluding Remarks

The finite volume based multi-block grid RANS code, **WAVIS** which have been extended for the viscous free surface flow using the Level-Set method, is utilized to the turbulent flow around a commercial container hull form. All the computational results are compared with the EFD data measured at KRISO towing tank and the nonlinear potential flow solutions.

The predicted global and local wave patterns show a good agreement with the EFD data in the highly viscous region together with the inviscid far outer region. A proper fine regular grid refinement around the free surface region makes it possible to reduce the numerical dissipation error, so that the Level-Set method can be superior in predicting the strong nonlinear ship waves to the nonlinear potential flow method. In predicting the resistance coefficients it is observed that the present method provides reasonable results in comparison with the EFD data. However, it is pending problem to reduce CPU time consumption for the viscous free surface flow computation.

It is quit certain that the Level-Set method can be a robust numerical scheme for the strong nonlinear ship wave problem including other various two-phase flows problems.

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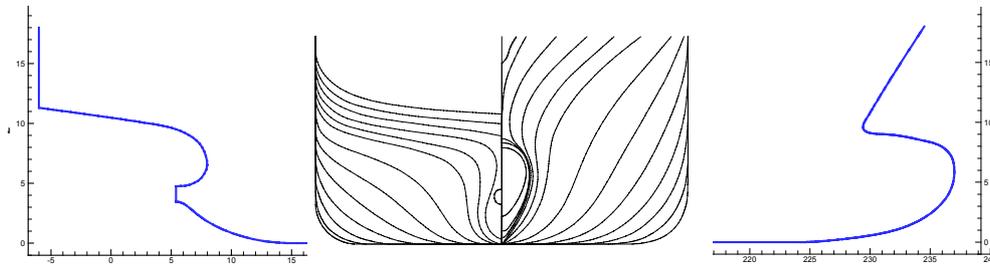
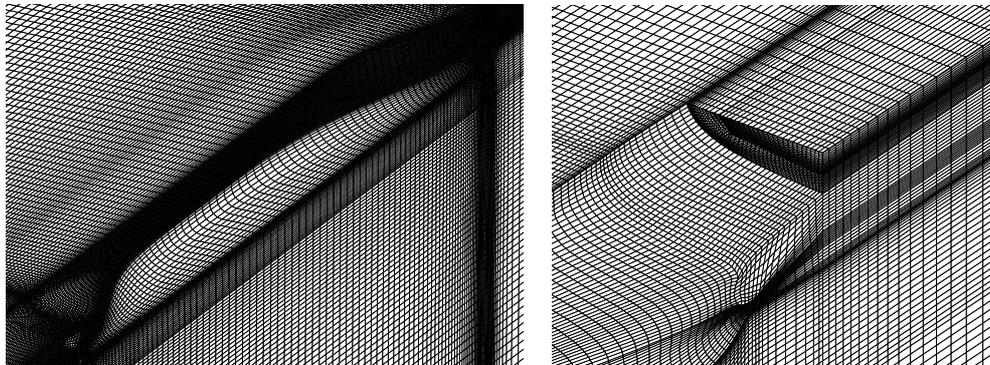


Fig. 1. Body plan & side profile of KRISO 3600TEU container ship (KCS)

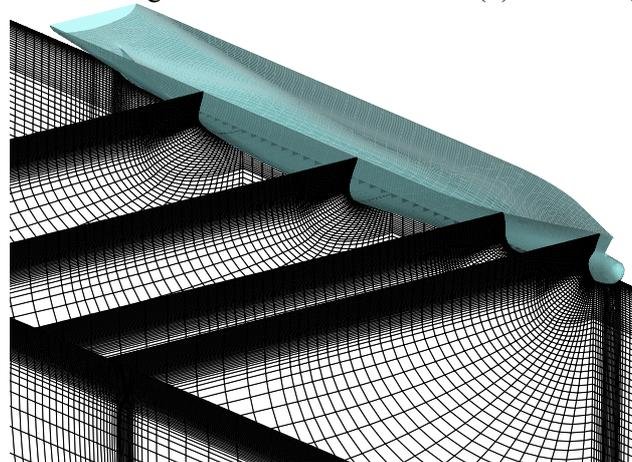
Table 1. Comparison of grid resolution

	Hull surface	Free surface	Total cells
Medium Grid	6,784	11,930	719,206
Fine Grid	8,084	27,720	1,622,096



(a) Hull surface grid

(b) Transom grid



(c) Free surface grid distribution

Fig. 2. Partial views of computational grid distributions around KCS

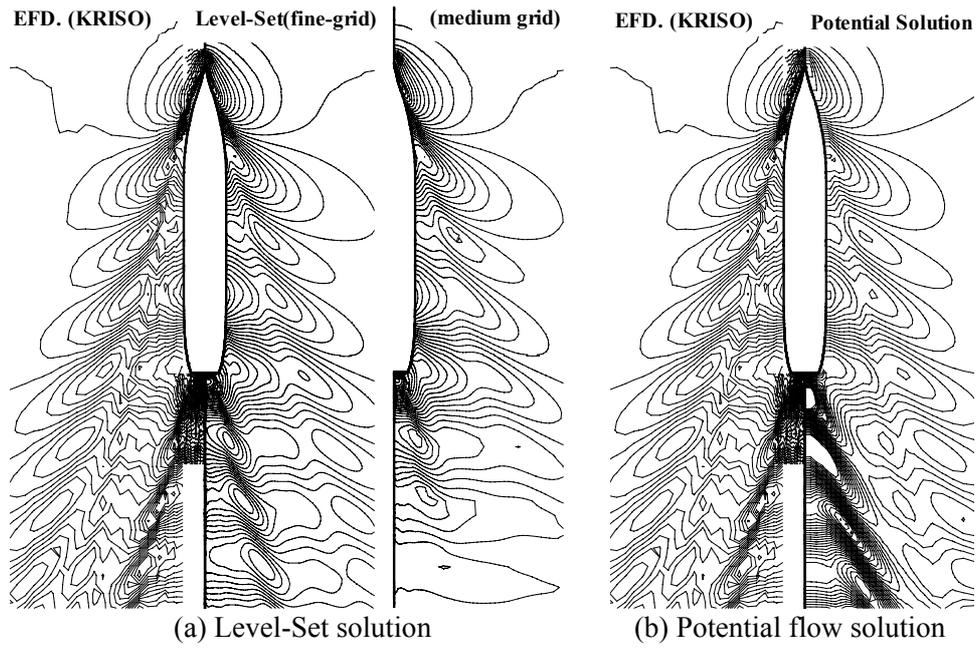


Fig. 3. Comparison of wave contours for KCS; $\Delta H (\Delta h/L) = 0.0005$

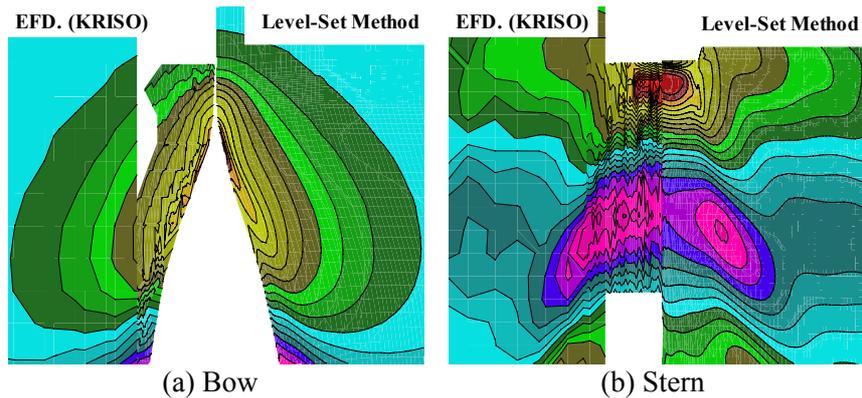


Fig. 4. Comparison of wave contours around the bow and the stern of KCS

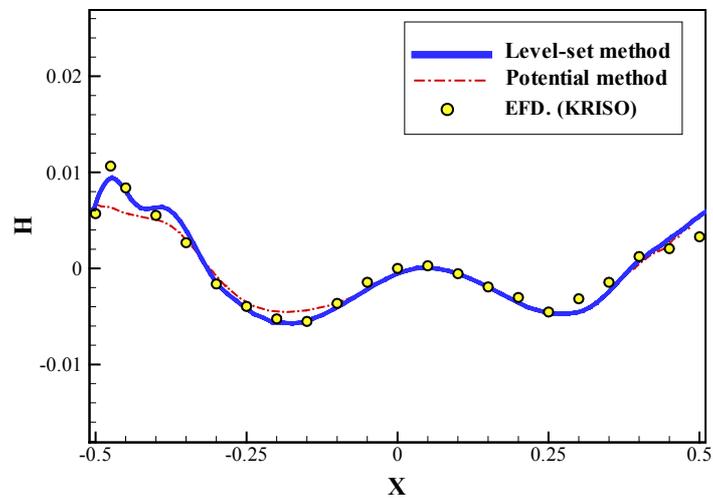


Fig. 5. Comparison of wave profiles along KCS hull surface

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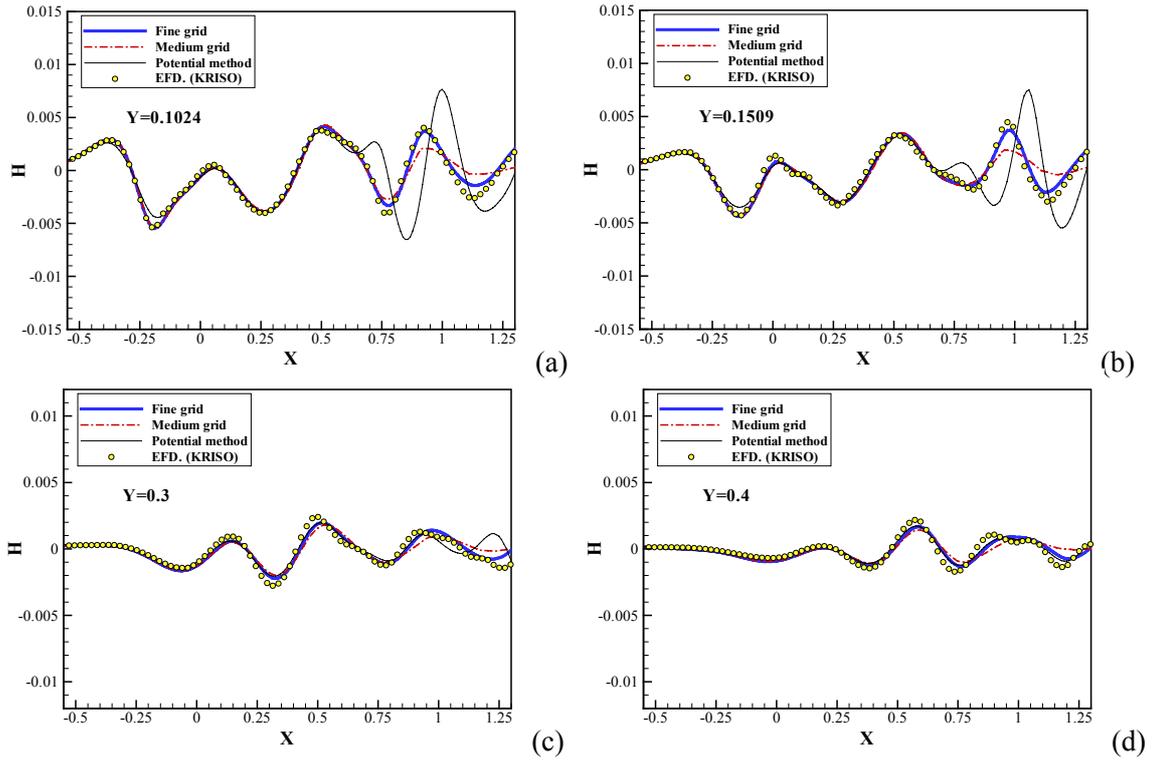


Fig. 6. Comparison of longitudinal wave cuts of KCS

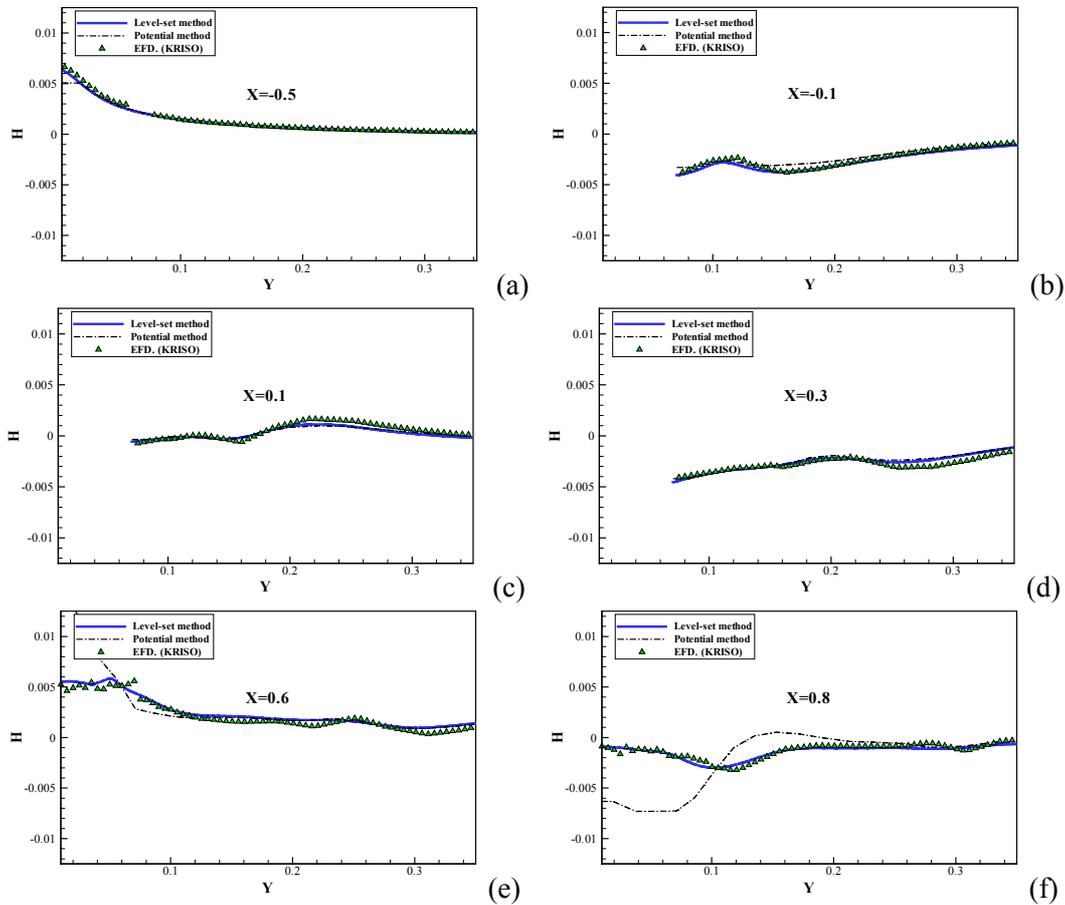


Fig. 7. Comparison of transverse wave cuts of KCS

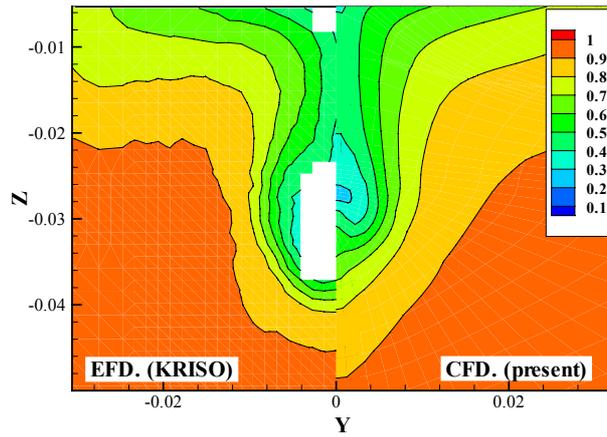


Fig. 8. Comparison of wake distribution at the propeller plane

Table 2. Comparison of resistance coefficients

	C_P	C_F	C_T
Medium Grid	0.845	2.837	3.682
Fine Grid	0.760	2.817	3.577
EFD (KRISO)	(0.730)	2.830	3.560