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phFlow Wavemaking Calculations for the KRISO Container Ship

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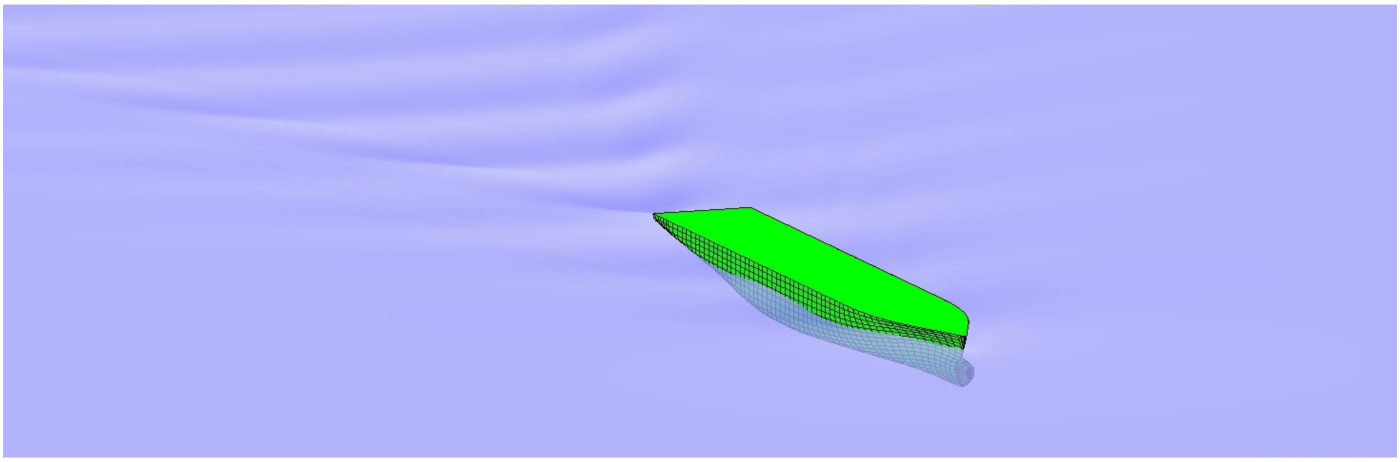
Perth Hydro Research Report R2019-05



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CONTENTS

1. Test case

The test case used is the KRISO Container Ship, or "KCS" (Van et al. 1997, Lee et al. 2003). Particulars of this ship are shown in Table 1.

Length between perpendiculars	230.00 m
Distance transom to aft perpendicular	6.00 m
Distance forward perpendicular to front of bulb	7.00 m
Length waterline	232.50 m
Beam	32.20 m
Draft	10.80 m
Depth	19.00 m
Displacement	52,030 m^3
Height of transom above still water level	0.50 m

Table 1: KRISO Container Ship particulars at full scale

Test case conditions are as used in Van et al. (1997) and shown in Table 2.

Froude number	0.260
Speed	12.4 m/s
Water depth	Deep
Ship vertical position	Fixed at static draft condition

Table 2: Test conditions used for KCS in this report

2. Ship mesh

The KCS has been meshed as follows:

- Read publicly-available IGES file into DELFTship
- Calculate hull sections to generate OCTOPUS hull file
- Generate surface mesh using OCTOPUS 3D mesher

No panels are used on the transom. The resulting ship surface mesh is shown in Figure 1.

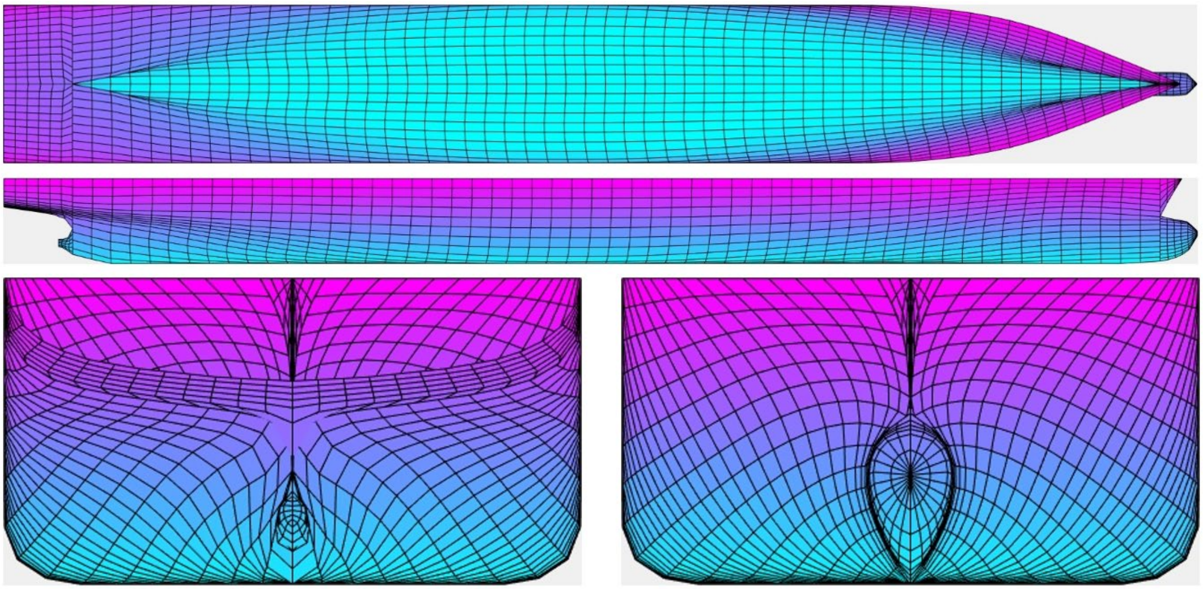

Figure 1: KCS surface mesh, up to draft of 17.0 m.

Ship collocation points are chosen as the “null point” of each ship panel, using the method of Hess and Smith (1964, eq. 35).

3. Raised free surface mesh

Raised free surface panels are set on a horizontal grid. Panel lengths in the x-direction are constant along the length of the ship, and uniformly increased at a constant expansion ratio astern of and ahead of the ship. Panel widths in the y-direction are constant in the inner region; in the outer region, panel widths are uniformly increased at a constant expansion ratio.

Free surface panel edges are matched to the forward and aft hull extremities at the panel height, as shown in Figure 3.

Free surface collocation points are chosen as ¼ of the way aft on each free surface panel to improve numerical stability, as done by Raven (1996, p.92).

Raised free surface mesh details for the test case are shown in Table 3.

Panel length (minimum)	1.80 m
Panel width (minimum)	1.80 m
Aft limit of mesh	$x = -2.0L_{PP}$
Forward limit of mesh	$x = 2.0L_{PP}$
Transverse limit of mesh	$y = 2.0L_{PP}$
Number of panels in x-direction	318
Number of panels in y-direction	56

Table 3: Raised free surface mesh characteristics for KCS test case

4. Combined ship and free surface mesh

Raised free surface panels are allowed to move vertically to follow the free surface, using successive over-relaxation, but requiring a minimum distance to the free surface of 80% of the panel length.

Only hull panels that lie at least partly below the raised free surface panels are used. The top hull panels are trimmed to the height of the raised free surface panels.

Once the hull panels are set, only free surface panels that lie partly outside the hull panels (from a top view) are used. Inner free surface panels are trimmed to match the hull outline. These irregular panels are called “infill panels”.

Views of the combined mesh for the fully-converged flow are shown in Figure 2, Figure 3 and Figure 4.

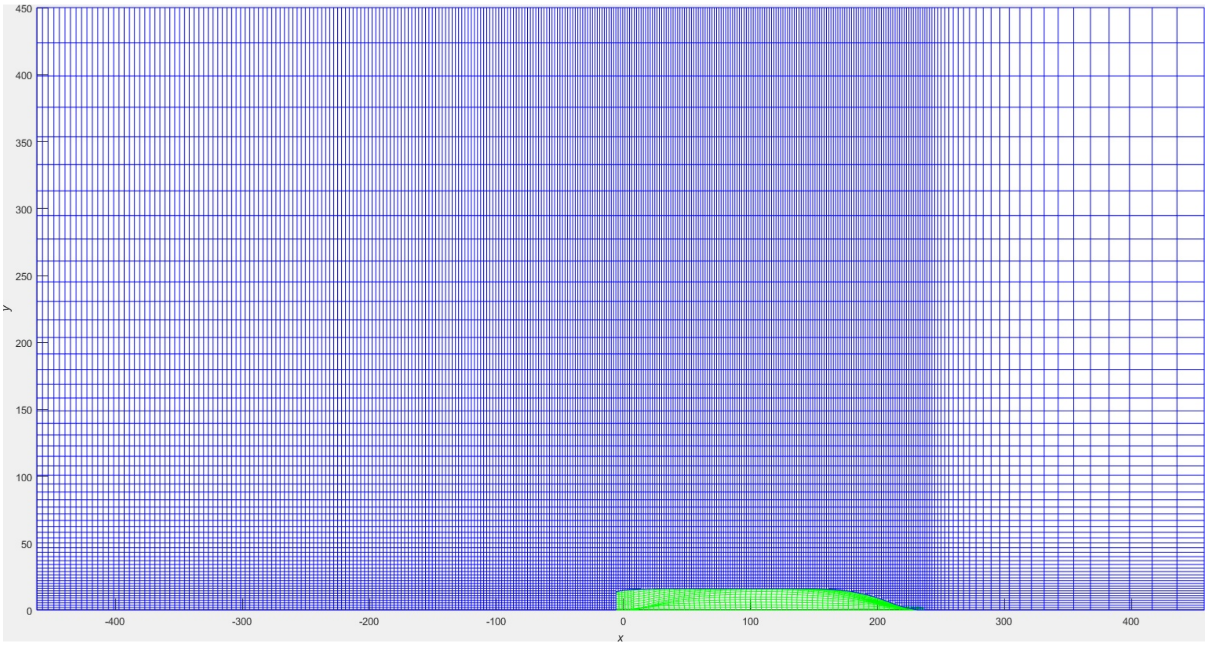

Figure 2: Hull panels (green) and raised free surface panels (blue) for KCS test case

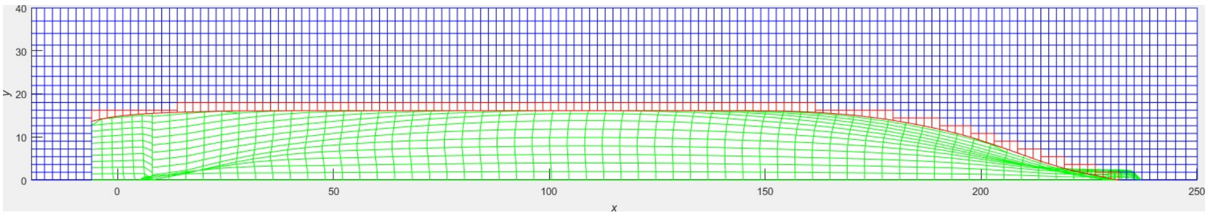

Figure 3: Close-up of free surface mesh around hull, showing regular panels in blue, and infill panels in red

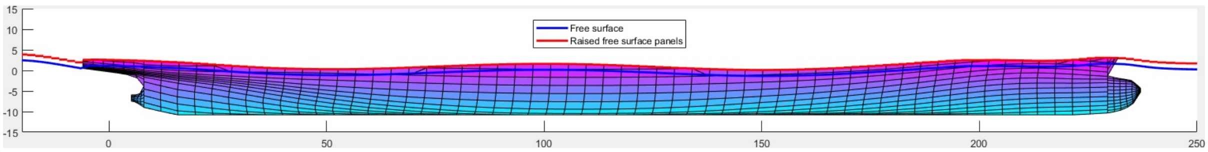

Figure 4: Profile view of combined mesh

Combined mesh details are given in Table 4. Port/starboard symmetry is assumed, so only panels on the port side are considered as unknowns.

Number of hull panels, N_h	909
Number of raised free surface panels, N_f	16658
Total number of panels, N	17567

Table 4: Number of panels on port side of combined mesh, for fully-converged flow

The combined mesh has N panels, with hull panels numbered $j = 1 \dots N_h$ and raised free surface panels numbered $j = N_h + 1 \dots N$.

5. Initial flow estimate

The first estimate for flow around the ship is calculated using a wall boundary condition on all hull panels, and a wall boundary condition at $z = 0$ for all free surface collocation points (x_m, y_n).

All ship and raised free surface panels are treated equally, as quadrilateral Rankine-source panels, each of constant source density across the panel.

The velocity $\boldsymbol{V}_{ij}$ induced at the collocation point of the i^{th} panel by a unit source density on the j^{th} panel is firstly calculated for all panel pairs using Hess and Smith (1964, eqs. 27-29). Care is taken to include the contribution from the starboard-side source panel corresponding to each port-side source panel.

The normal velocity (into the fluid) induced at the collocation point of the i^{th} panel by a unit source density on the j^{th} panel is then calculated as

$$\boldsymbol{V}_{ij}.\boldsymbol{n}_i \tag{1}$$

Following Hess and Smith (1964, eq. 48), the total normal velocity at the collocation point of the i^{th} panel, due to all source panels, each with unknown source density σ_j, is equal to the negative of the contribution made by the free stream. This is written as the matrix equation

$$\sum_j A_{ij} X_j = B_i \tag{2}$$

where, for the initial flow estimate,

$$A_{ij} = \boldsymbol{V}_{ij}.\boldsymbol{n}_i \tag{3}$$

$$X_j = \sigma_j \tag{4}$$

$$B_i = U n_i^{(x)} \tag{5}$$

In phFlow, we solve the matrix equation (2) for X_j using MATLAB's "mldivide" solver.

Once the panel source densities are calculated, the flow velocity at any collocation point may be calculated as

$$\boldsymbol{q}_i = -U\boldsymbol{i} + \sum_j \boldsymbol{V}_{ij}\sigma_j \tag{6}$$

Hydrodynamic pressure then follows from Bernoulli's equation. Pressure head at $z = 0$ beneath all raised free surface panels is shown in Figure 5.

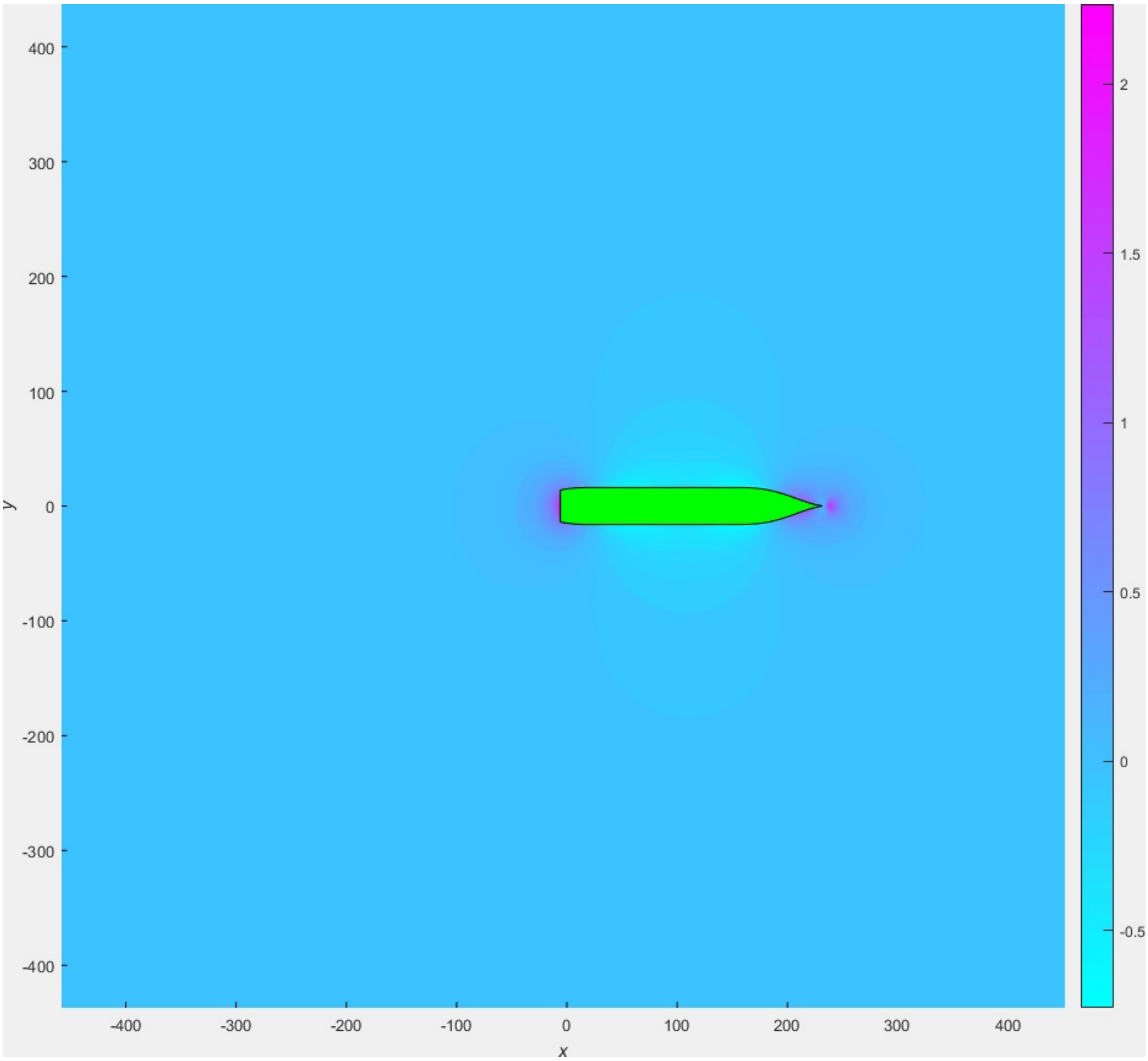

Figure 5: Initial flow estimate: colours show pressure head (in metres) at $z = 0$ beneath all raised free surface panels

6. Complete flow problem

The steady-flow problem in the ship's frame of reference consists of the following:

- Laplace's equation for incompressible, irrotational flow throughout the water. This is automatically satisfied by choosing the solution to be a linear superposition of a free stream and Rankine sources.
- Wall boundary condition on the hull surface, up to its intersection with the free surface. Here, the hull boundary condition is applied right up to its intersection with the raised free surface panels, using an analytical continuation of the flow above the free surface.
- Kinematic condition on the free surface (subscripts denote total derivatives along the free surface)

$$\underline{w} = \underline{u}\zeta_x + \underline{v}\zeta_y \quad \text{on} \quad z = \zeta \tag{7}$$

- Dynamic condition on the free surface

$$\tfrac{1}{2}\underline{u}^2 + \tfrac{1}{2}\underline{v}^2 + \tfrac{1}{2}\underline{w}^2 + g\zeta = \tfrac{1}{2}U^2 \quad \text{on} \quad z = \zeta \tag{8}$$

- Free surface height at transom must be less than or equal to the transom edge height.

7. Iterative method

We use an iterative method by writing the panel source strengths and flow velocities as their previous estimates, plus a small additive correction:

$$\underline{\sigma_j} = \sigma_j + \sigma'_j$$
$$\underline{u} = u + u'$$
$$\underline{v} = v + v'$$
$$\underline{w} = w + w'$$

The iteration process then continues until the corrections tend to zero.

8. Combined free-surface boundary condition

The free-surface kinematic condition is now written as

$$w + w' = (u + u')\zeta_x + (v + v')\zeta_y \text{ on } z = \zeta \tag{9}$$

Similarly, the free-surface dynamic condition becomes, ignoring terms second-order and higher in the correction terms,

$$\tfrac{1}{2}u^2 + uu' + \tfrac{1}{2}v^2 + vv' + \tfrac{1}{2}w^2 + ww' + g\zeta = \tfrac{1}{2}U^2 \text{ on } z = \zeta \tag{10}$$

We now partially differentiate (10) to substitute ζ_x and ζ_y into equation (9). This gives the combined free-surface boundary condition

$$\begin{aligned}&\left(2uu_x + vv_x + ww_x + vv_y\right)u' + u^2u'_x + uvv'_x + uvu'_y + \left(uu_y + uv_x + 2vv_y + ww_y\right)v' \\ &\quad + v^2v'_y + \left(g + uw_x + vw_y\right)w' + uww'_x + vww'_y \\ &= -gw - u^2u_x - uvv_x - uww_x - uvu_y - v^2v_y - vww_y \text{ on } z = \zeta\end{aligned} \tag{11}$$

On free surface panels immediately behind the wetted transom, we set the free surface height to the transom height. Differentiating the dynamic boundary condition (8), we have

$$\underline{u}\, d\underline{u} + \underline{v}\, d\underline{v} + \underline{w}\, d\underline{w} + g\, d\zeta = 0 \tag{12}$$

The change in free surface height $d\zeta$ is chosen to update the old free surface height ζ to the transom height, i.e. $d\zeta = z_{tr} - \zeta$. Equation (12) is now used as the free surface boundary condition on panels immediately behind the wetted transom, as follows:

$$uu' + vv' + ww' + gz_{tr} - g\zeta = 0 \text{ on } z = \zeta \tag{13}$$

After the velocity corrections u', v', w' are found for all free surface panels, the updated free surface height is calculated by rearranging equation (8) to give

$$g\zeta = \tfrac{1}{2}U^2 - \tfrac{1}{2}\underline{u}^2 - \tfrac{1}{2}\underline{v}^2 - \tfrac{1}{2}\underline{w}^2 \text{ on previous free surface} \tag{14}$$

9. Finite differencing

The right-hand side of equation (11) involves total derivatives along the free surface for the velocity components u, v, w from the previous iteration, each of which are known at the free surface collocation points from the previous iteration. These derivatives are estimated using second-order upwind finite-difference methods where possible, following Raven (1996, p90), noting that waves produced by the ship tend to occur downstream from the ship, and radiate outwards from the ship.

For infill panels, upwind differencing is used for x-derivatives, using the infill panel directly upstream and allowing for the offset dy between adjacent infill panels:

$$du = u_x dx + u_y dy \tag{15}$$

First-order downwind differencing is used for infill panel y-derivatives.

Derivatives with respect to y near the ship's centreline, ahead of and behind the ship, are calculated using the method of images.

10. Solution method

Calculated source strengths from the wall free surface approximation (Section 5) are used as the initial estimate. We again use the general matrix equation

$$\sum_j A_{ij} X_j = B_i \tag{16}$$

Now we are solving for the source strength *corrections* on all N panels

$$X_j = \sigma'_j \tag{17}$$

For $i = 1 \dots N_h$, the hull collocation points, A_{ij} and B_i remain unchanged from equations (3) and (5).

For $i = N_h + 1 \dots N$, the free surface collocation points, B_i is calculated using the right-hand side of equation (11) at the i^{th} free surface collocation point, at the free surface height given from the previous iteration. A_{ij} is calculated by calculating the contribution to the left-hand side of equation (11), at the i^{th} free surface collocation point, from the j^{th} source panel with unit source density.

For free surface collocation points directly behind the wetted transom, equation (12) is used instead of equation (11).

No special equations are applied at the outer boundaries, except the 2 rows at the upstream boundary, where flow is kept at the initial flow estimate (Section 5).

11. Results

Convergence was reached after 9 iterations. Calculated ship pressure resistance coefficient, as defined in Larsson (2003), was 0.00072. Calculations supplied by Dr Hoyte Raven for the same case showed a pressure resistance coefficient of 0.00051, while the average from CFD codes in Larsson (2003, Table 7a) was 0.00085, with standard deviation 0.00030.

Calculated wave profiles are shown below.

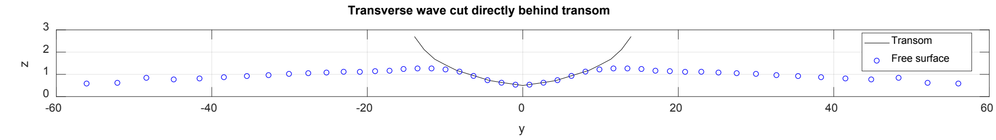

Figure 6: Transverse wave cut directly behind transom

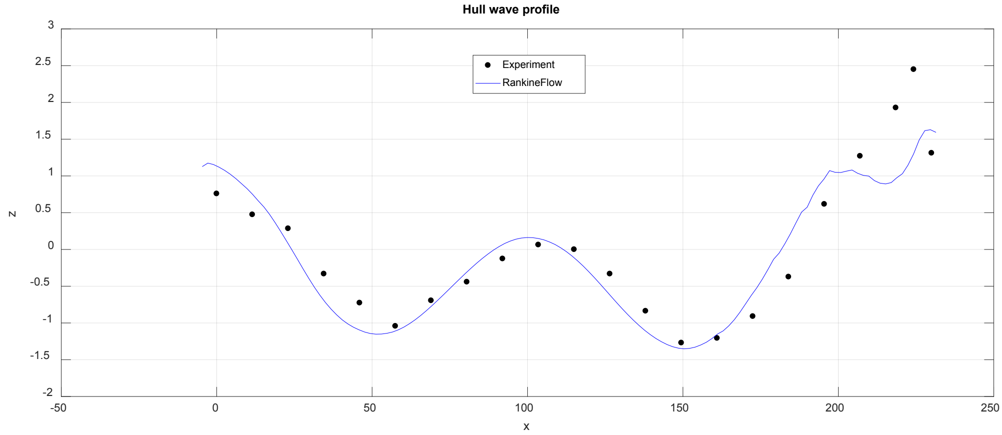

Figure 7: Calculated and experimental wave profile along the hull. Experimental results from Van (1997, Fig. 3)

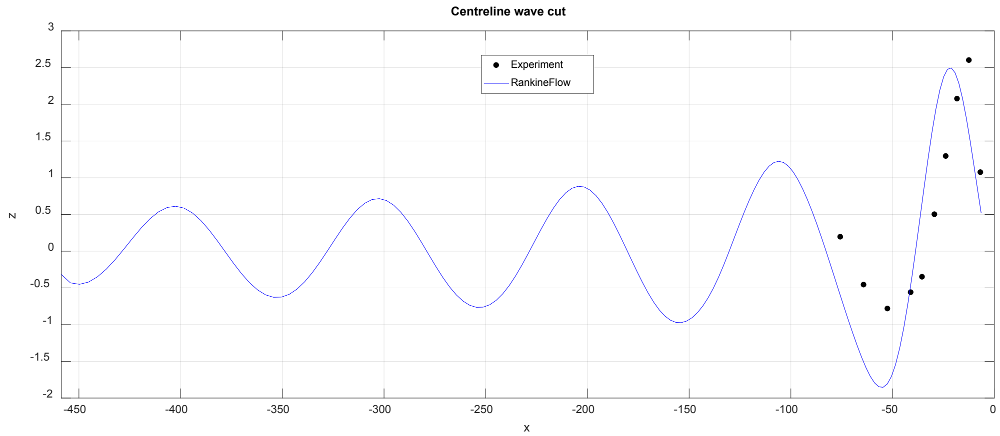

Figure 8: Calculated and experimental centreline wave cuts behind the ship. Experimental results from Raven & Starke (2002, Fig. 5)

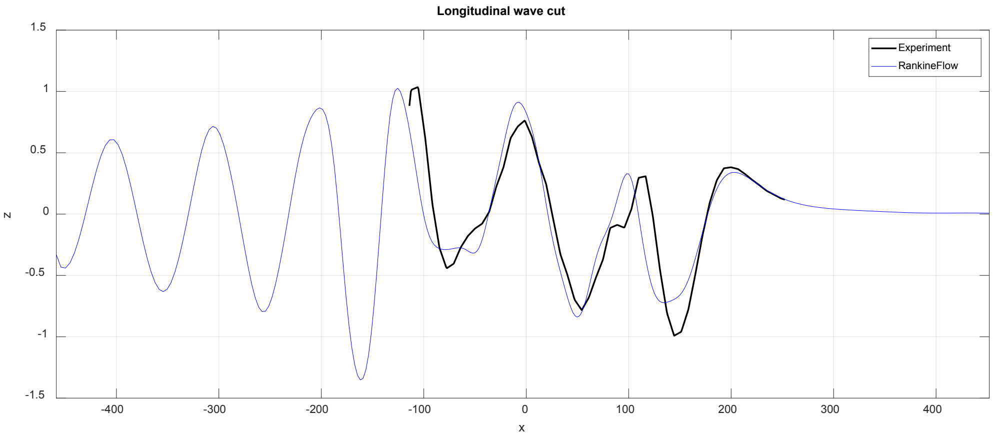

Figure 9: Calculated and experimental longitudinal wave cut at $y/L_{PP} = 0.1509$. Experimental results from Raven (2010, Fig. 13)

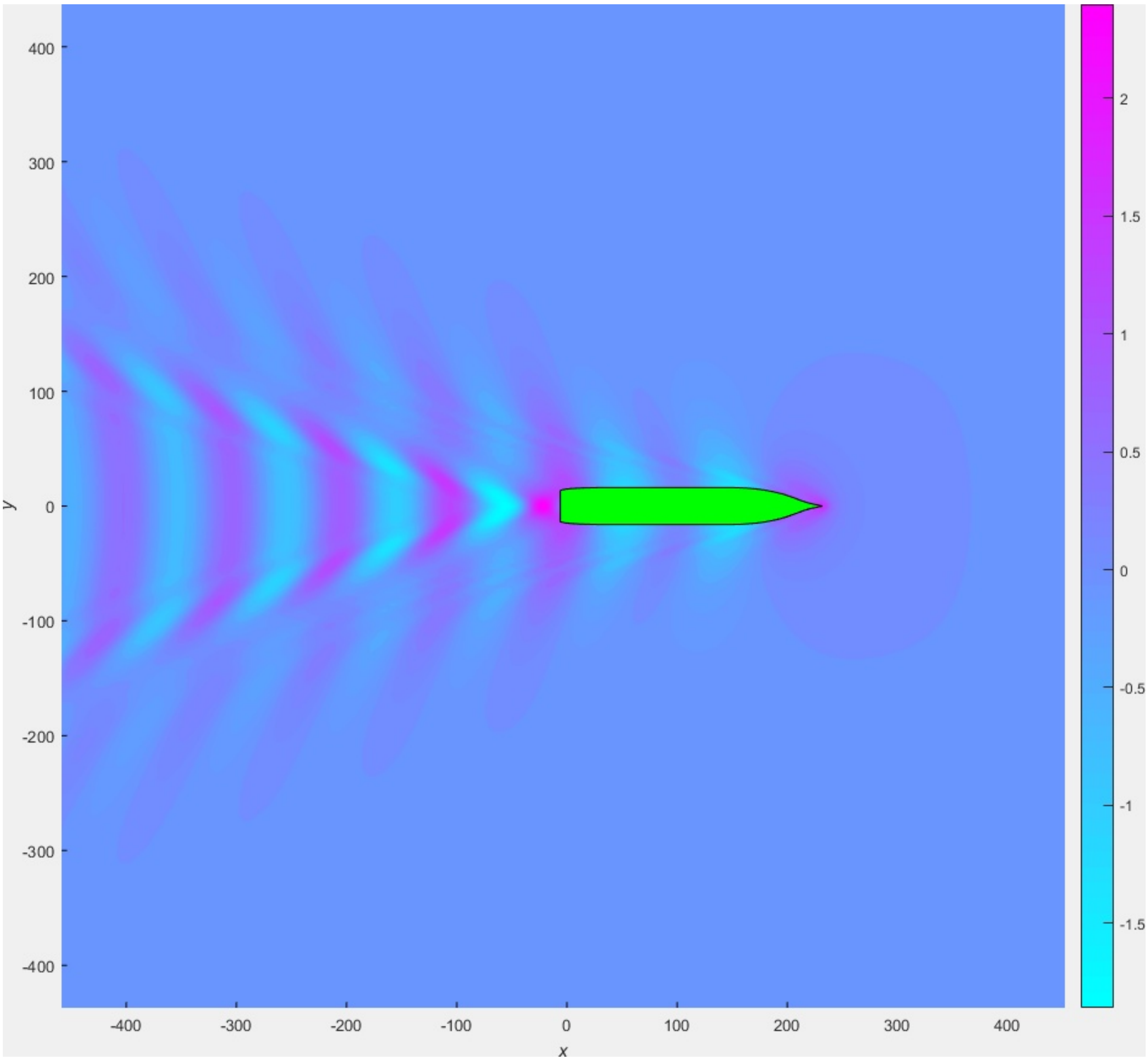

Figure 10: Free surface height contour plot, as calculated using phFlow for test case. Colours show free surface elevation in metres.

12. Acknowledgement

The author acknowledges valuable discussions on Rankine-source methods with Dr Hoyte Raven, of Marin, during development of the phFlow code.

13. Nomenclature

SI units are used throughout. All values are given at full scale.

$A_{ij} = N\text{x}N$ array used in matrix equation

$B_i = N\text{x}1$ array used in matrix equation

g = acceleration due to gravity

$\boldsymbol{i}$ =unit vector in x-direction

L = ship length between perpendiculars

N_h = number of hull panels in combined mesh

N_f = number of raised free surface panels in combined mesh

N = number of hull and raised free surface panels in combined mesh

$\boldsymbol{n}_i$ =unit normal vector into fluid from i^{th} panel

$n_i^{(x)}$ = x-component of unit normal vector into fluid from i^{th} panel

$\boldsymbol{q}_i$ =flow velocity at i^{th} collocation point

U = ship speed

$\underline{u}$ = flow velocity in x-direction, in ship-fixed frame of reference

$\underline{v}$ = flow velocity in y-direction

$\underline{w}$ = flow velocity in z-direction

u, v, w, σ_j = previous estimates

u', v', w', σ'_j = additive corrections to previous estimates

$u_{m,n} = u(x_m, y_n)$

$\boldsymbol{V}_{ij}$ = velocity induced at collocation point of i^{th} panel by unit source density on j^{th} panel

x = longitudinal coordinate, origin at aft perpendicular, positive forward

y = transverse coordinate, origin on ship centreline, positive to port

z = vertical coordinate, origin at still water level, positive upwards

x_m = x-position of free-surface collocation point

y_n = y-position of free-surface collocation point

z_{tr} = transom height

$\underline{\sigma_j}$ =source density of j^{th} panel

ζ = free surface height above still water level, positive upwards

14. References

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