CONTAINER SHIP DYNAMIC SINKAGE PREDICTION, USING THE NONLINEAR RANKINE-SOURCE PANEL CODE, PHFLOW

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SUMMARY

A validation study has been done into high-speed container ship dynamic sinkage in shallow water, using the nonlinear Rankine-source panel code, phFlow. The test case is the KRISO container ship, tested at 1:40 scale in the Duisburg towing tank. It was found that the nonlinear method departs rapidly from the linear method, as the ship speed comes close to the limit of steady subcritical flow. At such speeds, the nonlinear method predicts deeper wave troughs along the side of the hull, with similar wave crests at the bow and stern, compared to the linear method. Validation of hull wave profiles against model test results is the logical next step, to help resolve the remaining differences between predicted and measured dynamic sinkage. Further checking of the continuity equation throughout the domain is also desirable, because flow continuity becomes particularly important at high ship speed in a channel.

NOMENCLATURE

AP	Aft perpendicular
CoG	Ship centre of gravity
DTC	Duisburg Test Case container ship
FP	Forward perpendicular
KCS	KRISO Container Ship
KRISO	Korea Research Institute for Ships and Ocean engineering
RANS	Reynolds-averaged Navier-Stokes
SBSWT	Slender-body shallow-water theory
SWL	Static water level

1 OBJECTIVE

Model tests on container ships have shown large dynamic sinkage at high speed, that is not well-predicted by slender-body shallow-water theory. The difference has, in the past, put down to nonlinear terms in the free-surface boundary condition. The objective of this article is to see whether nonlinear effects do account for this large increase in sinkage at high speed.

2 INTRODUCTION

A method for predicting ship dynamic sinkage and trim is "slender-body shallow-water theory (SBSWT)", developed by Tuck (1966) for shallow open water. Later developments included extension to canals (Tuck 1967) and dredged channels (Beck et al. 1975). A summary of the methods, for a wide range of bathymetries, is given in Gourlay (2008). SBSWT is implemented in the computer codes "ShallowFlow" developed at Curtin University and "SlenderFlow" developed at Perth Hydro.

SBSWT was tested against full-scale measured midship sinkage of three Panamax and Post-Panamax container ships in the dredged Fremantle approach channel, at speeds of up to 16 knots (Ha & Gourlay 2018). Very good agreement was found between the predictions and measurements.

Conversely, SBSWT was tested against model-scale midship sinkage of the DTC container ship, measured at 1:40 scale in the Duisburg tank, in Mucha et al. (2016, Fig. 5). It was found that measured sinkage was 50% larger than the SBSWT predictions, at corresponding full-scale speeds of 11.7 knots and 12.6 knots.

SBSWT was tested against model-scale midship sinkage of the KCS container ship, measured at 1:40 scale in the Duisburg tank, in Mucha et al. (2016, Fig. 7). It was found that measured sinkage was 50% larger than the SBSWT predictions, at corresponding full-scale speeds of 12.0 knots and 15.0 knots.

For both sets of model tests, the agreement between SBSWT and experiment was much better at lower speeds.

The shape of the measured sinkage curves for the DTC in Mucha et al. (2016, Fig. 5) and for the KCS in Mucha et al. (2016, Fig. 7) suggest that, in each case, midship sinkage is reaching a trans-critical peak. A trans-critical sinkage peak in a channel (Algie et al. 2018) is characterized by a sudden increase in sinkage, as the continuity and Bernoulli equations force the flow past the ship at high speed. In this case, the velocity perturbations can no longer be considered small relative to the ship speed, and the assumptions of linearized flow velocities break down.

In this article, we explore the high sinkage values that occur for a ship in a channel, when the ship speed comes close to the limit of steady subcritical flow. We do this by calculating the sinkage using a linear theory and a fully-nonlinear Rankine-source panel code.

3 KCS TEST CASE

Calculations were done for the highest-speed KCS model test shown in Mucha et al. (2016, Fig. 7). All dimensions are given here at full scale. The KCS has principal particulars shown in Table 1.

Table 1. Principal particulars of KCS hull

Length between perpendiculars	230.00 m
Distance transom to AP	6.00 m
Distance FP to front of bulb	7.00 m
Length waterline	232.50 m
Beam	32.20 m
Depth	19.00 m
Design draft	10.80 m

The body plan and profile view of the KCS are shown in Figure 1.

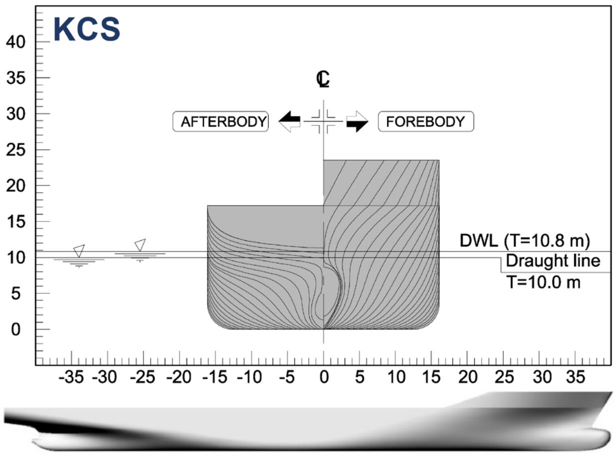

Figure 1. Body plan and profile view of KCS hull

The model tests described in Mucha et al. (2016, Fig. 7) involved towed model tests on the KCS bare hull, at 1:40 scale in the Duisburg tank. We shall consider the highest test speed (15.0 knots) from those tests. The test conditions are described in Table 2.

Table 2. Test conditions for KCS hull

Model scale	1:40
Tested draft (Mucha et al. 2016)	10.00 m
Tested displacement	47,400 m^3
Height of transom above still water level	1.30 m
Ship speed	15.0 knots
Water depth	13.0 m
Canal width	400.0 m
Froude length number	0.162
Froude depth number	0.683

We can estimate the upper speed limit of steady subcritical flow using the method of Schijf (1949, eq. 6) for a ship with long parallel midbody. This equation is also given in Gourlay (1999, eq. 11), together with other methods for predicting the steady subcritical speed limit. At speeds above this limit, no steady flow exists, and unsteady soliton-type waves are radiated ahead of the ship. At still higher speeds, the flow again becomes steady, and is known as steady supercritical flow.

For the KCS test case, the limiting Froude depth number for steady subcritical flow, with this ship and channel, is 0.70. Therefore the case modelled, with a Froude depth number of 0.683, is very close to the limit of steady subcritical flow. As discussed in Raven (2019, Section 3), we may expect that nonlinear effects may be particularly important at this speed.

4 PHFLOW CALCULATIONS

Perth Hydro has developed a nonlinear Rankine-source panel code entitled “phFlow”, for calculating flow around ships at forward speed in calm water. The objective of phFlow is to calculate the flow as accurately as possible, without including viscosity. The method is based on the raised free-surface panel method, developed for the RAPID code in Raven (1996). phFlow has been validated against model test results for the KCS container ship in deep water (Gourlay 2019a) and for the DTMB 5415 destroyer hull in deep water (Gourlay 2019b).

For this KCS test case in shallow water, a hull surface mesh was developed from the publicly-available IGES file. The surface mesh is shown in Figure 2. Port/starboard symmetry is assumed, so only panels on the port side are considered as unknowns.

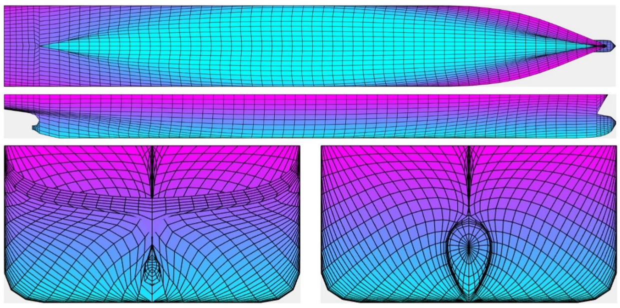

Figure 2. 2146-panel surface mesh for KCS hull, meshed to 17.0 m above keel. The transom is not meshed.

All ship hull panels, as shown in Figure 2, are used throughout the iteration process, including those above the free surface. Ship hull collocation points are chosen as the “null point” of each ship hull panel, using the method of Hess and Smith (1964, eq. 35).

Raised free-surface panels are set on a rectangular grid, as shown in Figure 3. Panel lengths in the x-direction (longitudinal) are constant along the length of the ship, and increased at a constant expansion ratio astern of and ahead of the ship. Panel widths in the y-direction (transverse) are constant in the inner region; in the outer region, panel widths are increased at a constant expansion ratio.

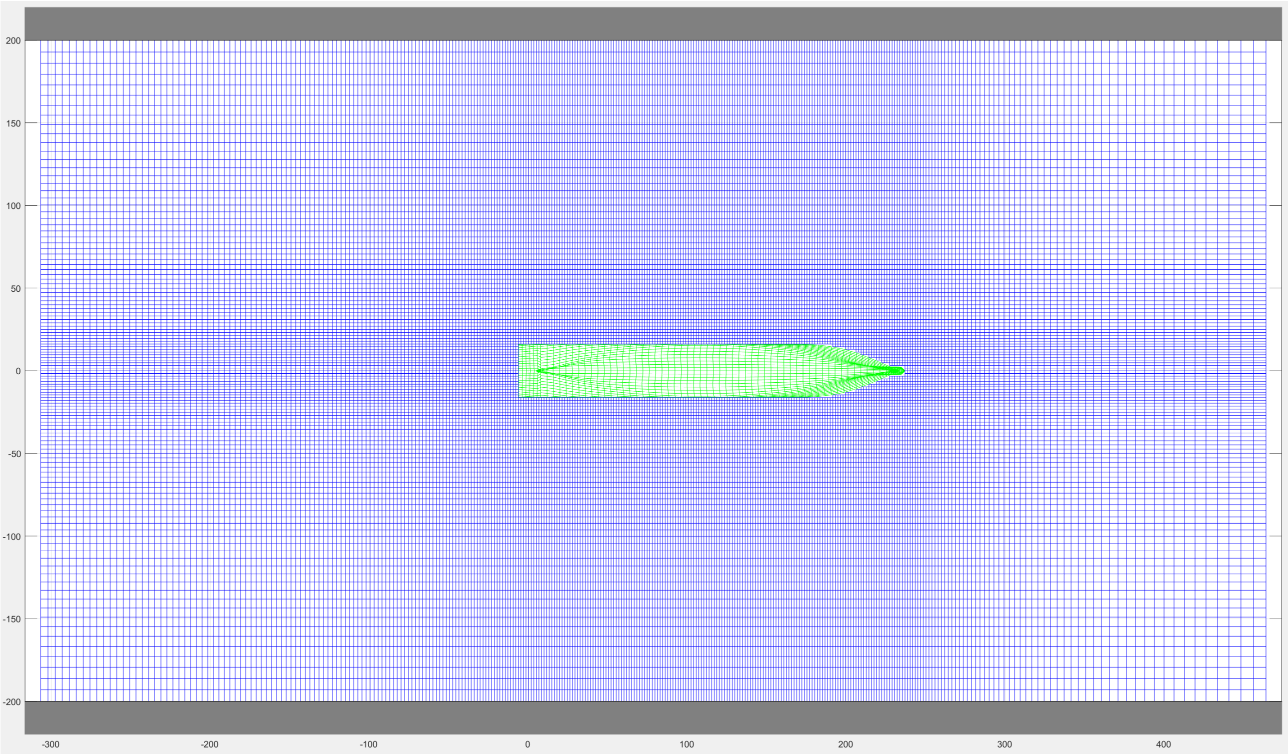

Figure 3. Hull panels and raised free-surface panels for KCS test case

Only free-surface panels that lie completely outside the hull, in planview, are used. In the original phFlow formulation (Gourlay 2019a), infill panels were used to bridge the gap between the ship panels and rectangular free-surface panels. However, this becomes tricky when allowing the ship to sink and trim. Testing showed that near-identical results were obtained for the deep-water test case studied in Gourlay (2019a), when the infill panels were left out and a small gap existed between the hull panels and free-surface panels. This method allows the same free-surface panels to be used whatever the ship sinkage and trim, simplifying the iteration process.

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 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.

The tank floor is made a symmetry plane, so images of hull panels and free-surface panels are applied beneath the tank floor. The tank walls are meshed from the floor up to approximately the raised free-surface panel height.

As this test case is close to the upper speed limit of steady subcritical flow, care is needed to ensure flow continuity within the domain. Following Raven (2019, Section 4), a grid of collocation points is set on the upstream boundary, at which the inflow speed is required to be equal to the ship speed. To achieve this, an additional grid of source panels is positioned one panel length upstream of the upstream-boundary collocation points. An additional row of sidewall panels is also included at the upstream boundary. The complete panelling is shown in Figure 4.

Details on the grid density and number of panels are shown in Table 3. The x-coordinate is zero at the aft perpendicular, positive forward; the y-coordinate is zero on the ship centreline, positive to port.

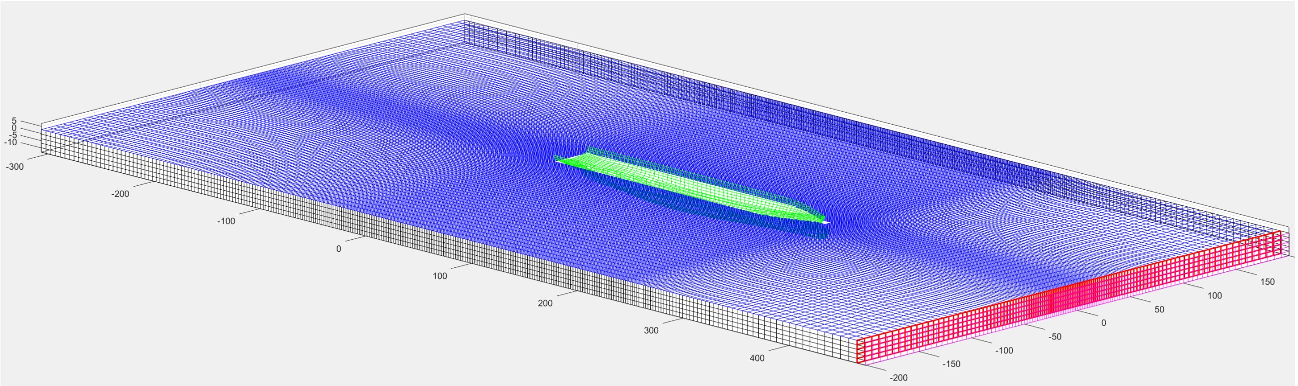

Figure 4. Complete panelling for KCS test case. Ship panels green; free surface panels blue; sidewall panels black; upstream collocation panels red; upstream source panels pink.

Table 3. Grid density parameters (port side)

xMin	-300 m
xMax	460 m
Free-surface panel length near ship	1.62 m
Free-surface panel width near ship	1.62 m
Free-surface panels in x-direction	315
Free-surface panels in y-direction	59
Free-surface panels	17212
Sidewall panels	1580
Upstream panels	295
Hull panels	1073
Total equations and unknowns	20160

The first estimate for flow around the ship is calculated using a wall boundary condition on all hull panels and tank wall panels, and a wall boundary condition at the still water level, for all free surface collocation points. This approximates the double-body flow around the ship in a canal. The resulting pressure head, beneath all raised free-surface panels, is shown in Figure 5.

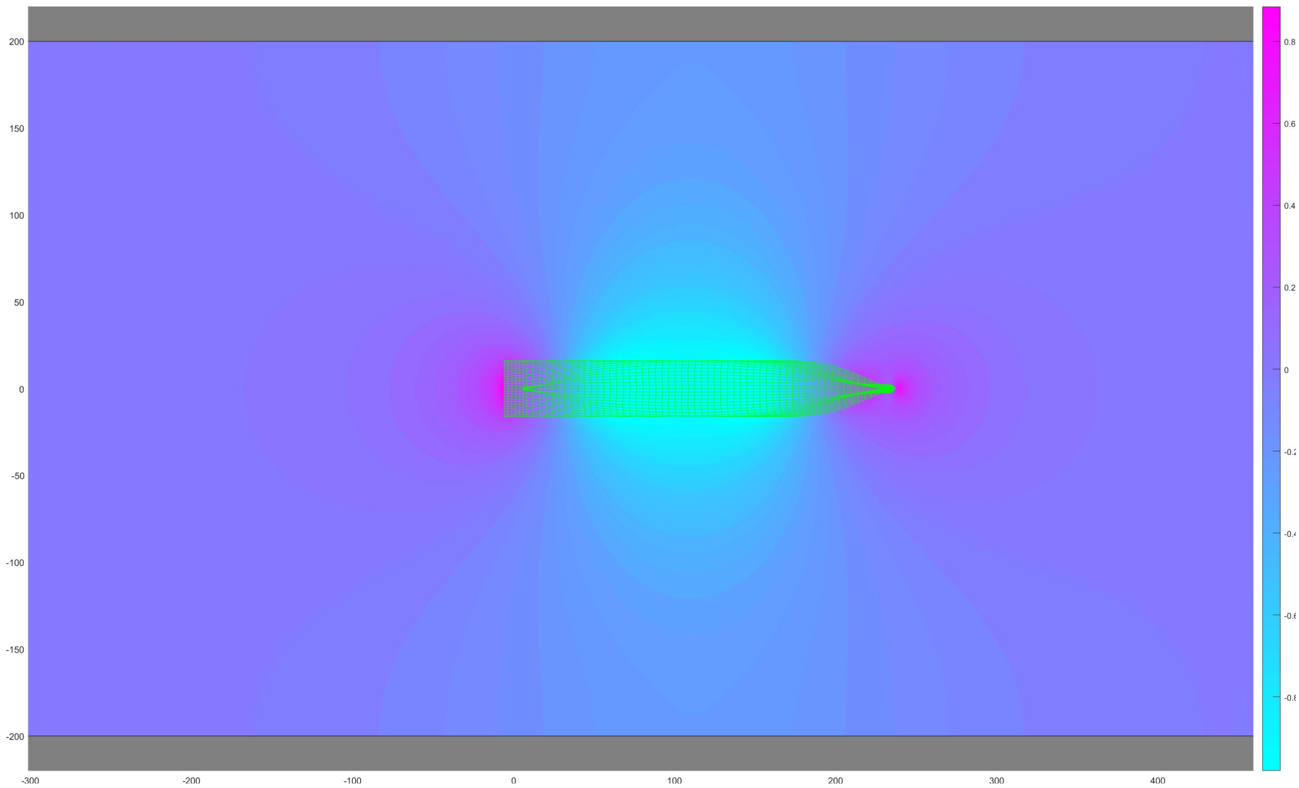

Figure 5. Initial flow estimate from double-body approximation; colours show pressure head (in metres) at SWL.

An iterative solution is used to update the panel source strengths, flow velocities and free surface heights, until the hull boundary condition, tank wall boundary condition, and nonlinear free-surface boundary conditions are all satisfied. The iterative solution process is as described in Gourlay (2019a), with one important difference: after each iteration, the pressure on all submerged hull panels is calculated using Bernoulli's equation and integrated to calculate the net vertical force and trim moment; the dynamic sinkage and trim are then adjusted to achieve equilibrium. In this way, the dynamic sinkage and trim converge to their steady-state values as the other flow parameters converge.

Because of the sharp transom on the KCS hull, care must be taken to ensure smooth detachment from the transom at high speed. This is achieved by requiring the free surface height at the transom to be equal to or lower than the transom edge.

Convergence of the KCS test case was achieved in 10 iterations.

5 WAVE PATTERN RESULTS

The converged free surface pattern for the whole domain is shown in Figure 6.

The converged free surface height directly behind the transom is shown in Figure 7.

Longitudinal wave cuts for the KCS test case, as compared to SBSWT (SlenderFlow) calculations, are shown in Figure 8 and Figure 9. SlenderFlow and phFlow predict identical free surface patterns ahead of the bow.

SlenderFlow calculations, being of first order in the shallowness and ship slenderness, contain the first-order wave drawdown along the length of the hull, but no Kelvin wave pattern. phFlow calculations show the wave drawdown, as well as the Kelvin wave pattern. In addition, the nonlinear nature of the phFlow solution results in a generally deeper wave trough along the side of the ship.

Behind the ship, phFlow shows a similar mean wave height to SlenderFlow, with the Kelvin wave pattern superimposed. However, we notice that the mean water level towards the downstream boundary is slightly below zero in the phFlow calculations. Although continuity is enforced at the upstream boundary, the chosen free-surface condition (Gourlay 2019a, eq. 11), which is based on derivatives, has some inherent drift. This means that continuity is not exactly conserved at the downstream boundary. Methods to correct this are the subject of ongoing research.

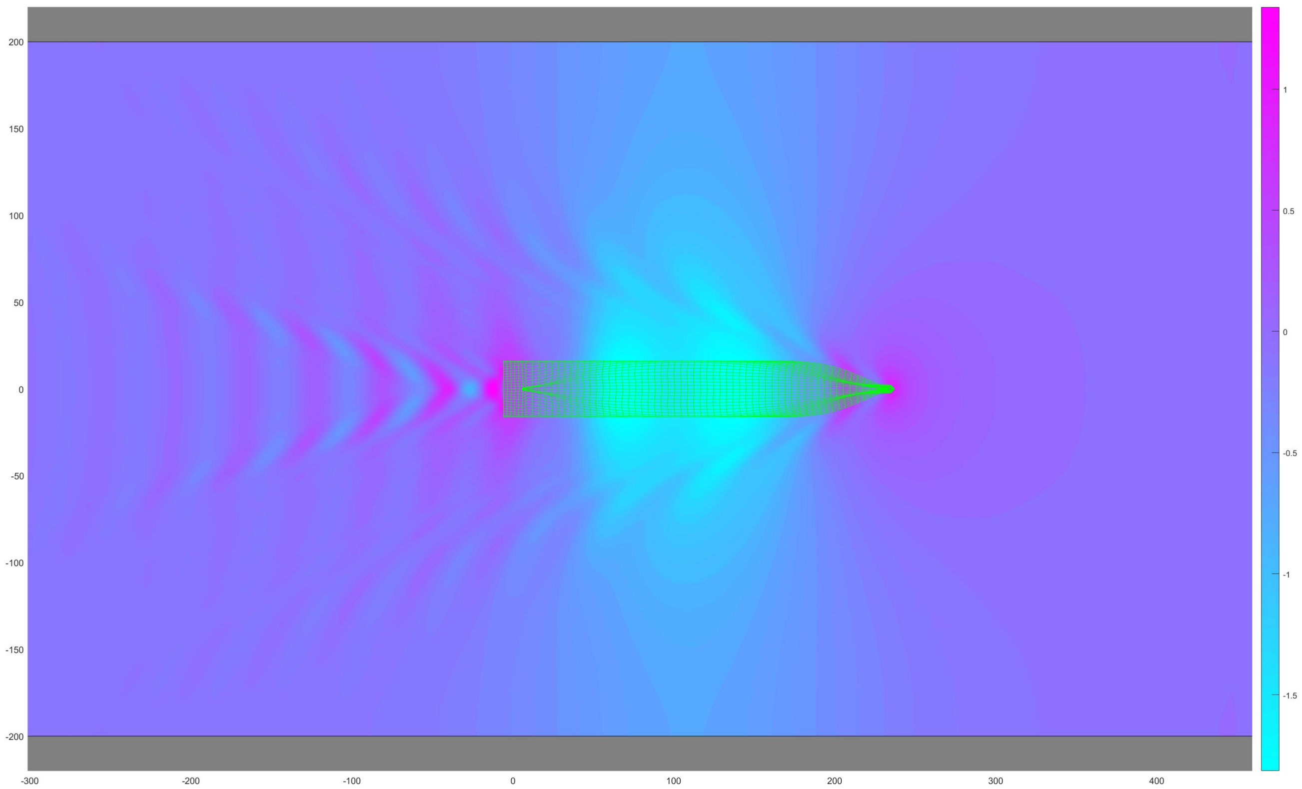

Figure 6. Converged free-surface elevations for KCS test case; colours show wave elevations (in metres).

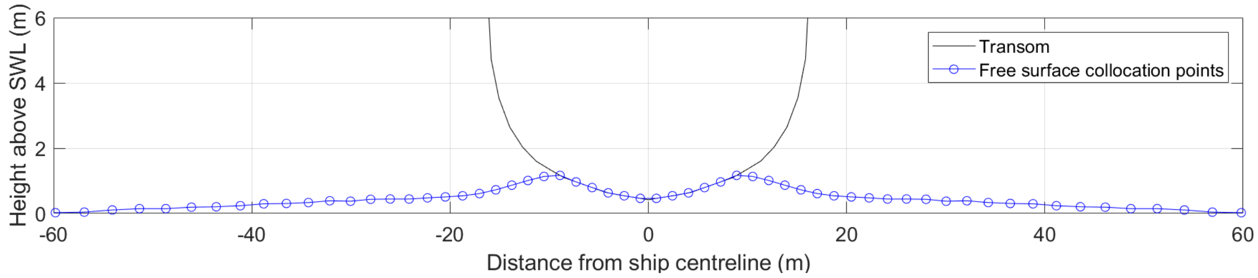

Figure 7. Transverse wave cut directly behind transom

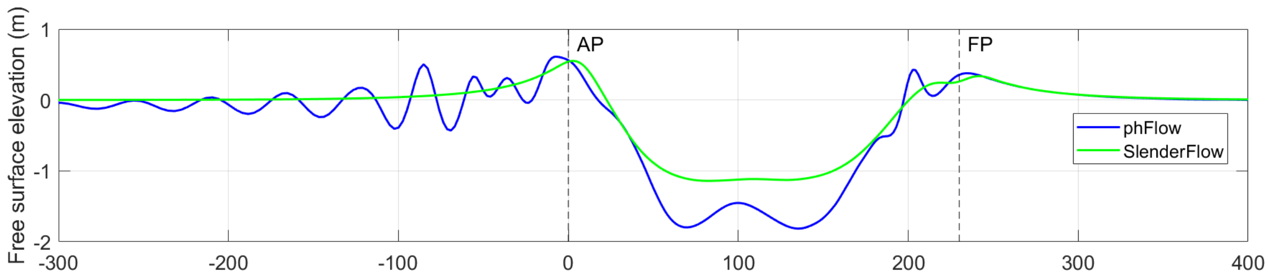

Figure 8. Longitudinal wave cut for KCS test case, at 17.0 m from ship centreline (0.9 m from side of ship)

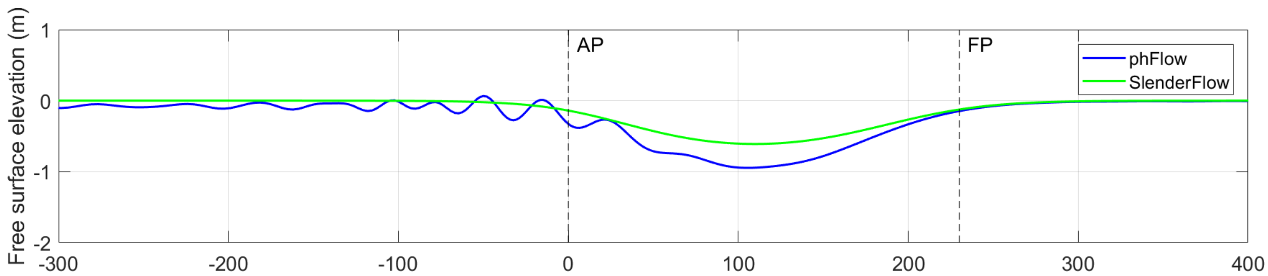

Figure 9. Longitudinal wave cut for KCS test case, at 100 m from ship centreline

6 SINKAGE RESULTS

Sinkage and trim values from SlenderFlow and model tests, for the KCS test case, are taken from Mucha et al. (2016, Fig. 7), together with results from other codes:

- GL Rankine (von Graefe 2014), an inviscid Rankine-source panel code, comparable to phFlow
- ISIS-CFD, a viscous RANS code (Queutey & Visonneau 2007)
- STAR-CCM+, a viscous RANS code (Cd Adapco 2015).

These results are reproduced in Table 4, together with calculated values from phFlow.

We see that the phFlow bow sinkage value is considerably larger than the SlenderFlow result, and close to the experimental value. As shown in Figure 8, phFlow shows a deeper wave trough along the forward part of the hull, as compared to the SlenderFlow calculations. This deep wave trough translates into a large sinkage at the bow. The nonlinear free-surface boundary condition implemented in phFlow, combined with the heavily restricted channel, produces a flow pattern that differs markedly from the linear predictions.

Table 4. Dynamic sinkage and trim results for KCS test case (Mucha et al. 2016, Fig. 7) @ 15 knots

	Midship sinkage	Bow-down trim	Stern sinkage (AP)	Bow sinkage (FP)
SlenderFlow	0.939 m	0.117°	0.705 m	1.173 m
phFlow	1.195 m	0.150°	0.894 m	1.496 m
GL Rankine	1.198 m	0.189°	0.819 m	1.577 m
ISIS-CFD	1.479 m	0.142°	1.194 m	1.764 m
STAR-CCM+	1.486 m	0.088°	1.309 m	1.663 m
Measurement	1.396 m	0.092°	1.212 m	1.580 m

The phFlow stern sinkage is larger than the SlenderFlow result, due again to nonlinear effects. However, the phFlow stern sinkage is well short of the measured value. As discussed in Gourlay (2014, Section 2.1), towed models tend to have larger stern sinkage than might be predicted by inviscid theory, due to viscous energy dissipation in the aft part of the boundary layer. This effect may be partly responsible for the difference in stern sinkage.

Comparison of hull wave profiles between phFlow and model tests, or other codes, is desirable to better understand the differences in stern sinkage for this test case. Previous comparisons show that the KCS hull wave profile in deep water is very similar between phFlow calculations and measured results (Gourlay 2019a, Fig. 7). This may not be the case in a shallow, narrow channel, however.

Both of the Rankine-source panel codes, phFlow and GL Rankine, give similar results for midship sinkage, with GL Rankine predicting larger bow-down trim. Again, comparison of wave patterns between the two codes would be beneficial, to better understand the differences.

At the second-highest speed of 12 knots in Mucha et al. (2016, Fig. 7), GL Rankine and SlenderFlow results are identical. This shows how quickly nonlinear effects become important, as the ship speed approaches the limit of steady subcritical flow.

Because the inviscid calculations of phFlow under-predict the measured stern sinkage, our thoughts turn to the importance of viscous effects. The viscous RANS results from ISIS-CFD and STARCCM+ are closer to the measured stern sinkage than the inviscid results in Table 4. It would be interesting to compare hull wave profiles between phFlow and one of the RANS codes, to help explain the different sinkage predictions.

As an aside, Deng et al. (2014, Figs. 2-3) presented RANS calculations at model-scale and full-scale for the DTC container ship at high speed in shallow water, showing that midship sinkage was similar in each case, so that Reynolds number is relatively unimportant for midship sinkage. However, stern sinkage was larger at model-scale than at full-scale. Therefore, the phFlow stern sinkage results may be closer to full-scale measurements than to model-scale measurements.

7 ACKNOWLEDGEMENT

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9 AUTHOR BIOGRAPHY

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