Sinkage and Trim of Modern Container Ships in Shallow Water

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Abstract

This paper concerns dynamic sinkage and trim of modern container ships. A review is made of changing container ship hull designs up to the present time, together with available model test data for sinkage and trim. Two potential flow methods (slender-body method and Rankine-source method) are discussed with reference to the model test results. It is shown that slender-body theory is able to give good predictions of dynamic sinkage and trim in wide canals or open water, while Rankine-source methods offer an accurate solution particularly for ships at high speed in narrow canals.

Keywords: sinkage, trim, shallow water, container ship

1. Introduction

The majority of Australia and New Zealand's container trade is still carried by Panamax container ships, with beam up to 32.3m, overall length up to 295m and draft up to 13.5m. Ports such as Brisbane, Fremantle, Melbourne and Sydney now accept Post-Panamax container ships with beam up to 40m and draft up to 14m. Ship resistance characteristics are such that larger ships use less fuel per transported container than smaller ships, so larger ships make more sense for long voyages.

Internationally, there is also a trend towards higher-capacity container ships. This is evidenced in the recent orders for Triple-E vessels with overall length 400m, beam 58.6m and draft 16.5m. These vessels will be used on the China-Europe routes, and have already called at the European ports of Antwerp, Hamburg and Rotterdam.

However, larger ships require deeper and wider channels, as well as longer berths with larger container cranes. Dredging has environmental implications on water quality, underwater noise, tidal streams and coastal wave climate. These costs and effects must also go into the analysis to support channel deepening. Notwithstanding this, channel deepening is on the wish list of many ports, with major channel deepening projects recently undertaken in Fremantle and Melbourne, and being planned for Wellington.

Whether or not a port should consider dredging and harbour expansion projects, one thing is very clear: we need more science to safely manage under-keel clearance (UKC) in all environmental conditions. This should include allowances for dynamic sinkage and trim (due to the Bernoulli effect when under way), wave-induced motions and heel due to wind or turning. Safe UKC management results in:

- *Safer shipping*. By ensuring consistently-low grounding risk in all environmental conditions.
- *Less dredging*. Therefore less cost and environmental impacts.
- *More cargo*. Existing ships can load deeper.
- *More efficient shipping*. Larger ships can be used, increasing fuel economy.

The new generation of larger container ships brings new challenges in safely managing under-keel clearance. Larger ships tend to have smaller wave-induced motions, but larger sinkage, than smaller ships, especially in shallow and restricted fairways. It is therefore timely to review the current state-of-the-art in ship sinkage and trim prediction for modern container ships.

2. Container ship hull shapes

A number of container ship research hullforms have been developed over the years, which are representative of designs of the time. Examples of these include:

- "Duisburg Test Case" ("DTC"), designed by the University of Duisburg-Essen, Germany in 2012, representative of a 14,000 TEU Post-Panamax container ship [1]
- "KRISO Container Ship" ("KCS"), designed by Korean Research Institute Ships and Ocean Engineering (KRISO), representative of a Panamax container ship [2]
- "JUMBO" designed by SVA Potsdam, Germany in 1995, representative of a 5,500 TEU Post-Panamax container ship [3]
- "MEGA-JUMBO" designed by VWS Berlin, Germany in 2001, the design ship for the Jade Weser port in Germany, representative of a 12,000 TEU Post-Panamax container ship [3]
- "Hamburg Test Case" ("HTC"), a model of the container ship "Teresa del Mar", built by Bremer Vulkan in 1986 and still in service [4]
- "S-175", a somewhat simplified hull shape used for model testing benchmarking [5]

In this article, the DTC, KCS, JUMBO and MEGA-JUMBO hulls have been developed from supplied IGES files, while the S-175 and HTC hulls have been digitized from the published lines plans. Calculated details of the modelled container ships are shown in Table 1 and Table 2. . Note that the KCS design draft is 10.8m, but it is modelled at 10.0m draft as used for model testing [6,7].

Table 1: Details of the modern container ships used for model test and numerical calculations. ▽ is the ship's displaced volume. Block coefficient is the ratio of displaced volume to (L_{PP}.Beam.Draft). Longitudinal centre of buoyancy (LCB) and longitudinal centre of floatation (LCF) are given as % of L_{PP} forward of Aft Perpendicular (AP).

Particulars	DTC	KCS	JUMBO	MEGA-JUMBO
L_{PP} (m)	355.0	230.0	320.0	360.0
Beam (m)	51.0	32.2	40.0	55.0
Draft (m)	13.0	10.0	14.5	16.0
	14.0			
	14.5			
Block Coefficient C_B	0.641	0.637	0.721	0.681
	0.654			
	0.660			
▽ (m^3)	150,910	47,197	133,901	215,775
	165,746			
	173,337			
Volumetric coefficient ▽/ L_{PP}^3	0.00337	0.00388	0.00409	0.00462
	0.00370			
	0.00387			
LCB (%)	49.48	48.89	49.30	49.97
	49.20			
	49.04			
LCF (%)	46.81	45.48	45.84	49.12
	45.88			
	45.38			

Table 2: Relevant details of the "Hamburg Test Case" and "S-175".

Particulars	Hamburg Test Case (HTC)	S-175
L_{PP} (m)	153.7	175.0
Beam (m)	27.5	25.4
Draft (m)	10.3	9.5
Block Coefficient, C_B	0.651	0.570
▽ (m^3)	28,332	24,053
LCB (%)	49.43	48.56
LCF (%)	46.58	45.97

We see a significant variation in block coefficient, which ranges between 0.57 and 0.70. Centre of buoyancy is slightly aft of midships for all hulls. For the MEGA-JUMBO, the LCF and LCB are virtually at the same position, whereas the LCF for the others is aft of the LCB by approximately 3% L_{PP}.

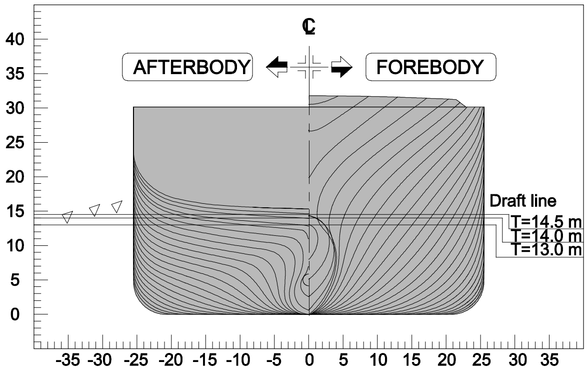

Figure 1: Body plan of DTC container ship, showing 50 evenly-spaced stations from transom to front of bulb.

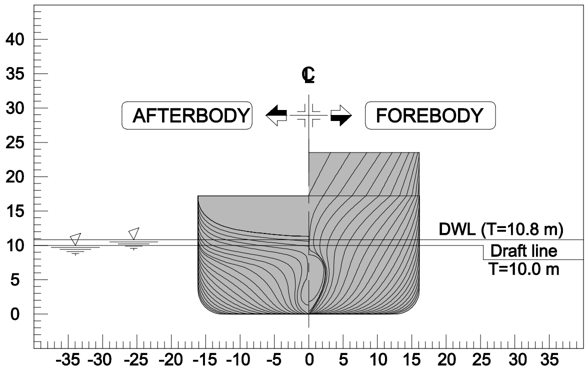

Figure 2: Body plan of KCS container ship, showing 50 evenly-spaced stations from transom to front of bulb.

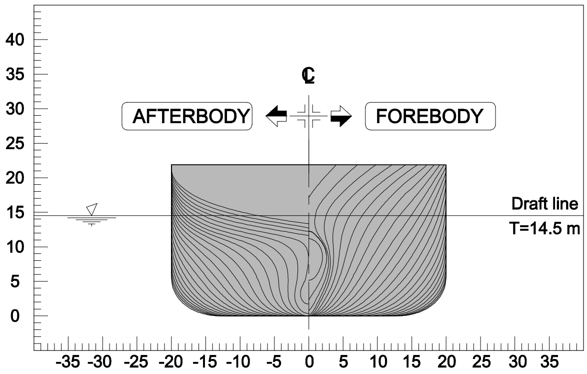

Figure 3: Body plan of JUMBO container ship, showing 50 evenly-spaced stations from transom to front of bulb.

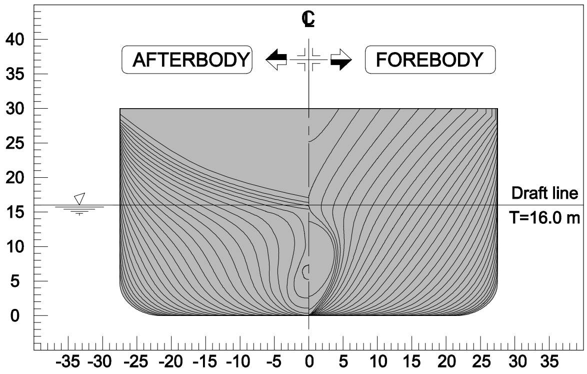

Figure 4: Body plan of MEGA-JUMBO container ship, showing 50 evenly-spaced stations from transom to front of bulb.

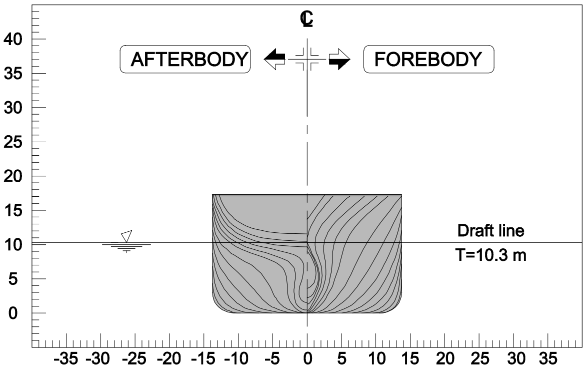

Figure 5: Body plan of HTC container ship, using stations given in [4].

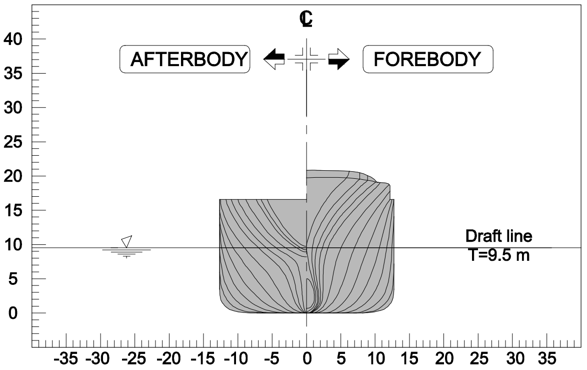

Figure 6: Body plan of S-175 container ship hull, using stations 0,0.25,..,1,1.5,..9,9.25,..,10

Body plans of the container ships are shown in Figures 1-6. The comparative body plans show significant changes in container ship design over the years: from the S-175 with its relatively small and low bow bulb, no stern bulb and sections that are close to vertical at the waterline, to the modern DTC with its high bow bulb, pronounced stern bulb and aft sections that are close to horizontal at the waterline. The only hull that has an immersed transom in the static condition is the JUMBO.

A comparison between the non-dimensionalized hull sectional area curves is shown in Figure 7.

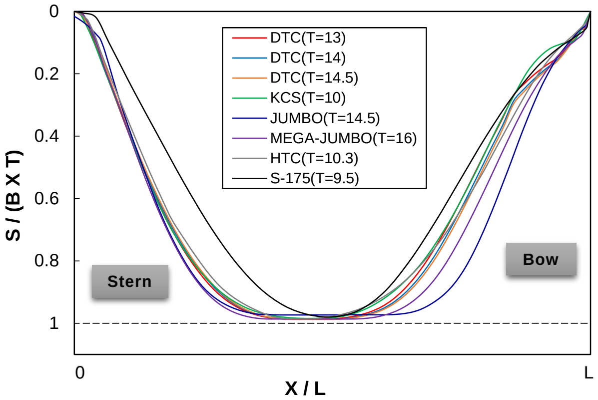

Figure 7: Comparative sectional area curves for each hull. Aft submerged extremity at $X=0$, forward submerged extremity at $X=L$.

We see that some of the hulls (JUMBO and MEGA-JUMBO) have long parallel midbodies reminiscent of bulk carriers, with rapidly-varying section areas near the bow. The S-175 has a sectional area curve with rather gradual slope near the stern and a comparatively short parallel midbody.

Figure 8 shows profiles, waterplanes and midship sections of all ships, scaled against L_{PP} in each case. We can see the significant differences in stern waterplane shape between the different hulls, which has an important effect on dynamic trim. In addition, we can see for the DTC that the changing draft also has a significant effect on the waterplane near the bow and stern.

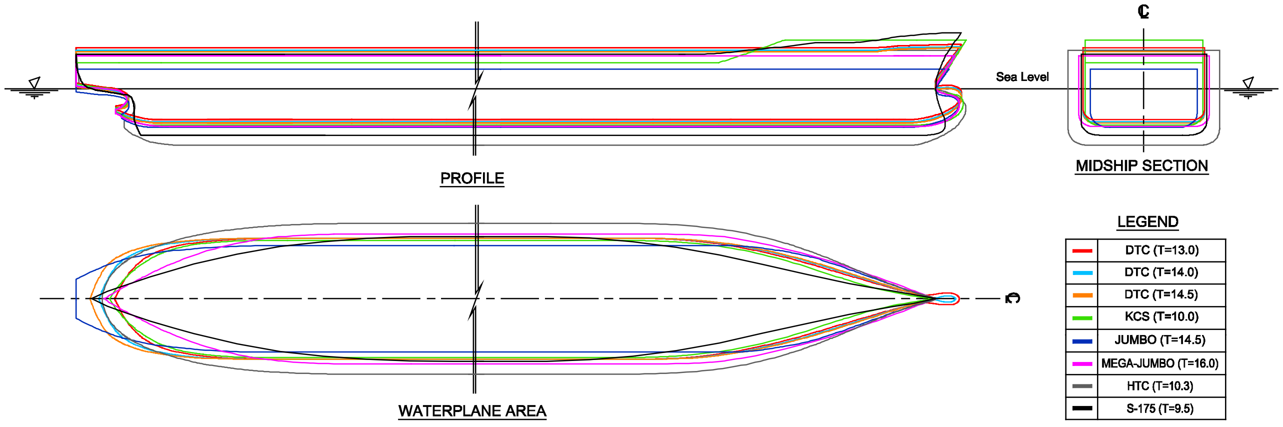

Figure 8: Ship profiles, waterplanes and midship sections of modelled container ship hulls.

3. Model test results for sinkage and trim

The DTC, KCS, JUMBO and MEGA-JUMBO have been extensively model-tested in recent years for shallow-water sinkage and trim. Tests on a 1:40 scale towed model of the KCS were carried out at the Development Centre for Ship Technology and Transport Systems (DST) in Duisburg, in the standard rectangular tank cross-section [6,7].

Tests on a 1:40 scale self-propelled model of the DTC were carried out in Duisburg in the standard rectangular tank cross-section [8,9]. Tests on the same model were undertaken at Federal Waterways Engineering and Research Institute (BAW) in Hamburg, in an asymmetric trapezoidal canal of similar cross-section area to the Duisburg tank. Tests on 1:40 scale self-propelled models of the JUMBO and MEGA-JUMBO were undertaken at BAW, in canals with 3H:1V sloping banks and varying widths [3]. We have used results from the largest and smallest canal widths here.

Comparative channel conditions for all model tests are shown in Table 3.

Table 3: Channel conditions used in model testing. DTC figures are for draft 13, 14, 14.5m respectively, and are shown for the rectangular and non-rectangular canals. KCS figures are for depth 11.5, 13.0, 16.0m respectively.

	DTC		KCS	JUM-BO	MEGA-JUMBO
	Rec.	Non-Rec.			
Canal width / L_{PP}	1.13	1.55	1.76	1.65	1.49
				3.90	3.50
Canal width / ship beam	7.84	10.78	12.55	13.21	9.75
				31.16	22.89
Canal : hull cross-sectional area ratio	9.79	10.33	14.67	14	10
	9.08	9.58	16.58	35	25
	8.77	9.25	20.41		
Canal depth / ship draft	1.23	1.23	1.15	1.14	1.13
	1.14	1.14	1.30		
	1.10	1.10	1.60		

Figure 9 shows the scaled midship sinkage S/L_{PP} as measured in the model tests. This is plotted against the non-dimensional "Froude depth number"

$$F_h = \frac{V}{\sqrt{gh}} \tag{1}$$

where V = ship speed, g = acceleration due to gravity and h = water depth. As an example, a container ship travelling in 16m water depth (including tide), at a speed of 12 knots, corresponds to F_h=0.49. Froude depth numbers typically range from 0.3-0.6 in port approach channels.

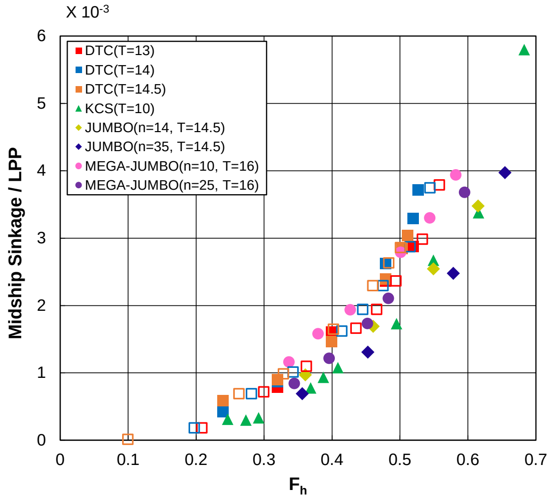

Figure 9: Measured midship sinkage from model tests (positive downward) as a function of depth Froude number F_h. Unfilled squares are for the DTC in the non-rectangular canal.

We see that the canal width is important for these results, with the JUMBO and MEGA-JUMBO having significantly larger sinkage in the narrow canal width.

The KCS tests were done at three different depths, but all collapse onto a single line with this scaling, as predicted using slender-body theory.

Figure 10 shows results of dynamic trim for the six container ship cases tested. Dynamic trim is quite small for all ships, with some ships bow-down and some stern-down. This is in line with full-scale measurements on 16 deep-draft container ships in Hong Kong [10], which showed that around of them trimmed bow-down and half of them stern-down. The effect of hull shape on full-scale measurements of dynamic trim is discussed in [11].

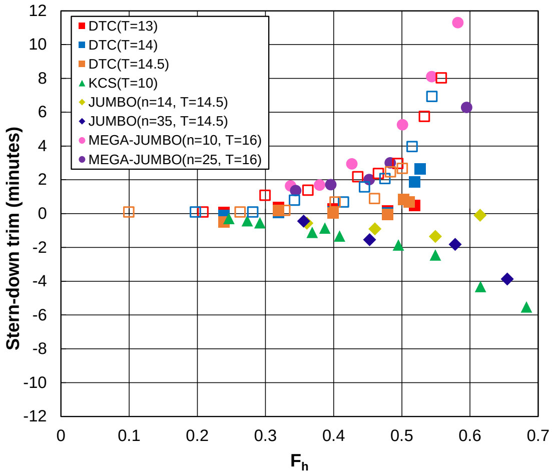

Figure 10: Measured dynamic trim (positive stern-down) as a function of depth Froude number F_h. Unfilled squares are for the DTC in the non-rectangular canal.

In this case we see that the DTC and MEGA-JUMBO generally trim stern-down, while the KCS and JUMBO trim bow-down.

Although dynamic trim is often said to correlate with block coefficient, as witnessed by the tendency of high-block-coefficient bulk carriers to trim strongly bow-down, no such correlation with block coefficient was seen in the container ships analysed here. For example, the DTC and the KCS have similar C_B, as do the JUMBO and the MEGA-JUMBO (see Table 1), but these groups show conflicting results of the dynamic trim.

We see by looking at the JUMBO and MEGA-JUMBO results that canal width has little effect on the dynamic trim, with the narrow canal giving a slight stern-down correction for both ships. The DTC is seen to have a more stern-down trim in the asymmetric canal than the rectangular canal; this is presumably caused by higher propeller RPM in the asymmetric canal tests [9].

4. Comparison with theoretical methods

We shall now compare the model test results with predictions from two potential-flow methods. The slender-body theory is based on the rectangular-canal slender-body theory of Tuck [12], as implemented in the computer program “ShallowFlow” [13]. This theory uses linearized hull and free-surface boundary conditions. The Rankine-source code “GL Rankine” [14] uses source patches on the hull and free surface, and exact hull and free-surface boundary conditions.

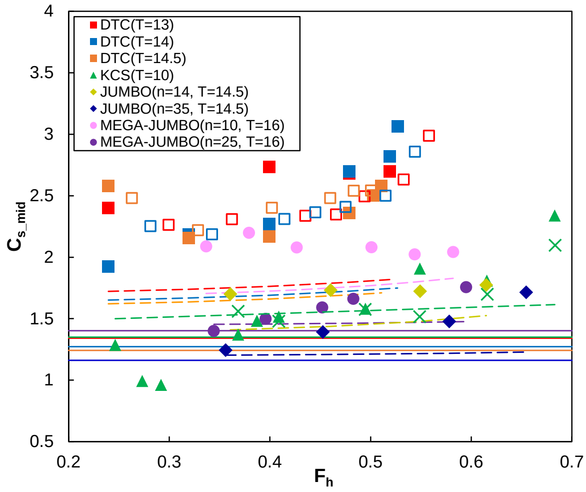

Figure 11: Measured and predicted sinkage coefficient for the container ships. Solid lines for Tuck’s method for open water, broken lines for Tuck’s method for canals and X for Rankine-source. Unfilled squares are for the DTC in the non-rectangular canal.

For ease of comparison across the speed range, results are here shown in terms of the midship sinkage coefficient C_{s_mid} [15] defined by

$$\frac{S_{mid}}{L_{PP}} = C_{s\_mid} \frac{\nabla}{L_{PP}{}^3} \frac{F_h{}^2}{\sqrt{1-F_h{}^2}} \qquad (2)$$

Figure 11 shows the comparison between the measured and calculated sinkage coefficients. We see that for the wide-canal cases (JUMBO n=35, MEGA-JUMBO n=25) at low speeds, the Tuck [12] and Rankine-source predictions are very close to the model test results. We see in these cases that channel effects are minimal, as the Tuck [12] results are very close to the open water [15] results.

As the Froude depth number increases above 0.6, or the canal becomes narrower, the Tuck [12] method starts to significantly under-predict the sinkage. This is thought to be due to the increasing importance of nonlinear effects at all speeds in narrow canals, or at high speed in wide canals. The Rankine-source method is seen to be closer to the model test results for the KCS at F_h>0.6.

Figure 12 shows the comparison between measured and predicted dynamic trim. We see that the theories generally predict a trim that is slightly more bow-down than the model test results. It is thought that this is due to the neglect of viscous boundary layer thickening towards the stern, as well as the low-pressure area forward of the propeller, both of which tend to make the trim more stern-down than the predictions.

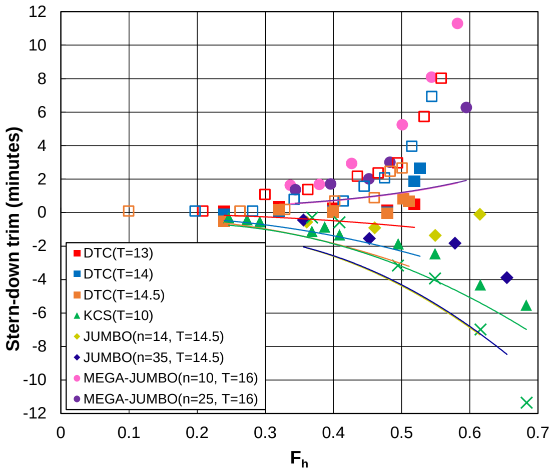

Figure 12: Calculated dynamic trim (positive stern-down) as a function of depth Froude number F_h. Solid lines for Tuck’s method for canals, X for Rankine-source. Unfilled squares are for the DTC in the non-rectangular canal.

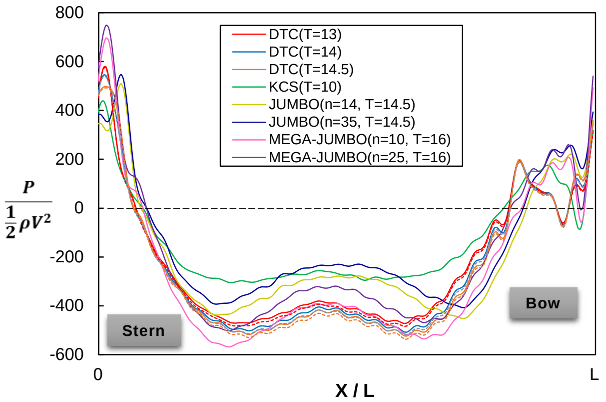

Figure 13: Pressure above hydrostatic (non-dimensional) along the hulls at $F_h = 0.5$, front of bulb at $X = L$, stern at $X = 0$, at tested depth. Broken lines for the DTC in the non-rectangular canal.

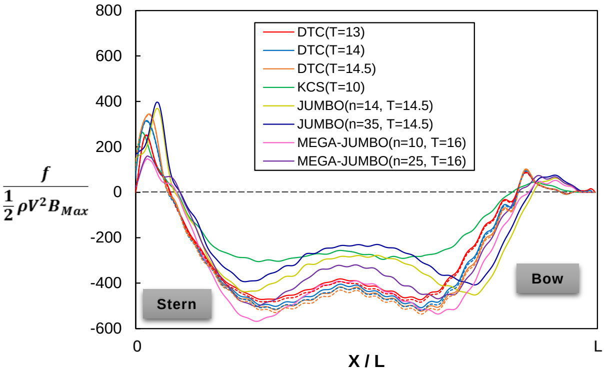

Figure 14: Vertical force per unit length $f=PB$, at $F_h = 0.5$. Front of bulb at $X = L$, stern at $X = 0$, at tested depth. Broken lines for the DTC in a non-rectangular canal.

Comparative hydrodynamic pressure along the hulls, for all ship and test cases, are shown in Figure 13 as calculated using Tuck [12].

We see that the hull pressure is characterized by deep low-pressure regions at the forward and aft shoulders. The effect of these on dynamic trim can be seen from the vertical force per unit length *f*, which is plotted for all ships in Figure 14.

If the centroid of this vertical force is ahead of the LCF, the ship will trim bow-down, and vice versa. We have already seen from the model test results that there is no clear correlation between dynamic trim and block coefficient; Figure 14 helps to explain why. The dynamic trim is governed by the *difference* between large quantities, the downward force at the forward and aft shoulder, and the upward force at the bow and stern. Small changes in hull shape will change the balance between each of these.

Indeed, we anticipate that good container ship design will aim to minimize dynamic trim, so as to minimize any adverse effects on resistance. This explains the small dynamic trim values measured in model tests and predicted theoretically.

5. An empirical correction for dynamic trim?

The Tuck [12] theory used here is an inviscid theory, which does not include the effect of boundary-layer thickening near the ship's stern. It also does not take account of the low-pressure region ahead of the ship's propeller. These effects are seen to give a model trim that is more stern-down than the predictions in the cases studied here.

Viscous effects on dynamic trim are scale-dependent, and may be expected to be less important at full scale, when the Reynolds number is large and the flow more closely approximates an inviscid flow. According to RANS-CFD calculations [16] for the DTC containership at 14m draft, dynamic trim is predicted to be 2.9 minutes more stern-down at model scale than at full scale, at 12 knots in 16m water depth (F_h=0.49). This difference is of similar magnitude to the difference between the model tests and slender-body predictions, so that the slender-body predictions may quite closely approximate the dynamic trim at full scale.

For comparison, the difference in dynamic trim between towed and self-propelled models of the DTC [9] was seen to be around 0.5 minutes more stern-down for the self-propelled model at F_h=0.5.

If we wish to more closely predict the dynamic trim at model scale, we can add a small stern-down empirical correction to the dynamic trim. A dynamic trim correction (in minutes stern-down) is sought of the form

$$\Delta\theta = cF_h^{\ 2} \qquad (3)$$

From an analysis of the theoretical and model test results, the constant *c* is found to have an average value of 12.21 and standard deviation of 6.81. At F_h=0.49, the correction is 2.7 minutes, which is very close to RANS-calculated difference between model scale and full scale, discussed previously. Therefore while this empirical correction may be applied to more closely match model test results, it is recommended that no such correction needs to be applied at full scale.

6. Future work

Other present and future research in the field of container ship under-keel clearance includes:

- Model tests on container ships at 3 different scales, to investigate the effect of scale on model test results (BAW, ongoing)
- Full-scale sinkage and trim measurements on 7 categories of container ships in the River Elbe (BAW, ongoing)
- Model-scale [17] and full-scale (CMST, ongoing) tests on container ship wave-induced motions in shallow water

7. Conclusions

Conclusions from the study were as follows:

- Container ship designs have changed appreciably from the S-175, with modern container ships tending to have high bulbous bows and broad, flat transoms
- Extensive model test data exists for sinkage and trim of modern container ship hullforms in shallow water
- Slender-body theory is able to accurately predict sinkage in wide canals, but under-predicts the sinkage in narrow canals
- Slender-body theory is able to predict dynamic trim with reasonable accuracy at model scale (except at high speed), and potentially with good accuracy at full scale
- Rankine-source theory provides a particularly good sinkage estimate for the KCS at high speed. Calculations for the other ship cases are desirable to assess this method further.

8. References

[1] El Moctar, O., Shigunov, V. and Zorn, T. (2012). Duisburg Test Case: Post-panamax container ship for benchmarking, Ship Technology Research Schiffstechnik, Vol. 59, No. 3, pp. 50-64.

[2] Lee, S.J., Koh, M.S., Lee, C.M. (2003). PIV velocity field measurements of flow around a KRISO 3600TEU container ship model, Journal of Marine Science and Technology, Vol. 8, No. 2, pp. 76-87.

[3] Uliczka, K., Kondziella, B. and Flügge, G. (2004). Dynamisches Fahrverhalten sehr großer Containerschiffe in seitlich begrenztem extremen Flachwasser, HANSA, 141.

[4] Gietz, U. and Kux, J. (1995). Flow investigations on the Hamburg Testcase model in the wind tunnel. Bericht 550, Technische Universität Hamburg-Harburg.

[5] ITTC (1987). Report of the seakeeping committee, S-175 comparative model experiments, Proceedings of the 18th International Towing Tank Conference (ITTC), Vol. 1 (18-24 October, Japan).

[6] Mucha, P. and el Moctar, O. (2014). Numerical Prediction of Resistance and Squat for a Containership in Shallow Water, Proceedings of the 17th Numerical Towing Tank Symposium (28-30 September, Sweden).

[7] Gronarz, A., Broß, H., Mueller-Sampaio, C., Jiang, T. and Thill, C. (2009). SIMUBIN - Modellierung und Simulation der realitaetsnahen Schiffsbewegungen auf Binnenwasserstraßen, Report 1939 B, Development Centre for Ship Technology and Transport Systems (DST).

[8] Mucha, P., el Moctar, O. and Böttner, U.C. (2014). Technical note: PreSquat - Workshop on numerical prediction of ship Squat in restricted waters, Ship Technology Research Schiffstechnik, Vol. 61, No. 3, pp.162-165.

[9] Mucha, P. and el Moctar, O. (2014). PreSquat - Numerische Vorhersagen von dynamischem Squat in begrenzten Gewässern, Bericht F005/2014, Institut für Schiffstechnik, Universität Duisburg-Essen.

[10] Gourlay, T.P. and Klaka, K. (2007). Full-scale measurements of containership sinkage, trim and roll, Australian Naval Architect, Vol. 11, No. 2, pp 30-36.

[11] Uliczka, K. and Kondziella, B. (2006). Dynamic response of very large container ships in extremely shallow water, Proceedings of the 31st PIANC Congress (14-18 May, Portugal).

[12] Tuck, E.O. (1967). Sinkage and trim in shallow water of finite width, Schiffstechnik, Vol. 14, pp. 92-94.

[13] Gourlay, T.P. (2014). ShallowFlow: A Program to Model Ship Hydrodynamics in Shallow Water, Proceedings of the ASME 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2014.

[14] Von Graefe, A. (2014). A Rankine source method for ship-ship interaction and shallow water problems, Ph.D. thesis, University of Duisburg-Essen.

[15] Tuck, E.O. (1966). Shallow water flows past slender bodies, Journal of Fluid Mechanics, Vol. 26, pp. 81-95.

[16] Deng, G.B., Guilmineau, E., Leroyer, A., Queutey, P., Visonneau, M. and Wackers, J. (2014). Simulation of container ship in shallow water at model scale and full scale, Proceedings of the 3rd National CFD Workshop for Ship and Offshore Engineering (25-26 July, China).

[17] Gourlay, T.P., von Graefe, A., Shigunov, V., and Lataire, E. (2015). Comparison of AQWA, GL RANKINE, MOSES, OCTOPUS, PDSTRIP and WAMIT with model test results for cargo ship wave-induced motions in shallow water. Proceedings of the ASME 34th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2015 (31 May – 5 June, Canada).