Australian Naval Architect 2007, Vol. 11, No. 2, pp 30-36.

Full-Scale Measurements of Containership Sinkage, Trim and Roll

Tim Gourlay & Kim Klaka
Centre for Marine Science and Technology
Curtin University, GPO U1987, Perth 6845, Western Australia

Abstract
We report on a recent project to accurately measure full scale sinkage, trim and roll of 16 deep-draft containerships entering or leaving a major container port. Measurements were performed using high-accuracy GPS receivers and a fixed base station. Results were used to calculate the sinkage of the bow, stern and bilge corners, as compared to the static condition. Overall dynamic draft increase and the governing factors affecting underkeel clearance of containerships are discussed.

Introduction

In early 2005 the Centre for Marine Science and Technology was contracted by Hong Kong Marine Department to perform a detailed study into sinkage and dynamic draft of containerships entering and leaving Kwai Chung, the busiest container port in the world. Part of this study was to carry out full-scale trials on some of the largest containerships, ranging in overall length from 277m to 352m, in order to accurately measure sinkage, trim and roll.

It has only been through the continually increasing accuracy of GPS receivers that full-scale squat measurements have become viable in the past decade. Whereas in model tests, the towing carriage acts as a fixed vertical reference, at full scale no such simple fixed reference exists. Inertial heave sensors are useful for performing seakeeping tests, since amplitudes rather than absolute motions are important in that case. However these sensors tend to “drift” over longer periods of time, so that they cannot accurately give absolute vertical motions.

GPS receivers have the advantage that they give absolute vertical motions relative to a fixed vertical reference on the earth (usually the WGS84 ellipsoid). For ship trials, these vertical heights can then be adjusted to be relative to nautical chart datum. In this way, once the tidal height is known, the height of the receiver above the static waterline can be calculated. Carrier-phase GPS receivers now have vertical accuracy in the order of centimetres, and can operate in kinematic mode to record the continually changing latitude, longitude and vertical height of points on a moving ship.

Measuring vertical motions using GPS

To measure sinkage and trim of a ship, two GPS receivers are positioned on the ship’s centreline, with one forward and one aft. Often the forward unit is mounted at the forecastle and the aft unit atop the bridge. To measure sinkage, trim and roll, three GPS receivers are needed onboard the ship. In this case, the units can be mounted at the forecastle, port bridge wing and starboard bridge wing. Sinkage, trim and roll are then calculated by assuming that the ship is a rigid body.

For high accuracy, an external reference GPS receiver is also required. This may be positioned either ashore or on a small escort vessel.

Once the onboard GPS receivers are fixed in place, a stationary reading of each receiver's vertical height is taken at the berth. This is then used as a reference value with which to compare the vertical height measurements whilst under way.

Shore-based receiver method

The shore-based receiver method is described in Feng & O'Mahony (1998). In this case, a GPS receiver is mounted ashore and kept in a fixed position for the duration of the measurements. Cross-correlating GPS signals between the moving receivers and the shore-based receiver then allows accurate position fixing of the moving receivers.

However, ship sinkage measurements must be taken relative to the instantaneous static waterline around the ship, and this changes as the tidal height changes. Therefore, results must be corrected for the fact that the static waterline height (tidal height) is changing with time and position. Also, the difference between the GPS vertical reference and the mean sea level (geoid undulation) must be accounted for.

Escort vessel method

The escort vessel method is described in Härting & Reiking (2002). In this case, the escort vessel first does its own sinkage and trim test using the shore-based method described above. This allows the vertical position of the escort vessel to be known for any given vessel speed. Then the escort vessel acts as a reference unit for the larger vessel.

The use of an escort vessel removes the error associated with estimating the tidal height at each time and position in the transit. This is because the escort vessel moves up and down with the tide by the same amount that the ship does, so any tidal height effects cancel out. In a similar way, geoid undulation may also be neglected when using this method.

Choosing the appropriate method

In choosing between the shore-based receiver and escort vessel methods for a particular application, the main deciding factors are: availability of tidal data; length of transit; sea state; and cost. These factors are discussed below with reference to performing trials in Hong Kong harbour.

Availability of tidal data:
Using a shore-based GPS receiver requires accurate knowledge of the tidal height at each point in the transit. If this cannot be calculated sufficiently accurately, then the escort vessel method should be used.

In the case of Hong Kong harbour, tidal variations are not too large (around 1 – 1.5m) and tidal heights are measured continuously at several points around the area.

Length of transit:
If using a shore-based receiver, errors increase as the baseline length (distance between shore-based receiver and moving receivers) increases. The baseline length always stays small when using the escort vessel method.

For the Hong Kong trials, the area of interest was around 4 nm (nautical miles) in length, and during this part of the transit the ship was never more than 2.5 nm from the shore-based receiver, so that baseline errors remained small.

Sea state:
The escort vessel method requires a fairly calm sea ahead of the ship, to have a stable vertical reference. Any swell, sea or wake from other vessels will cause an oscillatory vertical motion of the escort vessel, which may be difficult to average out.

Hong Kong has a fair amount of wave wake, generated by the very frequent shipping going into and out of the port. In addition, the easterly trade winds in winter cause high-frequency wind waves, while the summer monsoon brings significant south-westerly swells. This would have caused difficulties with gaining stable reference heights from the escort vessel.

Cost:
The use of an escort vessel entails additional costs as well as logistical difficulties.

All things considered, it was thought best to use the shore-based receiver method for these trials. For longer transits in calm water with little tidal data available, the escort vessel method is suitable and has been used successfully in Europe, as described in Härting & Reiking (2002).

Description of the trials

Trials location

Trials were conducted on vessels transiting to or from Kwai Chung, the Hong Kong container terminals, via the East Lamma Channel (see British Admiralty chart 3280 for details). For vessels leaving Kwai Chung, measurements were taken from the berth until the vessel passed approximate latitude 22°16’N. This transit includes an initial course towards the WSW, followed by a slow turn to port with final course SSE. The inward transits were the reverse of above.

The charted depth for this section of the transit varies from 15 - 35m. The transit is in essentially unrestricted water, with no channel blockage effects. The channel is well-sheltered from the prevailing swell.

Equipment

Trimble 5700 real-time kinematic, carrier phase GPS receivers were used. Three of these (with Trimble Zephyr antennas) were mounted on the vessel, with one at the bow and one on each of the bridge wings. A fourth receiver (with Trimble Zephyr Geodetic antenna) was mounted on-shore, at a secure location close to the container berths. This formed the base station with which to correlate the moving receiver results. This equipment setup gives a root-mean-square accuracy of 20mm for each moving receiver’s vertical position, as stated by the manufacturer for the baseline lengths used in these trials. Sampling rate was 1 Hz.

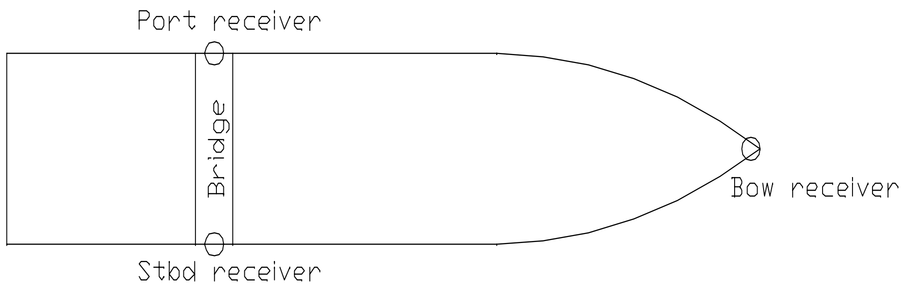

Figure 1: Typical GPS receiver locations on vessel

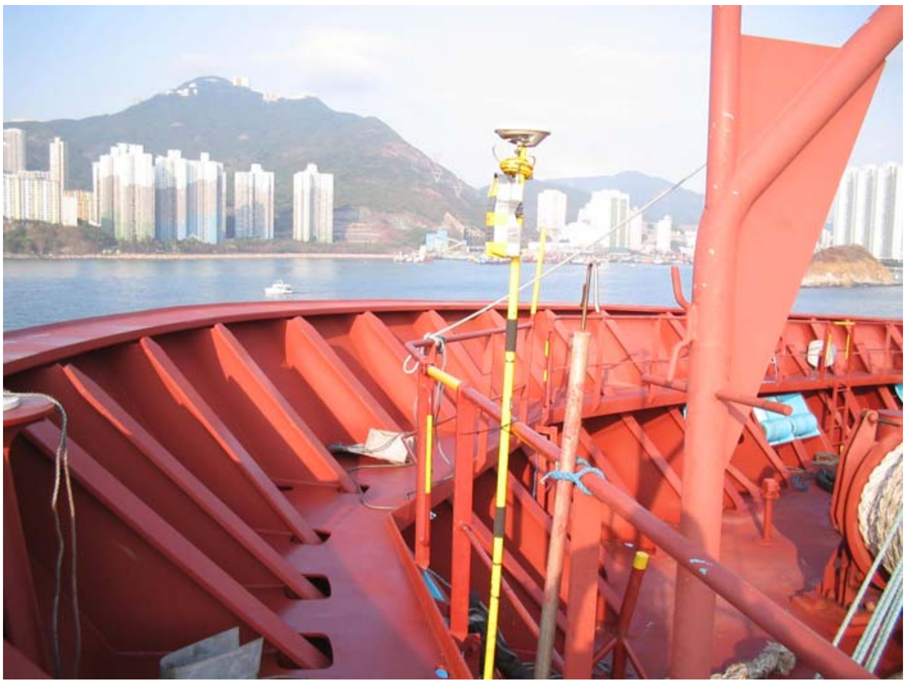

Figure 2: Typical bow receiver mounting

Arranging transits

Before commencing the trials, Hong Kong Marine Department and CMST spent considerable time liaising with pilots, container terminals, shipping lines and ship masters, organizing everything so that the trials could proceed smoothly. It was important that there was no interruption to any of the ships' usual operations.

Although ideally each individual transit should be arranged well in advance, this was impossible due to the changing ship schedules, as well as the safety requirement of only performing daylight transits. Instead, potential target ships were notified in advance and final confirmation of the transit given a few hours before each transit through the Pilots' Association. The Pilots' Association was invaluable in providing up to the minute schedules, liaising with ships' masters, and getting the CMST personnel to and from the ships with the pilots.

Through prior planning, round the clock monitoring of ship schedules, and a flexible approach to arranging transits, 20 transits were performed on 16 deep-draft containerships over a 9-day period. The vessels chosen were among the largest containerships currently in operation.

Trials procedure

Two CMST personnel performed the trials on the vessels. Both incoming and outgoing trials were conducted. The procedure for incoming transits is described below:

- CMST personnel board vessel with pilot, carrying equipment up ladder in backpacks
- Report to bridge, then set up equipment (5 – 10 minutes)
- Log data through to the berth, then take stationary reading at berth
- Remove equipment and disembark with the pilot

For outgoing transits the procedure was the reverse of above.

Data analysis

Trimble Geomatics software was used to take in the data from the three moving receivers and base station, and output (time, latitude, longitude, height) vectors for all three moving receivers.

Matlab software was then written for post-processing the results.

Calculating sinkage from GPS height measurements

This method follows that presented in Feng & O'Mahony (1998).

GPS height measurements are given not with respect to chart datum, but with respect to a mathematically-defined ellipsoid (the WGS84 ellipsoid) that only roughly approximates mean sea level.

We wish to ultimately measure height with repect to the local static waterline, so as to gauge the sinkage of the ship beneath its static floating position.

The first step in this process is to transfer the height measurements from the WGS84 ellipsoid to the geoid, which coincides with Mean Sea Level (MSL). The height of the geoid above the ellipsoid is known as the "geoid undulation" (*N*) which varies around the globe. Values of *N* for Hong Kong were taken from Chen & Yang (2001) and are around -1.6m to -1.7m in the area of interest.

Measured GPS heights relative to the ellipsoid (h_{measured}) are then transferred into heights relative to the mean sea level (h_{MSL}) as follows:

$$h_{\text{MSL}} = h_{\text{measured}} - N$$

These can then be transferred to the datum of Lowest Astronomical Tide (LAT), which is used for tidal measurements, as follows:

$$h_{\mathrm{LAT}} = h_{\mathrm{MSL}} + T_{\mathrm{mean}}$$

where T_{mean} is the mean tidal height, i.e. difference between LAT and MSL.

Instantaneous tidal height T is measured relative to LAT, since nautical charts normally use LAT as their datum. Therefore, the height of a GPS receiver above the instantaneous static free surface (h_{FS}) is given by

$$h_{\mathrm{FS}} = h_{\mathrm{LAT}} - T$$

Combining the above equations yields

$$h_{\mathrm{FS}} = h_{\mathrm{measured}} - N + T_{\mathrm{mean}} - T$$

This allows us to transfer the measured height h_{measured} of a GPS receiver above the WGS84 ellipsoid, into the actual height h_{FS} above the static free surface around the ship.

The rising of the ship ∇h_{FS} relative to the static free surface is the difference in h_{FS} between when the vessel is underway and when it is in its static free-floating position at the berth. Therefore

$$\nabla h_{\mathrm{FS}} = (h_{\mathrm{FS}})_{\mathrm{underway}} - (h_{\mathrm{FS}})_{\mathrm{static}}$$

Sinkage is defined as being positive downwards, so it is given by

$$\text{Sinkage} = -\nabla h_{\mathrm{FS}} = (h_{\mathrm{FS}})_{\mathrm{static}} - (h_{\mathrm{FS}})_{\mathrm{underway}}$$

or

$$\text{Sinkage} = (h_{\mathrm{measured}} - N + T_{\mathrm{mean}} - T)_{\mathrm{static}} - (h_{\mathrm{measured}} - N + T_{\mathrm{mean}} - T)_{\mathrm{underway}}$$

For these trials, the region of interest is small and T_{mean} varies little. Therefore the difference between T_{mean} at the berth and during the transit has been neglected, with a small associated error. This reduces the above equation to

$$\text{Sinkage} \approx (h_{\mathrm{measured}} - N - T)_{\mathrm{static}} - (h_{\mathrm{measured}} - N - T)_{\mathrm{underway}}$$

Therefore in order to calculate sinkage the following quantities are required:

- Measured GPS receiver heights through the entire transit, as well as a static reading at the berth
- Tidal heights at each time and location in the transit, as well as a static reading at the berth
- Geoid undulation N over the area of the transit

Other output quantities

Once the sinkage at each GPS receiver has been calculated over the entire transit, rigid-body dynamics are used to transfer sinkage at the three receiver locations into sinkage at other locations on the vessel, specifically the forward post, aft post, port bilge corner amidships and starboard bilge corner amidships. For consistency, the bilge corners have been taken to be 80% of the half-beam away from the centreline of the vessel.

These extremities of the vessel are the points on the hull that might come closest to the sea floor, and therefore should be taken into account when assessing grounding risk.

Note that the rigid-body assumption neglects any additional hogging or sagging of the vessel while under way, as compared to the stationary condition at the berth. In practice there may be slight additional sagging due to the generally depressed free surface height over the middle portion of the vessel.

For some vessel layouts, a fourth receiver could be mounted at the stern of the vessel to measure any additional hog or sag whilst under way.

Error analysis

The errors inherent in calculating sinkage of each receiver on the ship are as follows:

GPS vertical error relative to the WGS84 ellipsoid:
Expected vertical RMS error was given as an output from the Trimble Geomatics software. This was generally in the range 0.01- 0.02m.

Geoid undulation N:
The error in geoid undulation N over the area of interest is not known precisely. It is estimated that differences in N will have errors ranging from zero near the berth to around 0.02m at the end of the region of interest.

Static reading at berth:
In order to have a static position elevation at the berth, vertical elevations were averaged over 2 minutes at the berth once the ship had tied up. A small residual movement was normally present, however, due to slight rolling of the vessel or vertical movement due to seiching in the harbour. The RMS error in the static reading was estimated as 0.04m.

Measured tidal data:
The RMS error in the tide gauge at Kwai Chung is estimated to be 0.01m.

Sea surface slope:
Measured Kwai Chung tidal data was used for the entire transit, since the entire region of interest lay within a 2.5nm radius of the tidal measuring station, and the most important part of the transit was close to the measuring station.

Looking at measured tidal data from other stations in the area allowed an estimate to be made of the likely difference in tidal height between the end of the region of interest and Kwai Chung. We therefore estimate that the RMS error in tidal height due to sea surface slope ranges from zero near Kwai Chung to 0.03m at the end of the region of interest.

Total error at each receiver:
Since all of these data sources are added or subtracted in order to calculate the final sinkage value, the total error is found by summing the squares of the individual errors and then taking the square root. Therefore the estimated RMS error close to Kwai Chung is 0.05m, and at the end of the region of interest is 0.06m.

Total error in sinkage at vessel extremities:
The errors in bow sinkage will be as above, since a receiver was located directly there. Disregarding sag, the errors at the bilge corners will also be similar since these points are within the space bounded by the receivers. Stern sinkage error will be slightly larger due to the required extrapolation outside the area bounded by the receivers.

Dynamic sinkage

Measured sinkage along transit

Example measured sinkage results, as well as corresponding speed profiles, are shown in Figures 3 – 6. Since the transit was generally in a north-south direction, and distance along the channel is difficult to define when taking account of manoeuvring near the berths, results have been plotted as a function of midship latitude.

It can be seen that there is considerable oscillation in the sinkage of the port and starboard bilge corners. This is primarily due to roll, as very little heave or dynamic pitch was measured in any of the runs. Spectral analyses of the measured roll have been performed for the cases shown, with large peaks being found at a period of 14 seconds for Ship A and 18 seconds for Ship B. These periods match the calculated natural roll periods of the vessels.

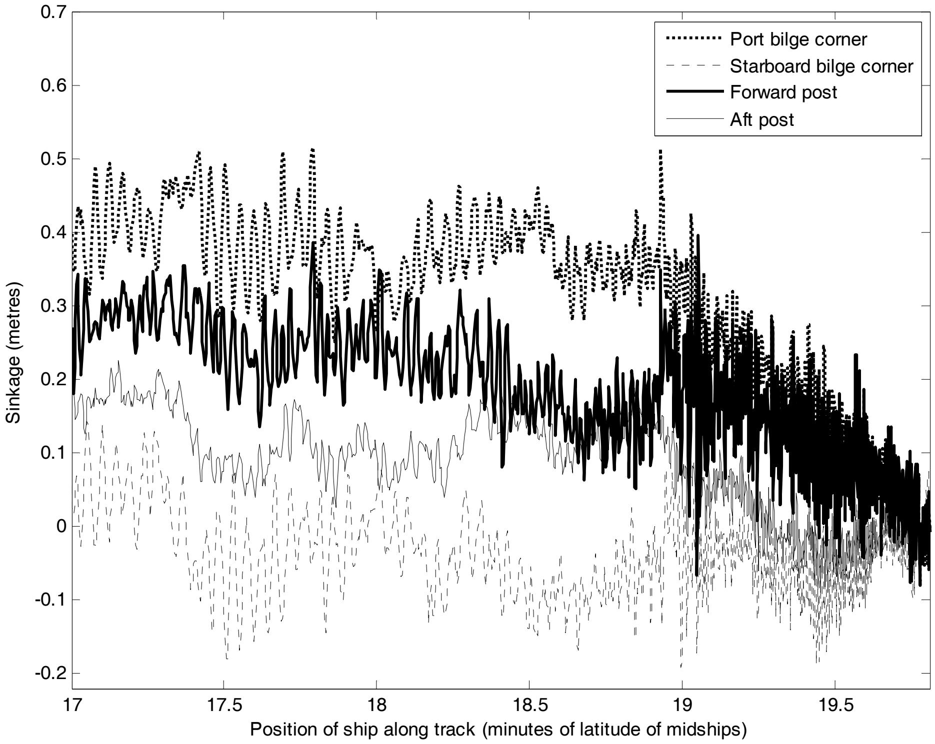

Figure 3: Ship A on inbound transit: sinkage at four points on vessel

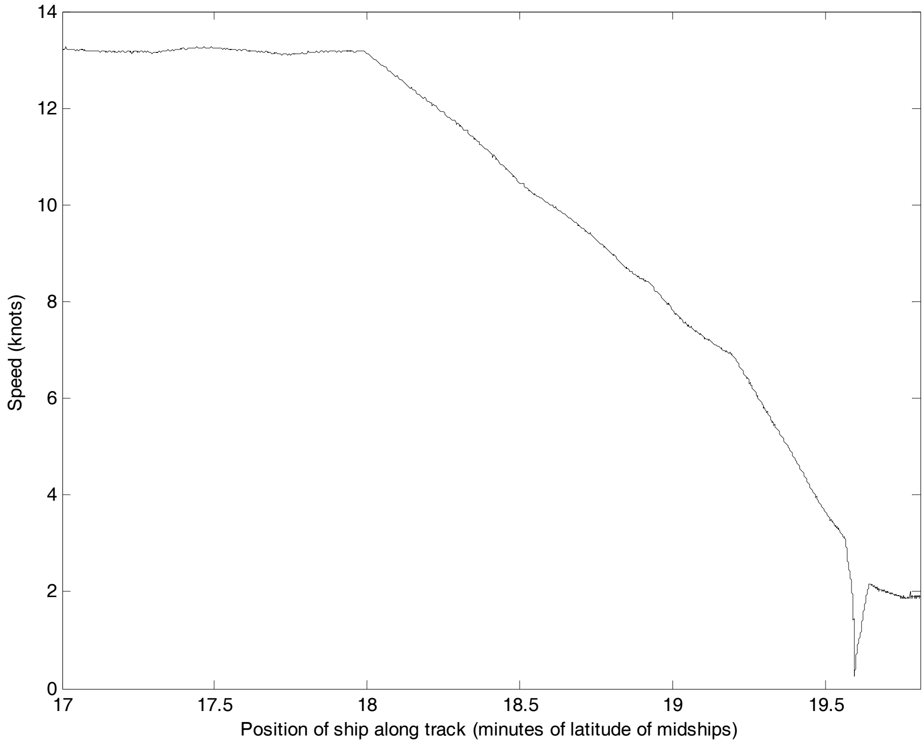

Figure 4: Ship A on inbound transit: ship speed over the ground

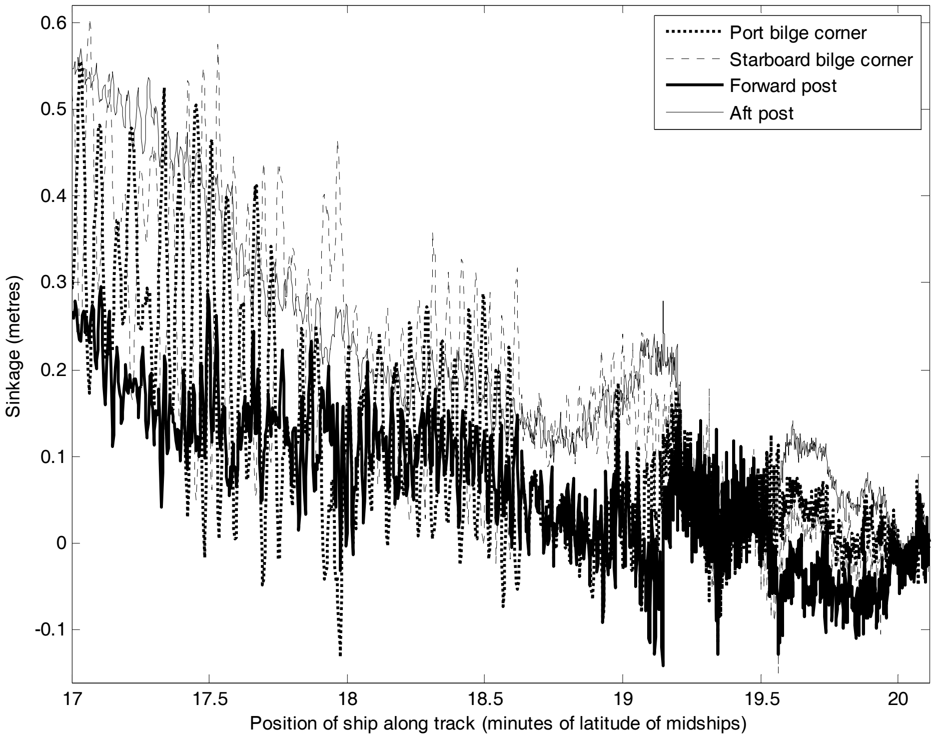

Figure 5: Ship B on outbound transit: sinkage at four points on vessel

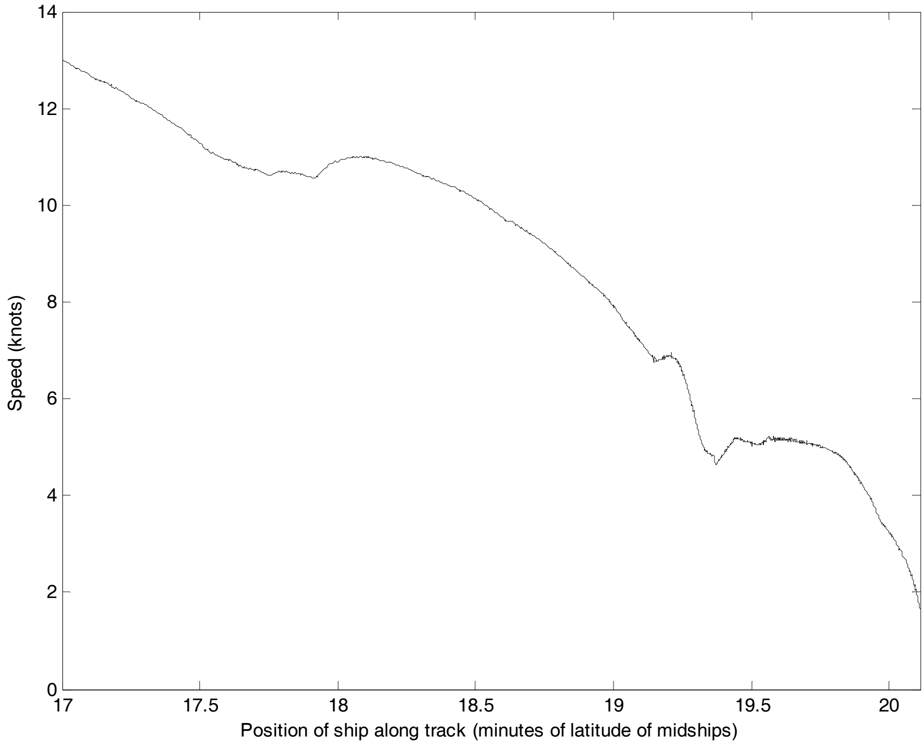

Figure 6: Ship B on outbound transit: ship speed over the ground

Maximum sinkage

The maximum sinkage almost invariably occurred at the bilge corner on the western side of the transit, due to the combined effects of easterly winds and a turn centred toward the east.

The maximum sinkage, as a percentage of length between perpendiculars, averaged 0.22, with standard deviation 0.13, minimum 0.13 and maximum 0.63.

Factors affecting sinkage for containerships

Dynamic trim

Full-form ships such as bulk carriers, with almost level static trim, tend to trim down by the bow when under way (see e.g. Dand & Ferguson 1973 for model test results). This is due to the longitudinal centre of buoyancy (LCB) being located well forward of the longitudinal centre of floatation (LCF). See Tuck (1966) for calculation of this effect based on potential flow methods.

For the containerships tested, it was found that in most cases there was little dynamic trim, and that this trim could be either by the bow or the stern, depending on the vessel.

Containerships have their LCB normally slightly aft of amidships and not far forward of the LCF. According to potential flow theory, these ships should experience a slight bow-down trim. However, the effects of the propeller inflow, as well as flow separation near the stern, both act to decrease the overall pressure near the stern and hence tend to trim the vessel by the stern. Therefore the overall dynamic trim of a containership is normally quite small, and may be either by the bow or the stern, depending on the hull shape, loading condition and propeller characteristics. Note that the static trim of the vessel will also affect the dynamic trim.

LCF sinkage

The LCF sinkage of containerships will generally be smaller than bulk carriers of similar length (or even similar displacement) due to their smaller volumetric coefficient c_∇, defined by

$$c_\nabla = \frac{\nabla}{L_{\mathrm{PP}}^3}$$

where ∇ is the ship displacement volume and L_{PP} is the length between perpendiculars. A frequently-used formula for LCF sinkage (Tuck 1966, Hooft 1974, Huuska 1976, Gourlay 2006) gives the LCF sinkage s_{LCF} as

$$\frac{s_{\mathrm{LCF}}}{L_{\mathrm{PP}}} = c_{\mathrm{s}}\, c_\nabla \frac{F_h^2}{\sqrt{1-F_h^2}}$$

Where

$F_h =$ Froude number based on water depth, i.e. $V/\sqrt{gh}$

$c_{\mathrm{s}} =$ LCF sinkage coefficient, normally in the range 1.2 – 2.4, according to model tests referenced above

Bulk carriers generally have volumetric coefficients 0.006 – 0.010, while containerships generally have volumetric coefficients in the range 0.002 – 0.005.

Therefore the LCF sinkage of a containership will generally be around half that of a bulk carrier of similar length.

Roll

We shall here take roll to mean the instantaneous heel angle experienced by the vessel, as compared to the steady-state heel angle whilst at the berth. This includes both dynamic oscillatory roll caused by swell or free decaying roll, as well as steady heel due to wind or turning.

For the containerships tested, roll was the most important factor governing maximum sinkage. Rolling of the vessel causes the bilge corners to be displaced vertically downwards, so that for a vessel with level static trim, the bilge corners of the ship are generally more vulnerable to grounding than the bow or stern.

This situation is very different to bulk carriers, which generally experience very small roll angles when transiting approach channels in calm conditions. For these ships, the large bow-down trim means that the bow is the point on the ship most vulnerable to grounding.

It is important to note that there is a considerable difference between containerships and bulk carriers in terms of roll characteristics. Containerships have a relatively high centre of gravity and low metacentric height, which translates into much larger heel angles during turns. Often containerships will be travelling quite quickly through turns, which also increases the turn-induced heel.

Wind heel is also much larger for containerships than for bulk carriers. Containerships tend to have larger above-water profile area, larger wind heeling lever arm, smaller displacement (for the same ship length) and smaller GM. These effects all combine to produce much larger wind heel angles for containerships than for bulk carriers.

During the course of these trials, it was noticed that wind and turning both had a significant effect on heel angle and hence sinkage at the bilge corner. These effects were difficult to separate, since they both acted in the same direction over most of the transit. In addition, an oscillatory roll motion was normally present, which may have been excited by changes in vessel direction, wind gusts or any refracted swell entering the area.

Wave-induced vertical motions

No significant swell was noticed in the Hong Kong approach channel during these trials, since it is well-protected from the north-east monsoon swell. However in any approach channel where swell is present, the resulting wave-induced heave, pitch and roll will all cause vertical motions of the ship and hence increase the sinkage.

Hull shape

Bulk carriers tend to have fairly long parallel midbodies. Therefore the combined effects of trim and roll mean that in a seaway the forward or aft (normally forward) shoulder of the bilge corners may be particularly vulnerable to grounding.

Containerships, however, have little if any parallel midbody. Therefore the forward and aft shoulders need not be considered; rather just the port and starboard bilge corners at their widest point.

Dynamic draft increase

For a ship that has level trim in the static condition, any sinkage at the bow, stern and bilge corners translates directly into an increase in dynamic draft and therefore a decrease in underkeel clearance.

However, for a ship that is trimmed by the stern in the static condition, sinkage at the bow or bilge corners does not translate directly into a decrease in underkeel clearance. Even if the ship is rolling considerably and the bilge corners are experiencing significant downward sinkage, the stern may still be most vulnerable to grounding, due to its already close proximity to the sea floor.

Therefore we shall here make a distinction between the concepts of “sinkage” at different points on the ship, and the overall “dynamic draft increase”.

The dynamic draft at each location on the ship can be found by adding the static draft at that point to the sinkage at that point. The point on the ship with the largest dynamic draft is the point most likely to hit the bottom. The overall dynamic draft is the maximum dynamic draft over the whole vessel.

The difference between the overall dynamic draft and the maximum static draft is the “dynamic draft increase”, and is the extra allowance that should be included if the ship is to avoid grounding.

Results

Figures 7 and 8 show the dynamic drafts at different points on the vessel for Ship A and Ship B.

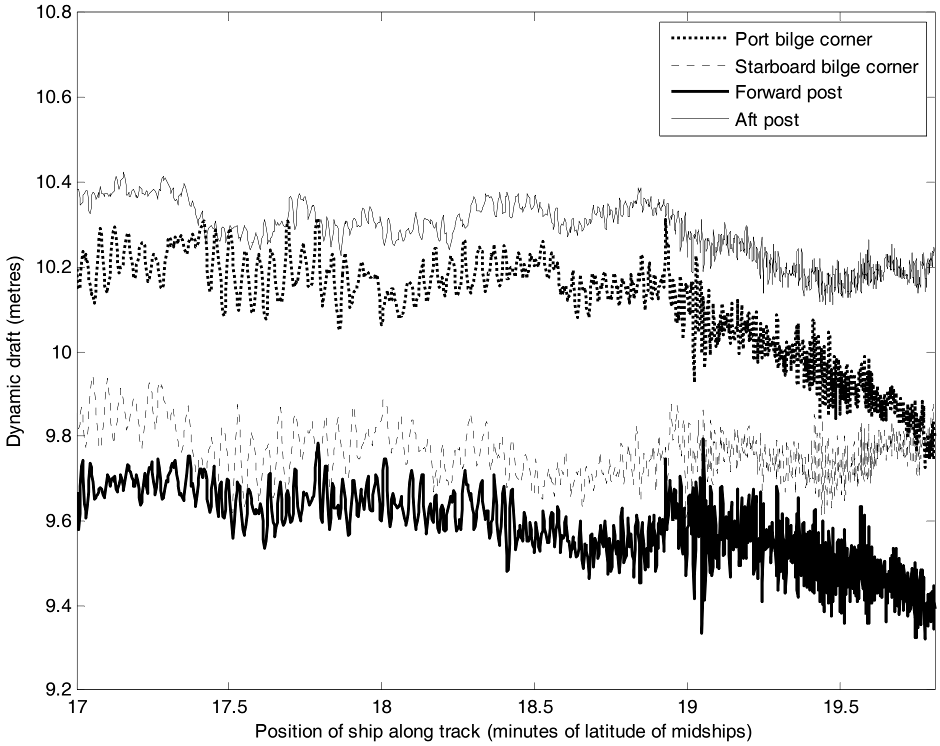

Figure 7: Ship A on inbound transit: dynamic draft at four points on vessel

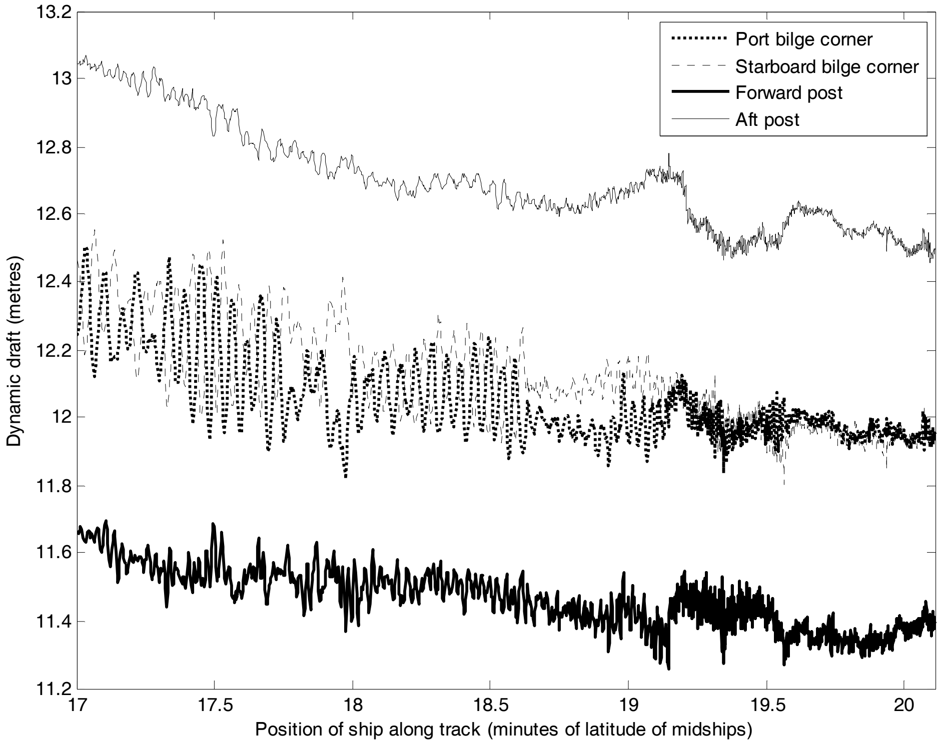

Figure 8: Ship B on outbound transit: dynamic draft at four points on vessel

Both Ship A and Ship B are trimmed appreciably by the stern in the static condition (near the maximum latitude shown on the graphs). Therefore, despite significant rolling and sinkage at the bilge corners, the stern still has the maximum dynamic draft and hence governs the overall dynamic draft.

The dynamic draft increase (DDI) is the overall dynamic draft, minus the maximum static draft (static stern draft in this case).

Across all vessels tested, the maximum DDI for each transit (as a percentage of the length between perpendiculars) averaged 0.16, with standard deviation 0.08, minimum 0.06 and maximum 0.39.

Effect of static trim on DDI of containerships

Most of the containerships tested were trimmed down by the stern in the static condition. For some ships the static stern-down trim is used to improve manoeuvring and propulsive efficiency, while for others it is used to offset a known propensity to trim by the bow when under way.

Despite the fact that maximum sinkage generally occurred at the bilge corners, maximum dynamic draft was normally at the stern due to the static stern-down trim.

This contrasts against the case of bulk carriers, which normally have almost level static trim, bow-down dynamic trim, and very little roll in calm water. Therefore, for bulk carriers in calm water, the bow usually has the largest dynamic draft and hence comes closest to the seabed.

Use of DDI for developing UKC guidelines

Dynamic draft increase is directly related to decrease in underkeel clearance, and so is the most important parameter to use when assessing grounding risk of a particular vessel. We have seen here that for containerships the DDI is usually significantly less than the maximum sinkage.

However, we would warn against using DDI values from vessels that are statically trimmed by the stern, when developing UKC guidelines for ports. This is because any DDI values obtained from stern-trimmed vessels will severely underpredict the DDI values for similar vessels with level static trim.

Maximum sinkage values from statically trimmed vessels will be similar to maximum sinkage values for level trim vessels. Therefore this is generally the best parameter to use in the first instance for developing generalized UKC guidelines for a port. Maximum sinkage values can then be converted into DDI values based on each particular vessel's static trim.

Conclusions

Real-time-kinematic GPS receivers, combined with a fixed shore receiver, have been used to measure the dynamic sinkage, trim and roll of 16 deep-draft containerships entering or leaving Hong Kong harbour.

The RMS error in downward sinkage of each point on the hull was estimated to be around 0.06m, including the effects of GPS error, tidal error, static height error and geoid undulation error.

Maximum sinkage generally occurred at the bilge corner, ranging from 0.13% to 0.63% of the length between perpendiculars over all vessels tested, with average 0.22%.

Due to static stern-down trim, maximum dynamic draft usually occurred at the stern. Dynamic draft increase averaged ranged from 0.06% to 0.39% of the length between perpendiculars over all vessels tested, with average 0.16%.

It was found that the important factors affecting sinkage and dynamic draft of containerships are quite different to the case of bulk carriers. For containerships, roll due to wind, turning or swell produces large sinkages at the bilge corners. For ships with close to level static trim, the bilge corners will normally come closest to the seabed. For ships trimmed statically by the stern, the stern will normally come closest to the seabed.

Acknowledgement

The authors acknowledge the support of the Hong Kong Marine Department in conducting this research, as well as the co-operation of the Hong Kong Pilots' Association and shipping lines involved in the project.

References

CHEN, Y.-Q. & YANG, Z.-J. 2001 A hybrid method to determine the Hong Kong geoid. Fédération International des Géomètres Conference “New Technology for a New Century”, Seoul, May 2001, Session 8.

DAND, I.W. & FERGUSON, A.M. 1973 The squat of full form ships in shallow water. *Trans. RINA* 115, pp. 237 – 255.

FENG, Y. & O'MAHONY, S. 1998 Precise measurements of ship squat with on-the-fly kinematic GPS. International Conference on Spatial Information Science and Technology, Wuhan.

GOURLAY, T.P. 2006 Flow beneath a ship at small underkeel clearance. To appear in *Journal of Ship Research.*

HÄRTING, A. & REINKING, J. 2002 SHIPS: A new method for efficient full-scale ship squat determination, *Proc. PIANC*, Sydney, pp. 1805 – 1813.

HOOFT, J.P. 1974 The behaviour of a ship in head waves at restricted water depth. *International Shipbuilding Progress* 244, Vol. 21, pp. 367 – 390.

HUUSKA, O. 1976 On the evaluation of underkeel clearance in Finnish waterways. Helsinki University of Technology Ship Hydrodynamics Laboratory, Otaniemi, Report no. 9.

TUCK, E.O. 1966 Shallow water flows past slender bodies. *Journal of Fluid Mechanics* 26, pp. 81 – 95.