FULL-SCALE MEASUREMENTS TO ASSESS SQUAT AND VERTICAL MOTIONS IN EXPOSED SHALLOW WATER

by

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ABSTRACT

The paper presents the results of full scale measurements performed on seven cape-size bulk carriers sailing inbound to the port of Flushing/Vlissingen (the Netherlands). The voyages of this type of vessels correspond to small under keel clearances (to a minimal value of 16%) and exposed wave conditions (with a wave height up to 2.6 m). The main interest in this paper concerns the vertical motions experienced by the vessels and the identification and assessment of the major factors influencing these motions. As the vertical ship motions for bulk carriers operating in coastal waters are mainly related to seakeeping and squat, the unsteady and steady ship motions were analysed separately.

The observations will be applied to validate a prediction tool for vertical ship motions, which is implemented by the Common Nautical Authority (Flanders / the Netherlands) to assess probabilistically the accessibility of deep-drafted vessels to the harbours along the river Scheldt.

1 INTRODUCTION

The shipping traffic to the Belgian and Dutch ports located at the Western Scheldt estuary and the river Scheldt follows an access channel of which the depth is restricted. As a result, deep-drafted vessels cannot always sail 24 hours a day on the river Scheldt. The period in which these vessels may proceed inbound or outbound is called the tidal window. The Common Nautical Authority (CNA) calculates these tidal windows and gives permission for the vessels to proceed.

In order to optimize the accessibility for deep-drafted vessels, the CNA is in the process of adopting a probabilistic access policy to determine the tidal windows. In a probabilistic approach a prediction tool for vertical ship motions is the basis for defining minimal under keel clearances. Some of the major phenomena influencing the vertical ship motions concern squat and seakeeping effects.

For the port of Flushing/Vlissingen (NL), part of the North Sea Port, the design vessel is a cape size bulk carrier with a draft of 16.5 m. As these vessels all have similar dimensions and hull shape, they are expected to have a very similar motion behaviour. As a consequence these vessels were an

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interesting test case for comparing ship motion predictions to actual measurements on board of the vessels.

For a total number of seven inbound bulk carriers, the ship motions were measured by the Dutch Pilotage. Then Flanders Hydraulics Research (FHR) together with Ghent University (UGent) related the position data with environmental data such as tide, current, bottom, waves and other shipping traffic. The analysis on both ship behaviour and environmental circumstances revealed the impact of operational, meteorological and environmental parameters on both squat and seakeeping.

2 TIDAL WINDOWS

Access channels to harbours are often subject to tide, so that arrival and departure of ships may be limited to a certain window. This tidal window is mainly determined by under keel clearances resulting from variations of the water level and is therefore of particular importance for deep-drafted vessels. Furthermore also other parameters such as air draft clearance, lateral and longitudinal current components, wind conditions or penetration of the keel into soft mud layers may be limiting factors for the tidal window (Eloot et al., 2009).

2.1 Keel clearance and vertical motions

During the transit of the ship through the access channel, a comparison between the vertical dimensions of the vessel and of the waterway should result into acceptable margins (Vantorre et al. 2013). Below the waterline, a suitable vertical distance should be maintained between the ship’s keel and the channel bottom. This distance also referred to as the under keel clearance (UKC) should accommodate the following functions:

- avoid contact between keel and bottom;
- guarantee the ship’s controllability and manoeuvrability.

The under keel clearance depends on a number of factors that may be related to the ship, the water level, hydro-meteorological conditions and the bottom:

- Ship related factors:
    - the **static ship’s draft (**aft and fore) in still water conditions;
    - hydrostatic impact of water **density** on the ship’s draft;
    - the vertical motion of the ship due to **squat**, which depends mainly on the ship’s speed through the water, the ship’s geometry, the water depth and the blockage;
    - **wave** induced vertical ship motions (heave, pitch, roll);
    - **wind** induced heel;
    - heel due to centrifugal forces in **bends.**
- Water level related factors:
    - **tidal** effects (astronomical);
    - meteorological effects (wind, discharge of fresh water).
- Bottom related factors:
    - dredging maintenance **depth**;
    - dredging execution tolerance;
    - sedimentation;
    - accuracy of bathymetric survey data;
    - nautical bottom.

Under keel clearance (UKC) related channel access criteria can be formulated in a deterministic or a probabilistic way, or in a combination of both.

2.2 Deterministic approach

Deterministic criteria mostly prescribe a minimum value for the gross under keel clearance (i.e. the difference between the bottom depth and the static draft), expressed either in metre or as a percentage of the ship's draft. This value depends on the channel, taking account of the local wave climate and the ships' speed range. In the channels giving access to the ports located along the river Scheldt, the following values are currently applied (Fig. 1):

- 15.0% of draft for *Scheur West* and *Scheur East*;
- 12.5% for the Dutch part of the *Western Scheldt*;
- 10.0% for the Dutch part of the *Western Scheldt* and for vessels with destination Flushing/Vlissingen ;
- 10.0% of draft for the Scheldt river on Belgian territory;
- 1.0 m for the Sea Canal from Terneuzen to Ghent (operated by vessels with draft up to 12.5 m).

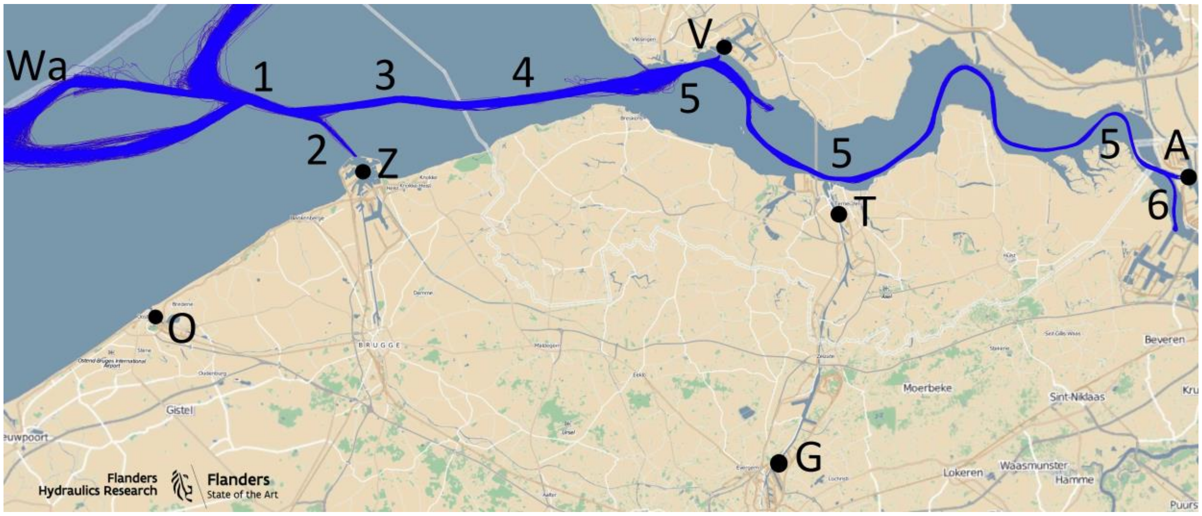

Figure 1: .Access channels and harbours in the Scheldt estuary: 1: Scheur West, 2: Pas van het Zand, 3: Scheur East, 4: Wielingen, 5: Western Scheldt, 6: Lower Sea Scheldt. A: Antwerp/Antwerpen (B), G: Ghent/Gent (B), O: Ostend /Oostende (B), T: Terneuzen (NL), V: Flushing/Vlissingen (NL), Z: Zeebrugge (B), Wa: Wandelaar (B).

2.3 Probabilistic approach

Probabilistic approach policies are based on an acceptable probability of bottom-ship contact during the passage of one single ship. Such an acceptable probability of bottom touch is related to the consequences of such a contact – as after all it is the risk (probability * consequence) which has to be kept under control – and an accepted return period for such an undesired event, so that the intensity of the shipping traffic making use of the channel is also important. However, a probability of bottom touch criterion needs to be accompanied by an additional condition to guarantee the manoeuvrability and controllability of the vessel, as these properties deteriorate significantly with decreasing under keel clearance. Such a criterion can be formulated in terms of either a minimum gross under keel clearance or a minimum manoeuvrability margin, the latter being defined as the time-averaged clearance under the ship, incorporating the effects of water depth, draft, squat and (wind and bends induced) heel, but excluding the oscillatory effects caused by wave action. The manoeuvrability margin criterion will overrule the probability of bottom touch criterion in areas protected from wave impact and in case of favourable weather conditions. PIANC (2014) suggests a minimum manoeuvrability margin of 5% of draft or 0.6 m, whichever is greater.

2.4 Probabilistic Policy Scheldt Harbours

Taking into account the expected beneficial effects on accessibility (Vantorre et al., 2014), the CNA is implementing a probabilistic method for providing tidal windows to the harbours along the river Scheldt. In order to assure the probabilistic calculations to be sufficiently safe, a validation project was initiated in which ship measurements in the Scheldt Estuary were compared to predictions of vertical ship motions. For the following reasons, at first, the validation project was restricted to inbound cape-size bulk carriers sailing to the port of Flushing/Vlissingen:

- very similar ship dimensions (length, beam, draft) and hull shape, allows to assess the influence of different operational and environmental conditions;
- small differences in water density along the trajectory, so that vertical motions due to density changes could be ignored;
- FHR possesses an exact scale model (292 m x 45 m x 16,5 m at scale 1/75) of the ships tested at full scale. Furthermore a wide range of towing tank results were available at UKC 10%; 20%, 35% and 100%. This opened the possibility to compare squat measurements at scale and in nature;
- open deck structure of bulk carrier was very suitable for installing the measurement equipment;
- the Dutch Pilotage developed a ship positioning system allowing to position the vessel in 6 degrees of freedom;
- the bulk carriers to Flushing/Vlissingen have a very restrictive current window, to ensure that the vessels arrive at the port 45 minutes after high tide, when current speeds are negligible. As a consequence the tidal conditions in all measurements are similar;
- as full ship types (such as a bulk carrier) squat by the bow, the influence of propulsion on the maximum ship squat is negligible.

Within this project the Dutch Pilotage provided positioning data, while FHR and UGent processed these data to ship motions in 6 degrees of freedom. Further processing allowed to assess both squat and seakeeping effects and to relate the results to the determining parameters.

3 SHIP MEASUREMENTS

For seven cape size bulk carriers the inbound trajectory from the anchorage area ‘Wandelaar’ to the Kaloothaven in the port of Flushing/Vlissingen was studied.

3.1 Trajectory

The trajectory covers the fairways Scheur West and Scheur Oost on Belgian territory, and the fairways Wielingen and the Western Scheldt on Dutch territory (see Fig. 1, Fig 2 and Fig. 3). This tidal environment is subject to consecutive zones with shallow and very shallow conditions and strong wave conditions. Due to operational limitations, shipping traffic is allowed up to a significant wave height of 3.0 m.

Figure 2: Measured trajectory for 4 bulk carriers sailing inbound to the port of Flushing/Vlissingen (NL)

Figure 3: Trajectory of Asian Blossom on July 27th 2015 to Flushing/Vlissingen (Kaloothaven)

3.2 Ship particulars

The dimensions of the seven bulk carriers measured, were very similar, as can be seen from Table 1. Except for the vessel Panormos, all vessels had an even keel draft of approximately 16.5 m. The vessel Panormos had a smaller draft and was trimmed by the stern.

Also the length between perpendiculars for the vessel Cape Canary deviates from the other vessels measured. The reason for the larger L_{PP} for Cape Canary was the bow shape of the vessel. Cape Canary was the only vessel that was not designed with a bulbous bow.

Vessel	Asian Blossom	Cape Canary	Wisdom of the Sea	Lancelot	Bulk Mexico	Cape Harmony	Panormos
Date	27/07/'15	29/07/'15	24/09/'15	8/10/'15	19/11/'15	29/06/'16	1/10/'16
L_{OA} (m)	292	292	292	291.8	292	292	292
L_{PP} (m)	283.8	288	283	282.2	278	282	282
B (m)	45	45	45	45	45	45	45
T_F (m) at 1025 kg/m³	16.43	16.5	16.4	16.44	16.5	16.5	15.55
T_A (m) at 1025 kg/m³	16.43	16.5	16.4	16.47	16.5	16.5	16.25
GM (m)	5.59	4.86	5.76	5.36	-	6	5.38

Table 1: Ship particulars of vessels measured

3.3 Ship motions

When analysing vertical ship motions the terminology as presented in Table 2 is applied throughout this document. A distinction is made between steady motions (low frequency) mainly related to ship squat and unsteady motions (high frequency) mainly related to seakeeping.

Table 2: Ship motions terminology

Motion	Steady	Unsteady
Heave	Steady heave	Unsteady heave
Roll	Heel	Unsteady roll
Pitch	Trim	Unsteady pitch

3.4 Measurement equipment

For manoeuvring marginal vessels the Dutch and Flemish pilotages apply an accurate positioning system called Full SNMS[5] (van Buuren, 2005). The Full SNMS positioning system is based on positions provided by two RTK-GPS antennas (called POS and HDG1) mounted on each bridge wing respectively (see Fig. 4). This setup allows to measure horizontal ship motions (surge, sway and yaw) relevant for manoeuvring purposes. Furthermore, based on the altitude of the GPS antennas the height of the vessel (referred to a vertical reference level) and the roll of the vessel can be assessed.

In order to perform a full six degrees of freedom measurement an additional pitch measurement had to be integrated in the Full SNMS setup. In 2013 the Dutch Pilotage made an investment to upgrade the positioning system with a third RTK-antenna (HDG2) mounted at the ship bow. By combining altitude measurement from the HDG2 antenna, with the altitude measurements of the other antennas the pitch motion could be obtained. The Full SNMS positioning system upgraded with a third antenna is referred to as the Full-Plus SNMS positioning system. In optimal conditions the Full-Plus SNMS positioning system has a measuring frequency of 5 Hz.

Figure 4: Positions and naming of GPS antennas

3.5 Vertical motions with respect to waterline

The Full-Plus SNMS positioning system provides ship motions with respect to an earth bound coordinate system. When assessing the hydrodynamics involved in vertical ship motions these ship motions should be referred to the static waterline (see Fig. 5).

At first the altitude measurements with respect to the GRS80 ellipsoid were converted to a geodetic reference level (NAP). Then for a static measurement (at negligible ship speed) the vertical antenna positions were compared to the water level in order to know the vertical distance between the antennas and the static waterline (ΔZ_{Static}). Finally, for a sailing vessel the vertical distance between the antennas and the instantaneous and local mean waterline (Z_{Tide} - $Z_{Antenna}$) were subtracted from the static vertical distance (ΔZ_{Static}) in order to assess the sinkage of the vessel at the position of the antenna.

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[5] SNMS: Schelde Navigator Marginale Schepen; Scheldt Navigator Marginal Vessels

In a tidal environment the accuracy of the measurement of the vertical ship motions with respect to the waterline (sinkage) depends on:

1. the accuracy of the altitude measurement on the antennas (0.03 m);
2. the accuracy of the conversion method to a geodetic reference level;
3. the horizontal distance of the antennas with respect to the outer contour of the vessel (limited impact as the antennas were installed on the bridge wings and at the bow);
4. the accuracy by which the water level along the trajectory could be reproduced (0.05 m).

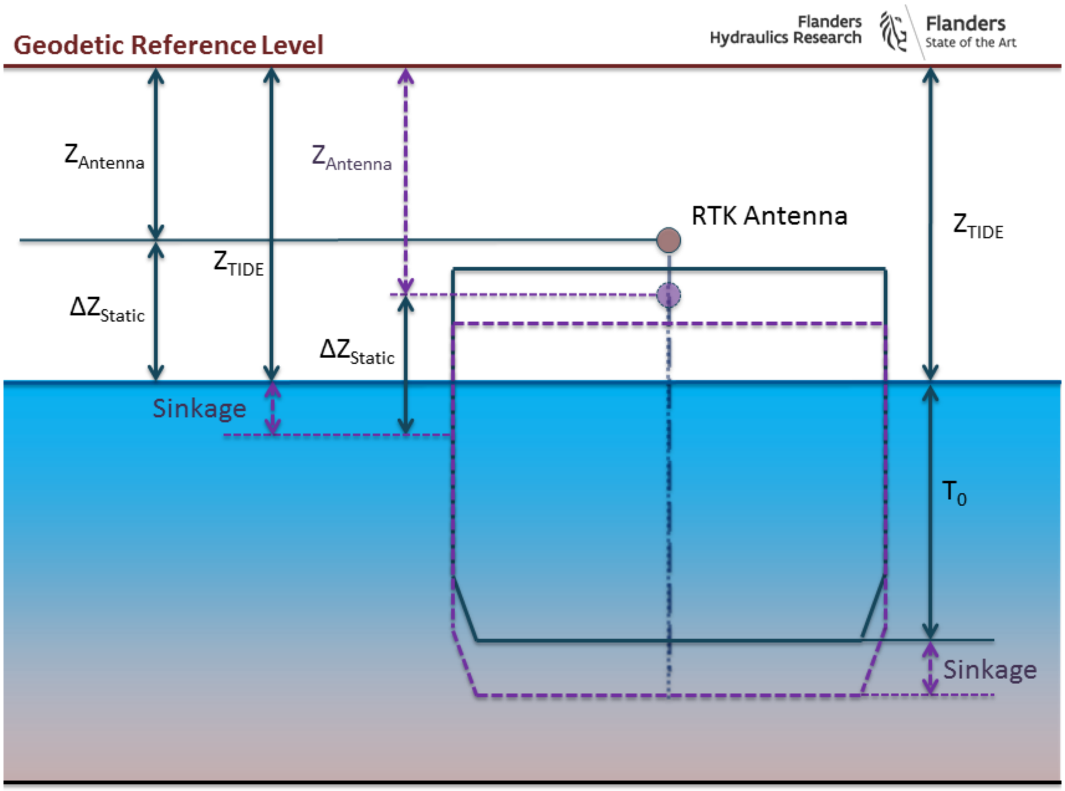

Figure 5: Calculating vertical motion with respect to waterline (sinkage). Full line: static condition; dashed line: sailing condition.

3.6 Steady and unsteady motions

Depending on the cause of the vertical ship motion, steady and unsteady motions can be distinguished. The following parameters are varying rather slowly and are associated to steady motions:

- ship speed influencing squat;
- under keel clearance and blockage influencing squat;
- tide;
- density;
- overtaking manoeuvres;
- bends;
- wind.

On the other hand unsteady motions can be the result of the following phenomena:

- ship response to waves (seakeeping);
- ship meetings (encounters);
- rudder deviations;
- wind gusts.

In order to separate the vertical ship motions in a steady part and an unsteady part, the following procedure was followed:

- The steady motions were calculated as the running average over a period of approximately 60 s taken on the full vertical motion signal. The period of the running average was defined as four times the dominant period obtained from a Fourier analysis for each degree of freedom separately (the dominant period was typically 15 s to 20 s).
- The unsteady motions were calculated by subtracting the steady motions from the full vertical motion signal.

4 ENVIRONMENTAL DATA

The main environmental parameters influencing the vertical motions of cape-size bulk carriers concern:

- water depth and blockage;
- current velocities;
- waves;
- wind;
- shipping traffic.

In the following sections the processing of environmental data is presented in order to assess the influence of the above mentioned parameters.

4.1 Tide and current

In section 3.5 it was already mentioned that reproducing accurately the water level along the trajectory is of utmost importance for the calculation of the ship’s vertical motions. Furthermore tide information is required to retrieve water depth information from a bottom survey.

In a first step the tide along the trajectory was derived from hindcast simulations performed with the numerical model ZUNOv4 (Dutch ministry of infrastructure and water management, Rijkswaterstaat). This model provides full area coverage and an update period of 30 minutes for both tidal levels and current vectors. By performing a geographical triangulated interpolation and a time interpolation the ZUNOv4 grid files could be projected on the shipping trajectory. However, when comparing the hindcast data with available tide stations in the environment (see Fig. 7), it was noticed that tide from the hindcast data differed up to 0.15 m to the tide measured in the stations. As a result a supplementary correction factor (both depending on place and time) was applied on the tide data retrieved from the ZUNOv4 grids. In Fig. 6 the tidal information from the hindcast model and measured in the tide stations is compared. Also the tide along the shipping trajectory is presented with and without correction factor applied.

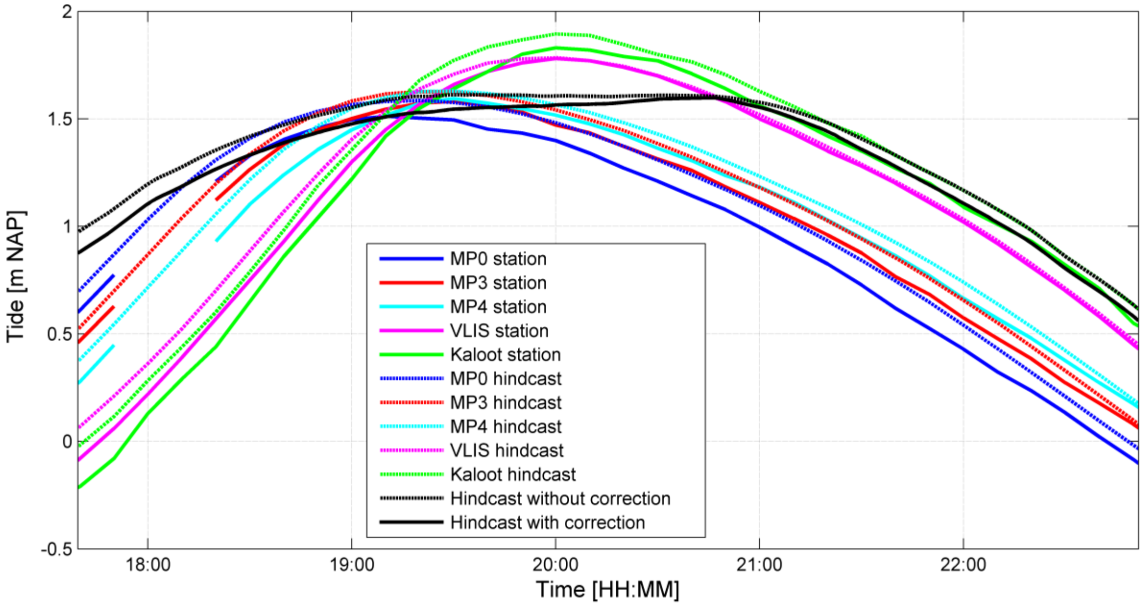

Figure 6: Reproducing tide along the trajectory of Cape Harmony (black), with (full line) and without (dashed line) correction factors

Figure 7: Tide measurement stations available along the trajectory

4.2 Bathymetry

In order to assess the water depth, under keel clearance and blockage along the trajectory, the bathymetry was retrieved from the most recent survey data available at the time of the ship measurements. The survey information from the Scheldt ECS database (Flemish Hydrography and Rijkswaterstaat) was used as an input. The survey data were projected on an automatically generated triangular grid with high resolution (10 m) at the shipping trajectory and courser resolution (50 m) on the edge of the fairway (see Fig. 8).

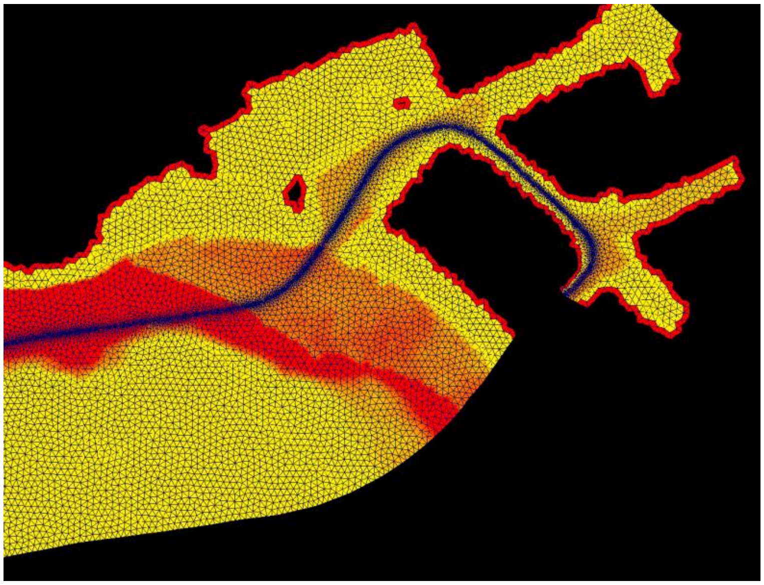

Figure 8: Scheldt ECS Survey data projected on an automatically generated grid (trajectory Asian Blossom)

4.3 Waves

At the time of the measurements, coastal wave spectra data were available at the positions presented in Fig. 9. Within the project the following parameters were derived from the directional (green) wave spectra:

- significant wave height [m];
- dominant wave direction [Deg];
- swell height (≤0.1Hz) [m];
- swell direction [Deg].

Figure 9: Wave rider buoys in the studied environment. Green buoys providing directional wave spectra

4.4 Wind

Wind conditions during the measurement were based on wind information from the measuring stations Westhinder and Wandelaar (see Fig. 9). As no impact of wind on ship motions could be observed, wind will not be discussed further in the paper.

4.5 Shipping traffic

Encounters with other shipping traffic may have a large effect on the squat of a vessel (Eloot et al., 2011). As a consequence when studying vertical ship motions, the impact of other shipping traffic should be taken into account. The presence of other shipping traffic was deduced from AIS-information provided by the Scheldt Radar Chain (SRC). A processing tool was developed in order to filter the AIS data of the vessels that operated in the proximity of a reference vessel (see Fig. 10) and subsequently provides a table with ship meetings. For the meetings performed during the seven ship measurements to Flushing/Vlissingen, no significant impact on vertical ship motions could be observed.

Figure 10: Presentation of the vessel Asian Blossom with filtered AIS-vessels

5 RESULTS

The graphs presenting the results can be provided with two horizontal axes (for an example see Fig. 11). The bottom axis shows the UTC-time of the trajectory (for date: see Table 1), while the top axis shows the running distance (s) along a reference trajectory. The geographical parameter, running distance, allows to compare different measurements. The origin of the running distance was defined at the breakwaters of the port of Flushing/Vlissingen (see Fig. 3) with positive values inside the harbour and negative values outside. In Table 3 the running distances corresponding to different fairways are presented.

Fairway	Country	Running distance	
		From	To
		[km]	[km]
Scheur West	BE	-60.0	-37.4
Scheur East	BE	-37.4	-26.0
Wielingen	NL	-26.0	-8.1
Western Scheldt	NL	-8.1	0.0
Port of Flushing/Vlissingen	NL	0.0	3.5
Kaloothaven	NL	2.5	3.5

Table 3: Running distances corresponding to fairways

5.1 Vertical motions

In Fig. 11 the vertical motions processed for the vessel Asian Blossom are visualised. In this figure the steady and unsteady part of the heave, pitch and roll motion at midship position are presented.

The following conclusion can be drawn from Fig. 11 .

- The filtering method for steady and unsteady motions (see section 3.6) gives satisfactory results.
- The unsteady motions are symmetrical (the mean value of the unsteady motions is negligible).
- Significant unsteady motions can be observed when the vessel was operating in the fairways Scheur, Wielingen and the downstream part of the Western Scheldt. The unsteady motions are rapidly decreasing when the vessel entered the Western Scheldt.
- The unsteady motions decrease significantly when entering the port (running distance = 0 km)
- The unsteady motions are related to sea conditions. The influence of waves on ship motions is studied in section 5.3.
- Significant steady motions were observed for heave and pitch. These motions correspond to the squat of the vessel. In section 5.2 squat will be discussed in detail.
- The steady roll angle is negligible. This indicates the small influence of wind on the vertical ship motions (the wind condition was WSW 7).

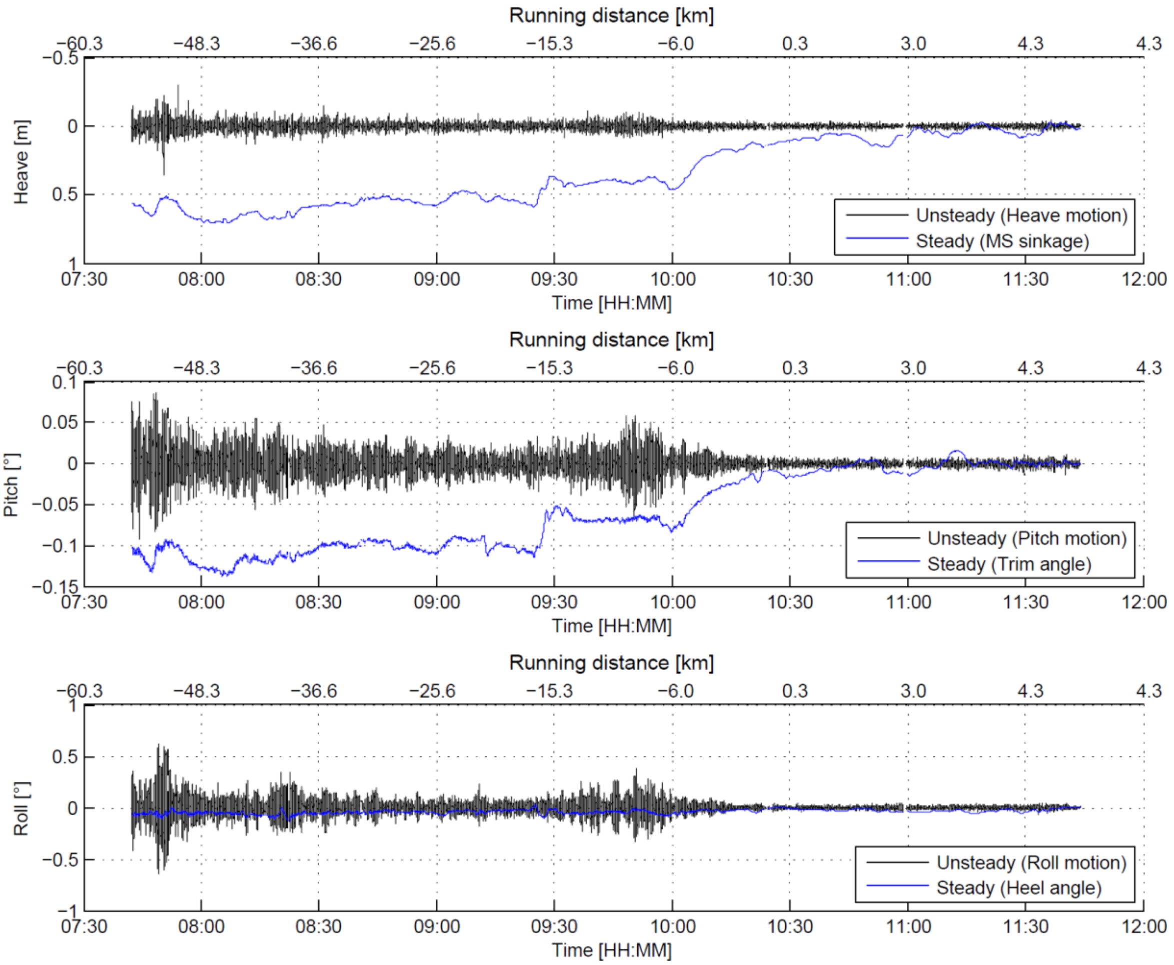

Figure 11: Vertical motions at midship position for Asian Blossom sailing to Flushing/Vlissingen

5.2 Squat (steady motions)

According to PIANC (2014) squat is defined as follows:

> *Squat is a steady downward displacement consisting of a translation and rotation due to the flow of water past the moving hull. This water motion induces a relative velocity between the ship and the surrounding water that causes a water level depression in which the ship sinks. Shallow water and channel banks significantly increase these effects. The velocity field produces a hydrodynamic pressure change along the ship that is similar to the Bernoulli effect since kinetic and potential energy must be in balance (Newman, 1977). This phenomenon produces a downward vertical force (causing sinkage, positive downward displacement) and a moment about the transverse axis (causing trim) that can result in different values at the bow and stern. Thus, squat is composed of this overall decrease in UKC due to sinkage and change in trim.*

From the measurements, squat was defined as the vertical motions corresponding to steady heave and steady pitch or trim (see Fig. 11). For ship types with a full hull form in even keel conditions, maximum squat always occurs at the bow, so that in this paper only bow squat will be discussed.

The major parameters influencing the ship squat are:

- ship particulars;
- ship speed through water;
- under keel clearance and blockage.

As the measurements were performed on very similar vessels with (except for the vessel Panormos) very similar loading conditions, it may be expected that the squat behaviour of the tested vessels is also similar.

In Fig. 12 the results of bow squat, ship speed[6] and gross under keel clearance are presented. It can be observed that the largest squat motions appeared on the vessel Asian Blossom when operating in the fairway Scheur West. For this vessel both the influence of ship speed and UKC is clearly demonstrated.

The vessel Asian Blossom applied in the fairway Scheur West a speed of approximately 12 kn (s = -55 to -42 km) leading to a bow squat varying between 0.75 m and 1.05 m. The evolution of squat in this area is clearly related to the evolution of the water depth. The most shallow parts of the fairway (UKC 24% at s = -54 km and s= -46 km) corresponded to the largest squat values (app. 1.0 m), while a very deep part of the fairway (s = -52 km) resulted in a squat value that was limited to 0.75 m.

When operating in the fairways Scheur East and Wielingen the variations in ship speed immediately result in important changes in ship squat. The most striking example is the speed drop of the vessel Asian Blossom in the fairway Wielingen (at s = -15 km). A ship speed decreasing from 10.5 kn to 8.2 kn resulted in a decrease of squat from 0.85 m to 0.54 m at more or less constant UKC.

Also for the other vessels the relation between ship squat, speed through water and UKC can be observed from Fig. 12.

As a result of the different loading condition, the squat behaviour of the vessel Panormos deviates from the other vessels (Härting, 2009). However, when comparing the squat behaviour of the other six vessels it can be noticed that at similar conditions the squat of Cape Canary and Cape Harmony was smaller than for the other vessels. This was for example the case at s = -50 km. At that position the ship speed of Cape Harmony was identical to the ship speed of Wisdom of the Sea (9.5 kn), while the bow squat of Cape Harmony was 0.18 m smaller. At the same position it was observed that the bow squat of Cape Canary was very close to the squat of Wisdom of the Sea (0.58 m), while the speed of Cape Canary was 1.0 kn larger than the speed of the Wisdom of the Sea. For the vessel Cape Canary the smaller values of bow squat could be associated to the different bow shape of the vessel. From the L_{PP} (see Table 1) and from photographs of the vessel in ballasted conditions it could be observed that Cape Canary was the only vessel without a bulbous bow. As a bulbous bow alters the pressure distribution at the ship bow, an increase of bow squat is likely. This effect is confirmed by the observations on the vessel Cape Canary. On the other hand for the vessel Cape Harmony, no different bow shape could be observed. The smaller bow squat experienced on the vessel Cape Harmony could not be explained.

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[6] If not specified otherwise, ship speed refers to ship speed through water.

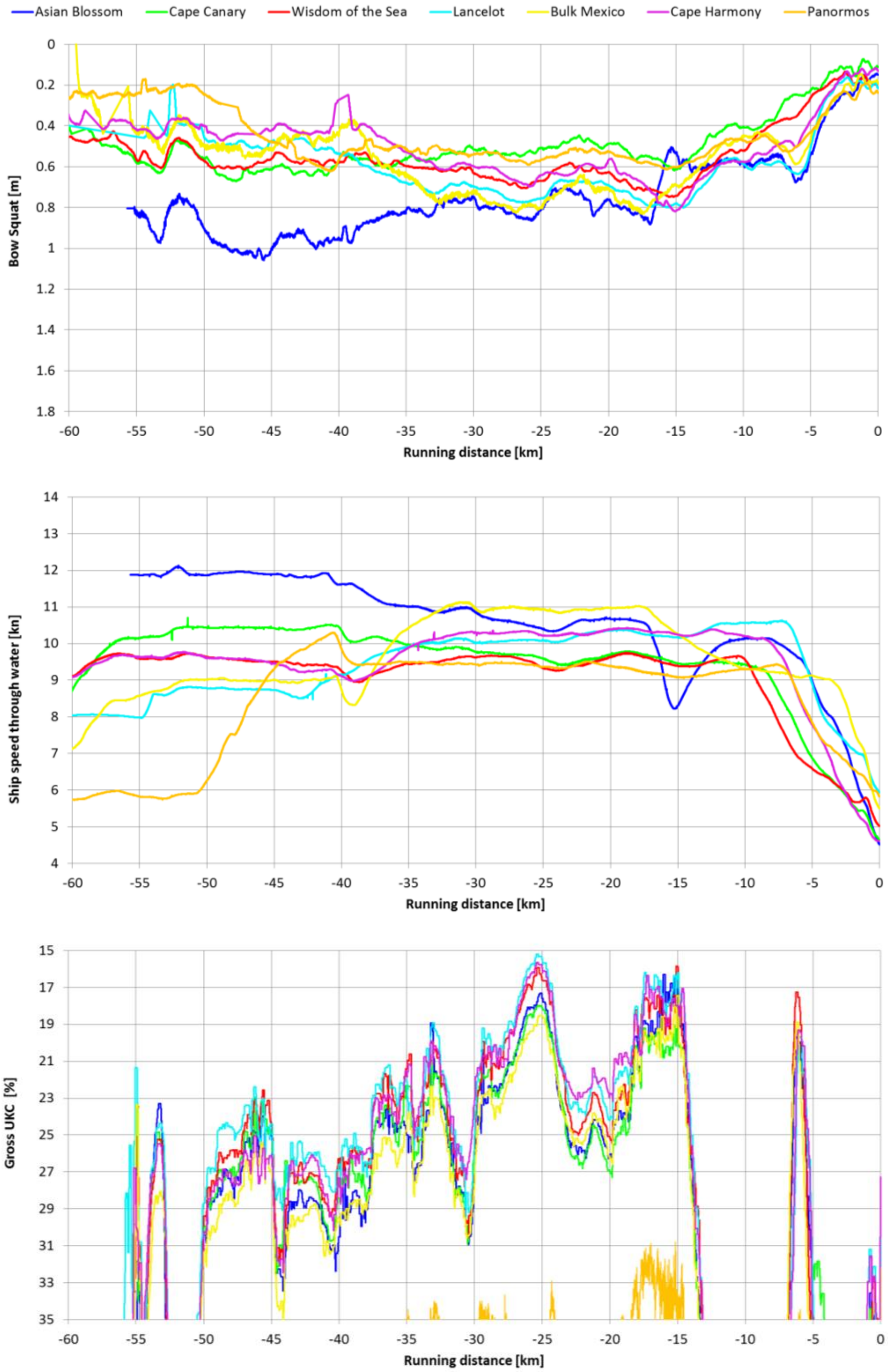

Figure 12: Squat (top), Ship speed (centre) and UKC (bottom) for seven full-scale measurements

5.3 Seakeeping (unsteady motions)

The unsteady heave, pitch and roll motions are mainly resulting from the wave climate present in the fairway. In order to compare the unsteady vertical motions for different ship measurements, the envelope of the unsteady motions at the bow (see Fig. 13) was calculated for a ship position at the FP at port side and at starboard side. The maximum unsteady motion was obtained by taking the maximum from the port and starboard envelope and is presented in Fig. 14 for the seven measurements performed.

Fig. 14 reveals the large deviation in unsteady ship motions, leading to a sinkage of almost 1.0 m for the vessel Bulk Mexico and much smaller values for the other vessels. For the vessels Cape Canary, Wisdom of the Sea, Cape Harmony and Panormos the unsteady vertical motions are limited to a maximum value of 0.25 m.

Now a comparison is made between the unsteady ship motions and the wave parameters deduced from directional wave spectra (see section 4.3). When observing the significant wave heights (see Table 4) it can be noticed that the largest wave heights were present during the passage of Asian Blossom. Despite the much smaller unsteady motions experienced on the vessels Cape Canary, Wisdom of the Sea and Cape Harmony, the significant wave height for those vessels was larger than for the vessel Bulk Mexico. It can be concluded that the significant wave height does not show any relation with the unsteady motions of a cape-size bulk carrier. The swell (see Table 5) on the other hand reveals to be a more appropriate parameter for assessing seakeeping of cape-size bulk carriers. The largest swell values were present for the vessel Bulk Mexico. The swell for Bulk Mexico (0.27 m) was approximately 2.25 times the swell for Asian Blossom (0.12 m), while the unsteady vertical motion for Bulk Mexico (0.95 m) was 2.20 times the value for Asian Blossom (0.43 m). Also for the other measurements a strong dependency of seakeeping and swell can be observed.

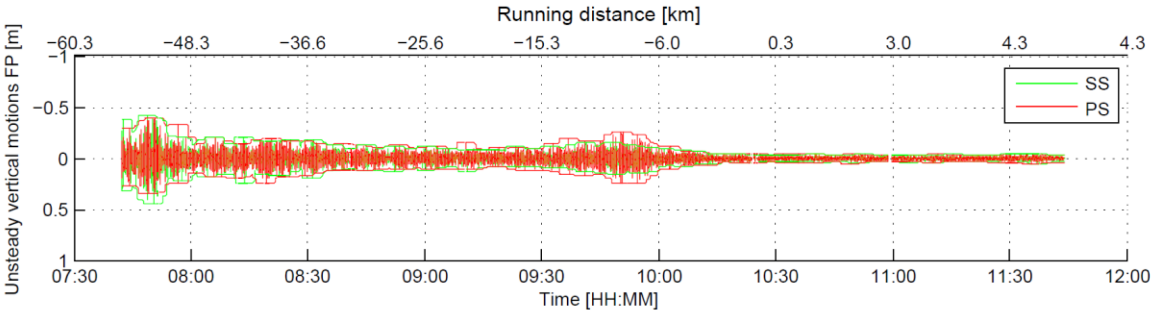

Figure 13: Envelope of unsteady vertical motions at bow of Asian Blossom

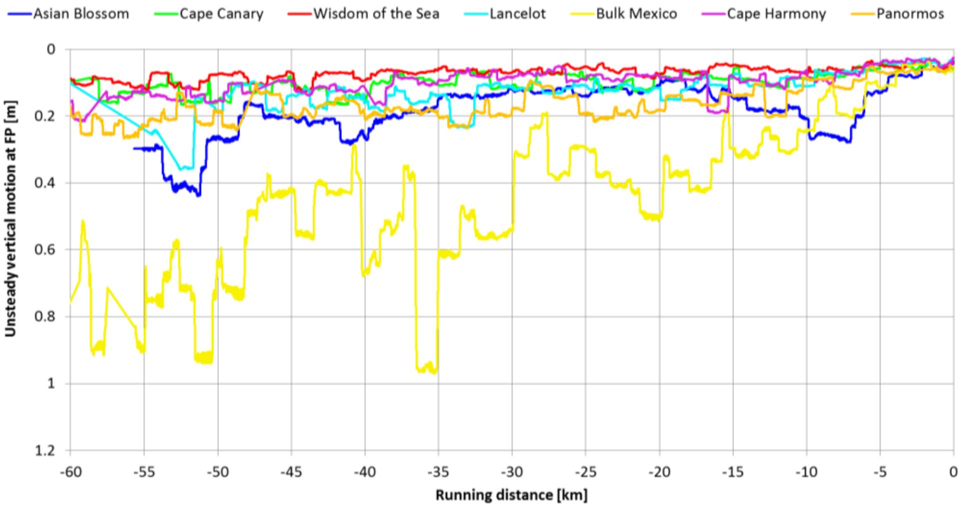

Figure 14: Unsteady vertical motion at bow (envelope) for seven full-scale measurements

	Significant Wave Height [m]						
	Asian Blossom	Cape Canary	Wisdom of the Sea	Lancelot	Bulk Mexico	Cape Harmony	Panor-mos
Kwintebank	2.26	1.36	1.29	0.86	1.18	1.36	0.86
Westhinder	2.59	1.40	1.61	0.98	1.34	1.96	1.22
Bol van Heist	1.87	1.16	0.99	0.75	0.90	no data	0.76

Table 4: Significant wave height during seven measurements

	Swell [m]						
	Asian Blossom	Cape Canary	Wisdom of the Sea	Lancelot	Bulk Mexico	Cape Harmony	Panor-mos
Kwintebank	0.11	0.07	0.06	0.06	0.27	0.07	0.07
Westhinder	0.15	0.08	0.08	0.07	0.28	0.12	0.10
Bol van Heist	0.10	0.07	0.04	0.07	0.26	no data	0.09

Table 5: Swell during seven measurements

6 CONCLUSIONS

By combining ship measurements with accurately reproduced water levels, the vertical ship motions could be processed for seven cape-size bulk carriers operating in a tidal environment subject to exposed and shallow water conditions.

The vertical ship motions were split in steady motions related to squat and unsteady motions related to seakeeping. Furthermore the environmental conditions such as tide, current, waves, bottom, wind and other shipping traffic were processed in order to analyse all significant parameters influencing the vertical ship motions.

The squat measurements did clearly reveal the effects of ship speed and under keel clearance. Furthermore, despite the very similar ship particulars for six vessels, different squat behaviour was noticed for two of them. This indicated that the bow shape may have an important effect on the (bow) squat of the vessel.

The unsteady motions corresponding to seakeeping show large variety for the seven measurements. In four measurements the vertical motions resulting from waves are limited to 0.25 m, while in one measurement unsteady vertical motions up to 1.00 m were reached. Seakeeping of cape-size bulk carriers is related strongly to the swell conditions, while no relation with the significant wave height could be observed.

The vertical motion measurements will be applied to validate a prediction tool for vertical ship motions, which is implemented by the Common Nautical Authority (Flanders / the Netherlands) to assess probabilistically the accessibility of deep-drafted vessels to the harbours along the river Scheldt.

7 ONGOING AND FUTURE WORK

The processing method and the results presented in this report, provide valuable validation data for prediction tools for vertical ship motions. The following items for future work are in progress:

- Comparison of full-scale squat measurements to towing tank results (FHR/UGent);
- Developing a squat formula for cape-size bulk carriers by combining full-scale and towing tank data (FHR/UGent);
- Comparison of full-scale steady and unsteady motion measurements to results of squat and seakeeping software (CNA);
- Measurement campaign on container vessels to the port of Antwerp (upstream the river Scheldt, see Fig. 1) which will take account of supplementary effects such as bending, wind, ship meetings, rudder and propeller application and density effect (Flemish Pilotage/FHR/UGent).

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