VERIFICATION OF RAOS IN SEA TRIALS

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SUMMARY

A method to estimate the directional wave spectrum from measured ship motions is currently under development. The algorithm relies on response amplitude operators (RAOs) to link ship motions to the sea state. In order to verify numerically obtained RAOs in realistic sea states, two campaigns of extensive sea trials were performed on the RV Simon Stevin in the North Sea close to Ostend. Ship motions were recorded in six degrees of freedom, in this paper analysis was restricted to roll and pitch. Data from several directional wave buoys in the vicinity of the trial runs were available. RAOs were calculated using *OCTOPUS* and *HYDROSTAR*. Spatial and temporal fluctuations were found in the wave buoy data, so there is some uncertainty in the wave spectrum seen by the vessel. Considering these uncertainties, *HYDROSTAR* gave reasonable agreement for pitch, larger discrepancies were found for roll especially close to the resonance frequency.

1 INTRODUCTION

This work is part of a project that aims at developing a novel algorithm for estimating the directional wave spectrum from motions of a vessel underway. Knowledge of the sea state is one important factor for achieving safe operations at sea. In many areas wave rider buoys are routinely operated providing the directional wave spectrum with high reliability. However, with few exceptions, the measurement sites are restricted to coastal areas. Larger areas are covered by hydrodynamic models which utilize several data sources including wave buoys and satellites for sea climate estimates and forecasts, one example is given in (EMWF, 2018). Despite these tools, visual wave observations are routinely performed onboard and entered into the ship's log. In these observations the directional wave spectrum is reduced to a few parameters for each detected wave system, namely significant wave height and period and the wave direction. This simplified model of the sea state may not be sufficient for safe operations, estimating the full directional spectrum onboard is hence desirable.

There are different approaches in the literature for estimating the sea state parameters from ship motions. While a complete review is beyond the scope of this paper, it can be stated that most publications fall into two categories, the Bayesian modelling (Iseki, Ohtsu, 2000; Nielsen, 2005) and parametric methods (Hinostroza, Soarez 2016). A more detailed and comprehensive overview on literature is given in (Pascoal et al, 2017). In the latter group the wave spectrum is approximated by a spectral function with several parameters such as JONSWAP. The parameters are then determined from the motion spectra. In the current project a different approach is chosen, the wave spectrum is expanded into angular distribution functions at each frequency point, the expansion coefficients are determined from the measured motion spectra. The method is described in more detail in (Schwarz-Röhr et al., 2016), first results of sea trials are reported in (Schwarz-Röhr et al., 2015).

For all methods the quality of the sea state estimates depends on the accuracy of the model that relates ship motions to the exciting wave fields. In the spectral domain ship responses are modelled by the response amplitude operators (RAOs). Several methods for the calculation of RAOs using different approximations and therefore with different limitations are known. In this paper data of sea trials are used to study whether RAOs calculated by two software packages, Octopus and Hydrostar, are suitable for sea state estimates.

The trials took place in two dedicated campaigns (1-3 Aug 2017, 6-8 Nov 2017) in the North Sea close to Ostend. In this area directional spectra of several wave buoys are available. By means of the calculated RAOs predicted motion spectra were calculated from the wave data and compared against ship motion measurements.

Details on the vessel (RV Simon Stevin), the instrumentation and the track layout are presented in the next chapter. The subsequent chapter discusses the calculation of the RAOs. The evaluation of wave buoy data and the calculation of the predicted motion spectra is explained in chapter 4, followed by the presentation of experimental results.

2 EXPERIMENTAL SETUP

Trials runs were performed in two campaigns (1-3 Aug 2017, 6-8 Nov 2017) on the RV Simon Stevin operated by the VLIZ (Flanders Marine Institute), the ship particulars are given in table 1. Trials took place in Belgian waters close to Ostend (figure 1). The water depth in the operational area was generally greater than 20 m with the exception of a few sandbanks where the water depth could be as low as 12 m.

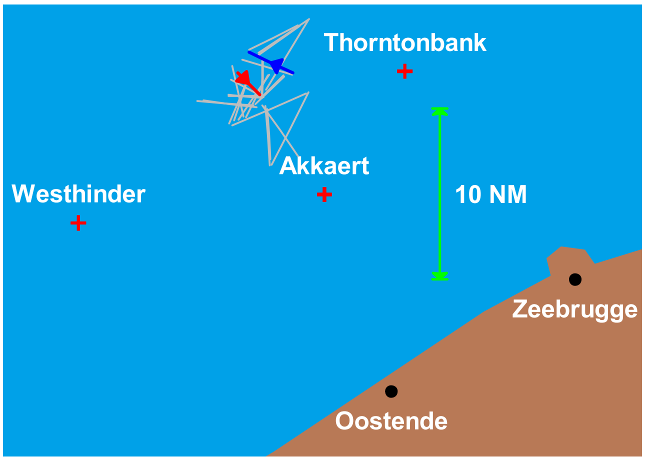

Figure 1. Tracks of sea trials for November 7th together with the closest directional wave buoys. The two trials discussed in the text are marked red (trial #11) and blue (trial #3).

Table 1: Ship particulars of the RV Simon Stevin

Length	36 m
Beam	9.4 m
Draught	3.6 m

The motions were measured in all six degrees of freedom by two independent devices, namely an Octans IMU which is installed permanently on the Simon Stevin and a GPS/IMU based system developed by Flanders Hydraulics Research (FHR). Motion data from both devices agree very well. The speed through water is logged onboard and included in the Octans data. Heading and speed over ground is obtained from the FHR measuring system based on GPS data.

In total 43 trial runs were conducted, a duration of 30 minutes per trial run was considered sufficient to obtain proper averaging of the motion spectra. The speed was kept constant during each trial run. Courses were set in steps of 45°, the speed was varied from 3 knots to 12 knots. Due to weather and traffic conditions not all combinations are available.

3 RAO CALCULATIONS

Two software packages, the strip theory code *Octopus* 6.4.14 and *Hydrostar* V8.00 were used to calculate the RAOs. As shown in the following section a huge angular spread was found in the wave buoy data necessitating RAOs for almost all directions of wave incidence. As a compromise between accuracy and computational time, RAOs were calculated in steps of 5° and interpolated to 1° for data evaluation.

The required hull models were created from the lines plan provided by Damen Shipyards. The hull file for Octopus is composed of 27 stations placed more densely at bow and aft compared to the midship section. The Hydrostar model is composed of 1083 quadrilateral panels.

The stability data gave no indication of the current metacentric height $\overline{GM}$ and the radii of gyration, the latter were estimated from the empirical rules given in (Journee, Adegeest, 2003) to k_{xx} = 3.2 m, k_{yy}= 8.0 m and k_{zz}= 8.03 m. $\overline{GM}$ was adjusted iteratively such that the roll resonance in the RAOs matches the clearly visible peak in the motion spectra, a metacentric height of 0.7 m was found.

The strip theory approach used in Octopus is described in detail in (Journee, Adegeest, 2003), basically the hull is divided into sections along the longitudinal axis. In each section two dimensional potential theory is applied to calculate hydrodynamic and wave loads as if the section were infinitely long. Within this approximation all diffracted and radiated waves propagate perpendicular to the longitudinal ship axis which is observed experimentally in the midship sections only. Thus this approach is well suited for long and slender ships, according to (Journee, Adegeest, 2003) the ratio of length to breadth should be greater than three “at least from the practical point of view”.

Potential theory does not handle viscous damping. The semi-empirical Ikeda method offered by Octopus was applied in the RAO-calculations, the parameters are given in table 2. Setting the WAVAMP parameter asks Octopus to determine the roll amplitude at which the nonlinear damping terms are linearized. This parameter was set to 1 m. In the initial calculations a very low roll damping was found in the RAOs, thus additional damping was introduced by adding a fictitious bilge keel with parameters given in table 2.

Hydrostar solves the hydrodynamical problems in three dimensions and is therefore not limited to slender ships (Chen, 2004). This software offers different methods for introducing additional damping. Following the recommendations in the manual (Bureau Veritas, 2018), linear damping was introduced in the damping matrix by means of the parameter LINVISCOUSDAMPING. The damping was set to 4.5% of the critical damping.

Table 2. Damping and bilge keel parameter used in *Octopus*

Type	Name	Value
WAVE AMPLITUDE FOR LINEARISATION	WAVAMP	1 m
HEIGHT OF BILGE KEEL	HBK	0.16 m
DISTANCE OF A.P.P. TO AFT END B.K.	XBKA	11.24 m
DISTANCE OF A.P.P. TO FORWARD END B.K.	XBKF	20.88 m

4 WAVE DATA

Directional wave buoys in the vicinity (figure 1) of the operational area provided wave spectra. The wave buoy data contain data sets for each half hour of the day, a sample is shown in figure 2. There are three data records with the mean wave direction $\theta_m(f)$, the wave power $S_B(f)$ and the wave spread $\sigma(f)$ for each frequency point. Here f denotes the sea state frequency as measured at a fixed point in space. The complete directional wave spectrum spectrum $S(f,\theta)$ is given by

$$S(f,\theta) = D(\theta,\theta_m)\, S_B(f) \tag{1}$$

The angular distribution function $D(\theta,\theta_m)$ is not clearly defined in the wave buoy documentation. In this paper the distribution function

$$D(\theta,\theta_m) = \cos^{2s}(\theta - \theta_m) \tag{2}$$

was adopted. The spread values σ in the data sets are read as standard deviation which are related to the parameter s by (Kuik et al., 1988)

$$\sigma = \sqrt{\frac{2}{s+1}} \tag{3}$$

A sample of a resulting directional wave spectrum is shown in figure 4.

In order to calculate the motion spectrum an intermediate variable

$$S_n(f,\theta) = |h_n(f,\theta)|^2\, S(f,\theta) \tag{4}$$

is introduced, where n denotes the degree of freedom and $h_n(f,\theta)$ the corresponding RAO in terms of the sea state frequency. $S_n(f,\theta)$ can be read as the directional motion spectrum in terms of the sea state frequency.

On a moving vessel wave power at a sea state frequency f is observed in the motion spectrum at the encounter frequency f_E

$$f_E = f\left(1 - \frac{v_0 \cos(\mu)}{\frac{g}{2\pi}\tanh\left(\frac{2\pi h}{\lambda_W}\right)}\, f\right) \tag{5}$$

Here g is the gravitational acceleration, v_0 denotes the ship speed through water and μ the angle between the wave vector and the ship velocity. An angle μ of zero corresponds to waves from aft. The hyperbolic tangent depends on the ratio of water depth h to wavelength λ_W, this term equals one in the deep water approximation. Considering the water depth of 20 m and a lower frequency limit of 0.15 Hz as indicated by the buoy spectra (e. g. figure 2) results in an upper limit for the wavelength of roughly 65 m. The hyperbolic tangent deviates from unity by less than 5% under these conditions, the deep water approximation is used for data processing.

The motion spectrum $S_n^e(f_E)$ at a certain encounter frequency f_E is obtained by summing all contributions of $S_n(f,\theta)$ for which equation (5) holds such that the total power is preserved.

5 SAMPLE RESULTS

As the experiments were performed in real seaway, several uncertainties limit the precision of the estimated motion spectra. In some cases several independent wave systems were observed visually which cannot be represented properly by the single angular distribution function in the wave buoy data. The wave spectra obtained from the different wave buoys showed both temporal and spatial fluctuations even for the duration of one 30 minutes trial run. Temporal fluctuations are illustrated by two consecutive datasets for the wave buoy closest to the operational area (Thorntonbank) in figure 2. The spatial variations are apparent in figure 3, here the power spectra of the neighbouring buoys (Akkaert, Westhinder) for one point in time are shown.

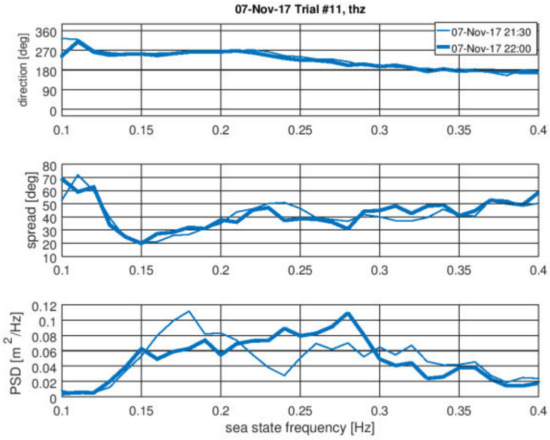

Figure 2. Two consecutive data records of the wave buoy at Thornton Bank with panels for mean wave direction, spread and power as a function of frequency.

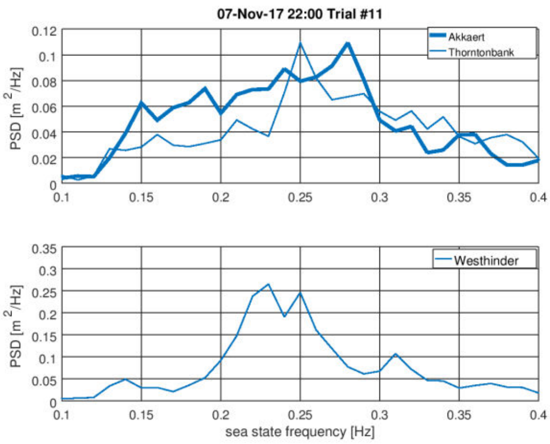

Figure 3. Comparison of power spectra measured by the three wave buoys close to the operational area indicating the spatial variation of the wave field. The mean wave direction and the wave spread are not shown here as they do not differ much among the data sets.

During the experiments different sea states in wave height, period and direction were observed, the wave spread in the important frequency range was between 30° and 40° in all trials.

Results of two trial runs are discussed in detail in the following paragraphs. The first case (trial #11) is marked red in figure 1, there are almost beam sea conditions with an angle between mean wave direction and heading of 73° from aft, the speed through water is 4.7 knots. The water depth is between 27 m and 28 m. The wave buoy data is shown in figure 2, the dataset for 22:00 hours is used in the calculations. The spread leads to a rather wide angular distribution in the directional wave spectrum as shown in figure 4.

The resulting motion spectra using the RAOs of *Octopus* and *Hydrostar* are compared against the measured data in figure 5. The RMS values obtained by taking the square root of the area under the power spectra are given in the legend. In addition the wave encounter spectrum is plotted in the upper panel, the legend contains the significant wave height.

The curves indicate that roll damping close to the resonance is not modelled very well by both programs, the peaks in the predicted roll power are approximately five times higher than the measured one. It should be noted that the corresponding roll amplitudes differ by a factor of $\sqrt{5} \approx 2.25$ in this case. Since the roll damping plays a dominant role close to the resonance only, measured and predicted RMS values are in much better agreement.

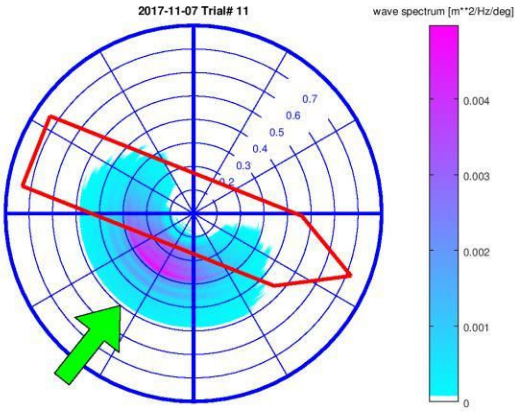

Figure 4. Directional wave spectrum calculated from the data in Figure 2 (22:00) by means of the angular distribution function. As a rough measure of the main wave direction, the green arrow indicates the average of the buoy's directional data close to the maximum of power (0.23 Hz - 0.3 Hz).

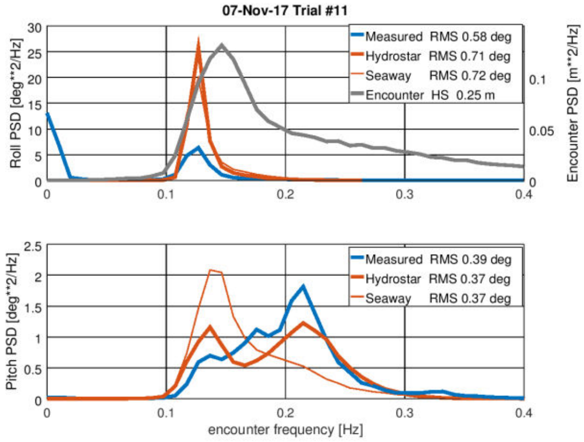

Figure 5. Comparison of measured and calculated motion spectra for the trial of Fig. 2 and Fig. 3. The wave encounter spectrum is plotted in the upper panel on a separate y-axis.

Regarding the pitch reasonable agreement between measured motion and the Hydrostar prediction is found, while the Seaway calculation does not reflect the shape of the measured motion spectrum. This result was found in the majority of cases.

In order to understand the reason for the discrepancies in the motion predictions, it would be desirable to relate these to the RAOs and the underlying terms in the equation of motion. However, this turned out to be unfeasible, because the motion prediction contains contributions for the whole angular distribution of the wave spectrum and the RAOs change remarkably with the wave angle. This is illustrated in figure 6, where three pitch RAOs from the main lobe of the wave spectrum are shown.

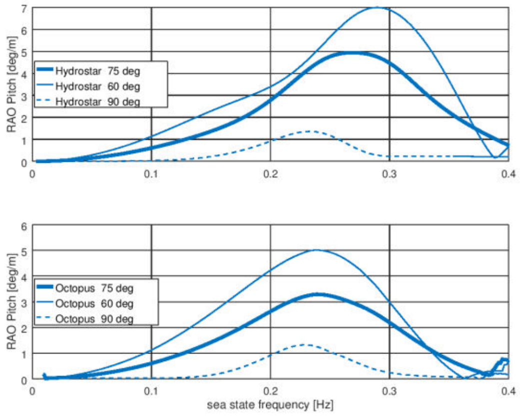

Figure 6. Amplitude of pitch-RAOs for 5 knots. The thick line corresponds to the mean wave direction, the other curves are 15° closer to bow and aft respectively.

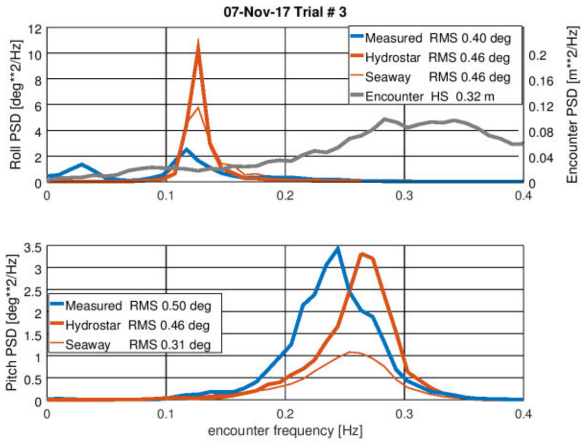

Figure 7. Comparison of measured and calculated motion spectra. Calculations are based on the RAOs from Hydrostar and Seaway. The wave encounter spectrum is plotted in the upper panel on a separate y-axis.

A similar results is obtained in the almost head sea example (trial #3) marked in blue in figure 1, here the mean wave angle is 163° from aft, the speed through water 6.9 knots. The initial and final water depth is 25 m, during 20% of the track a sandbank with a minimum water depth of 12 m was passed. The motion spectra are shown in figure 7. Again the measured roll is smaller than the calculated one. For pitch calculated and measured motions have a very similar shape but appear at different encounter frequencies. This might be caused by inaccurate parameters in the calculation of the encounter spectrum, candidates are wave direction, heading and speed through water.

The two trial runs discussed here are typical in several aspects: both RAOs exhibit too low damping at the roll resonance, pitch is modelled more accurately by Hydrostar, probably because the length to breadth ratio is too low for strip theory.

6 CONCLUSIONS

Extensive sea trials were performed in order to verify RAOs calculated by Hydrostar and Seaway. Measurements took place in the North Sea close to Ostend. The required directional wave spectra were derived from wave buoy data. Motion measurements were done in six degrees of freedom, in this paper roll and pitch are analysed.

The sea climate during the trial runs poses some challenges for the data interpretation: in the coastal area spatial and temporal fluctuations are quite common, the wave spectrum seen by the vessel during one track is therefore not very well defined.

Considering these uncertainties, reasonable agreement was found for pitch using *Hydrostar*, larger deviations were found in the *Octopus* calculations, probably because the strip theory is no strictly applicable to this vessel. The roll damping was poorly modelled by both software packages in the default settings. Obviously the RAOs as tested here cannot directly be used for the sea state estimating algorithm. Adjusting the damping parameters based on empirical data will be required. Since wind sea was dominating, a rather large directional wave spread was observed. This means that RAOs of many different angles contribute to the motion spectrum, thus optimizing RAO parameters is not straightforward and left for future work.

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