FULL SCALE MEASUREMENT OF SHIP MOTIONS TO VALIDATE STRIP THEORY

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SUMMARY

Ship motion measurements were conducted on the SA Agulhas II (L = 121.3 m) on a regular voyage in the Southern Ocean. Two gyro- and accelerometer-based sensors were used at different locations in the ship, with one close to the centre of gravity. Thus linear accelerations could be obtained that were unmasked by rotational influences. RAOs were computed numerically for roll, pitch, heave and surge. These were used with accessible wave data to compute motion spectra that could be compared with the measurements.

Initially, only wave data recorded on board from visual estimation were available. These were used with a spread in frequency to compute motion spectra. Allowing for errors in the visual observations it was still not possible to get a reasonable agreement with the measured spectra for all degrees-of-freedom. Later, when directional wave spectra from a re-analysis of remote sensing data became available, a much better agreement could be achieved.

1 INTRODUCTION

The work presented in this paper is part of a larger project, whose purpose is to estimate the directional wave spectrum from the observable ship motions in deep as well as shallow water (Nielsen 2005, Nielsen et al. 2013, Schwarz-Röhr et al. 2016). The transition between deep and shallow water for waves depends on the ratio between water depth and wave length, whereas for ship motions it depends on the ratio between under-keel-clearance and the ship's size. It seems advisable at first to establish a benchmark case in deep water, where conditions are simpler.

Oscillating ship motions can be divided into high frequency structural vibrations and lower frequency oscillations, in which the ship can be regarded as a rigid body, and these are the ones considered in this paper. The three rotational and three translational degrees of freedom are described in a co-ordinate system which coincides with the ship's body-fixed frame when it is travelling with constant speed at its equilibrium attitude. The motions are governed by forces and moments induced by waves. Water waves are a stochastic phenomenon and realistic seaway is described by a directional spectrum.

The reaction of a ship to a particular harmonic wave can be calculated numerically depending on speed and angle of incidence in the form of Response Amplitude Operators (RAO). Within the limitations of linear theory, the calculations can be extended to non-harmonic excitations. Although the ship motions are recorded as a time series, analyses can only be done in the frequency domain. The approach followed here consists of using the available wave data and the theoretical response characteristics, compute the expected motion spectra for several degrees of freedom and compare to actual observations. It is so intended to validate the process of comparing measured ship motions to predicted ones in a realistic full scale environment. As opposed to model tank experiments there is no need to correct for scale effects. However, uncertainties are introduced by the input sea state and the actual vessel characteristics (mass distribution, damping) on which the RAOs are based.

Trials were carried out on the 123m research vessel "Agulhas II" in the Southern Ocean, where sea conditions were quite stable. Initially, only visual observations of the sea state were available. Later, directional wave spectra modelled by ECMWF from remote sensing data were added into the analyses.

2 SEA TRIALS

The S.A Agulhas II is a South African Polar Supply and Research vessel (PSRV). Designed to carry cargo, personnel (50 crew and 100 scientists), bunker oil, helicopter fuel and also equipped with laboratories, the PSVR S.A Agulhas II was built by STX Finland at the Rauma Shipyard. Figure 1 shows a photograph of the ship.

Figure 1. Photograph of the SA Agulhas II. (Bekker, A. et al 2018)

Table 1. S.A Agulhas II specifications

Lpp	121.8 m
Beam	21.7 m
Draught, design	7.65 m

Measurements were performed during her voyage Cape Town – Antarctica – Cape Town from 28th June 2017 to 12th July 2017. Ship motions were recorded using autonomous sensor boxes with low cost gyros and accelerometers. Sensor boxes were placed at two locations on the vessel. The first sensor was located in the engine control room within a few metres of the centre of mass of the vessel, this sensor measured accelerations in three dimensions and the roll and pitch rate. The second sensor box was located on the observation deck above the navigation bridge giving full 3d-information on both accelerations and angular rates. This sensor had GPS-reception to provide accurate time and position tags. Using correlation between the angular rates from both sensors it was possible to synchronise the sensors and to demonstrate a nearly perfect agreement of the angular data.

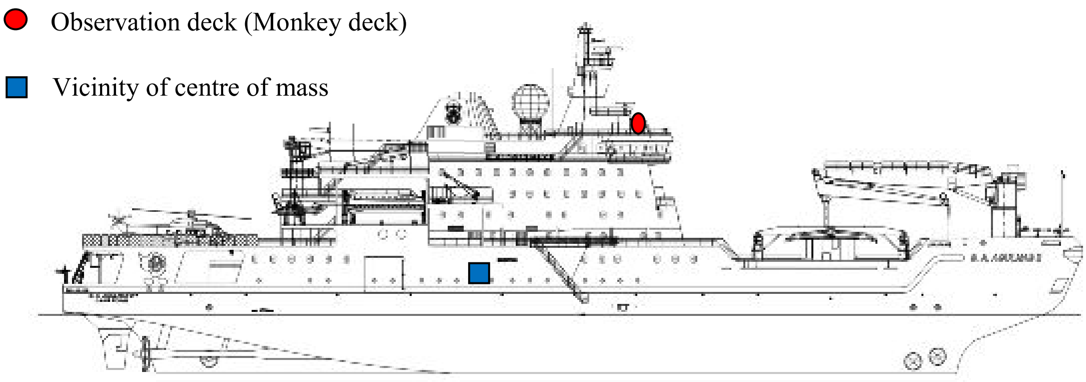

Figure 2. Location of the sensor boxes on the SA Agulhas II (Bekker and Omer, 2018)

3 FUNDAMENTAL RELATIONS

The sea state is generally described by the directional wave spectrum $S(\omega,\alpha)$, which gives power density for a certain wave direction α and sea state frequency ω, the latter is measured at a fixed point in space. The abovementioned RAOs $h_n(\omega,\alpha)$ are defined as the ratio of the complex ship motion amplitude $A_n(\omega)$ to complex wave amplitude $A(\omega,\alpha)$

$$A_n(\omega) = h_n(\omega,\alpha)\, A(\omega,\alpha) \tag{1}$$

for a single wave excitation. Here $A_n(\omega)$ is the complex amplitude of ship motion in the n-th degree of freedom, n=1...3 denotes the linear motions in x-, y- and z-directions, n=4…6 the rotations about the corresponding axes. Taking the magnitude squared of the previous equation leads to a relationship of the corresponding power spectra $S_n(\omega)$

$$S_n(\omega,\alpha) = |h_n(\omega,\alpha)|^2\, S(\omega,\alpha) \tag{2}$$

For a general directional wave spectrum, the contributions for waves of different angles are added by integrating over the wave direction

$$S_n(\omega) = \int |h_n(\omega,\alpha)|^2 S(\omega,\alpha) d\alpha \tag{3}$$

So the power spectra of ship motions can be predicted from knowledge of the RAOs and the directional wave spectrum.

The spectra $S_n(\omega)$ and $S(\omega)$ in equation (3) are given in terms of the sea state frequency. In order to compare these to measurements obtained on a moving vessel they have to be transformed to encounter spectra. For the experiments the deep water assumption is valid. In this case the encounter frequency ω_e as observed on a moving vessel is related to the sea state frequency by

$$\omega_e = \omega\left(1 - \frac{v}{g}\omega\right) \tag{4}$$

Here

$$v = v_0 \cos\alpha \tag{5}$$

denotes the component of the vessel's velocity vector in the direction of the waves, v_0 is the ship speed and α the angle between the wave vector and the ship velocity. An angle α of zero degrees means waves from aft. The constant g is the gravitational acceleration. The sea state spectra are transformed to encounter spectra by (Price, 1974)

$$S_n^e(\omega_e) = \frac{S_n(\omega)}{\left|\frac{d\omega_e}{d\omega}\right|} \tag{6}$$

4 RAO COMPUTATIONS

Oscillating ship motions appear in six degrees of freedom: three modes of translation (surge, sway and heave) and three modes of rotation (roll, pitch and yaw). For a particular ship speed and incident wave angle, the RAOs give amplitude and phase for each mode of the ship motion in relation to wave height and wave frequency.

RAOs may be obtained from model experiments or computed using specialised software. In strip theory (Bertram et al, 2006, Journee and Adegeest, 2003) the forces and moments on a three-dimensional floating body can be determined using results from two–dimensional hydrodynamics coefficients and exciting wave loads. The ship is considered as being made up of a finite number of transverse two dimensional strips or cross sections that are rigidly connected to each other. Each strip is treated hydro-dynamically as if it were a segment of an infinitely long floating cylinder. In the experimental test cases the amplitudes of pitch and roll remained moderate with less than 5°, so that linear theory should still be applicable. Two alternative software packages were used to determine the RAOs of the vessel: a commercial program SEAWAY (Octopus Office) and an open source program PDstrip. Both require a hull form description as well as hydromechanics input data. For the SA Agulhas II a 3D-laser scan was performed while the ship was in dry dock.

The required mass and stability parameters were provided by the loading computer. The radius of inertia for roll k_{xx} was chosen such that the resonance peak in the RAOs matches the resonance peak in the roll motion spectra. This technique is not applicable for pitch because the resonance is not very pronounced here. Therefore the radius of inertia was approximated by means of (Journee and Adegeest 2003)

$$k_{yy} \approx 0.22 \cdot L \ \ to \ 0.28 \cdot L$$

with the ship length L, the proportionality factor was tuned to 0.24. Viscous damping was modelled by the Ikeda method with the parameters given in table **2.**

Table 2. Input data for RAO computations.

Stability and Mass data		
Draft	D	6.67 m
Metacentric height (corr.)	GM	1.41 m
Radius of Inertia Roll	k_{xx}	6.45 m
Radius of Inertia Pitch	k_{yy}	30.31 m
Damping		
Amplitude for Linearisation		5 m
Damping: Bilge Keel		
Height	HBK	0.39 m
Dist. APP to aft of BK	XBKA	42.44 m
Dist. APP to fwd end of BK	XBKF	78.81 m

As a comparison between the two software packages, figure 3 shows the RAO-pitch amplitudes for the SA Agulhas II for a speed of 8.25 knots and two different angles of wave incidence. For the other degrees of freedom there is a similarly good agreement except for roll, where viscous damping seems to be insufficiently modelled in PDstrip. Therefore, it was decided to use the RAOs as computed by SEAWAY.

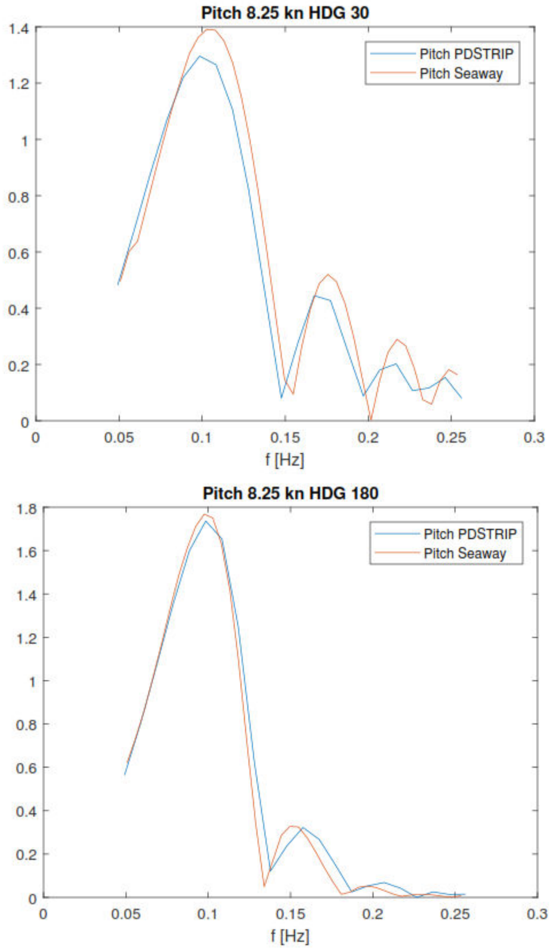

Figure 3. Comparison of RAOs calculated by two different strip theory programs.

5 EXPERIMENTAL DATA

For the data processing a coordinate system with the origin in the center of gravity was chosen. The x-axis is oriented midships pointing to the bow, the y-axis points to portside, the z-axis upright. Roll, pitch and yaw are defined as right handed rotations around the corresponding axes as demonstrated in figure 4. The sensors provide time series of the sensor accelerations and the angular rates in the local frame of the sensors which rotated with respect to the horizontal frame due to roll, pitch and yaw motions. In principle the vector components have to be rotated into the horizontal frame. Since amplitudes of roll and pitch turned out to be less than 5° and 4° respectively, the rotational rates needed no transform within the accuracy of the measurements.

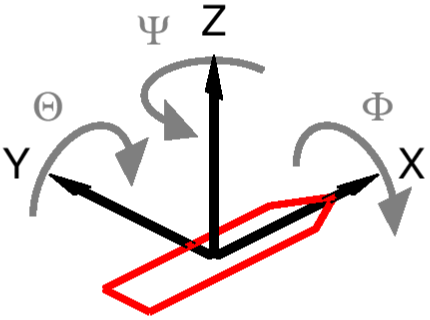

Figure 4. The coordinate system used in this paper. The angles for roll Ψ, pitch Θ and yaw Ψ are counted positive in the direction of the arrows.

In contrast the acceleration vector has to be transformed into the earth frame in order to remove the gravitational acceleration. This requires knowledge of the roll, pitch and yaw angles which are denoted by ϕ,θ,ψ respectively. These angles were calculated from the angular rates. As a first step offset and drift were removed from the angular rates by means of a high-pass filter.

The filtered signals were integrated in time domain, a second high-pass filter step was necessary to remove the long term sensor drift. The rotation from the sensor to the horizontal frame is accomplished by the transform matrix R which is composed of three rotation matrices for the individual axes:

$$R \;= R_\psi \cdot R_\theta \cdot R_\phi \tag{7}$$

with

$$R_\phi = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi & cos\phi \end{pmatrix}, R_\theta = \begin{pmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{pmatrix},$$

$$R_\psi = \begin{pmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

The results shown in the following sections are obtained from the sensor located at the center of gravity. This sensor provides rotational rates and linear accelerations for all degrees of freedom at a sample rate of 8 Hz. Segments of the data stream where wave conditions as well as course and speed were nearly constant were selected for processing, the duration of one segment ranges from 2 hours to 4 hours. Power spectra of motion were calculated using the Welsh method with N=512 points per FFT and 75% overlap, this leads to more than 400 averages in the Welsh algorithm. The power spectra were found stable against variations of the FFT-length, this indicates that the duration of the time series is sufficient for estimating the power spectra. Power spectra for angular motion were obtained by integrating in Fourier space, namely dividing by ω_e^2.

Regarding the rotational degrees of freedom only pitch and roll were examined. During all of the measurement runs the ship was steered by autopilot, which creates rudder moments to counteract any yaw motion. Therefore, the measured yaw spectrum is not the direct ship response to the waves as described in the corresponding RAO and was not considered in the present analysis.
Wave data were obtained by visual observations recorded by the South African weather service meteorologists on board. These observations were recorded on a 3-hourly basis and consist of estimations of characteristic height, peak period and peak direction for both, swell and wind sea. At a later stage directional wave spectra could be incorporated. These became available after a re-analysis of remote sensing data by ECMWF.

6 RESULTS

6.1 BASED ON VISUAL OBSERVATIONS

Wave data consist of estimations of significant height $H_{1/3}$, peak period (Tp) and peak direction for both, swell and wind sea. For our analyses we used only data sets, where the ship was on a steady heading with constant speed for several hours and the estimated wind sea was negligible. As for the available information, the exciting wave "spectrum" was thus reduced to a single point.

To calculate motion spectra from the visually estimated peak period a frequency spread was introduced with the sole purpose of avoiding a singularity. For simplicity, a Bretschneider Spectrum

$$S(\omega) = \frac{A}{\omega^5} e^{-\frac{B}{\omega^4}} \tag{9}$$

was used, where the parameters A and B are related to significant wave height and peak frequency. For a narrow banded spectrum (ocean swell) (Bjornsson, 2013),

$$B = \frac{5}{4}\omega_p^4 \quad \text{with} \quad \omega_p = \frac{2\pi}{T_p} \quad \text{and} \quad A = \frac{1}{4} H_{1/3}^2 B \tag{10}$$

Then, computation of the motion spectra is done via equation (3) with the angle index of the RAOs selected according to the ship's heading and the recorded wave direction. The result is transformed to encounter frequency to compare with the measurements.

As an example a data set recorded on July 5th, 2017 was selected where the ship's speed was 7.5 kn. The entries in the meteorologists' log are given in the first column of table 3:

Table 3. Visual observation data recorded

	recorded observations	modified values
Significant height [m]	7	6
Peak period [s]	11	13
Peak direction [˚ port bow]	15	35

Entering these values, the computed spectra (green) are shown in figure 5 in relation to the measured spectra (blue). Apart from pitch the computed spectra come out far too small and, apart from roll, they appear at too high frequencies. Given some uncertainties in the visual estimates, it seems justified to modify these values to a certain extent. Using the parameters in the right hand column of the table we get the spectra plotted in red. Now, the computed roll spectrum is too narrow, but agrees in total power with the measured one. The comparisons for pitch, heave and surge improve somewhat, but are still far from satisfactory.

The measured spectrum of surge seems to be corrupted at low frequencies. To calculate the motion spectra for heave, surge and sway, as outlined in chapter 5, the observed angles must be used to transform the linear accelerations from the sensor system to the horizontal system. This is challenging where small errors in the angles can cause a spurious coupling of the gravitational acceleration into the linear degrees of freedom. The low frequency artifact in surge can be attributed to this source. As the roll amplitudes are generally larger than pitch, the uncertainty in sway will be considerably higher, whence it was decided to exclude sway from the present analysis.

Modification of the wave incidence angle from 15° to 35° port was necessary to fit the total power in roll. The roll RAO exhibits a strong resonance. The measured spectrum, on the other hand, is considerably wider. This could indicate the presence of an angular spread in the exciting wave spectrum. Ten more data sets have been investigated, all leading to similar qualitative statements. No attempt has been made here to do a variational calculation to fit the parameters to the measured data or to include an angular spread. The results with the Agulhas II show however that, even for ocean swell, three wave parameters (height, period and direction) are not enough to account for the observable ship motions.

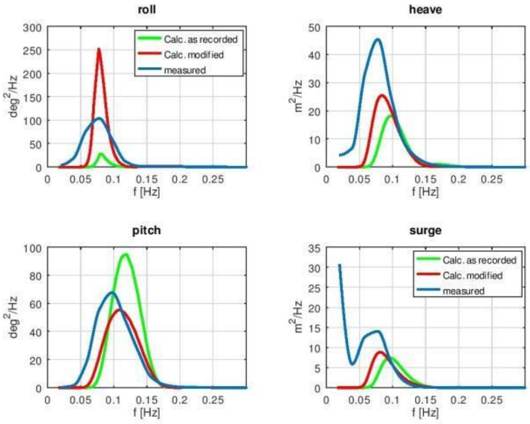

Figure 5.Power spectra of ship motions, measured (blue) and computed with two parameter sets (green and red)

6.2 BASED ON DIRECTIONAL WAVE SPECTRA

For analyses of past measurements ECMWF provides directional wave spectra modelled from remote sensing data on a narrow grid of positions and time. The closest grid point was taken without interpolation to compare with the Agulhas data set of July 5th 2017. The wave spectrum is given with a frequency spacing of about 0.01Hz and an angular resolution of 15˚. The peak of the wave spectrum was found at 20˚ on the port bow with a period of 13.5s and the significant height was 6.9m, in fair agreement with the visual recordings.

Calculated motion spectra were generated by applying equation (2) to all of the wave grid points and integrating over angles after a power conserving transformation to encounter frequency. The result is shown in figure 6. The measured spectra for pitch and heave are now reproduced very well and, apart from the low frequency limit, surge also matches closely. The wave spectrum exhibits a spread of about 0.04Hz in frequency and 40˚ in angle and this, obviously, is substantial to make the computed spectra agree with the measured ones in position and width.

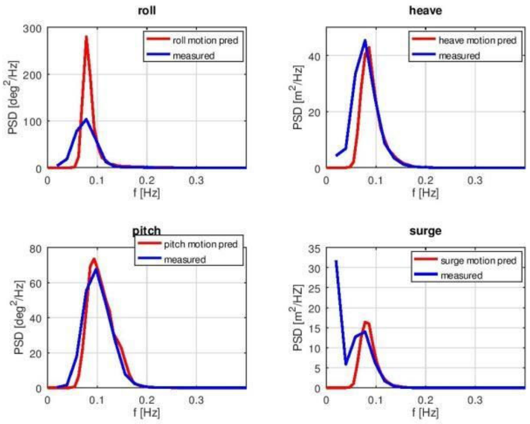

Figure 6. Power spectra of ship motions, measured (blue) and computed from the full 2D-wave spectrum supplied by ECMWF (red)

There remains a question about the shape of the peak in the computed roll spectrum. It should be noted that the power spectra depend on the square of the RAOs. To correctly represent roll damping in the RAO a delicate adjustment is required. Possibly, in a natural environment, a roll moment from rudder action, if by the autopilot, could manifest itself as additional damping.

7 CONCLUSIONS

Oscillating ship motions were measured on a large research vessel in the open ocean. These were compared in the frequency domain with predictions obtained from available sea state data and RAOs computed by strip theory. A good agreement would be desirable for practical purposes of seakeeping. It was found that a sea state reduced to peak values of direction, period and height is not sufficient to account for the observed motions, even when a long-crested ocean swell is dominant. A full directional wave spectrum improves the agreement between prediction and measurement considerably. The reason for a general tendency to overestimate the roll response remains to be investigated.

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