Proceedings of the Twentieth (2010) International Offshore and Polar Engineering Conference
Beijing, China, June 20–25, 2010

ISBN 978-1-880653-77-7 (Set); ISSN 1098-6189 (Set); www.isope.org

The On Board Wave and Motion Estimator OWME

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ABSTRACT

Vessels and floating structures are subject to wave induced motions affecting and often even preventing their operation. A system to predict short periods of quiescent vessel motions a few minutes in advance could reduce the costly 'Waiting on Weather'. The Joint Industry Project 'On board Wave and Motion Estimator (OWME)' developed a system capable of predicting the vessel motions on board in real time up to two minutes in advance. It measures remote wave profiles by means of nautical radar, uses linear wave theory to propagate the waves in time and space and estimates the ship response to the predicted wave field. This paper describes the concept and shows results of a first field trial aboard an offshore support vessel in mild sea conditions.

KEY WORDS: Real Time Vessel Motion Prediction; Radar; Wave Propagation; Wave Profile; WaMoS II; OWME; wave spectrum

INTRODUCTION

The Offshore industry employs many vessels and floating structures which are subject to wave induced motions. Several offshore operations such as the float over installation of a platform topside, connect operations for LNG-offloading or the landing of a helicopter only need a short period of quiescent vessel motions to be conducted safely. These kind of operations would benefit from a deterministic real time prediction of such quiescent periods.

The Joint Industry Project 'On board Wave and Motion Estimator (OWME)' aimed to develop, demonstrate and validate a system capable of predicting the vessel motions on board in real time. The system is designed to predict the vessel motions at zero forward speed in mild to moderate sea states.

Regardless of the actual design, a real time motion prediction system has to solve three principle tasks:

- The actual directional sea state and weather conditions have to be obtained.
- The sea state at the vessels location has to be predicted for the time horizon of the motion prediction.
- The vessel response to this predicted wave environment has to be computed.

These three tasks have to be solved in real time and continuously, with high update rates and low processing times, otherwise the prediction arrives to late to be useful. In OWME, solutions for these three tasks were developed, mainly by improving existing technologies and integrating them into a working wave and motion predictor.

This paper gives an overview of the OWME system and the results of a first field trial, focussing on the method to derive wave trains using the WaMoS II system and the wave field prediction.

OWME SYSTEM OVERVIEW

Figure 1 shows the design and data flow of the OWME system and the set-up used for its validation. The first step of the processing chain is to measure the waves that are approaching the vessel. When measuring the distant wave field, the wave travel time from the measurement location to the ship position can be exploited to extend the prediction horizon which depends on the distance of the measurement point to the vessel, wave period and directional wave spreading. Therefore, only remote sensing techniques with a good spatial coverage allow to achieve the prediction horizon with this approach.

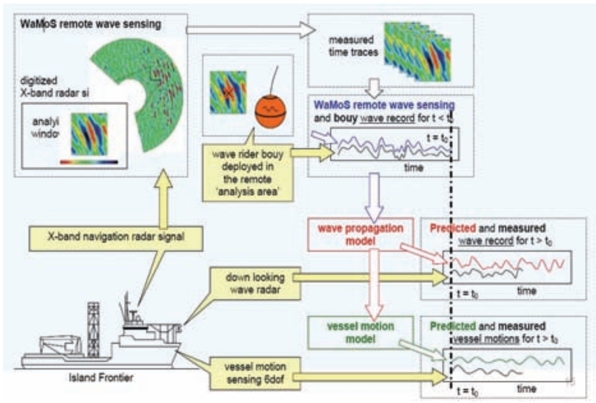

Fig. 1: OWME system overview

The OWME predictor uses nautical X-Band radar to measure the waves in a distance of 500m to 2000m off the vessel. The individual waves are extracted from sequences of radar images for a number of analysis areas placed within the radars field of view. By means of a recursive window placement tool, one of these areas is always positioned in the direction of a wave system traveling towards the vessel.

The second step is to predict the wave field at the vessel location. At predefined spots within the measurement area, time traces of the wave profiles are derived and fed into a numerical wave propagation model that computes the wave elevations at the location of the vessel.

Finally, a numerical model is used to compute the vessels response. Applying linear ship motion theory on the predicted waves, the vessel motions in all six modes are computed. Depending on the actual task, the predicted vessel motion can be evaluated to support operations. In OWME, the task was to predict quiescent periods that allow for instance to land a helicopter.

Important technical tasks in this approach are the update rates of the system and the computational time required to conduct the several steps of data processing: The longer the data processing takes, the shorter the prediction time will be. In the OWME project, all data processing steps were completed within 13 seconds on a quad-core PC. Using remote sensing up to 1 nm ahead, this allows a prediction time of 2 minutes which is sufficient for the target motion critical offshore operations.

WAVE PROFILE MEASUREMENTS

The wave profiles are derived from the images of a nautical X-Band Radar. These images contain back scatter signatures of the sea surface waves that can be exploited to derive 'sea surface elevation maps' showing individual waves in the radars field of view over time. In OWME, the Wave Monitoring System WaMoS II of OceanWaveS GmbH is used for this task.

Measurment Principle of WaMoS II

WaMoS II consists of a high-speed video digitizing module and a software package to analyze the stored radar raw data, running on a standard PC. The software controls the radar, the data storage, carries out the wave analysis and displays the results. The hardware can be interfaced to any conventional navigational X-band radar. The data is displayed locally and is also transferable via Modem or Internet (Figure 2).

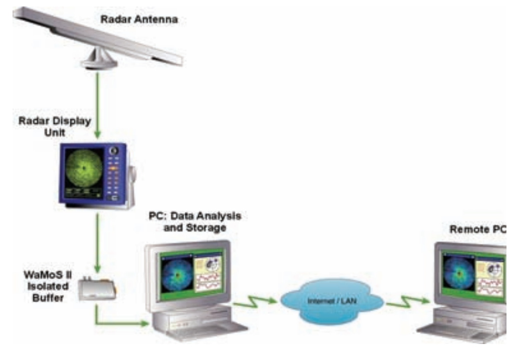

Fig. 2: Sketch of WaMoS II

The data basis for a typical WaMoS II wave measurement consists of a sequence of $N_x=32$ radar images as shown in Figure 3. In the near range of nautical radar images, radar signatures of the sea surface are visible (*sea clutter*). This radar back scatter results from the interaction of the incident radar beam and ripple waves (cm-scale) that are generated by the surface wind. A restriction for WaMoS II measurements is therefore the presence of wind. Depending on the local conditions, a minimum of 3-5 m/s wind speed is required to receive a significant amount of sea clutter. This base signal is modulated by the presence of long ocean waves due to various effects (Alpers et al, 1981). For nautical radar, two important factors are 'tilt modulation' and 'shadowing': Slopes reflect the incident radar beams directly to the radar antenna, resulting into areas of high radar back scatter intensity (green to red colors). Due to the low grazing angle of a nautical radar, areas behind a wave are often shadowed by the wave crests, resulting into dark stripes in the radar image. An image sequence allows to capture the wave motions, as the stripes are moving along with the waves that generated them.

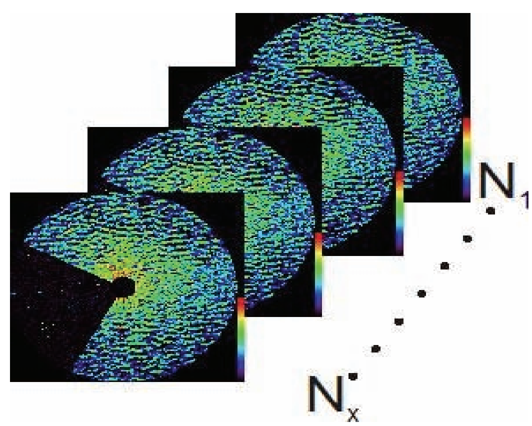

Fig. 3: Radar image sequence with wave patterns. The back scatter is color coded.

To analyze the pattern, an image sequence is transformed into a 3D image spectrum by applying a three dimensional *Fast Fourier Transform* (FFT). By filtering, distortions due to the imaging process are compensated and the wave signal is extracted from the 3D image spectrum. This filter is based on the linear dispersion relation of ocean surface waves. The result of this process is a full 3D wave spectrum. By integration over all frequency layers and directions, 2D and 1D wave spectra are derived. In addition to these data products, statistical sea stare parameters like significant wave height *Hs*, peak wave period *Tp*, wave length λp and direction are obtained for up to four wave systems.

Deriving the Sea Surface Elevations

In addition to the standard analysis described above, WaMoS II has the capability to derive maps of the sea surface elevation, showing individual waves and their development in time and space. To retrieve these maps, sequences of nautical radar images are inverted by applying a method proposed by Nieto et al. (2004). This approach considers shadowing to be the main imaging mechanism of ocean gravity waves in nautical radar images and is based on linear wave theory. It is assumed that the sea surface elevation consists of a linear superposition of several individual sinusoidal waves (*partial waves*). By means of a FFT, a band pass filter based on the gravity wave dispersion relation and the application of a transfer function, amplitude (A_i) and phase (φ_i) of a number *N* of *partial waves* are determined. The surface elevation $\eta(x,t)$ at a given point and time is then given by a summation over all partial waves by

$$\eta(\mathbf{x},t) = \sum_{\vec{k},\omega} A_i \cos(\mathbf{k}_i \mathbf{x} - \omega_i t + \phi_i) \qquad (1)$$

where *x* is the position vector, *t* the time, *k* the wave vector, ω the angular wave frequency. The data output of this tool is either the full 3D spectrum including all measures needed in Eq. 1 to reconstruct the sea surface or the sea surface elevations directly by a back transform, as sketched in Figure 4. When using this tool, all WaMoS II standard data products are still available, which is important for OWME as the 2D wave spectra are used later on.

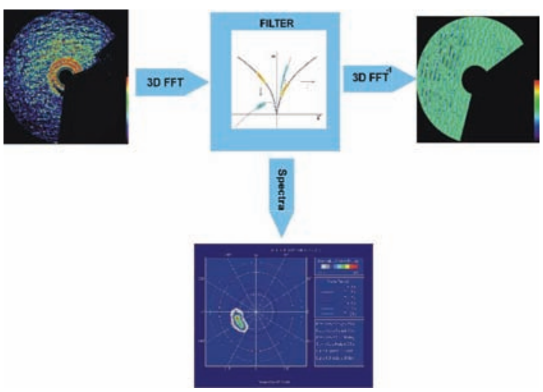

Fig. 4: Inversion method. The filtered image spectra can be transformed into sea surface elevation maps

Data Resolution and Measurement Accuracies

The sea surface elevation maps derived by inverse FFT have the same resolution in time and space as the input radar images. A typical WaMoS II radar image covers a radius of 2 km around the radar antenna with a spatial resolution of 5m to 7.5m. The temporal resolution of the raw data is defined by the antenna rotation time and is usually in the order of 1-2.5s. In Table 1, the accuracies of WaMoS II statistical sea state parameters relevant for OWME are listed as certified by GL.

Table 1: Range and Standard deviation of WaMoS II sea state parameters

Parameter	**Range**	**Std. Deviation**
Sign. Wave Height	0.5 -20 m	10% or 0.5 m
Wave Period	3.5-40 s	0.5s
Wave Direction	0-360°	2°

Data Sampling and Up Date Rates

To allow a continuous data acquisition, the raw data sampling and the analysis is executed by two independent software modules running in parallel. The data sampling module stores all individual radar images to disk, from where they are read and assembled to sequences of *Nt* images by the analysis software. While processing a sample, *X* new images are taken and stored. Depending on the radar repetition rate Δt_1 (typical range Δt_1 = 1s – 3s), several new images are recoded in the time Δt_2 needed to complete an analysis cycle. Thus, Δt_1 is the temporal resolution of the measurement while Δt_2 is the update rate of the measurement. This setup leads to a certain redundancy in the data processing, as can be seen from Figure 5: As the analysis resumes with the latest image acquired, the next analysis cycle evaluates the *X* new images combined with (Nt-*X*) images which were already processed in the previous cycle. When aiming for high update rates, this redundancy is unavoidable as a complete series of a sufficient number of subsequent images is needed for the 3D FFT. The overlap times can be exploited to minimize errors when catenating several single WaMoS II measurements to long time traces .

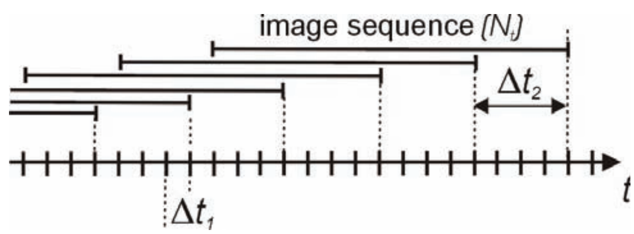

Fig. 5: Data sampling and update rate.

With the OWME set-up, completing an analysis cycle takes about 5-10s. This time plus the duration of the whole processing chain defines the update rate of the system.

Placing Analysis Areas

It is of advantage not to apply the inversion process to full area visible in the radar images but to choose smaller sub areas. One reason for this is to minimize the analysis time which allows faster up-date rates, a second reason is to optimize the quality of the input data.

Reducing the amount of input data is an easy way to speed up the data processing. It is possible to restrict the analysis to those parts of the radar image that shows signatures of waves approaching the vessel.

This option was chosen as it has a second advantage: The imaging of waves in a radar image is to some extend depending on their orientation towards the radar antenna. Wave fronts that are directly facing the the antenna are much clearer imaged than wave crests perpendicular to this direction. Focusing on this area reduces the number of partial waves needed to reconstruct the sea surface and reduces the risk to include radar disturbances in other parts of the image into the analysis.

Suitable analysis areas can be identified from the 2D spectra and the statistical wave parameters provided by WaMoS II. A flexible analysis window was introduced that is placed by a recursive positioning tool. This algorithm uses the peak wave direction of the actual spectral measurement to choose the window position for the next calculation. As all recursive procedures might become unstable with time, this selection is cross checked using a fixed 'control window'. A window is set in a fixed distance to the radar antenna and a look direction relative to the ship heading. The window size is 960 x 960m, thus still showing a relatively large part of the sea surface. Figure 6 shows an example. It can be seen, that the analysis window is placed in an area, where clear stripes are visible, resulting into a wave elevation map of high quality.

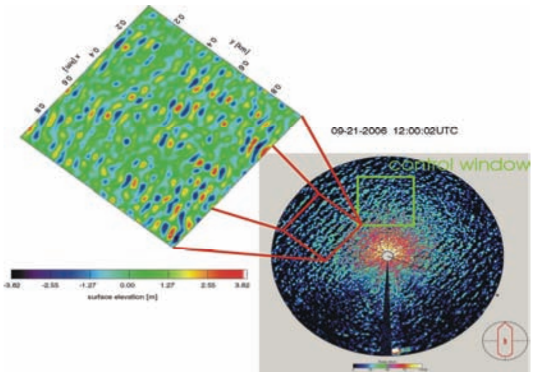

Fig. 6: Analysis area and resulting sea surface elevation map

In between two subsequent measurement cycles, the sea state can be assumed to be stable. Thus, the adjustment will result in small changes from cycle to cycle, only. This is important, as several individual measurements have to be combined to get the appropriate input for the wave propagation module, as described below. The window positioning tool can be extended to place several windows to use the OWME predictor also in cross seas. Still, it has to be noted, that for the research reported here, only one wave system was monitored.

WAVE PROPAGATION

The theoretical model used to describe the wave field is a linear superposition of cosine waves with different frequencies traveling in different directions. Rewriting Eq. 1 and introducing k as wave direction independent wave number and μ as the wave direction gives:

$$\zeta_j(x,t) = \sum_{n=1}^{N/2}\sum_{m=1}^{M} A_{nm} e^{i(\omega_n t - k_n x_j \cos\mu_{mn} - k_n y_j \sin\mu_{mn} + \varphi_{mn})} \quad (2)$$

where:
M = Number of directional Components
N = Number of frequencies
x_j, y_j = coordinates of location j
ω_n = Frequency of component n
k_n = Wavenumber of component n
μ_{mn} = Propagation direction of component m for frequency ω_n
A_{mn} = Amplitude of Component with frequency ω_n in direction μ_{mn}
φ_{nm} = Initial phase angle of component *mn*

Having a directional frequency domain description of the measured wave field available, it can be used to calculate the wave elevation at a desired point in space and moment in time by substituting the corresponding values for x_j, y_j, and t. However, these values cannot be chosen freely: the spatial temporal zone where predictions can be made based on a measurement in a finite spatial and temporal domain is limited to the so-called predictable zone. This is explained in the next paragraph.

Predictability

Assuming that no information about the wave field is available beyond the actual spatial-temporal measurement zone , the wave elevation can be derived only in a limited spatial-temporal predictable zone as

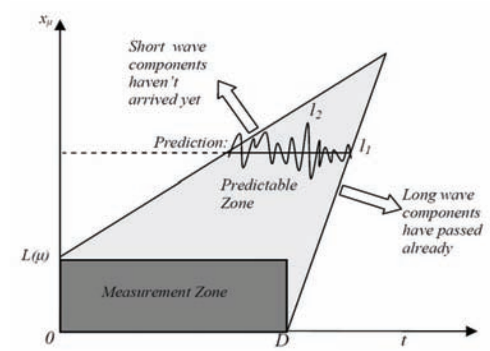

Fig. 7: Predictable zone for components traveling in direction μ

indicated in Figure 7.

In this diagram, the abcissa represents the time t while the ordinate shows the distance x. The predictable zone is indicated for a single wave travel direction μ. The duration of a measurement is indicated in the Figure by D, the spatial length of the measurement zone is $L(\mu)$, as defined in Figure 8. For an accurate wave prediction, all used components have to originate from the measurement zone that forms a rectangle of the dimension $D * L(\mu)$ in the space-time diagram in Figure 7 (dark gray). In this case, the prediction point in time and space should be within the predictable zone (light gray). This zone is a triangle which is bounded by two straight lines l_1 and l_2 which are specified in the equations below.

$$l_1: x = c_{g,high}(t - D) \quad (3)$$

$$l_2: x = c_{g,low}t + L \quad (4)$$

Here, $c_{g,high}$ and $c_{g,low}$ are the group velocity of the longest and shortest wave components present in the measurement respectively. The reason for this limitation is that at any prediction point in space and time below l_1 the longest wave components that were identified in the measurement zone have passed the prediction site already. Similarly, for any point above l_2, the shortest wave components have not reached the prediction location, yet. Therefore, no optimal prediction can be expected when predicting outside the indicated predictable zone. A more detailed explanation on predictability can be found in Wu (2004).

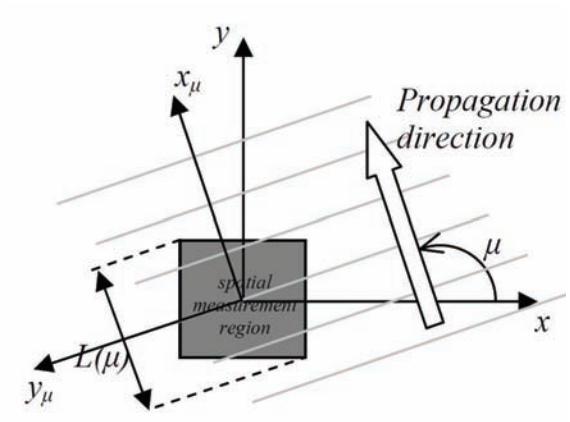

Fig. 8: Projected measurement region size

Deriving Time Traces

As indicated by the second horizontal line in the diagram in Figure 7, the prediction based on a measurement of duration *D* at a given projected distance from the measurement location is limited to the predictable zone within the light gray triangle. Therefore, the length of a time trace needed for useful prediction is defined by the sea state (governing the bounding group velocities), distance of the measurement site to the vessel and the prediction horizon aimed for.

The period of time corresponding to 32 WaMoS II images amounts to roughly 42 seconds for the set up of the OWME validation, which is relatively short. If the wave components resulting from the three dimensional FFT of the radar images were to be used directly for the propagation, the obtainable forecast time would be rather limited due to a very limited predictable zone. For that reason time traces of the wave elevation of sufficient length at several locations were created from the radar measurements by concatenating time traces from subsequent sets of 32 images. These time traces were combined and correlated to find a new wave field representation that provides a much larger predictable area. With this approach, the measurement duration was extended to approximately 670 s, corresponding to 512 raw image takes. While concatenating the time traces, the above mentioned redundancy of subsequent WaMoS II measurements can be used to compensate edge effects or other disturbances in the raw data. The procedure for obtaining this new wave field representation is presented in detail in Naaijen et al. (2009).

Calculate Ship Motions

Having available a wave field representation, it is possible to predict the wave related ship motions, in a straight forward way by using frequency domain transfer functions:

$$X_i \; x,t = \sum_{n=1}^{N/2} \sum_{m=1}^{M} H_{inm} A_{nm} e^{i \quad {}_n t - k_n x_j \cos \quad {}_{mn} - k_n y_j \sin \quad {}_{mn} \quad {}_{mn}} \qquad (5)$$

where

H_{inm}= frequency and direction dependent transfer function for motion i
X_i = motion in direction i

(i = 0..6, for surge, sway, heave, roll, pitch, yaw)

Motion transfer functions can be obtained by linear diffraction/radiation theory as was done for the OWME basin experiments.

VALIDATION

Basin Tests

The OWME concept was verified against scale model tests both in long crested and short crested waves. Extensive short crested model tests were conducted in MARIN's Seakeeping & Manoeuvring Basin which measures 170 x 40 x 6 m. In this basin a sea area of 1.2 x 1.2 nautical miles including the selected field trial vessel could be modeled at scale 1:70. The model tests proved the concept and the accuracy of the wave propagation and vessel motion prediction model (Naaijen et al., 2009). In order to mimic the WaMoS II system, a large number of probe measurements in short crested waves were carried out and correlated to find a WaMoS II-type of wave field representation as described in Naaijen (2009). With this representation, a prediction was made at a remote location in the basin where a probe measurement was available for validation purposes. In Figure 9, an example of the comparison between measured and predicted wave and vessel motions for a JONSWAP sea state with Hs = 2.5, Tp= 9.0 and γ=3.3 is presented.

The directional spreading was included by means of the following spreading function:

$$D \quad = D_0 \cos^{2s} \quad - \quad {}_0 \qquad (6)$$

With

$$D_0 = \frac{1}{\int \cos^{2s} \quad - \quad {}_0 \; d} \qquad (7)$$

and

$$S \quad , \quad = S \quad D \qquad (8)$$

Where

D = Spreading Function
μ_0 = Main wave directional
s = Spreading parameter
$S(\omega,\mu)$= Directional wave spectrum

The spreading parameter of s = 10 (corresponding to the amount of directional spreading generally present in wind seas) is used for the data comparison given in Figure 9.

Comparison for wave elevation is presented in the upper most time trace. The distance (projected in the direction of the main wave direction) amounts to approximately 800 m for the shown example providing a prediction horizon of approximately 75 s. Since also motion measurements of a ship model were carried out at that same location, a direct comparison of measured and predicted ship motions is shown for heave and pitch as well.

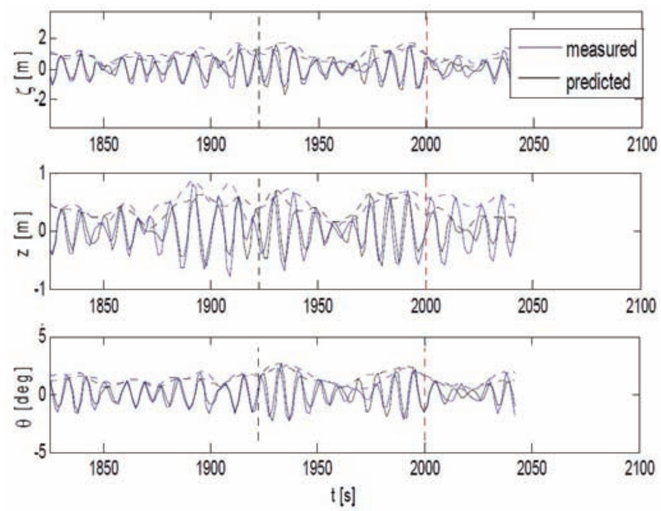

Fig. 9: Time traces of predictions and measurements from basin experiments for surface elevation (top), heave motion (middle) and pitch motion (bottom).

The data example shows an excellent deterministic correlation between measured and predicted wave elevation, thus proving that the prediction model is sufficiently accurate for the task. In addition, a good agreement was obtained for heave and pitch. Due to the strong non-linearity of the roll damping, predictions with linear roll motion transfer functions result in a less accurate prediction. No attempts were made in this project to tune roll damping coefficients for the considered sea state.

Full Scale Test

After the successful scale model tests, in September 2008 the OWME system was installed on an 80m offshore support vessel operating on Dynamic Positioning (DP) on the Gulfaks oil field. The field trials were conducted by MARIN's Trials & Monitoring group in close co-operation with OceanWaveS, TU-Delft, Seaflex and Statoil. For the offshore trials the vessel was not only equipped with the WAMOS II X-Band radar but also with a bow mounted down-looking radar (DLR) and with an accurate motion sensor unit. Furthermore for validation purposes, a directional wave rider buoy was deployed in the WAMOS window about 1 nm from the vessel. The wave rider buoy was deployed on September 23 and was retrieved on September 25. In this period, a complete comparison data set was acquired. Each of the components of the OWME concept i.e. the wave sensing, the wave propagation and the vessel motion prediction could be tested separately as well as in combination. During the trials, all sensor signals were continuously recorded at a high frequency rate with accurate synchronization to avoid delays and phase shifts.

Environmental Conditions during the trial

Figure 10 shows the development of the sea state during the trial period. The diagrams show the significant wave height (*Hs*), peak wave period (*Tp*) and peak wave direction (θ_p) measured by WaMoS II in comparison to the wave rider buoy deployed for the experiment. Unfortunately, unusual calm wind and sea state (Hs < 2.5m) conditions were prevailing for most of the trial period. In particular, on September 24th , the wind speed was too low to generate sufficient sea surface roughness for radar wave measurements. Such periods can be identified in the diagram from a severe scatter in WaMoS II peak wave direction, as the system can not detect a distinctive peak wave system. Therefore, these periods had to be excluded from the analysis of the OWME system performance. In the remaining part of the time series, deviations between WaMoS II *Hs* and the reference buoy measurements generally lie within the standard deviation of 0.5m as specified in Table 1.

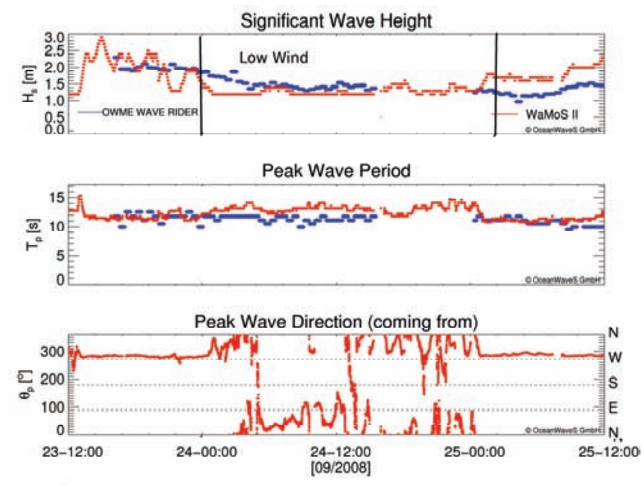

Fig. 10: Wave conditions during the sea trial

Technical performance of the WaMoS II system

During the sea trial, a total of 53000 analysis cycles of the WaMoS II processing chain were completed. In this time, no major data loss was detected.

Figure 11 shows the update rates of WaMoS II sea surface elevation maps during the trials. The analysis time can vary, depending on the raw data quality and CPU workload. It can be seen, that the vast majority of all measurements (99%) are completed within a maximum time frame of about 10s with an maximum (35%) at 5s analysis time.

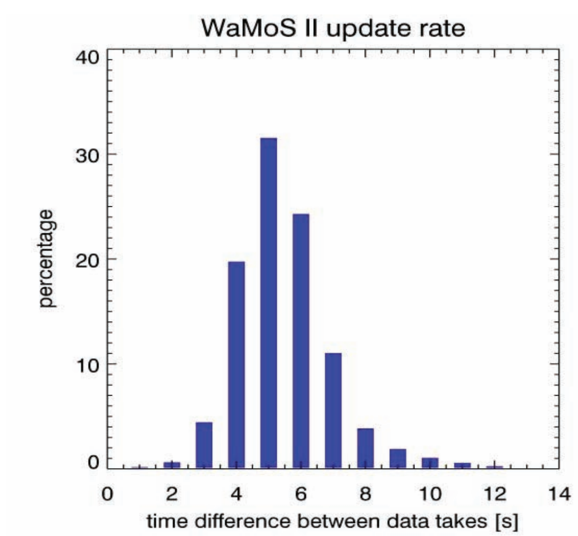

Fig. 11: WaMoS II update rate

To get the total update rate, the processing time of the subsequent analysis steps, i.e. the wave propagation and motion prediction, has to be added, leading to a final up date rate of 13s (using a commercial quad-core PC). From these results, it can be concluded that the wave profile retrieval is stable and fast enough for the purpose of OWME.

Results of the Ship Motion Prediction

The calm conditions during the trial reduces the number of evaluable data sets to two days (23rd and 25th of September), at which wave height and wind speed were sufficient for wave measurements to validate the OWME prediction.

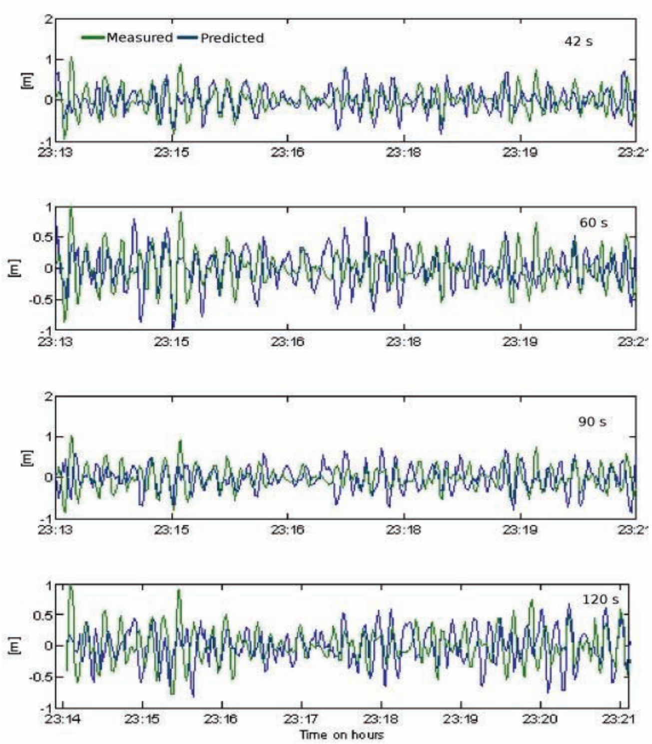

Fig. 12: Comparison of heave measurement (green) to prediction (blue) for 42,60,90 and 120 s prediction time

This data was divided into a total of 96 samples of 30 minutes duration, each. For 20 samples with stationary sea conditions, OWME predictions of the vessel motions were made for 42, 60, 90 and 120 seconds ahead and compared with the actual vessel motions as measured. Figure 12 shows an example of this kind of comparisons.

The time series in Figure 12 show the measured heave motion (green) in comparison to predictions of the OWME system (blue) for prediction time horizons of 42, 60, 90 and 120 seconds. Despite significant deviations in the actual amplitudes and phasing, the envelopes of predicted and measured motions showed a promising correlation in view of the ultimate aim of the project i.e. to predict quiescent motion periods.

Evaluation of the Trial

The above results show that the OWME system is working stable and prove that it is feasible to predict quiescent periods of vessel heave motion up to two minutes in advance. Thus, it can contribute to the workability of offshore operations in otherwise limiting sea states.

It is however noted that the OWME system was developed for and is so far only tested in mild sea states. The data collected during the trial is sufficient to demonstrate the workability of the overall concept. Still, further development is identified to improve reliability and accuracy of the system and a longer testing phase is needed to validate and quantify the accuracy of the system for a wider range of sea states and weather conditions. In particular, no noticeable multi modal seas such as combinations of different swells and wind seas were encountered over the trial period.

An obvious limitation of the system is that it can not operate under no wind conditions due to the lack of sufficient sea clutter. For the majority of sea areas, it can be expected that calm wind coincides with calm sea conditions, i.e. conditions in which the prediction of quiescent periods is not needed. However for operations in noticeable swell area's such as West of Africa, this might limit the applicability of the system.

CONCLUSIONS

Summary

Within the European Joint Industry Project 'On board Wave and Motion Estimator' (OWME) a system to predict quiescent periods for a time horizon of up to 2 minutes was developed and tested under real conditions. It is designed to predict the motions of an arbitrary stationary ship or floater in mild to moderate sea states. The OWME predictor uses the wave radar WaMoS II to measure the remote waves at a distance from 500 to 2000m from the vessel, propagates the measured profiles in space and time to the location of the vessel and calculates the vessel motions. The system was developed mainly by improving existing technologies and integrating them into an efficient real time on board wave motion predictor.

Conclusions from the Field trial

The OWME modules for wave propagation and vessel motion prediction were successfully verified against scale model tests both in long crested and short crested waves in MARIN's Seakeeping & Manoeuvring Basin.

A field trial aboard an 80m offshore support vessel showed that the system is working stable and is capable to predict the wave envelopes and to identify quiescent periods of vessel motion for a prediction horizon of up to 120s. An update rate of 5-10s was achieved during the trials. Due to the limited range of sea states encountered, only the performance in mild single directional sea states (1 peak spectra) could be tested.

Applicability

The technology is in particular relevant for smaller vessels of the type that are increasingly undertaking operations such as well intervention, drilling, survey and installation, operations for which safety and workability are paramount. The concept is also of interest for trading ships to avoid severe wave impacts and excessive motions by warning for severe incident wave elevations and excessive motions and loads. It has to be noted, that the applicability of the system is limited by the local wind speed as the X-Band Radar measurement requires a minimum wind speed of approximately 3-5m/s to retrieve a clear wave signal. As calm wind usually coincide with calm sea conditions in most sea areas, this still allows a wide range of applications.

Outlook

With these promising results, the OWME partners lead by MARIN plan to continue to work on the OWME concept, refine and enhance it, to make offshore operations safer and more efficient. Additional application will be developed in order to predict 2nd order wave drift forces for wave force feed forward in Dynamic Positioning. At the same time OceanWaveS will continue the verification of the sea surface elevation data determined by WaMoS II within the coming years in a large experiment off the coast of California.

ACKNOWLEDGEMENTS

OWME has been conducted as a Joint Industy Project with the following participating companies: Statoil, Total, SBM/SBM Gusto, Seaflex/Kongsberg, TU-Delft ,OceanWaveS, University of Oslo and MARIN. The project received the Eureka status and support from the Dutch Ministry of Economic affairs through SenterNovem.

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