Port of Melbourne – DUKC® Implementation

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Abstract

Port Phillip Heads (PPH) is rightly considered one of the most treacherous stretches of water in the world with numerous shipwrecks located in its surrounds. Deep draft vessels entering or departing the Port of Melbourne (Australia's largest container port) must negotiate a passage through this energetic and complex environment and under certain conditions wave-induced vessel motions at PPH can limit access to the Port. To ensure the safety of vessels transiting the Port of Melbourne, the Port of Melbourne Corporation (POMC) engaged OMC-International to configure and install a DUKC® system at the port. The combined wave and vessel motion forecasts at PPH produced by the DUKC® have been validated by full scale vessel motion measurement and analysis. This work enabled a successful implementation of a DUKC® system at a port that contains one of the most challenging stretches of navigable water in the world. Through a scientific approach of identifying and predicting relevant UKC components the DUKC® ensures that safety at the Port of Melbourne meets world's best practice.

1 Introduction

Port Phillip Heads (PPH) is rightly considered one of the most treacherous stretches of water in the world with numerous shipwrecks located in its surrounds. At PPH Southern Ocean swell waves interact with strong tidal currents over a complex bathymetry leading to a wave climate that is both spatially and temporally highly complex. Deep draft vessels entering or departing the Port of Melbourne (Australia's largest container port) must negotiate a passage through this energetic and complex environment. Under certain conditions wave-induced vessel-motions at PPH can limit access to the Port.

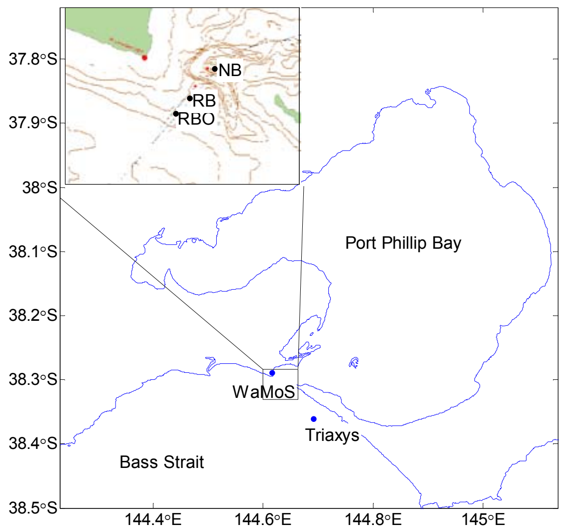

Figure 1: Location of Port Phillip Heads at the entrance to Port Phillip Bay together with the location of the WaMoS and Triaxys instruments. Key wave modelling locations are Nepean Bank (NB), Rip Bank (RB), and Rip Bank Outer (RBO). The insert indicates the complex bathymetry within PPH.

To ensure the safety of vessels transiting the Port of Melbourne, the Port of Melbourne Corporation (POMC) engaged OMC-International to configure and install a DUKC® system at the port. DUKC® is a proprietary under keel clearance (UKC) management system (installed at 18 ports world wide) that predicts the UKC of vessels taking account of the latest environmental, vessel and transit information. The prediction of vessel motions subject to the complex wave climate in PPH was the main technical challenge to a successful DUKC® implementation at the Port of Melbourne.

Waves interacting with opposing currents shorten and steepen, and conversely lengthen and flatten for following currents. Accounting for this change in wave height and length is vital for the accurate prediction of vessel wave response. Depending on vessel particulars and stability characteristics, significantly different wave response motions occur. This knowledge is encapsulated in OMC's SPMS vessel motion model, which is used by the DUKC®.

Previous research (Lesser et al., 2007) aiming to understand the behaviour of waves in PPH yielded some important findings. While extremely dynamic and energetic, the waves in PPH are predictable. Using the 1D action balance equation and a prediction of the strength and direction of the tidal currents, a wave transformation algorithm had been developed that enabled the spectral wave conditions at locations in PPH to be predicted given measurements of the wave conditions offshore.

The DUKC® system is a proprietary UKC management system that enables ports to determine if proposed vessel transits are safe. This is achieved through calculating allowances for each of the UKC components that apply during a transit and contribute towards the nett UKC. Vessel wave response motions are of particular importance in PPH. These are the vertical vessel motions (heave, pitch, and roll) that are induced by the vessel responding to the wave field that it encounters. A wave response allowance is calculated by combining the wave spectrum with a response amplitude operator (RAO) that is produced by OMC's numerical ship motion model, SPMS.

In calculating the wave response allowance at the Port of Melbourne the DUKC® was required to: i) optimally combine two independent wave measurements from an offshore Triaxys buoy and from a WaMoS wave radar (Reichert et al., 1998) mounted on Point Lonsdale Lighthouse on the western side of PPH, ii) forecast each of these measurements from the measurement time (prior to departure) to the time of arrival at PPH, and iii) account for the strong currents in PPH affecting the calculation of the RAOs in the SPMS through their impact on the wave dispersion relation.

The resulting forecasts of vessel wave response allowance were validated against full scale vessel motion analysis (FSVMA) measurements. This validation confirmed the successful implementation of a DUKC® system at a port that contains one of the most challenging stretches of navigable water in the world. Through a scientific approach of identifying and predicting relevant UKC components the DUKC® ensures that safety at the Port of Melbourne meets world's best practice.

2 Wave Forecasting

Wave measurement in PPH is unique in Australia. In addition to directional wave measurement from an offshore moored Triaxys buoy, real time information about spatially varying wave conditions in PPH is available from a WaMoS wave radar. By analysing radar backscatter the WaMoS software computes directional wave spectra and wave parameters for spatial analysis windows selected within the overall image.

The uncertainties associated with these wave measurements are not constant, but vary depending on the conditions. Therefore neither wave source could automatically be considered better than the other and the relative certainty of the sources could vary with time. The challenge for the DUKC® prediction system was how the two sources of wave information could be combined to produce the best forecast of anticipated wave conditions with a desired level of confidence. A sufficient level of conservatism is required to anticipate any deterioration in wave conditions.

This unique measurement situation created specific requirements for the wave forecasting system. These were to:

- spectrally combine two wave sources of varying quality,
- deal explicitly with spectral uncertainty,
- vary with forecast location, forecast horizon and desired confidence level, and
- be modular enabling future improvements to be easily incorporated.

To meet these requirements the wave forecasting system was designed in a modular format utilising infopipes (Hunag et al., 2001). Infopipes is a concept where information flow can be explicitly controlled by combining predefined modules. For the wave forecasting system 5 basic modules were created: a wave source, a spectral forecaster, a wave transformer, a spectral combiner, and an error adding module. The interface between the various modules was defined as a data packet that contained a best estimate of the wave spectrum and a measure of the uncertainty and requested confidence level associated with the spectrum. With a common interface the infopipes modules could be easily joined together. The behaviour of the various modules is described below.

The source module obtains the latest measured wave from a database of measurements. After appropriate filtering and smoothing it returns the best estimate spectrum together with a variance spectrum based on the uncertainty of the measurement and an error spectrum based on this uncertainty and the confidence level of the wave requested.

The forecast module applies a spectral forecast method to the wave packet based on a form of the General Linear Model (GLM)

$$y^f = ry^m + (1-r)\bar{y} + n\sigma\sqrt{1-r^2} \quad (1)$$

where y is the spectral energy and the over-bar indicates the climatic average, r is the lag correlation between the forecast y^f and measured spectra y^m, n is the number of standard deviations of error to be applied to the forecast, and σ is the standard deviation of the spectra about the climate mean. Essentially this algorithm transitions a measurement towards the climate mean with the addition of uncertainty as determined by the confidence level n.

The wave transform module incorporates the offshore to onshore wave transformation algorithm described by Lesser et al. (2007).

The spectral combiner uses the Best Linear Unbiased Estimate (BLUE) algorithm to optimally combine the independent forecasts of wave conditions in PPH from the WaMoS and the transformed Triaxys instruments. The BLUE algorithm is based on the theorem that two independent estimates of a phenomenon are optimally combined when they are weighted relative to the inverse of their respective variances. This yields an estimate with minimised uncertainty. Mathematically, the optimum (BLUE) of x is given by

$$\hat{x} = w_1 x_1 + w_2 x_2 \qquad (2)$$

where $w_1 = \dfrac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2}$ and $w_2 = \dfrac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}$. As well as producing the optimal best estimate spectra the BLUE algorithm also calculates the optimal variance spectra which allows the confidence level associated with the best estimate to be optimally calculated.

Finally, the error adder module combines the best estimate spectrum with the error spectrum to return a single spectrum at the forecast horizon with the level of confidence requested.

A diagram of the final infopipes network developed for the Melbourne DUKC® system is depicted in Figure 2. The figure illustrates how the independent wave forecast from the WaMoS and Triaxys instruments are ultimately combined by the BLUE algorithm. An additional benefit of the system is its redundancy. If, for example, the WaMoS instrument fails the waves can still be forecast using the Triaxys source. Another benefit of the modular design is that the modules are exchangeable, if at some later stage the PoMC wish to use a different wave forecasting module, for example the Wave Spectral Predictor (WaSP) (Hibbert et al., 2007), only the Spectral Forecaster on the Triaxys branch of the network need be replaced. This has clear benefits for maintenance and development of such systems.

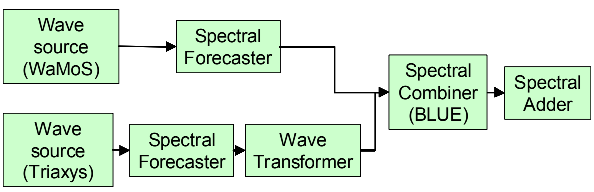

Figure 2: Diagram of the infopipes network used to construct the PoMC DUKC® wave forecasts. The modular infopipes representation allows the information flow to be easily visualised. This allows the features of the forecast system to be easily understood and if necessary updated or replaced without affecting the remaining structure.

With the development of the wave forecaster the DUKC® is provided with wave spectra of a required confidence level at predetermined locations and requested times. The next step for the implementation of the DUKC® system at the Port of Melbourne required enhancements to the SPMS model used to calculate the vessel RAOs.

3 RAO calculation

Vertical displacements of a ship subject to waves are caused by heave, roll and pitch motions. These motions are illustrated in Figure 3. Response amplitude operators (RAOs) are defined as the vessel's response to excitation by a regular wave train of unit amplitude, for specified wave period and direction. The response operators used in the DUKC® are computed as motion amplitudes and phase lags in heave, roll and pitch, using frequency domain analysis by the SPMS model.

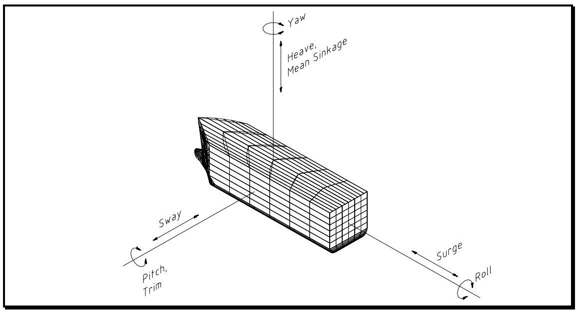

Figure 3: A vessel in waves responds with 6 motions. Only the heave, pitch and roll motions have a vertical component. For computing a vessel wave response allowance only these motions need be considered.

The SPMS model computes hydrodynamic coefficients (added mass and damping) and wave exciting force coefficients and phases for heave, roll and pitch motions, plus appropriate coupling coefficients. These added mass, damping and wave exciting force coefficients are computed using a strip theory approach, extended to include the effects of small underkeel clearances. Shearing forces and bending and torsional moments along the vessel are also calculated by the model. Forward speed of unrestrained vessels is incorporated by modifying the wave encounter frequency and by adjusting the slope of the hydrodynamic mass along the length of the ship. Provision is made in the analysis to include additional roll damping due to viscous effects. Hydrodynamic and wave exciting force coefficients are dependent on the ratio of water depth/vessel draft.

When waves propagate through a current field the dispersion relationship is affected. This has the effect of changing the wave length for a given wave period. If this effect is not taken into account the model will incorrectly compute the hydrodynamic coefficients leading to inaccurate RAOs. For the PoMC DUKC® system the SPMS model was modified to include the effect of the strong currents that occur in PPH on the wave dispersion relation. The impact of these changes on the computed wave response allowance will be illustrated in the FSVMA analysis.

4 FSVMA and DUKC® validation

To confirm that the wave forecasting model and the RAOs calculated by the modified SPMS model are performing as expected they were verified as part of the FSVMA studies performed on the PoMC DUKC® during its commissioning.

A FSVMA analysis is performed by fixing 3 GPS receivers to a vessel prior to its transit: one at the bow and one on each of the bridge wings. A fourth receiver is positioned on land to act as a base station. By calculating the differential position of the mobile receivers relative to the fixed base station sub decimetre precision of the 3 dimensional position of the onboard receivers can be achieved. These data allow the vessel motions and UKC components that occur during the transit to be established. By comparing the various UKC allowances calculated by the DUKC® against those measured by FSVMA the accuracy of the DUKC® modelling can be validated.

Table 1: Particulars of selected FSVMA vessels.

Parameter	Vessel 1	Vessel 2
LBP [m]	218.00	187.10
Beam [m]	32.20	30.20
Draft [m]	9.66	8.40
Displacement [t]	40575	29656
GMf [m]	2.76	2.57
KG [m]	12.21	11.56
Transit type	export	export
Calculation time	06:10	13:15
Time at PPH	10:33	17:32

For the POMC DUKC® 11 FSVMAs were performed. This paper will concentrate on two of these. The details of these transits are presented in Table 1. These transits were conducted under both strong (Vessel 1) and mild (Vessel 2) current conditions and demonstrate the importance of taking the currents into account when calculating the vessel RAOs. The environmental conditions prevailing at the time of transit are listed in Table 2. As the table shows during the Vessel 1 transit the ebb current at Rip Bank exceeded 1.9 m/s (3.7 knots), while for the Vessel 2 transit the ebb current only reached 0.7m/s (1.4 knots).

Table 2: Environmental conditions in PPH prevailing during the FSVMA transits. Note that the current data is calculated rather than measured.

Parameter	Vessel 1	Vessel 2
Offshore Hs swell [m]	2.01	1.11
WaMoS Hs swell [m]	2.80	1.47
Current at Rip Bank Outer	1.46m/s, 207N	0.64 m/s, 227N
Current at Rip Bank	1.99m/s, 206N	0.71 m/s, 219N
Current at Nepean Bank	1.92m/s, 223N	0.90 m/s, 218N

4.1 Wave forecasting

The results of the infopipes wave forecasting network for Rip Bank in PPH are shown in Table 3. The DUKC is run prior to sailing to confirm that a proposed transit is safe. This is the calculation time detailed in Table 1. As both of the transits are exports this means that a forecast horizon of 4 – 4.5 hours is required for anticipating the wave conditions in PPH. For import transits the forecast horizon is only in the order of 1 hour. This different forecast horizon impacts on the level of uncertainty assigned in the forecast module.

Table 3: Wave transformation information flow for the selected FSVMA Transits. Each box indicates the swell height and uncertainty on the completion of its process.

Parameter	Vessel 1	Vessel 2
Triaxys Hs swell [m]	2.01 ± 0.10	1.11 ± 0.10
Forecast Triaxys Hs swell [m]	1.96 ± 0.36	1.12 ± 0.21
Forecast Triaxys transformed to Rip Bank [m]	2.59 ± 0.51	1.12 ± 0.27
WaMoS Hs swell [m]	2.80 ± 0.58	1.47 ± 0.44
Forecast WaMoS Hs swell [m]	2.23 ± 1.04	1.41 ± 0.67
Result of BLUE [m]	2.54 ± 0.46	1.17 ± 0.25
Spectral Adder (conservative swell height) [m]	2.91	1.38

Reading Table 3 in conjunction with Figure 2 the flow of the wave information and uncertainty can be studied. The effect of the spectral forecasting can be seen in the increasing uncertainty. In the Vessel 1 transit the WaMoS uncertainty increases from 0.58 m to 1.04 m, and in the Vessel 2 transit uncertainty increases from 0.44 m to 0.67 m. The magnitude of the increase differs because larger magnitude waves have larger uncertainties. It can also be seen that for the large swell during the Vessel 1 transit the best estimate forecast reduces. This is because the climate mean swell height is around 1.3 m and the best estimate forecast is being transitioned to this mean value. The best estimate of the Triaxys forecast in the Vessel 1 transit increases during the onshore transformation. This is because the wave is encountering the strong (2 m/s) ebb currents at Rip Bank. With the weaker currents experienced during the Vessel 2 transit the transformation does not have a significant effect on the best estimate.

The result of the BLUE module indicates how the wave estimates are being combined. For the Vessel 2 transit, as the transformed Triaxys forecast has a lower uncertainty (0.3 m) than the WaMoS forecast (0.67 m), the Triaxys best estimate (1.12 m) is more heavily weighted than the WaMoS best estimate (1.41 m) resulting in a combined best estimate of 1.17 m. A similar result is seen for the Vessel 1 transit. It is important to note though that the error of the combined wave forecast is lower than either of the contributing forecasts. Finally the best estimates are combined with the error at the requested confidence level returning a single conservative wave spectrum for use by the DUKC® wave response model.

4.2 Wave response validation

The DUKC® wave response allowance is produced by combining the wave forecasts with SPMS calculated RAOs. The allowance includes a safety factor such that the chance of an actual vessel wave response exceeding or breaching the allowance is negligible. The vessel wave response allowance is validated through FSVMA studies, as presented in Figure 4 and Figure 5. In these figures the actual vessel wave response motions as recorded by the 3 GPS receivers are contrasted with the calculated allowance. The impact of ignoring currents in the RAO calculation is also illustrated.

In the Vessel 1 export transit, moderate vessel motions are experienced by the vessel with a peak of about 1.5 m downwards displacement near Rip Bank Outer. Interestingly a clear wave group signal is seen in the measured wave response signal. The measured wave response is within the range allowed for by the DUKC® confirming that in this case the DUKC® wave response allowance provided an adequate level of safety. Contrasting the case of including and excluding currents from the RAO calculation, it is clear that ignoring the effect of the waves in calculating the RAOs would result in the wave response allowance being overestimated by 0.8 – 1.0 m. While the safety is not compromised in this case, by ignoring waves potentially an additional 0.80 m of draft for this vessel would have been lost.

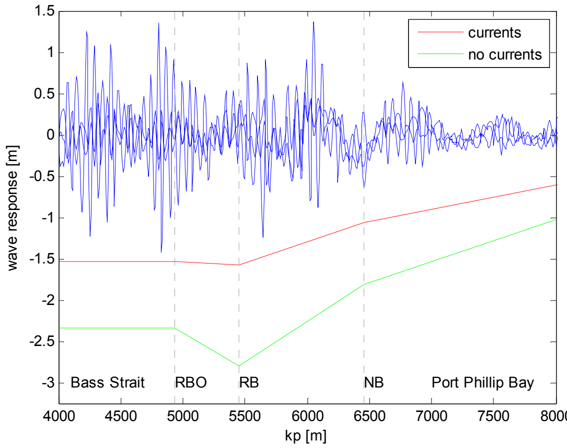

Figure 4: FSVMA analysis of Vessel 1 transiting PPH on 8 July 2007. The measured maximum downwards wave response is contrasted with the wave response allowance calculated by the DUKC both with and without allowance for the currents in the RAO calculation. In this case not accounting for currents greatly overestimates the wave response allowance, reducing yield.

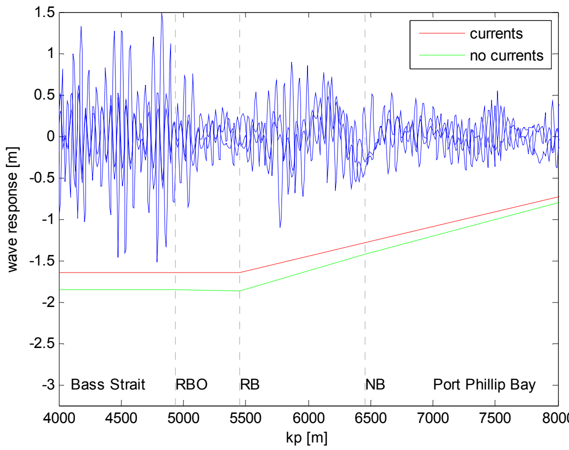

Figure 5: FSVMA analysis of Vessel 2 transiting PPH on 21 March 2007. The measured maximum downwards wave response is contrasted with the wave response allowance calculated by the DUKC both with and without allowance for the currents in the RAO calculation. In this case the weaker currents reduce the impact of ignoring them in the RAO calculation.

For the Vessel 2 transit the measured wave response is within the wave response allowances validating the calculated vessel wave response allowance. In this case the impact of the currents on RAOs and subsequent vessel wave response allowance is less because of the weaker currents.

5 Conclusion

The combination of highly energetic and dynamic waves with a narrow passage and strong tidal streams makes PPH a particularly challenging stretch of water for transiting vessels. As part of the approach to Australia's largest container port it is vital that under keel clearance safety is maintained at all times. Through the detailed understanding of wave behaviour coupled with wave forecasting and vessel RAO calculation the allowance for wave response in the PoMC DUKC® is calculated. This allowance has been verified against independent measurements of vessel motions and allows the PoMC to have confidence that vessel safety at the Port of Melbourne meets world's best practise.

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