SHIP OPERABILITY PREDICTED FROM LONG TERM DIRECTIONAL WAVE RECORDS

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SUMMARY

Ship operability assessments have traditionally been made using wind and wave data derived from wave atlases, however there are several drawbacks, including the fact that they are usually based on observation rather than measurement, and that spreading or directional effects are lost – such as the separation of sea and swell directions. An alternative approach is demonstrated here, instead of the data summarised in the wave atlas scatter diagram, long term hourly historical wave buoy data may be used. Detailed data sets, including directional wave spectra, are available for a number of specific locations. Direct use of many years' hourly wave data involves significant computational effort, but results may be achieved within a reasonable time. The technique is demonstrated with the examples of four naval ships and two sites. Analysis considered two main themes, the differences in the ship performance calculated when (a) using wave buoy data rather than wave atlas data for the same sea area and (b) using the most complex available model of the ocean waves compared with the simplified wave descriptions in common use. For (a) the wave buoy data both looked rather different than the wave buoy data for the same nominal area, and produced rather different ship performance results. For (b) it was shown that there were also significant differences between the operability calculated for the four different ships at one of the sites. The implications for operability assessment in the ship procurement process are briefly discussed.

1. INTRODUCTION

Ship operability and survivability assessments have traditionally been made using wind and wave data derived from wave atlases e.g. Global Wave Statistics (GWS), [1]. The approach has worked well but there are several drawbacks:

- wave atlas data is always questionable since much of it is based on human observation;
- extrapolating the wave statistics to the '100 year wave' or other extremes is difficult because of the paucity of observations at the highest wave heights;
- there is evidence, for example [2], that with long term climate change, seas in the North Atlantic, and to a lesser extent the North Sea, are becoming rougher;
- the sensitivity of the operability calculation to the accuracy of the wave atlas definition is unquantified; and
- the calculations universally assume long-crested or short-crested waves from a single principal direction; in reality, there is usually more than one wave system, originating from different directions, which complicates the vessel response.

More recently, satellite altimeter based atlases have addressed the point regarding objectivity, but the other points remain. What alternative source could be used to combat these drawbacks? Hindcast wave data i.e. models of the waves estimated from large area or global wind records [3], [4] are certainly an option and have been used to create wave atlases [5]. However, the accuracy of the hindcast is subject to the success of the wind-wave model.

Moored wave buoys are scientific instruments that can measure the ocean wave properties in detail. Though they do not have the global coverage possible from wind-wave models, some buoy networks have provided detailed information for a limited number of sites for over 50 years. This paper considers the use of such long term resources for ship design and assessment. The majority of buoy data is omnidirectional, meaning that wave energy spectra are measured but distinguishing the wave source directions is not possible. More advanced buoys [6], [7] have additional instrumentation so that the directionality of the waves can be estimated. The method is to use a spreading function which is applied to the omnidirectional energy spectrum. This paper specifically considers the use of such directional wave information.

The calculation of ship motions in directional waves is well known as an extension of the linear theory of ship motion in long crested waves. Reference [8] is an early publication, and the method appears in textbooks, for example [9]. Nevertheless, the calculation is rather more involved than the long crested case, and usually calculations are made more straightforward by applying a symmetrical spreading function e.g. 'cosine squared' type. Application of fully directional, asymmetrical wave spectra to predict the ship motions remains relatively rare, but has been used in the case of specific seakeeping trials for code validation purposes e.g. [10]. Similarly longer term directional buoy data has been applied on the time scale of a few days for particular voyages e.g. from a series of buoys along a route in [11].

There have been some studies to compare different wave data sources, for example [12] compared GWS with hindcast data, and [13] compared 20 year extreme waves extrapolated from GWS and from wave buoy data.

However, motion calculation from discrete long term fully directional wave data (as opposed to atlas data) in the manner of the present paper does not seem to have been demonstrated for ships.

2. WAVE DATA SOURCES

2.1 DIRECTIONAL WAVE BUOYS

The United States National Oceanographic and Atmospheric Administration has an extensive archive and ongoing programme of buoy measurements available through its National Data Buoy Center (NDBC) website. Some sites have been operating for up to 20 years, although it appears that there is currently a policy to allow download of only 10 years archived data. As far as wave measurements are concerned, most sites measure omnidirectional wave height and period. About 20 buoys have directional wave measurements, most of which are not in the open ocean but in coastal waters.

The directional data is archived efficiently by parameterisation of the directional wave spectra according to a Longuet-Higgins [6] coefficient scheme - in addition to the omnidirectional significant wave height, two (peak) frequency parameters and two directional parameters are stored for each frequency ordinate. This is sufficient to allow construction of multimodal 2D fully directional wave spectra.

Data from two locations differing widely in the character of their location were chosen to demonstrate the effects of directionality of the waves. Two locations were chosen for further study, 44014 'Virginia Beach', located off the Eastern USA coast of Virginia state and 51028 'Christmas Island' (Kiribati), in the Pacific Ocean. For these locations, data from years 1997-2007 was uploaded from the NDBC; there are periods of downtime within the data, however, so that for both sites only around 7 years continuous data is available.

2.2 COMPARISON WITH WAVE ATLAS

With the aim of comparing the wave data from the two chosen buoys, wave atlas equivalent data was sought from the same ocean areas. The atlas data was taken from Global Wave Statistics [1], Area 54 corresponding with the 51028 Pacific buoy, and Area 23 with the 44014 East coast buoy.

ALL DIRECTIONS

PERCENTAGE OF OBS = 100%
(INCLUDING x.xx% DIRECTION UNKNOWN

SIGNIFICANT WAVE HEIGHT (m) \ ZERO CROSSING PERIOD (s)	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
TOTAL	10	94	260	309	203	88	29	8	2			1000
>14												~
13-14												~
12-13												
11-12												
10-11												1
9-10												1
8-9					1	1						2
7-8				1	1	1	1					5
6-7			1	2	3	2	1	1				10
5-6			2	5	7	5	2	1				22
4-5		1	5	14	16	10	4	1				52
3-4		2	17	37	35	18	7	2				117
2-3		9	49	83	61	27	8	2				239
1-2	1	31	110	123	65	21	5	1				356
0-1	8	51	76	44	14	3						196

Table 1 Scatter Diagram GWS Area 23 (US East Coast)

ALL DIRECTIONS

PERCENTAGE OF OBS = 100%
(INCLUDING 2.42% DIRECTION UNKNOWN

SIGNIFICANT WAVE HEIGHT (m) \ ZERO CROSSING PERIOD (s)	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	>13	TOTAL
TOTAL	1	17	98	222	268	205	113	49	18	6	2	1000
>14												~
13-14												~
12-13												~
11-12												~
10-11												~
9-10												~
8-9												~
7-8												~
6-7												1
5-6					1	1	1	1	1			6
4-5				2	5	8	8	5	3	1		32
3-4			2	12	30	37	28	15	6	2	1	133
2-3		1	16	65	106	92	52	21	7	2	1	362
1-2		8	59	126	119	65	24	7	2			411
0-1	1	8	20	18	7	2						56

Table 2 Scatter Diagram GWS Area 54 (Pacific)

It is noted that the actual number of observations given in the table does not agree with the nominal total of 1000; for Area 23 the sum of data in the table is 996 and for Area 54 it is 999. The sum of the row and column sums also differ, between 999 and 1001. This reflects rounding errors in the data when reporting at 0.1% (i.e. 1 in 1000) resolution.

Scatter diagrams have also been constructed from the buoy data (without rounding error), as follows:

Total Observations: 61022 *Period at lower bound of 'bin', frequency at upper bound

Tz [s]*	2.86	2.86	3.33	4.00	5.00	6.67	7.14	7.69	8.33	9.09	10.00	11.11	12.50	14.29	16.67	20.00	25.00	Row	Cum.
Freq [Hz]	0.401	0.351	0.301	0.251	0.201	0.151	0.141	0.131	0.121	0.111	0.101	0.091	0.081	0.071	0.061	0.051	0.041	Total	Total
Significant Wave Height [m] (top of bin) 8												0.002		0.008				0.01	0.0
7.5												0.005	0.011	0.005				0.02	0.0
7											0.003	0.008	0.016					0.03	0.1
6.5											0.007	0.026	0.015	0.002				0.05	0.1
6										0.005	0.011	0.038	0.018	0.002				0.07	0.2
5.5									0.003	0.028	0.048	0.038	0.026	0.005				0.15	0.3
5							0.002	0.005	0.025	0.057	0.082	0.066	0.057	0.016	0.003			0.31	0.6
4.5						0.002	0.008	0.051	0.074	0.098	0.152	0.143	0.088	0.046	0.010			0.67	1.3
4					0.005	0.021	0.072	0.182	0.213	0.275	0.357	0.298	0.157	0.075	0.011			1.67	3.0
3.5					0.034	0.110	0.251	0.349	0.351	0.413	0.372	0.323	0.277	0.107	0.015			2.60	5.6
3					0.310	0.459	0.605	0.634	0.711	0.706	0.523	0.408	0.293	0.118	0.023			4.79	10.4
2.5				0.007	1.588	1.042	1.005	1.037	0.908	0.846	0.731	0.652	0.470	0.193	0.025	0.007		8.51	18.9
2				0.270	4.562	1.478	1.637	1.567	1.352	1.291	1.280	1.360	0.724	0.223	0.008	0.013		15.77	34.6
1.5		0.003	0.182	2.804	8.409	2.383	2.332	2.204	2.571	2.894	2.289	1.698	0.851	0.210	0.021	0.016		28.87	63.5
1	0.015	0.197	1.232	3.163	7.166	1.876	2.273	3.586	5.018	4.756	2.252	1.332	0.808	0.385	0.162	0.002		34.22	97.7
0.5	0.025	0.025	0.020	0.057	0.267	0.082	0.144	0.290	0.452	0.395	0.218	0.082	0.075	0.105	0.025			2.26	100.0
Col. Total	0.039	0.225	1.434	6.301	22.341	7.453	8.328	9.905	11.678	11.765	8.325	6.478	3.889	1.499	0.303	0.038	0.000		
Cum. Total	0.0	0.3	1.7	8.0	30.3	37.8	46.1	56.0	67.7	79.5	87.8	94.3	98.2	99.7	100.0	100.0	100.0		100.0

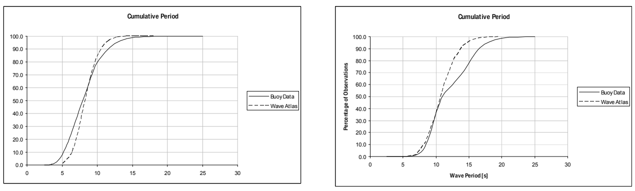
Table 3 Scatter Diagram Buoy 44014 Virginia Beach

Total Observations:57325 *Period at lower bound of 'bin', frequency at upper bound

Tz [s]*	2.86	2.86	3.33	4.00	5.00	6.67	7.14	7.69	8.33	9.09	10.00	11.11	12.50	14.29	16.67	20.00	25.00	Row	Cum.
Freq [Hz]	0.401	0.351	0.301	0.251	0.201	0.151	0.141	0.131	0.121	0.111	0.101	0.091	0.081	0.071	0.061	0.051	0.041	Total	Total
Significant Wave Height [m] (top of bin) 8																		0.00	100.0
7.5																		0.00	100.0
7																		0.00	100.0
6.5																		0.00	100.0
6																		0.00	100.0
5.5																		0.00	100.0
5																		0.00	100.0
4.5																		0.00	100.0
4														0.007	0.030			0.04	100.0
3.5								0.009	0.017	0.094	0.065	0.042	0.045	0.105	0.277	0.070		0.72	99.2
3					0.002	0.024	0.065	0.124	0.422	1.069	1.063	0.790	0.368	1.286	1.523	0.218	0.002	6.96	92.3
2.5					0.103	0.274	0.632	1.371	3.437	6.931	6.099	2.694	2.715	7.687	3.808	0.534	0.012	36.30	56.0
2				0.002	0.490	0.508	1.117	2.427	5.475	8.763	5.666	3.407	6.834	8.119	2.278	0.311	0.014	45.42	10.6
1.5				0.005	0.181	0.080	0.192	0.532	1.164	1.354	1.033	1.455	2.422	1.404	0.331	0.017		10.17	0.4
1				0.014	0.028	0.007	0.009	0.019	0.030	0.045	0.024	0.026	0.023	0.019	0.003			0.25	0.1
0.5	0.005	0.007	0.017	0.010	0.026	0.009	0.007	0.003	0.019	0.024	0.009	0.009		0.002				0.15	0.0
Col. Total	0.0	0.0	0.0	0.0	0.8	0.9	2.0	4.5	10.6	18.3	14.0	8.4	12.4	18.6	8.3	1.1	0.0		
Cum. Total	0.0	0.0	0.0	0.1	0.9	1.8	3.8	8.3	18.9	37.1	51.1	59.5	71.9	90.6	98.8	100.0	100.0		100.0

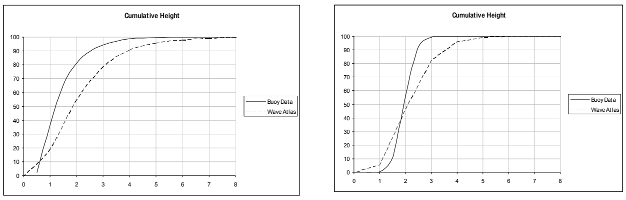
Table 4 Scatter Diagram Buoy 51028 Kiribati (Pacific)

It is not easy to compare these GWS and buoy derived scatter diagrams directly because of differences in the 'bin' sizes, however the cumulative distributions of height and period are co-plotted in Figures 1 and 2. It is assumed (for the GWS data) than the modal period of the waves exceeds the zero crossing period by a factor of 1.41, which is strictly only true for spectra of open ocean form [9].



East Coast USA Pacific

Figure 1. Cumulative distribution of Tz [s]



East Coast USA Pacific

Figure 2. Cumulative distribution of Hs [m]

Clearly, the wave statistics from the two different sources are significantly different. This is somewhat to be expected as the Global Wave Statistics area is relatively large. It could also be a result of genuine change in the wave characteristics at these sites as a result of climate or other long term change, the atlas data is rather older than the buoy data. However, assuming the buoy data is more reliable, there are strong implications for the designers of maritime vehicles and platforms as these specific locations are clearly not well represented by the atlas data.

3 REPRESENTING THE WAVE SPECTRA

For the two selected locations, wave spectra were created for each available hourly time step from the NDBC buoy data (several thousand spectra), or randomly within each 'bin' of the scatter diagrams, at a level consistent with the resolution of the scatter diagram (one thousand spectra).

The modelling of wave spectra may be considered on a scale of increasing complexity levels as follows:

1. Two parameter fit (P-M or JONSWAP)
2. Torsethaugen spectrum (idealised but double peak)
3. Omnidirectional spectrum (multi peak)
4. Crossing long crested spectra (or 6 parameter)
5. Idealised spreading function ($\cos^2$ or 10 parameter)
6. Non-uniform spreading function

For this study, long crested idealised spectra (Level 1) were used to model both the atlas and buoy wave data.

The NDBC recommend scheme for creation of the 2D wave spectrum was used in this study:

$$S(f,A) = C11(f)D(f,A)$$

Where S(f,A) is the directional wave spectrum, f is the wave frequency (Hz), and A the Azimuth angle measured clockwise from true North to the direction the wave is from. C11(f) is the omnidirectional wave spectrum.

D(f,A) is the directional spreading function, of which several alternatives are possible, but that suggested by NDBC is:

$$D(f,A) = \frac{1}{\pi}\begin{bmatrix} 0.5 + R_1\cos(A-\alpha_1)\ \ldots \\ \qquad +R_2\cos(2(A-\alpha_2)) \end{bmatrix}$$

R_1 and R_2 are the first and second normalized polar coordinates of the Fourier coefficients and are non-dimensional. α_1 and α_2 are respectively mean and principal wave directions. The parameters R_1, R_2, α_1 and α_2 are recorded as time histories in the NDBC data.

The frequency dependent spreading function D(f,A) should, in theory, be a fully positive function with an overall integral of unity, so that the total energy of the omnidirectional spectrum is preserved when the energy is spread in different directions. In practice, the equation above does lead to occasional negative areas.

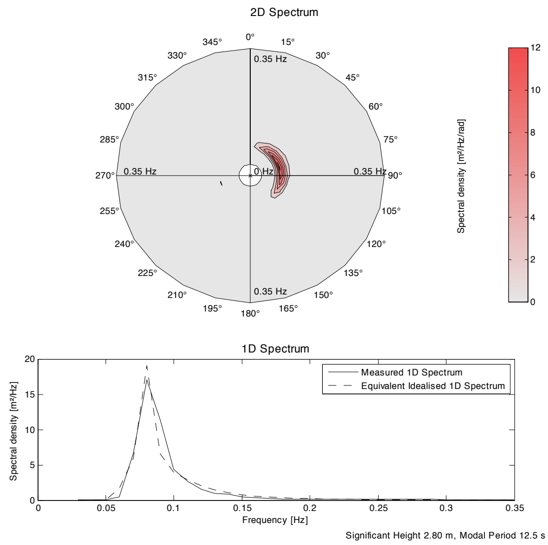


Figure 3 Buoy 44014: 15 Apr 1997 00:00;
Even spreading, close to idealised spectrum

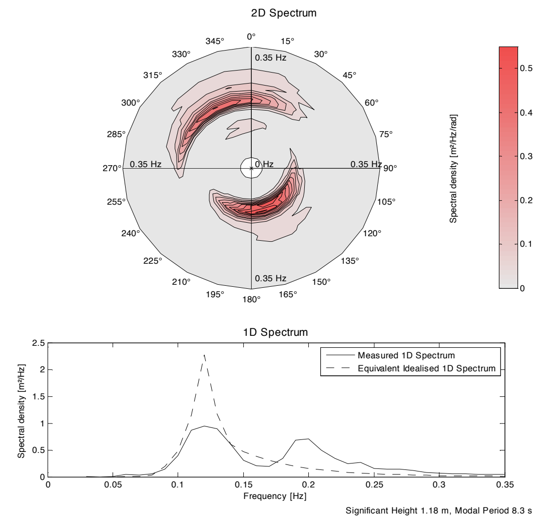


Figure 4 Buoy 44014: 21 Apr 1997 04:00; Bimodal spectrum, opposing directions

The authors chose to force the energy to be zero in those areas which had negative energy by direct calculation; the overall effect of this course of action is to lose a little of the 'negative' wave energy so that (depending on the matching with the RAO) the ship motions might be slightly higher than expected using the full extent of the wave energy. It was found that the 'lost' energy was typically less than 5% of the total. The resulting error in computed ship responses would be expected to be rather lower when the period content of the waves is taken into account, and this would well within the range of accuracy of motion prediction.

Figures 3 and 4 give examples of these Level 1, 3 and 6 wave spectra created from the buoy data. With the double peak spectrum of Figure 4 especially, it can be seen that the common step of making the 'Level 1' simplification of using an idealised, long crested (single peak) spectrum is a significant one.

4. APPLYING RAOS TO WAVE DATA SET

4.1 GENERAL

Motion Response Amplitude Operators (RAOs) were generated for four different ships with a linear strip theory code. These included RAOs at specific points on each ship away from the centre of gravity.

Motion RAOs were applied in the standard way for long crested waves. For short crested waves, the analysis included a vector sum of the individual response spectra in each direction, analogous to the method shown in Lloyd [9]. This has been implemented, along with further analysis, in a new MATLAB based program called SHREWD, Ship Response in Extensive Wave Dataset.

The four ships were:

'Auxiliary': L~180m Δ~30,000T
'Cruiser': L~200m, Δ~20,000T
'Destroyer': L~140m, Δ~5500T
'Frigate': L~120m, Δ~4500T

4.2 SEAKEEPING PERFORMANCE IN WAVE DATA SET

A brief study of the absolute seakeeping performance of the example ships was performed. This focused on the roll and pitch as example lateral and vertical plane motions respectively. Analysis has taken the form of polar plots of limiting wave height from SHREWD rather than examination of the RMS motions directly. The concept is akin to gradually increasing the sea state until some limiting motion occurs – this point is the limiting wave height. For this study, data for waves over all the years of buoy data are included. Universal motion limits of 4 degrees RMS roll and 1.5 degrees RMS pitch were used. One would expect the limiting wave height to be lowest in beam seas for roll, and lowest in head seas for pitch.

Figure 5 and 6 give examples for roll and pitch respectively. For each ship / sea area / speed combination, there are four plots, corresponding to (reading top to bottom then left to right):

- 'Real 1D spectrum' (Level 3 above)
- 'Idealised spectrum' (Level 1 above)
- 'Fully directional spectrum' (Level 6 above)
- Wave Atlas data equivalent

The limiting wave height is given as the shaded area on the polar plots, indicating where all motions are below the defined limits. The ship operability is not directly proportional to the area which is shaded.

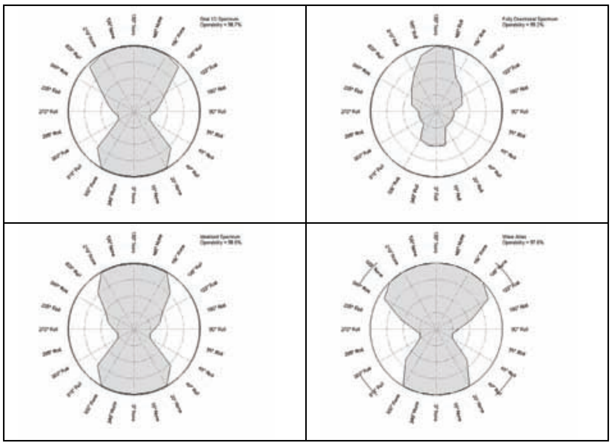


Figure 5 Limiting wave height for Roll: Auxiliary, East coast

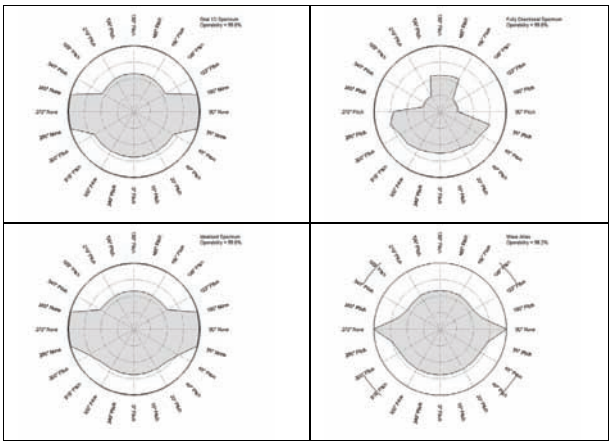


Figure 6 Limiting wave height for Pitch: Destroyer, East coast

In general, these limiting height polar plots are symmetrical about head seas, because the idealised or long crested source waves are also symmetrical about the principal direction. The exceptions are the full 2D spectra (Level 6) where the wave data and therefore the ship responses are not symmetrical about any particular direction.

4.3 DISCUSSION

After examination of the plots of Figure 5 and 6, and others like them, several observations can be made.

In general, the 'Real 1D' and 'Idealised spectrum' plots are similar, suggesting that the idealised spectra are a reasonable representation of fully developed spectra.

The 'Wave Atlas' data (also formed from idealised spectra) also has the same general form, though some of the 'lobes' of the plots may differ somewhat in shape. These observations are consistent with those made about the wave atlas data above.

The 'Fully directional spectrum' results are by contrast usually quite different from the others, and usually the limiting wave height is much lower in head and following seas. One might have supposed that the fully directional spectra, with more spreading of energies would lead to reduced roll in general, and hence higher limiting wave heights. On closer inspection, it appears that the beam sea performance is similar or marginally better, which is consistent with that hypothesis. It is the limiting height in head and following seas that is reduced; this is also consistent with the picture of well spread energies, because in long crested head seas one would theoretically expect zero roll, whereas with spreading there is always some wave energy in the off-head seas directions to create roll. It can be seen that the directionality leads to a reduction in the area of the limiting wave height envelope, though not necessarily operability.

The relative performance of the ships is as might be expected by their size, for example, the crusier and auxiliary appear only slightly limited in roll in the buoy 51028 area.

5. OPERABILITY CALCULATION

Seakeeping prediction has been extended within SHREWD to include ship operability calculations.

The aim of the 'Operability' calculations is to establish an overall figure expressing the percent of operating time that the ship is available to perform its task without limitations due to the weather. Operability is, in general, calculated a similar way as recommended by Standardised Naval Agreement (STANAG) 4154. 'PTO' is the Percent Time Operable, and is the inverse of the percentage downtime.

It is required to develop a set of motion or other response limits for the ship mission under examination, then to calculate the ship motion/response under all wave conditions at the location in question; the ship is operable if the motion/response is less than each and every one of the threshold limits. This process is repeated for different operating speeds, and if a Mission Speed Profile (MSP) is employed, this can lead to a single figure of percentage operability for a particular sea area.

The percentage operability concept is a comprehensive measure of the ship seakeeping performance in likely-to-be-encountered sea conditions, though the overall percentage operability figure is not particularly sensitive to the merits of the ship e.g. high figures can be obtained if the wave climate is benign, for a wide range of similar sized hulls.

SHREWD applies the criteria to the motions predicted at each step of the large hourly wave data base and the ship is either operable or not in each of these hour steps; the percentage operability is literally the percentage of the hourly wave time history where the ship is operable. A separate pre-processor has been employed to generate an equivalent hourly wave time history for a given wave atlas scatter diagram, so that SHREWD can handle wave atlas data in a similar way.

5.1 CURRENT LIMITATIONS OF SHREWD

In the case of the angular motions and rigid body motions at different locations, operability is easily verified by directly comparing the RMS motion with the criterion.

In the case of exceedance type events (propeller emergence, slamming, deck wetness), comparison with the criteria is more difficult as these quantities are not calculated directly. The method outlined in Lloyd [9] is followed in this case. The relative velocity and acceleration must be derived from the relative displacement spectra with frequency manipulation, in order to obtain the mean motion period. The number of exceedance events per hour can then be calculated from RMS displacement level given the exceedance criterion e.g. 20 slams per hour.

The current 'slamming' calculation in SHREWD is unsophisticated, and involves a simple statistical calculation of the probability of keel emergence. Refinements such as inclusion of critical pressures or threshold slamming velocities could be included at a later stage.

SHREWD also does not have human factors capability. Inclusion of these motions, notably MSI (Motion Sickness Incidence), MII (Motion Induced Interruption) and possibly SMM (Subjective Motion Magnitude) would increase the applicability of the SHREWD code.

For extension to the '2D' waves case, linear superposition is assumed, so that the motions in short crested seas are calculated as the vector sum of a large number of long crested seas results.

This requires a great deal more computation time, since a simple long crested seas calculation for a particular case is expanded to 24 calculations i.e. 360° in 15° steps. However, though arduous, the calculation of the motions in short crested seas is straightforward.

The calculation of exceedance events per hour in short crested seas is open to some interpretation, since these are non-linear with respect to the wave height and are not the result of a simple vector sum as with the linear motions.

The approach currently used in SHREWD is to calculate the number of exceedance events per hour from the relative motion, as a 1D calculation, in each of the 15° directions available, and then to sum these to give an equivalent short crested number of events per hour. It might be argued that a more rigorous approach would be to construct RMS relative motions in short crested seas, as the vector sum of the responses in each 15° direction, and then calculate the mean motion periods and a single number of events per hour.

5.2 OPERABILITY CRITERIA

Typical missions were chosen for the four ships under study motion criteria sets were chosen using the guidelines of STANAG 4154. These typically consist of Transit and Patrol criteria with specific mission criteria added. The human factors criteria MII and MSI were not calculated with SHREWD.

5.3 RESULTS

Example results are given here for a small selection of the large number of calculations made; the full collection involves limiting wave height plots and percentage operability charts for a matrix of the four ships in each of the two sea areas, at a wide range of speeds.

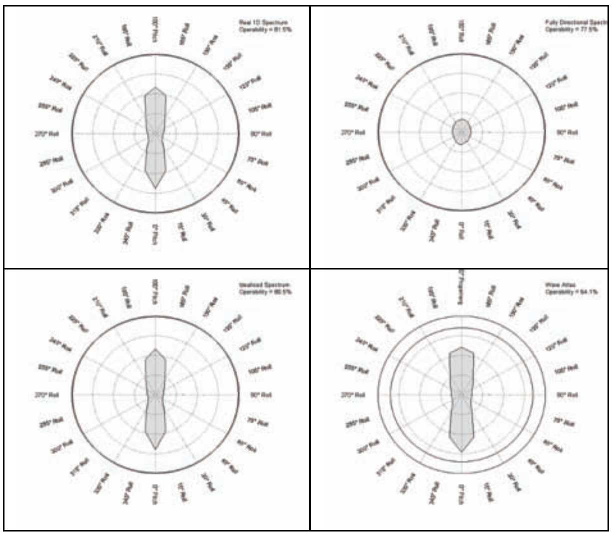


Figure 7 Limiting wave height across all motions/responses: Frigate, Pacific

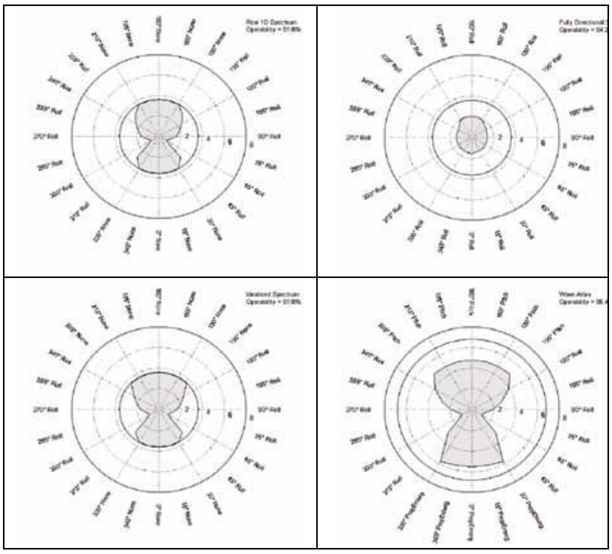


Figure 8 Limiting wave height across all motions/responses: Cruiser, Pacific

Similar comments generally apply as for the roll and pitch plots discussed earlier (which are operability plots for a single limiting criteria – roll or pitch). In general, the left hand two plots of each set of four show a very similar limiting wave height envelope; these are both long crested seas simulations. These are generally of similar shape as the bottom right hand plot (wave atlas equivalent), though particularly for the 50128 buoy / Area 54, there is a large difference in the maximum wave heights suggested from these two sources, leading to visual extension of the limiting height envelope being particularly noticeable in head and following seas.

As for roll and pitch only, the results from the most highly defined ‘2D’ waves appear significantly different from the other ‘1D’ plots. The maximum wave height for full operability is usually much smaller, though not necessarily at all headings. For example, the cruiser (Figure 8) shows a higher limiting wave height at 60 and 75 degree headings relative to the waves for the full directional spectrum compared with the others, whilst the limiting height in head and following seas is much lower. It is also interesting to note that the ship is limited by roll in head and following seas in the fully spread realisations (Figure 8, top right), which is not possible if the waves are modelled as long crested as with the other plots. The wave atlas calculation shows a pitch limitation in head seas, and propeller emergence limitation in following seas, for example.

The polar plots of limiting wave heights give interesting indications of the motion limits (and hence hints where designs might be improved), but, as discussed above, the limiting height at each heading arises from just one extreme of the wave data set considered in each case. It is the percentage operability PTO that gives the fairest, most comprehensive indication of the ships’ performance in the different wave data models or sources, and relative to each other.

PTO results for the ships are shown in Tables 5 and 6 where it can be seen that the results are quite different for the two sea areas.

Operability Percentages		Area 44014					
		5 knots	10 knots	15 knots	20 knots	25 knots	30 knots
Auxiliary	Wave Atlas 1D	95.1	91.9	90.9	89.6		
	Ideal 1D Spectrum	94.9	94.5	94.4	94.7		
	Real 1D Spectrum	95.6	95.1	94.8	95		
	2D Spectrum	95.1	94.4	94.2	95		
	Range	**0.7**	**3.2**	**3.9**	**5.4**		
Cruiser	Wave Atlas 1D	95.3	93.7	89.2	88.1	88.6	89.4
	Ideal 1D Spectrum	93.4	93.6	92.1	91.9	92.5	93.8
	Real 1D Spectrum	93.9	94.3	92.7	92.3	93	94.2
	2D Spectrum	92.9	93.4	91.2	90.2	90.7	93.5
	Range	**2.4**	**0.9**	**3.5**	**4.2**	**4.4**	**4.8**
Frigate	Wave Atlas 1D	77.6	83	83.5	82.8	82.5	82.4
	Ideal 1D Spectrum	80.5	92.3	94.2	94.7	94.7	94.4
	Real 1D Spectrum	81.5	92.9	94.5	94.7	94.5	94.1
	2D Spectrum	77.5	92.3	95.2	96.1	96.3	96
	Range	**4**	**9.9**	**11.7**	**13.3**	**13.8**	**13.6**
Destroyer	Wave Atlas 1D	80.3	74.6	75.7	77	77.5	76
	Ideal 1D Spectrum	83.1	83.7	84.9	87	89.4	87.8
	Real 1D Spectrum	84	84.4	85.3	87.4	89.4	87.9
	2D Spectrum	80.9	81.1	80	83.5	87.5	82.9
	Range	**3.7**	**9.8**	**9.6**	**10.4**	**11.9**	**11.9**

Table 5: Percentage operability results for Buoy 44014 / Area 23 (Virginia Beach, USA)

Operability Percentages		Area 51028					
		5 knots	10 knots	15 knots	20 knots	25 knots	30 knots
Auxiliary	Wave Atlas 1D	91.1	88.5	88.1	88.3		
	Ideal 1D Spectrum	81.9	82	81.8	85		
	Real 1D Spectrum	87.2	86.1	84	86.7		
	2D Spectrum	93.8	93.6	94.8	97.1		
	Range	**11.9**	**11.6**	**13**	**12.1**		
Cruiser	Wave Atlas 1D	90.3	88.8	84.6	84.8	86.4	87.9
	Ideal 1D Spectrum	67	72	73.3	76.8	81	82.8
	Real 1D Spectrum	58.3	71.4	73.7	78.2	81.8	84
	2D Spectrum	50.2	73.9	75.3	76.8	84.2	93.9
	Range	**40.1**	**17.4**	**11.3**	**8**	**5.4**	**11.1**
Frigate	Wave Atlas 1D	64.1	80	83.5	84	84.5	84.7
	Ideal 1D Spectrum	46.2	85.2	93	94.9	95.3	95.2
	Real 1D Spectrum	47.6	86.6	94.1	95.3	94.4	93.6
	2D Spectrum	26.6	96	99.5	99.8	99.8	99.8
	Range	**37.5**	**16**	**16**	**15.8**	**15.3**	**15.1**
Destroyer	Wave Atlas 1D	68.1	67.5	71.8	75	76.9	75.1
	Ideal 1D Spectrum	47	56.2	65.7	73.5	81.2	85.1
	Real 1D Spectrum	48.2	58.4	67.6	75	83.3	87.1
	2D Spectrum	33.3	45.4	48.2	67.4	85.2	78.7
	Range	**34.8**	**22.1**	**23.6**	**7.6**	**8.3**	**12**

Table 6: Percentage operability results for Buoy 51028 / Area 54 (Kiribati, Pacific Ocean)

Considering Table 5 the Buoy 44014 / Area 23 data (off Virginia State), there are usually only small differences between the calculations performed using the buoy data alone, irrespective of the complexity of the wave description. Typically, the results disagree by less than 2% in operability. The PTO for the wave atlas data is slightly different, typically at 4% difference from the other PTO figures for the cruiser and auxiliary, but as much as 13% different for the smaller frigate and destroyer examples. The difference appears more marked at speed, the PTO in the wave atlas data being rather lower. This is perhaps to be expected given that Figure 2 shows a greater proportion of higher waves in the atlas data compared with the buoy data.

In Table 6, for the Pacific buoy/sea area, the story is generally similar. All the ships appear to be sensitive to the sea conditions at low speeds, and the PTO reduces significantly at 10 and 5 knots for the buoy data. The wave atlas results disagree strongly with this trend, especially at low speeds, with PTO in the wave atlas seas higher by as much as 40% compared with results from the buoy data.

There are also marked differences between the PTO results with the 'Level 3' full 2D wave realisation when compared with the 'Level 2' long crested results. These range from 21% lower operability with Level 3 (frigate, 5 knots) to 11% higher operability (auxiliary, 15 knots). The range for the 44014 buoy was rather smaller at -5 % to +2%. These differences are likely to be even more marked when considering only higher sea states rather than the whole range – the lower, more probable sea states contribute most towards the PTO figure, the differences tend to be due to the differing performance in higher sea states.

The PTO results, averaged over all speeds, are plotted in Figure 9 and 10. These clearly illustrate the difference in PTO attributable to the level of detail in wave modelling.

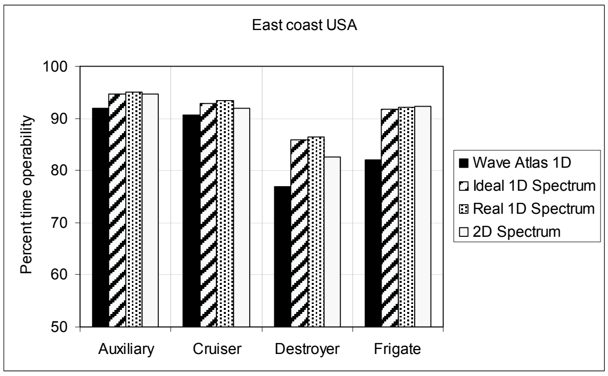


Figure 9 Average PTO (East coast USA)

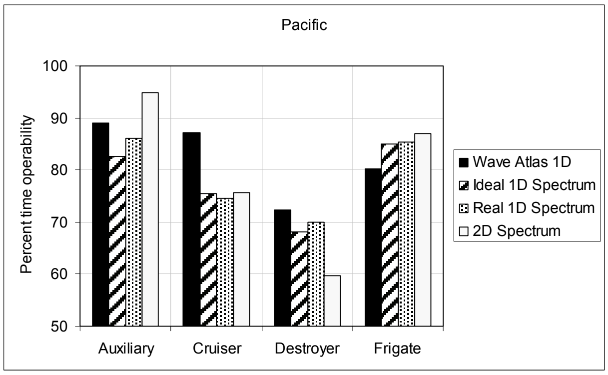


Figure 10 Average PTO (Pacific)

These results, particularly for the Pacific buoy, therefore suggest that making full 'Level 3' wave modelling is indeed a worthwhile exercise. Certainly in terms of the ship motions and associated responses, widely different results were obtained with the most complex wave description compared with more simple ones. Even if (as for the 44014 buoy site) there is not a large difference in performance predicted due to the wave complexity, that difference would remain unknown and therefore an unquantified risk if the full calculation were not performed.

It is therefore recommended that directional wave modelling in the way of the SHREWD code is worthy of pursuit by designers for operability assessments.

6. CONCLUSIONS

This paper has shown an assessment of the seakeeping performance of a range of ships in long term wave data at various levels of complexity.

First, a review of wave data sources was made, and long term wave data from the US NOAA National Data Buoy Centre was selected for further use. Over 10 years worth of hourly wave data for two locations was downloaded for use on this project.

The research work of the project then considered two main themes, the difference in the ship performance calculated when:

(a) using wave buoy data rather than wave atlas data for the same sea area; and
(b) using the most complex available model of the ocean waves compared with the simplified wave descriptions in common use.

Significant results have been obtained for both (a) and (b) using a new code SHREWD developed for the project. For (a) the data from both wave buoys differs from the wave atlas data for the same nominal area, and indeed produced different ship performance results. The main conclusion is that even the most trustworthy wave atlas data must be seen as indicative and subject to considerable uncertainty. For more reliable ship operability performance predictions, wave buoy data should be used. The use of full directional wave spectra is particularly important when specifying a maximum wave height envelope for operations as the influence of realistic wave spreading is generally to reduce the limiting wave height.

For (b) it was shown that there were large differences between the operability calculated for four different example ships at a range of speeds, for one of the sea areas, and smaller differences at the other. Such differences might be enough to change the perception of the abilities of a ship and demonstrate that an assessment of operational capability in realistic operating wave conditions should be pursued.

Designers should note the differences between the wave measurements and the data available in the traditional, or more recent, wave atlases. This could perhaps be seen in the context of climate change, and should involve consideration of the theory of extrapolation of rare events against such (perhaps) non stationary statistics. The magnitude of PTO variation between the four wave complexity models could make the difference between passing, or failing, operability criteria at the design stage.

The variation in operability appears dependant on the ship response (though not necessarily ship size), perhaps suggesting that the degree of matching between wave frequency content and ship response is important. In order to quantify differences in operability resulting from different levels of fidelity in wave modelling a full assessment using the above method is recommended.

The computer code SHREWD described herein provides a platform to perform operability assessments with the most complex wave data.

7. ACKNOWLEDGEMENTS

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