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DIRECTIONAL SPREADING IN TWO-PEAK SPECTRUM AT THE NORWEGIAN CONTINENTAL SHELF

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ABSTRACT

In practical applications, it is usually assumed that the wave spectrum is of a single mode form, and well modeled by a JONSWAP or Pierson-Moskowitz spectrum. This assumption is of a reasonable accuracy for severe sea states. However, moderated and low sea states are often of a combined nature, consisting of both wind-sea and swell and should be characterized by a double peak spectrum. The present paper discusses two-peak spectra observed in Norwegian waters, which are particularly affected by swell. The analysis is based on 5-year of directional data from Haltenbanken. A directional distribution for swell is suggested. Further, a procedure for including directional spreading in two-peak spectra is proposed. The method is illustrated for the two-peak Torsethaugen frequency spectrum (Torsethaugen, 1996), which is currently used by the Norwegian industry.

INTRODUCTION

The Pierson-Moskowitz and JONSWAP spectra are commonly used for engineering applications. Both spectra are of a single mode nature, characterizing pure wind-sea conditions. Several studies document that these spectra are of a reasonable accuracy for severe sea states. However, moderated and low sea states are often of a combined nature, consisting of both wind-sea and swell and should be characterized by a double peak spectrum.

Combined wind-sea and swell sea states are discussed in the literature (Strekalov and Massel (1971), Ochi and Hubble (1976), Guedes Soares (1984,1992,2001), Torsethaugen (1993, 1996)). In load and response analysis, say for the roll motion of a turret moored FPSO; it is frequently useful to supplement a two-peak spectrum with information about the directional spreading of wave energy. Wave directionality is within linear wave theory commonly modeled by a directional spectrum $S(f,\theta) = S(f) \cdot D(f,\theta)$, where $S(f)$ is the frequency spectrum, $D(f,\theta)$ is the directional distribution, f is the frequency and θ is the direction. Directional information as obtained from measurements is normally limited to four, or sometimes nine Fourier coefficients (e.g. cloverleaf buoy which measures additionally the curvatures of the wave surface). There are many possible directional distributions with more or less the same first two or four Fourier coefficients. Therefore for practical applications some a priori selection of type of directional distribution is needed. An overview of commonly used directional distributions as the cos-2s distribution, wrapped normal distribution, sech-2 distribution, Poisson distribution and von Mises distribution, is given by Krogstad et al. (1997). Ewans and van der Vlugt (1998) discuss bimodal directional distributions obtained by use e.g. of the Maximum Entropy Method or Maximum Likelihood Method, that are today considered as a more accurate description of the directional spreading in wind-sea components. For a wind-sea typically modeled by a Pierson-Moskowitz or JONSWAP spectrum, the cos-2s distribution is commonly adopted as the favored one for engineering purposes. There are limited investigations reported about directional spreading of swell. Krogstad and Barstow (1999) conclude, based on directional data from several projects as PAROWS, EU MAST WAVEMOD and SCAWVEX, and WADIC, that swell data cluster around the Poisson distribution. In a recent paper

Ewans, analyzing swell data sets measured off the west coast of New Zealand, suggests adopting the wrapped normal distribution for directional spreading of the swell component (Ewans, 2001).

The present paper discusses two-peak spectra observed in the Norwegian waters, which are particularly affected by swell. The analysis is based on 5-year of directional data from Haltenbanken. A directional distribution for swell is suggested. Further, a procedure for including directional spreading in two-peak spectra is proposed. The method is illustrated for the two-peak Torsethaugen frequency spectrum (Torsethaugen, 1996).

WAVE DATA

The present study is based on 5-year of directional wave data measured by the NORWAVE (ODAS 492-494) heave/pitch/roll buoy at Haltenbanken (7°55'E, 65°03'N), as a part of the Oceanographic Data Acquisition Project (ODAP). The buoy was manufactured by Bergen Ocean Data. The data were recorded in 34 minutes intervals each third hour in the period 1980.03.15-1985.03.04. The sampling frequency was 1Hz. The buoy record time series of heave pitch and roll as well as compass heading. For details concerning the buoy, see e.g. Lygre and Krogstad (1986). There are indication that the buoy gives broader directional spreading than most other directional instruments see Allender et al. (1989), Forristal and Ewans (1998). The reason for the possible excessive spreading is partly explained, as discussed by Barstow and Krogstad (1997), by occasional spikes (or large excursions) in the compass series. Quantisation errors in pitch and roll data registration may also be a possible reason for the broader spreading. These errors were investigated in the 1990-ties. Occasional spikes in the compass series are smoothed in the data collected more recently. The data used in the present study have not been reprocessed.

The data records considered herein cover sea state parameters, some average directional characteristics and the first four Fourier coefficients for each frequency in the range 0.0-0.5 Hz. The Fourier coefficients are obtained from cross-spectral analysis of the vertical displacement and two orthogonal slope signals (Long, 1980). The data coverage in the recorded period was 66%.

It should be noticed that this data set was previously analysed by several authors, e.g. Krogstad et al. (1997), Forristal and Ewans (1998). Some of the results of Krogstad et al. (1997) are adopted herein.

TWO-PEAK SPECTRUM

The Haltenbanken area is very much affected by swell. A more or less constant swell component from the North Atlantic is always present.

For a given sea state the frequency spectrum at Haltenbanken typically includes contributions from both a swell and a wind-sea component, thus requiring a two-peak spectrum model. A convenient model for combined seas is then to simple add two frequency spectra

$$S(f) = S_{sw}(f) + S_{w}(f) \tag{1}$$

where $S_{sw}(f)$ is the swell spectrum and $S_{w}(f)$ is the wind sea spectrum (Strekalov and Massel (1971), Ochi and Hubble (1976), Guedes Soares (1984,1992,2001), Torsethaugen (1993, 1996)).

The Torsethaugen two-peak spectrum is applied herein. This spectrum was established primarily for one location (Statfjord Field) at the Norwegian Continental Shelf but in qualitative terms is expected to be of much broader validity, and is currently used by the Norwegian industry.

An attractive feature of the Torsethaugen spectrum is that limited information about the sea-state is required as the spectrum is completely defined given the significant wave height and spectral peak period. The model split the energy into a swell component and wind-sea component, using a modified JONSWAP spectrum for both peaks. But it should be noticed that the spectrum does not necessarily need to have two *pronounced* peaks.

In the Torsethaugen model, each sea state is classified as *swell dominated* sea or *wind dominated* sea according to the criterion (Torsethaugen, 1996):

$$\begin{array}{ll} swell & if\ T_p > T_f \\ windsea & if\ T_p \le T_f \end{array} \quad \text{where} \quad T_f = a_f H_{mo}^{1/3} \tag{2}$$

where T_p is the peak period, and $a_f = 6.6$ is adopted from the JONSWAP experiment (Hasselmann et al. (1973)). If $T_p \le T_f$, the local wind-sea dominates the spectral peak, if $T_p > T_f$ the swell dominates the spectral peak.

The Torsethaugen spectrum is an average wave spectrum derived by analyzing data from the Norwegian Sea, introducing various empirical factors, and the spectrum should not be used uncritically. Obviously, if for a particular sea state a measured spectrum is available, a two-peak spectrum having several free parameters (e.g. Ochi-Hubble is using 6 parameters), is expected to give a better fit to measured data than does the Torsethaugen spectrum. If a structural response is very sensitive to a particular frequency range it is thus recommended to verify the Torsethaugen spectrum versus measured data for the specific location. As shown by Torsethaugen, for the Haltenbanken area the Torsethaugen spectrum increases the average wave steepness for high sea states and reduces the average wave steepness for lower sea states as compared to the JONSWAP spectrum.

From the criterion of Eq. (2), it follows that 58 % of the sea states at Haltenbanken are dominated by swell. This number coincides well with the result obtained by Torsethaugen (1996) for the Statfjord Field, which has very similar wave climate to Haltenbanken. At Statfjord, 59% of the sea states were swell dominated.

It should also be kept in mind that measured spectra may possess multiple peaks caused by other effects than the presence of wind sea and swell, e.g. due to non-linear interactions. The latter category of multi-peak behavior is not the objective of the present paper.

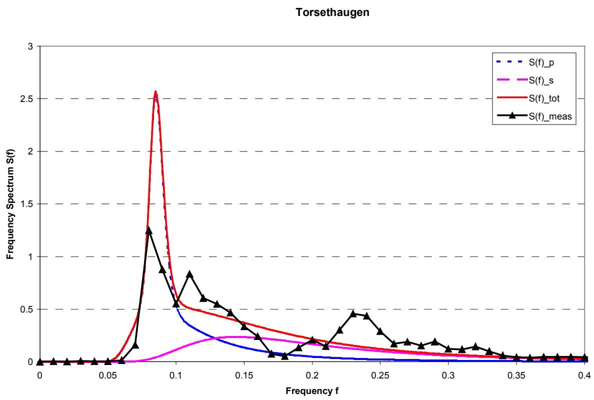

Figure 1 Measured frequency spectrum and Torsethaugen spectrum, March 15th, 1980 at 15.00. Hmo=1.27m, Tp=11.8s; wind-sea: Hmo=0.78m, Tp=6.9s and swell: Hmo=1.00m, Tp=11.8s

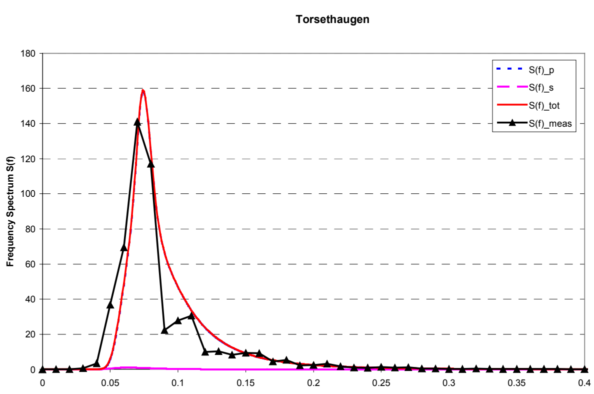

Figure 2 Measured frequency spectrum and Torsethaugen spectrum, December 29th, 1980 at 03.00. Hmo=9.41m, Tp=13.5s; wind-sea: Hmo=9.37m, Tp=13.5s and swell: Hmo=0.86m, Tp=15.9s

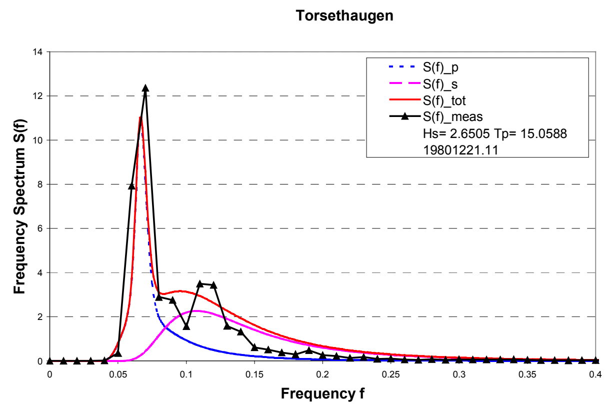

Figure 3 Measured frequency spectrum and Torsethaugen spectrum, December 21st, 1980 at 11.00. Hmo=2.65m, Tp=15.1s; wind-sea: Hmo=1.93m, Tp=9.3s and swell: Hmo=1.82m, Tp=15.1s

Figure 1-Figure 3 show some measured frequency spectra and the corresponding Torsethaugen spectrum for the sea states. In Figure 1, the secondary peak at 0.23Hz is not reflected by the Torsethaugen spectrum, while for the spectra in Figure 2 and Figure 3 the Torsethaugen spectrum, being an average spectrum, gives a reasonable fit to the data.

WAVE ENERGY SPREADING

The directional distribution, $D(f,\theta)$, can be expressed in terms of a Fourier series

$$\begin{aligned} D(f,\theta) &= \frac{1}{2\pi}\left[1+2\sum_{n=1}^{\infty}(a_n(f)\cos(n\theta)+b_n(f)\sin(n\theta))\right] \\ &= \frac{1}{2\pi}\left[1+2\sum_{n=1}^{\infty}r_n(f)\cos(n(\theta-\theta_{Mn}(f))\right] \end{aligned} \quad (3)$$

where a_n, b_n, r_n are Fourier coefficient, and $\theta_{Mn}(f)$ is the mean wave direction for frequency *f*.

It follows from Eq. (3) that

$$\theta_{M1} = \arctan(b_1 / a_1) \quad (4)$$

$$r_n = \sqrt{a_n^2 + b_n^2} \quad (5)$$

The first four Fourier coefficients a_1, b_1, a_2 and b_2 can be estimated from cross spectral analysis of measured buoy data (Long, 1980). As noted above, these four coefficients are not sufficient to precisely describe the directional distribution, but can be used to calculate some useful model-free parameters. These parameters include the mean wave direction θ_{M1}, θ_{M2}; the first σ_1 and second σ_2 directional spread (circular standard deviation of the D distribution). The mean wave direction can be estimated by Eq. (4) (or the corresponding expression for the second order coefficients), and

$$\sigma_1 = \sqrt{2(1-r_1)} \tag{6}$$

$$\sigma_2 = \sqrt{(1-r_2)/2} \tag{7}$$

An alternative spreading measure is the spreading factor $\phi(f)$,

$$\phi(f) = \left\{ \frac{1}{2} \left[1 + (a_2^2 + b_2^2)^{1/2} \right] \right\}^{1/2} = \sqrt{(1+r_2)/2} \tag{8}$$

The factor $\phi(f)$ was introduced by Haring and Heideman (1980) and predicts the reduction in the in-line particle velocities under waves due to directional spread (the square root of the in-line variance ratio) (Ewans, 2001). $\phi(f)$ is equal to 1 for unidirectional waves and 0.707 for omnidirectional waves. Forristal and Ewans (1998) investigate the spreading $\phi(f)$ and the integrated spreading $\bar{\phi}$, and show that the factors are latitudinal dependent.

The unidirectivity index, *UI,* is an integrated measure of the uni-directionality of the spectrum over frequency,

$$UI = (a^2 + b^2)^{1/2} \tag{9}$$

where

$$a = \frac{\int S(f)\cos[\theta_{M1}(f)]df}{S(f)df} \tag{10}$$

$$b = \frac{\int S(f)\sin[\theta_{M1}(f)]df}{S(f)df} \tag{11}$$

If $\theta_{M1}(f)$ is constant through the spectrum, then UI=1, if not, then UI<1. The *UI*-index is not sensitive to small differences in the wave direction.

Several authors use the unidirectivity index to described wave directionality, e.g. Allender et al. (1989), Krogstad et al. (1997). Herein the *UI* index is used as (part of) a swell selection criterion. Note that whereas $\phi(f), \sigma_1(f)$, $\sigma_2(f)$ and $\bar{\phi}$ give information about directional spreading about the mean direction , the index *UI* gives information about the variation of the mean direction with frequency. (E.g., *UI* is less than 1 if two long-crested wave trains of different headings are present.)

For a two-peak spectrum expressed as a sum of a swell component and a wind-sea component, the total directional frequency spectrum $S(f,\theta)$ can be expressed as

$$S(f,\theta) = S(f)D(f,\theta) = \sum_{j=1}^{2} S_j(f,\theta) = \sum_{j=1}^{2} S_j(f)D_j(f,\theta) \tag{12}$$

where the component directional distribution is

$$D_j(f,\theta) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}(a_{jn}\cos(n\theta) + b_{jn}\sin(n\theta))\right] \tag{13}$$

where j=1 is the swell component and j=2 is the wind-sea component. The frequency dependence of the Fourier coefficients is omitted for brevity of notation.

It then follows that

$$\begin{aligned} D(f,\theta) &= \sum_{j=1}^{2} w_j(f)D_j(f,\theta) \\ &= \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}(A_n\cos(n\theta) + B_n\sin(n\theta))\right] \\ &= \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}(R_n\cos(n(\theta - \Theta_{Mn}))\right] \end{aligned} \tag{14}$$

where

$$w_j(f) = S_j(f)/S(f) \tag{15}$$

$$A_n(f) = \sum_{j=1}^{2} w_j(f)a_{nj}(f) \tag{16}$$

$$B_n(f) = \sum_{j=1}^{2} w_j(f)b_{nj}(f) \tag{17}$$

$$R_n(f) = \sqrt{A_n(f)^2 + B_n(f)^2} \tag{18}$$

$$\Theta_{Mn}(f) = Arc\tan(B_n(f)/A_n(f)) \tag{19}$$

Thus the Fourier coefficients for the combined spectrum is expressed in terms of the Fourier coefficients for the swell and the wind-sea components. The mean wave direction is obtained as $\Theta_{M1}(f)$, and the total circular spreading $\Sigma_1(f)$, $\Sigma_2(f)$ are in analogy with Eq. (6) and Eq. (7) obtained as

$$\Sigma_1(f) = \sqrt{2(1 - R_1(f))} \tag{20}$$

$$\Sigma_2(f) = \sqrt{(1 - R_2(f))/2} \tag{21}$$

Eqs. (14)-(21) express the directional statistics of the combined spectrum in terms of the statistics of the underlying swell and wind sea component statistics.

DIRECTIONAL SPREADING FOR TWO-PEAK SPECTRA AT HALTENBANKEN

The Haltenbanken data are first categorised into wind-sea and swell *dominated* sea states according to the criterion of Eq. (2), see Table 1. A total of 7790 sea states for which directional information is available are included in the analysis. For each class of H_{m0} values, the sample average spreading characteristics are calculated, including circular spread at the spectral peak period and the unidirectivity index. Table 1 shows that the *UI*-index increases with the wave height. This is because low and moderated seas are often of combined nature where wind-sea and swell have different directions.

Table 1: Directional parameters

Hm0 (m)	Swell dominated seas			Wind dominated seas		
	No. Obs.	$\overline{UI}$	$\overline{\sigma}_1$ *	No. Obs.	$\overline{UI}$	$\overline{\sigma}_1$ *
0.-2.0	2156	0.766	44.6°	1245	0.839	36.9°
2.-4.0	1689	0.842	44.8°	1497	0.895	39.4°
4.-6.0	493	0.920	46.3°	423	0.947	41.4°
6.-8.0	113	0.957	44.3°	112	0.972	38.5°
8.-10.0	31	0.974	42.8°	18	0.976	36.2°
10.-12.0	12	0.980	39.2°	-	-	-
>12.0	1	0.970	35.3°	-	-	-

* The value refers to the spectral peak period

As opposed to the *UI*-index, the average circular spreading at the spectral peak decreases with increasing wave height. This should be expected as more severe sea states are typically more unidirectional. The data analysis further shows that for increasing *UI* value within each wave height class the average circular spread tends to decrease. For example, for swell dominated seas, $0. < Hmo \leq 2.0m$ and *UI*>0.97, the average circular spreading is 35.4°, while for *UI*>0.99 it is 31.9°, confer Figure 4 and Figure 5. A high *UI* value and reduced spreading indicate that only one wave component is present, in this case swell.

In order to establish directional distribution for swell, sea states are selected according to the following criteria:

- only swell dominated seas according to the criterion $T_p > T_f$, confer Eq. (2)
- $0. < Hmo \leq 4.0m$
- *UI* ≥0.99

A total of 71 sea states fulfil these criteria. All wave spectra were plotted and visually inspected. 14 spectra are judged to have significant contribution from wind-sea (significant energy at higher frequencies), and are therefore excluded from further analysis. As an example, Figure 6 shows the spectrum for a

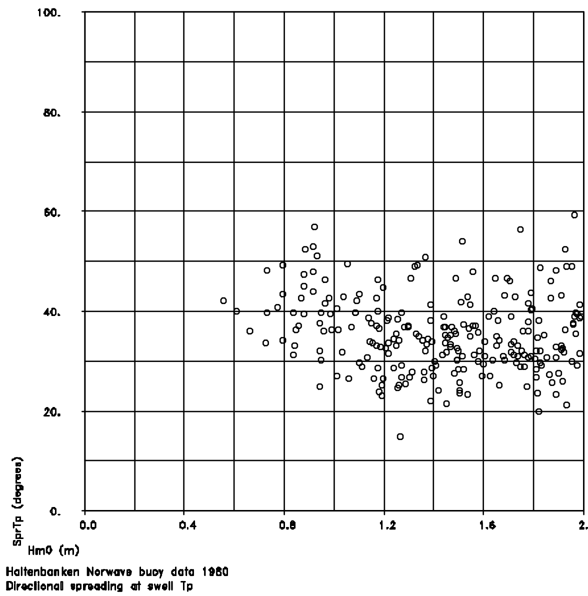

Figure 4 Circular spreading at the spectral peak as a function of Hmo, swell dominated sea, 0<Hmo<2.0, *UI* ≥0.97, $\overline{\sigma}_1 = 35.43^\circ$.

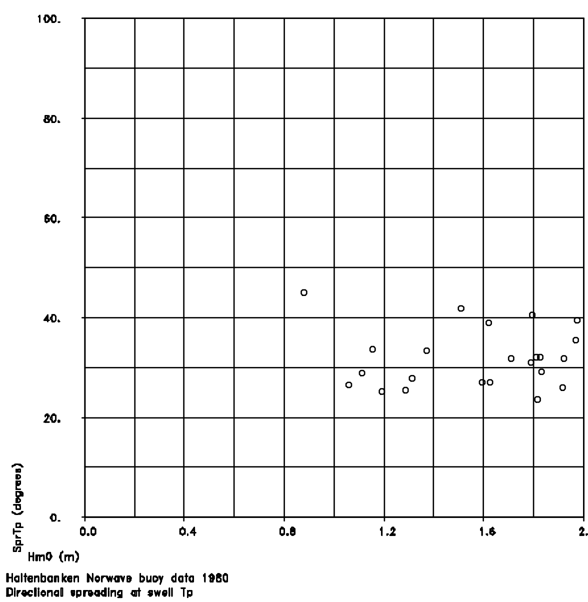

Figure 5 Circular spreading at the spectral peak as a function of Hmo, swell dominated sea, 0<Hmo<2.0, *UI* ≥0.99, $\overline{\sigma}_1 = 31.88^\circ$.

rejected sea state. Note that the peak frequency of 0.1Hz as shown in the figure is somewhat different from the peak period Tp=8.8s. Tp was calculated from the raw data while Figure 6 presents the smoothed and interpolated into 0.01Hz bands frequency spectrum.

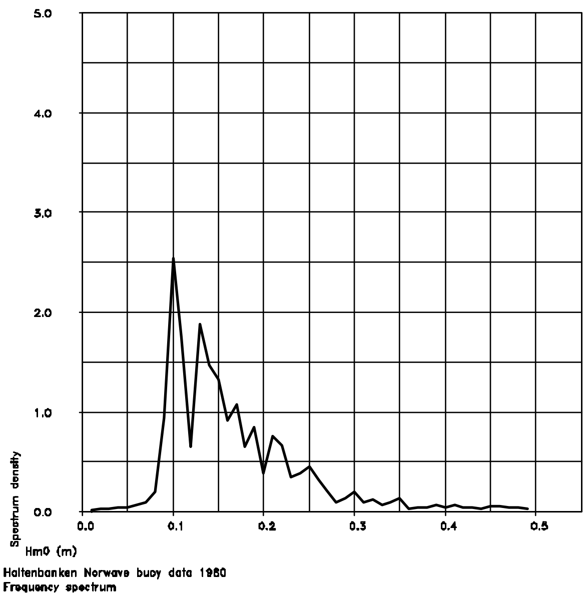

Figure 6 Empirical frequency spectrum, Hmo=1.79m, Tp=8.8s. At the spectral peak the circular spreading $\sigma_1 = 40.44^\circ$ and $\phi = 0.947$.

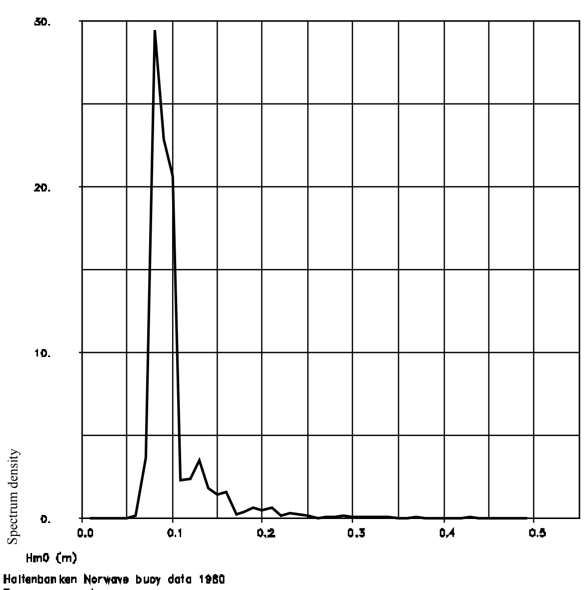

Figure 7 Empirical frequency spectrum, Hmo=3.88m, Tp=11.6s. At the spectral peak the circular spreading is $\sigma_1 = 17.24^\circ$ and $\phi = 0.969$.

There are five cases for which the average circular spreading at the spectral peak is higher than 39° and with narrow frequency spectrum (not significant contribution from the wind-sea). It is difficult to explain the high spreading in these cases. The spreading could e.g. be caused by instrumental error or by superposition of two swell components. These 5 sea states are also excluded from the analysis. It is assumed that the remaining 52 spectra are representative for pure swell conditions, and the directional distribution for swell is established from this data set. The lowest observed circular spreading at the spectral peak is $\sigma_1 = 17.24^\circ$, see Figure 7. Motivated by the findings of Krogstad and Barstow (1999), where it is concluded that swell data cluster around the Poisson distribution, the directional spreading of swell is in the following modelled by the Poisson distribution. For the wind-sea component, the cos2s model is applied.

The directional distributions are then, for the swell component,

$$D_{swell}(f,\theta) = D_1(f,\theta) = \frac{1}{2\pi}\frac{1-X^2}{1-2X\cos(\theta)+X^2} \qquad (22)$$

where $0 < X < 1$, and for the wind sea component,

$$D_{wind-sea}(f,\theta) = D_2(f,\theta) = \frac{1}{2\pi}\frac{\Gamma(s+1)}{\sqrt{\pi}\Gamma(s+1/2)}\cos^{2s}(\frac{\theta}{2}) \qquad (23)$$

where $s > 0$. The relations between the distribution parameters and the Fourier coefficients are

$$s_1 = 2/\sigma_1^2 - 1 = r_1/(1-r_1) \qquad (24)$$

$$s_2 = \frac{1+3r_2+\sqrt{1+14r_2+r_2^2}}{2(1-r_2)} \qquad (25)$$

$$X_1 = r_1 \qquad (26)$$

$$X_2 = \sqrt{r_2} \qquad (27)$$

For the *swell component*, the Poisson parameter X is calculated as function of frequency from Eq. (26) for each of the 52 identified swell sea states. The following parametric frequency model is adopted

$$X(f) = X_p(f/f_p)^{\nu} \qquad (28)$$

where X_p is the *X*-parameter at the peak frequency, f_p is the peak frequency and ν is an exponent. The model is fitted by linear and non-linear regression, see Figure 8 and Figure 9. Only data points for which $f/f_p < 3$ and $S(f)/S(f_p) > 0.01$ are included to excluded points that are obviously not swell, and to ensure a good signal level. The following best fit parameter values are obtained

$$X_p = 0.9\,; \qquad \nu \;=\; \begin{cases} 2.21 & f/f_p \le 1 \\ -0.35 & f/f_p > 1 \end{cases} \tag{29}$$

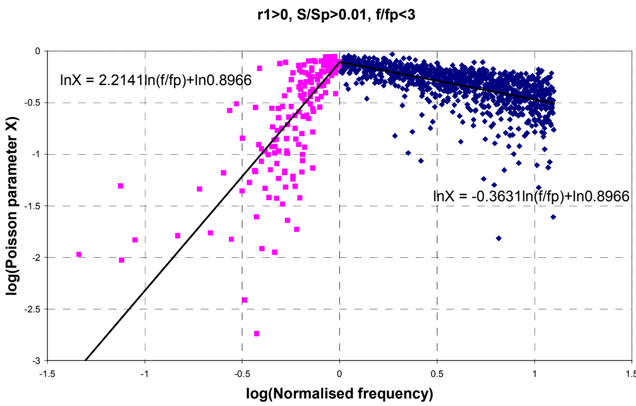

Figure 8 Poisson parameter X as function of normalised frequency, logarithmic plot.

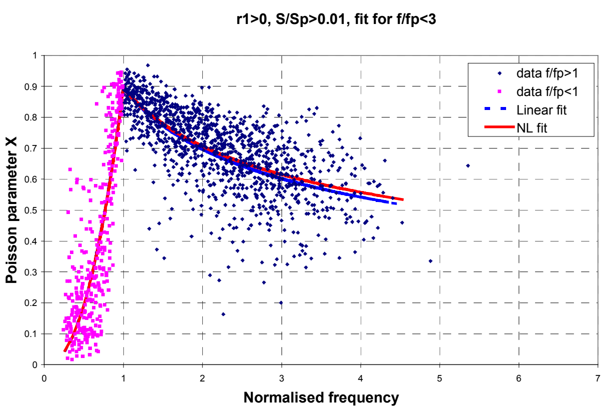

Figure 9 Poisson parameter X as function of normalised frequency.

For the *wind-sea component*, the parametrization of the cos-2s distribution is expressed as (Krogstad et al. 1997)

$$s = s_p (f/f_p)^{\mu} \tag{30}$$

where s_p is the *s*-parameter at the peak frequency, and μ is an exponent. The following parameter values are adopted from Krogstad et al. (1997) as reasonable values for the Haltenbanken area:

$$s_{1p} = 3.6; \quad s_{2p} = 6\,; \; \mu \;=\; \begin{cases} 5.0 & f/f_p \le 1 \\ -0.9 & f/f_p > 1 \end{cases} \tag{31}$$

Next the total directional frequency spectrum is established. Adopting a two-peak Torsethaugen frequency spectrum, the relative weights for respectively the swell and the wind-sea component as expressed by Eq. (15), can then be calculated as function of frequency. The directional distribution of the swell sea component is modelled by Eqs. (22), (28), (29), whereas the wind-sea component is modelled by Eqs. (23), (30), (31). A required input parameter is additionally the mean wave direction (as function of frequency) for the swell and wind-sea components.

As an example the sea state considered in Figure 3 is analysed (December 21st, 1980 at 11.00). Figure 10 shows the observed mean wave direction as function of frequency. Based on Figure 10, the mean swell direction is taken as 240^0 and the mean wind-sea direction as 300^0.

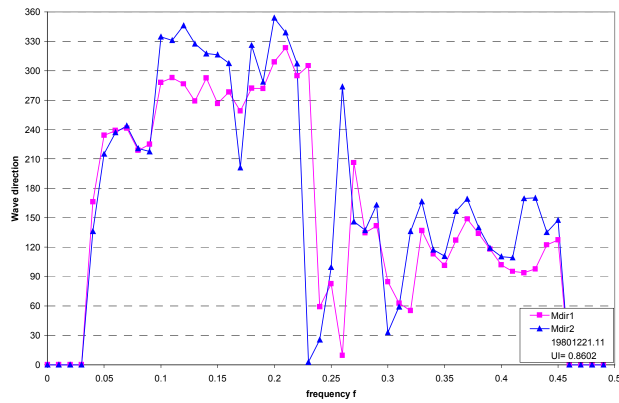

Figure 10 Measured mean direction, December 21st, 1980 at 11.00. Same sea-state as in Figure 3.

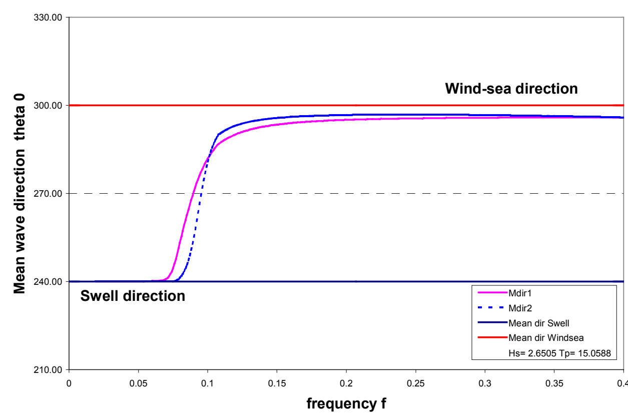

Figure 11 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Estimated mean wave direction as function of frequency.

Figure 11 shows that for the combined sea state the estimated mean direction shifts from about 240^0 for $f < 0.07s^{-1}$ to about 295^0-300^0 for $f > 0.15s^{-1}$.

From Figure 12 it follows that the combined model gives a good fit for the circular frequency Σ_2 for almost the whole range of frequencies, while Σ_1 gives a good fit for swell frequencies. For the wind-sea area Σ_1 underestimates the spreading, because the wind-sea spreading as defined by Eq. (24) does not reflect the high spreading that is actually present in the analysed data for the given sea state. Generally, the Σ_2 seems to be less prone to errors in the data than Σ_1, see e.g. Krogstad et al. (1997). Note also that the local Σ_1-maximum of about 52^0 in the area between the swell peak frequency and the wind-sea peak frequency where both sea state components contribute ($f \approx 0.09Hz$) is caused by i) a high spreading of wind sea for $f < f_{p,wind-sea}$ and, ii) different mean wave directions for the two sea state components.

Figure 13 shows the spreading factor ϕ as function of frequency. The correspondence between the measured and estimated spreading is good at the peak period, as should be expected from the results for Σ_2 reported in Figure 12.

Next Figure 14 to Figure 17 show the combined directional distribution $D(f,\theta)$ as calculated by Eq. (14) for different frequencies. The figures also show the maximum

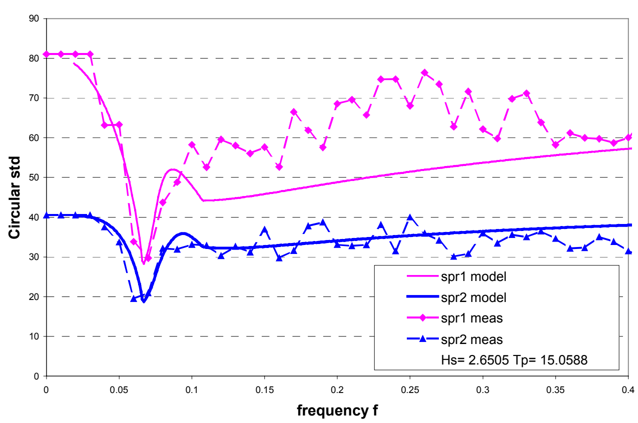

Figure 12 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Measured and estimated circular standard deviation as function of frequency.

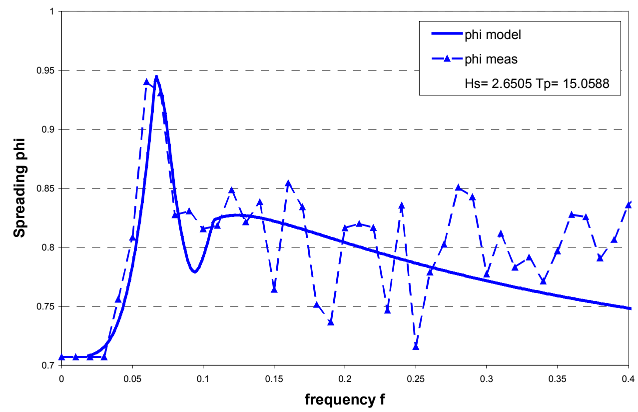

Figure 13 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Measured and estimated spreading factor ϕ as function of frequency.

entropy estimate, following Lygre and Krogstad (1986), based on the Fourier coefficients as estimated from Eqs. (16),(17) (not based on the actually measured cross-spectra values).

For swell dominated frequency (Figure 14) and wind-sea dominated frequency (Figure 17) the directional distribution is symmetrically distributed about the mean direction (respectively 240^0 and 300^0). For frequencies where both swell and wind-sea contributes (Figures 15-16), the directional distributions exhibit a bimodal character, reflecting wave energy in both the swell and wind-sea direction.

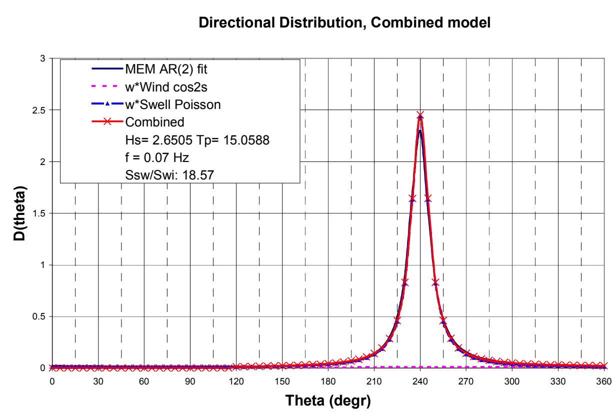

Figure 14 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Estimated directional distribution $D(f,\theta)$ for f=0.07Hz.

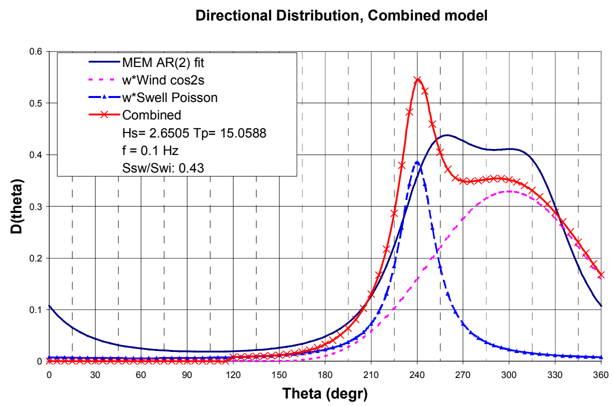

Figure 15 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Estimated directional distribution $D(f,\theta)$ for f=0.10Hz.

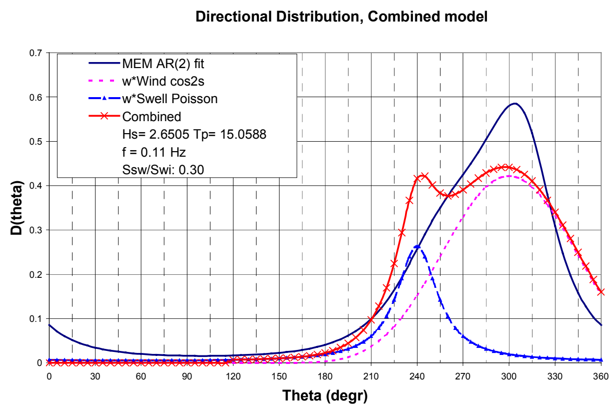

Figure 16 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Estimated directional distribution $D(f,\theta)$ for f=0.11Hz.

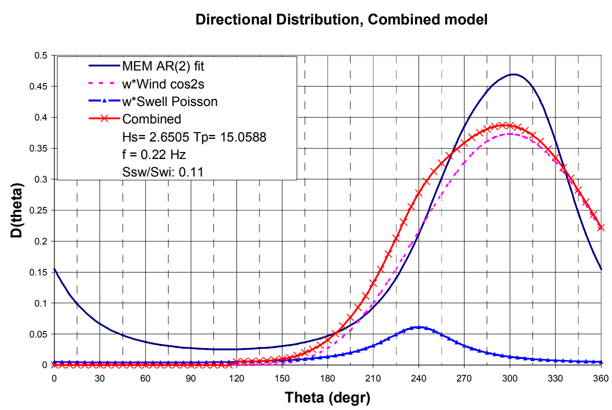

Figure 17 Directional distribution for combined sea-state. Torsethaugen two-peak frequency spectrum. Sea-state as in Figure 3. Estimated directional distribution $D(f,\theta)$ for f=0.22Hz.

CONCLUSIONS

Two-peak frequency spectra at Haltenbanken are discussed based on 5-year of directional wave buoy data. The location is strongly affected by swell. Wave reflection from the rocky coastline may also be present in the area.

The directional spreading of swell is described by the Poisson distribution, and a parameterization of the model is made by analyzing swell sea states selected according to a set of criteria. A procedure for including directional spreading in two-peak spectra is proposed by weighting directional statistics for the swell and the wind-sea components. The method is illustrated for the two-peak Torsethaugen frequency spectrum (Torsethaugen, 1996) for a given sea state, and the model predictions are shown to correspond reasonable well with measured statistics.

As there are indications that the NORWAVE buoy gives broader directional spreading than most other directional instruments the suggested swell distribution should be verified by data collected by other instruments if they become available.

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