S. PETER KJELDSEN

THE PRACTICAL VALUE OF DIRECTIONAL OCEAN WAVE SPECTRA

Multimodal directional seas, which often contain steep nonlinear wave groups, can create a more severe vessel design environment than simple unimodal directional seas. Using a multimodal description, a method to forecast steep wave conditions that adversely affect the operation and safety of ocean vessels is presented. Modern wave laboratories can accurately simulate multimodal directional seas to investigate the motion response of ocean vessels to realistic forcing functions.

EXAMPLES OF SENSITIVITY TO DIRECTIONAL SEA STATES

A three-dimensional sea state can be well described statistically by its directional spectrum. A multimodal directional sea state is defined as a sea state that gives two or more distinct energy peaks at different directions. Wind seas and swell systems from different directions often occur simultaneously and can be identified easily in standard polar spectral energy plots.[1]

The directional spectrum has become appreciated more and more in recent years as an important engineering tool. For example, Marintek A/S began simulating directional wave spectra in its Ocean Laboratory (model basin) in 1980. Much evidence now indicates that directional seas can produce a more severe ship design environment than, for example, simple long-crested seas with identical significant wave height, H_s. Simulation experiments have shown that, for a given H_s, torsion moments on a tension leg platform are larger in directional seas than in seas approaching from only one direction. Similar results were found for an offshore loading system consisting of a double-articulated riser connected to an offshore buoy, a storage tanker, and a shuttle tanker, in which directional seas produced yaw motions that created large forces and moments. Such large forces were not present in long-crested seas. Knowledge of wave directionality is also important to assess accurately the accumulation of fatigue damage on North Sea steel jacket structures.[2] Directional information is essential to estimate phase lag and coherence between sea loading and the response of various members of a spatial jacket structure.

An accurate description of directional seas is also very important for calculations of sea loads on ship hulls. Fukuda[3] compared results for vertical bending moments on tankers and cargo ships in both long-crested and short-crested directional seas. Clarke, Price, and Temarel[4] performed numerical simulations of bending moments, including slamming and whipping effects, in a frigate hull driven by various directional spectra. Sea states with large directional spreading resulted in smaller bending moments.

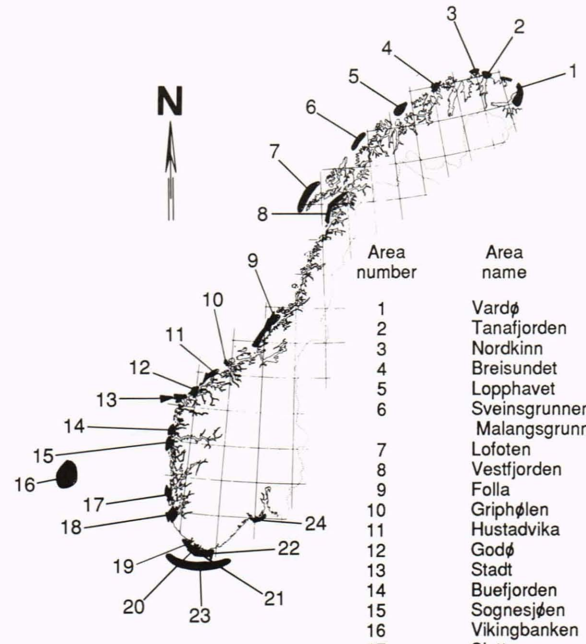
A unimodal directional sea contains only one wave system with directional spreading. Design applications very often use a two-parameter directional spectrum with 90° spreading described by the function $\cos^{2s} \theta/2$, where s is the directional spread parameter. The Labrador Sea Extreme Waves Experiment (LEWEX) full-scale sea trials demonstrated the inadequacy of such sea state modeling. More complete knowledge of the various modes contained in a multimodal directional sea state can reveal strong variations in ship response with heading, and can result in a substantial improvement in ship operability.

The most severe limitations of a unimodal description for directional spectra, however, appear when designing weather-vaning systems for ocean vessels or dynamic positioning systems for semi-submersible platforms. The design requirements for such systems generally become more severe in multimodal directional seas, since mooring forces are functions of the slow drift in surge, yaw, and sway motions.

MULTIMODAL DIRECTIONAL SEAS IN COMBINATION WITH CURRENT SHEAR

In Norway, twenty-six trawlers and freighters were lost in capsizing accidents in a period of only nine years. Altogether, seventy-two lives were lost. The shipwrecks from these and other accidents are not randomly distributed along the coast of Norway, but are concentrated in the twenty-four specific areas illustrated in Figure 1. Wave refraction calculations confirm that these areas have a concentration of wave energy during certain weather conditions. Most of these areas can be classified as part of the shelf and coastal waters, where gravity waves interact with strong currents and local topography.[5]

An encounter with a steep wave condition can be disastrous, even for a large ship. In September 1979, the Norwegian ship *Austri*, loaded with a cargo of pig iron, was suddenly hit by a large wave breaking over the starboard bow in the narrow passage outside Slettringen in area 15—Sognesjøen—in Fig. 1). The ship heeled over by nearly 30° and, before it could restore itself, was hit by a new wave from another direction. The new wave



Area number	Area name
1	Vardø
2	Tanafjorden
3	Nordkinn
4	Breisundet
5	Lopphavet
6	Sveinsgrunnen–Malangsgrunnen
7	Lofoten
8	Vestfjorden
9	Folla
10	Griphølen
11	Hustadvika
12	Godø
13	Stadt
14	Buefjorden
15	Sognesjøen
16	Vikingbanken
17	Sletta
18	Skotamedgrunnen
19	Siregrunnen
20	Listafjorden
21	Lista
22	Ryvingen
23	Skagerak Vest
24	Faerder–Tvistein

Figure 1. Twenty-four areas on the Norwegian coast that are the sites of steep and dangerous waves during certain weather conditions (depending on wave direction, wave height, and the position of coastal eddies).

increased the heel to nearly 40°, causing the cargo to shift, and the ship had to be abandoned, with no emergency calls transmitted. Shortly after, the rescue float capsized in surf near the shore and five lives were lost. The abandoned *Austri* with its shifted cargo was in fact quite stable, and maintained a list near 80°, although it drifted and turned until it struck a rock near the shore and broke in two (Fig. 2). A court of inquiry[6] later showed that the vessel had been passing through a focal point in one of the wave refraction areas.

Storm surges and related effects may, at times, give rise to an unusually large flux of water in the Norwegian Current that travels up the west coast of Norway. The current meandering is enhanced by a sudden outflow of brackish water from the Baltic Sea, and develops to an unusually large scale. With westerly winds, a setup occurs in the Baltic Sea, and a sudden change of wind direction can then release a volume flux of up to 1.4 × 10^6 m^3/s. This front travels about 30 km/day north along the Norwegian coast, producing large eddies with diameters of up to 100 km.[7] The passage of such eddies creates very large current velocities even at great depths. Such unusual meandering is observed by satellites equipped with infrared sensors that measure the sea surface temperature. Interaction between gravity waves and the eddies can lead to the development of dangerous, plunging, and breaking waves in deep waters at predictable times and locations both on the shelf and in the coastal areas.

Figure 2. The Norwegian ship *Austri* (499 gross register tons), which capsized from waves in area 15 of Figure 1 and subsequently broke into two pieces.

In December 1984, the freighter *Sun Coast* was lost at Stadt in area 13 of Figure 1. The vessel encountered two large breaking waves, which caused the cargo to shift. Only four of a crew of six were rescued. A court of inquiry[8] revealed that steep transient wave conditions can suddenly and unexpectedly occur at this location, when waves arriving from certain critical directions are influenced by the local topography. On this occasion, a large current eddy had been located in the vicinity (see Fig. 3). Similar eddies were present in seventeen of the twenty-six cases where ship accidents have occurred during a nine-year period.

In an attempt to reduce such accidents, a mathematical model to forecast steep wave conditions off the Norwegian coast has been developed. Trial forecasts have been produced that can warn mariners of severe steep and breaking waves. The mathematical model, developed as part of a research program entitled "Ships in Rough Seas," is based on extensive model-basin wave-focusing experiments. The ultimate stability of small vessels in beam seas is directly related to the crest front steepness, ϵ, of the approaching wave. The crest front steepness, as obtained from a surface elevation time series, is defined in Figure 4 (ϵ can also be defined in space[9]).

Figure 4 also shows how rms crest front slope, ϵ_{rms}, is directly correlated with the properties of the directional wave spectrum and can be calculated from m_0 and m_2, the zeroth and second spectral moments. Using such a relationship, crest-front wave slopes can be forecast, including refraction of the directional spectrum by both current meanders and local topography. Such forecasts are based on estimates of "critical threshold values" for both wave direction and wave height for each of the twenty-four areas shown in Figure 1. Daily forecasts are checked against critical threshold values stored in a data bank. For each area, a forecast of critical wave conditions for specific types and sizes of vessels derived from model experiments[9] can then be prepared. The general mathematical model[10] that takes account of the effects

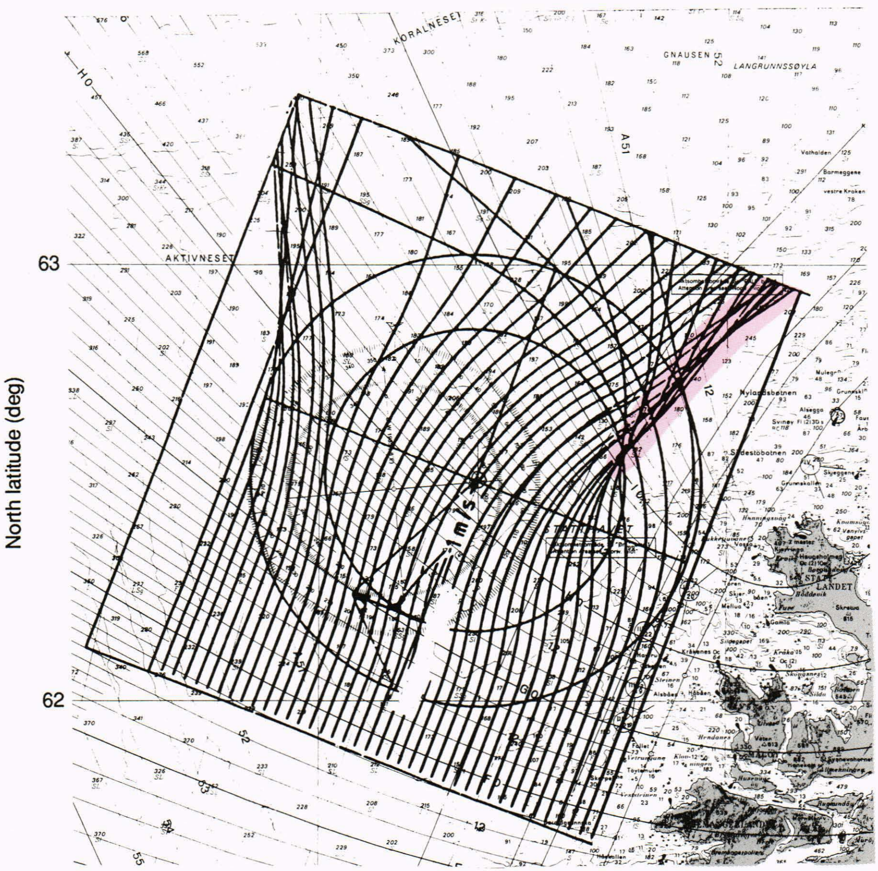


Figure 3. Reconstruction of the position for current meandering at the date and time when the *Sun Coast* capsized in area 13 of Figure 1. A current eddy of 60-km diameter rotates clockwise at a velocity of 1 m/s. Wave rays approaching from the southwest interact with the eddy, crossing on its leeward side to produce hazardous conditions (red tint) for ocean vessels.[8]

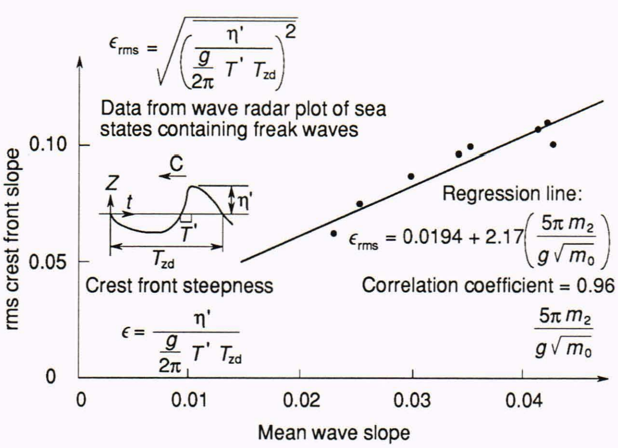


Figure 4. Root-mean-square value of crest front slope, ϵ_{rms}, as a function of the zeroth and second spectral moments, m_0 and m_2, repectively (g is the acceleration caused by gravity). Data were obtained with a wave radar installed on a platform on the Norwegian Continental Shelf. Results from eight time series that contained freak waves are plotted. For this work, a freak wave is defined as a wave with a height greater than twice the significant wave height, H_s. The definition of crest front steepness, ϵ, for single waves is shown in the lower left corner, as obtained from surface elevation time series. The term η' is the wave crest elevation, T_{zd} is the zero downcross wave period, c is the wave phase velocity, and T' is the time fraction between the zero upcross position and the crest position (Z is the vertical coordinate measured from mean water level and t is the time coordinate).

of multimodal directional seas and strong ocean currents is not limited, of course, to Norwegian waters. Similar areas with critical wave conditions occur off Newfoundland and Nova Scotia, Greenland, Alaska, Chile, northwest India, and southeast Africa—the last caused when swell from the Southern Ocean encounters the strong Agulhas Current.

The LEWEX experience supports the validity of the forecast model. During LEWEX, a steep critical wave was measured near 42.5°N, 55.0°W in a strong current shear where the Labrador Current from the north meets the Gulf Stream from the south.[11] Other examples of measurements of critical waves are given in Ref. 12. An expert committee of the International Ships and Offshore Structures Congress[7] has recommended use of the crest-front steepness parameter in future analytical, experimental, and full-scale scientific work.

LEWEX SEA-KEEPING TRIALS

Full-scale sea-keeping trials were performed in LEWEX with the research vessels HNLMS *Tydeman* and the CFAV *Quest* at three separate locations; concurrent (side-by-side) sea-keeping trials were performed at two of the three. Ship motions in six degrees of freedom were measured independently by four teams of scientists, two on each vessel. Multimodal directional seas were measured simultaneously with many independent sensors. Subsequently, a statistical estimate of the multimodal directional seas served as an input to model basin experiments at Marintek.[13] Ultimately, six legs from the full-scale sea-keeping trials, each of 20-min duration, were selected for simulation of the *Tydeman* motions at a 1/30 scale.

MODEL EXPERIMENTS IN MULTIMODAL DIRECTIONAL SEAS

The directional ocean wave model basin at Marintek is 80 m long by 50 m wide and is equipped with a hydraulically controlled movable bottom, permitting experiments at any depth between 0.3 and 10 m. The basin is equipped with two wave generator systems, which, when combined, can produce multimodal directional seas. Directional sea systems are simulated using a wave generator that drives 144 identical flaps, each individually controlled by an interactive computer system. One hundred twenty different frequencies are combined to produce a specified directional ocean wave spectrum.[14] The basin is also equipped with a 50-m-wide hydraulic double-flap wave generator. Sea-keeping tests are performed in the basin with computer-controlled free-running models. Model speed, heading, pitch, roll, heave, sway, surge, and yaw are measured accurately by an optical positioning system, using infrared light-emitting diodes and movable cameras installed at the tank walls. Computer-controlled techniques allow the testing and tuning of active antiroll fins and autopilot and dynamic positioning systems. Quantities such as vertical and lateral acceleration, propeller speed, shaft torque, rudder force and angle, quantity of water on deck, and amount of slamming can all be monitored.

Figure 5 shows model results when simulating the conditions encountered by the *Tydeman* at various headings in LEWEX on 14 March. Figure 5A shows the geometry. The associated directional wave spectrum is shown in Figure 5B, as measured by the Norwegian Wavescan buoy. A directional spectral model with an angular spread of 50° was used to simulate the Wavescan-measured spectrum. Pitch and roll motions

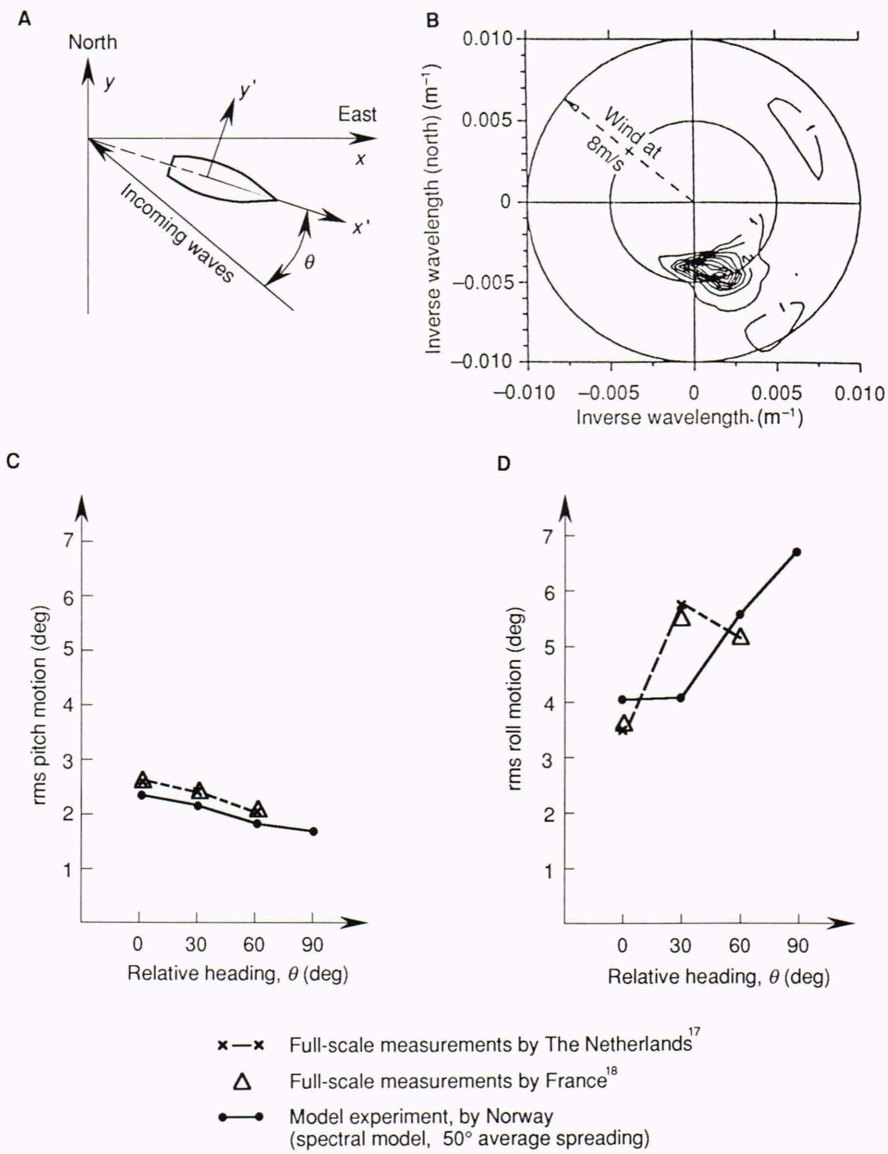
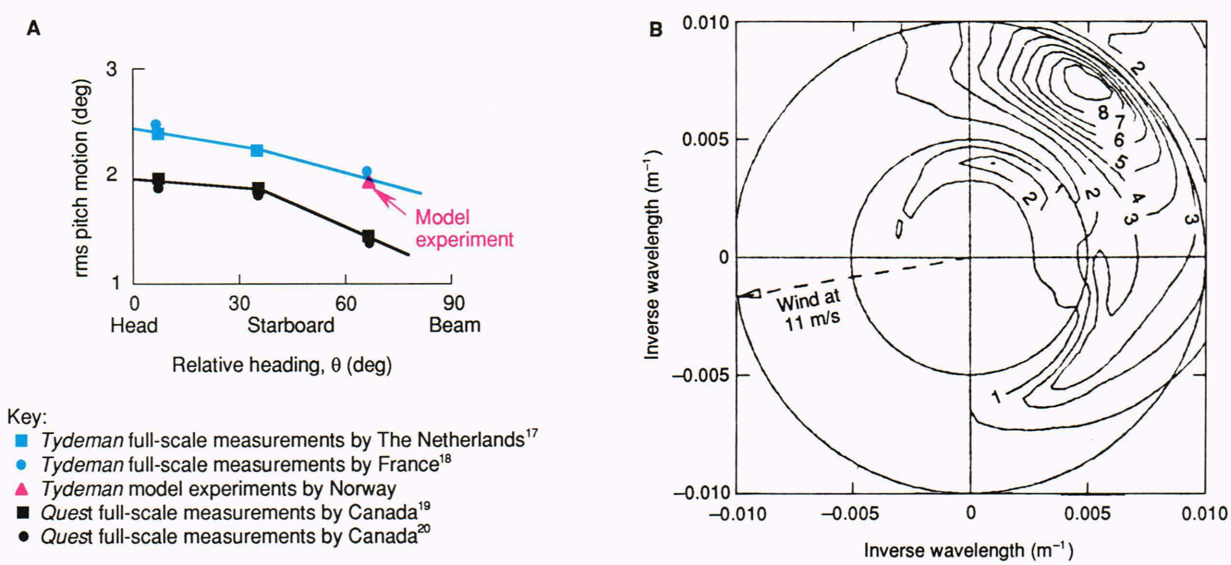


Figure 5. Results of *Tydeman* sea-keeping experiments during LEWEX, 14 March 1987. Results of model experiments are compared with full-scale measurements from Refs. 17 and 18. **A.** Definition of θ, relative heading (0° = head seas, 90° = beam seas). **B.** Directional wave number spectrum (m^4) from Wavescan buoy at 1459 UT. H_s = 3.7 m. Spectrum is shown in direction from which waves are propagating.[15] **C.** Pitch motion versus heading. **D.** Roll motion versus heading.

are shown in Figures 5C and D as functions of relative heading, using results from both model experiments and full-scale measurements. Agreement between modeled and measured motions is better than 0.5° in five out of six cases.

Figure 6 shows an example from 23 March, when both the *Tydeman* and the *Quest* were executing parallel sea trials, with motions of each monitored independently in a very complex wave situation. Figure 6A shows measured pitch motion as a function of relative heading. Each of the independent sets of measurements is in excellent agreement for each vessel. A single data point from the model basin experiment performed at Marintek also shows excellent agreement with the full-scale measurements in that very complex directional wave system, as shown in Figure 6B. For that simulation, a simplified model of the directional wave spectrum was used, with a wind sea coming from 56° having a 32° (average) directional spread superimposed on a swell coming from 146°. For the wind sea, H_s was 2.48 m, and for the swell, H_s was 0.83 m in that simulation.

The encounter wave frequency, ω_e, (i.e., the wave frequency encountered in the reference frame of the ship) indicated that the *Tydeman* was quite close to resonance in both roll and pitch in that situation. For example, if the wind speed had increased slightly from 11 m/s to 13 m/s (26 kt), its associated equilibrium spectrum would have produced resonances for the speed and heading values illustrated in Figure 6C. With the ship at **a** heading directly into the primary sea at a speed of 11.6 kt, resonance occurs simultaneously in both pitch and roll. Conditions are not much improved if the ship is at **b** and heading instead directly into the swell at a speed of 9.9 kt; again, there are resonances in both roll and pitch. Such an assessment of potential resonances is possible, of course, only with a detailed knowledge of the multimodal directional spectrum. In this example, the swell was modeled at H_s = 3.0 m.



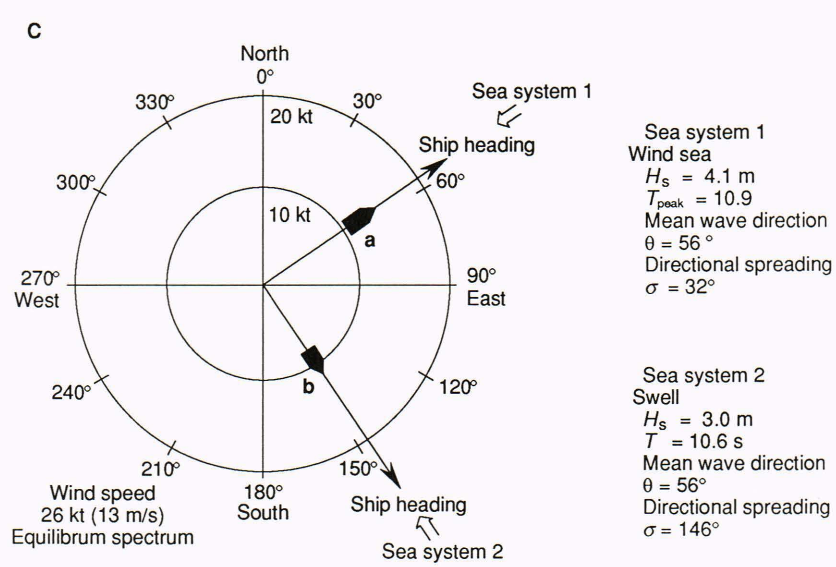


Figure 6. Results of parallel seakeeping experiments with the *Quest* and the *Tydeman* during LEWEX, 23 March 1987. **A.** Model experiments compared with full-scale measurements from Refs. 17–20. **B.** Directional wave number spectrum from Wavescan buoy at 1759 UT. **C.** Illustration of *Tydeman* headings and speeds that would produce resonance conditions. The ship at **a** is traveling toward wind sea at 11.6 kt; the one at **b** is traveling toward swell at 9.9 kt.

Long-term wave statistics for the North Atlantic show that bimodal seas occur about 40% of the time. Navigators normally adjust both speed and heading to avoid large motion responses. As the above example from LEWEX illustrates, however, multimodal seas limit the available options and compress the range between best and worst headings. Multimodal short-crested seas may even introduce an unexpected heading-versus-response dependency, for example, as experienced by the *Quest* during LEWEX (see the article by Nethercote in this issue). Full loss of operability therefore becomes possible in much lower sea states than would be predicted for a unimodal directional sea.

NONLINEAR SHIP MOTIONS

One goal of LEWEX was to explore the limits of linear sea-keeping theory, for which rms pitch increases linearly with increasing mean wave slope if the wave frequency and the ship heading and speed are constants. Figure 7 shows full-scale measurements of rms pitch as a function of calculated mean wave slope taken on each of seven days during LEWEX. On 8 and 14 March, both the speed and the heading of the *Tydeman* were nearly identical. Further, the directional properties of the wave spectra (as indicated by the unidirectivity index, UI, which indicates the percentage of total energy contained in the primary wave system)[15] were quite similar. Figure 7 also shows the results from the model experiment simulating the conditions of 14 March, confirming linearities. A dotted line is drawn between the origin and the results from 14 March extrapolating to large mean wave slopes. The 8 March data, however, are located above this line, showing that pitch motion clearly exceeds the linear extrapolation.

Since linear systems driven with Gaussian inputs have a zero-valued bi-spectrum, the energy in the bi-spectrum represents a direct measure of nonlinearity. Figure 8 shows the calculated bi-spectrum of pitch motion for 8 March, clearly indicating the nonlinear response that occurred on that day. Of all ship motions measured that day, the pitch motion contained the most significant nonlinearities.

Very long sea-keeping runs under stationary, well-controlled conditions are required to obtain good estimates of bi-spectra. Such long runs are very difficult to achieve in full-scale sea trials because sea conditions often change too rapidly. As an alternative, experimentation in a modern wave laboratory is often a more practical method for investigating nonlinear ship motions. In such a laboratory, statistics from many short runs can be efficiently combined to simulate the very long sea-keeping runs of a full-scale sea trial.

It is fairly rare to have six-degree-of-freedom model results and full-scale trials for comparisons. Data obtained from the LEWEX research program have therefore been proposed as the basis for an international development of standard sea-keeping data.[16] Several numerical models based on traditional sea-keeping theory will, in the near future, attempt to simulate the ship motions that were measured in the LEWEX research program.

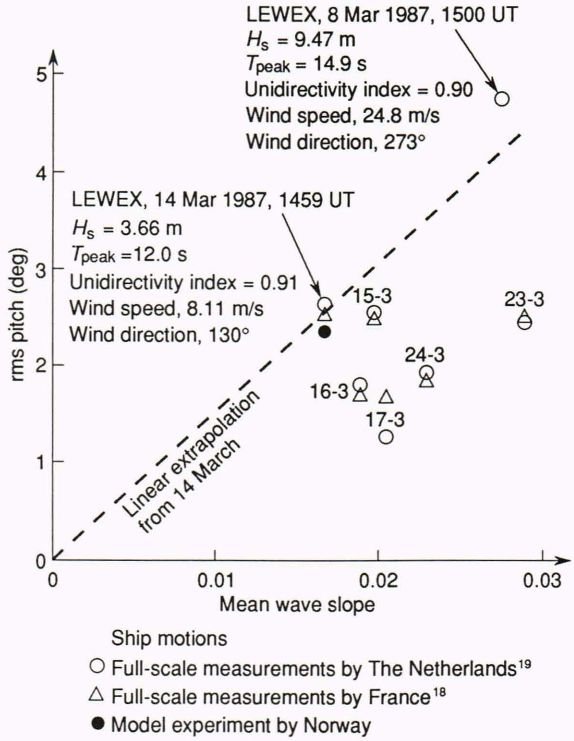


Figure 7. Measured rms pitch of the *Tydeman* shown for various calculated mean wave slopes for each of seven days during LEWEX. For ship motion measurements on 8 March 1987, the associated directional wave spectra are hindcasted from the 3G-WAM model (personal communication, J. Ooms, Laboratory for Ship Hydrodynamics, Technical University of Delft, The Netherlands, 1989). Other measurements of ship motions are from Refs. 18 and 19. Results from sea-keeping trials with nearly the same headings but with different directional spectra are shown for 15, 16, 17, 23, and 24 March.

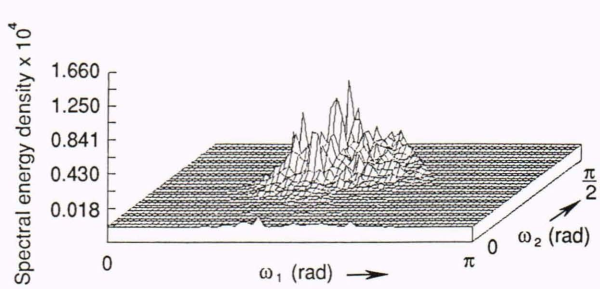


Figure 8. Nonparametric bi-spectrum estimate of pitch motion of the *Tydeman* on 8 March 1987 when $H_s \approx 9.5$ m. The maximum value reached was 0.93 (personal communiation, J. Ooms, Laboratory for Ship Hydrodynamics, Technical University of Delft, The Netherlands, 1989; see also Ref. 21). The term $\omega = 2\pi/\tau$ is the cyclic frequency of pitch motion. For calculation of bi-spectra, see Ref. 22.

CONCLUSIONS

A unimodal short-crested sea is an inadequate description of the driving forces on an ocean vessel, and is therefore also inadequate to predict the vessel's operational performance. Long-term wave statistics show that about 40% of all sea states that occur in the North Atlantic are multimodal. To conduct realistic operational studies in the future, this multimodal behavior of the sea must be recognized and adequately modeled.

Multimodal short-crested sea states compress the range between best and worst headings. The compressed range can cause full loss of operability in sea states lower than might be expected with a unimodal sea. Multimodal short-crested seas may even introduce an unexpected heading-versus-response dependency.

Multimodal short-crested seas increase the encounter probability for nonlinear wave groups containing steep elevated waves that can drastically affect the stability or operation of smaller vessels. Forecasts of critical wave conditions in local areas, based on calculated critical threshold values for wave direction and wave height, are possible, but wave–current interactions must be taken into account.

Critical wave conditions depend on the class of vessels under consideration. Experience gained in carefully controlled model experiments can provide detailed response data for any class of vessels.

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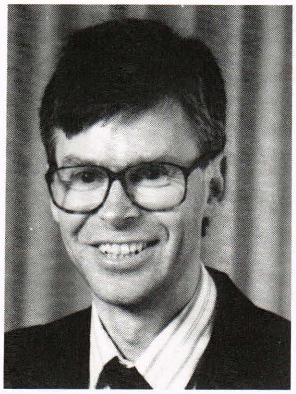
THE AUTHOR



S. PETER KJELDSEN is a senior research engineer at Marintek A/S, Trondheim, Norway. In the later stages of LEWEX, he was chairman of the NATO Research Study Group on Full-Scale Wave Measurements.