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THE CFAV *QUEST*'S LEWEX EXPERIENCE

The seakeeping performance of the CFAV *Quest* during the Labrador Sea Extreme Waves Experiment demonstrates the inadequacy of unidirectional sea-state descriptions and, even more important, demonstrates deficiencies in the unidirectional sea-state model's accepted successor, the unimodal, two-parameter spectrum with 90° cos^2 spreading.* A more complete, often multimodal, sea-state description can reveal strong, unexpected variations in ship response with heading, and can result in substantially improved ship operability assessments.

INTRODUCTION

A Canadian Forces Auxiliary Vessel, CFAV *Quest*, was one of two vessels participating in the Labrador Sea Extreme Waves Experiment (LEWEX). The *Quest* carried scientists and equipment from six agencies within Canada and the United States. Its work program supported the goals of two Research Study Groups (RSG1 and RSG2) of the NATO Defence Research Group Special Group of Experts on Naval Hydrodynamics and Related Problems (SGE[Hydro]), and provided open ocean data for the Labrador Ice Margin Experiment (LIMEX '87).

The *Quest* is a 2200-tonne twin-screw diesel-electric vessel that primarily supports underwater acoustics research at the Defence Research Establishment Atlantic (DREA). The ship is ice-strengthened to allow summer scientific cruises to the Canadian eastern Arctic. Figure 1 shows a view of the *Quest*; the following are its nominal particulars:

Figure 1. The CFAV *Quest*.

Displacement	2200 tonnes
Length between perpendiculars	71.63 m
Molded breadth	12.80 m
Midships draft	4.82 m
Installed shaft power	2000 kW
Speed	14.5 kt

The *Quest* supported the LEWEX goals relevant to the NATO SGE(Hydro) RSG1 Group on Full Scale Wave Measurement and, coincidentally, LIMEX '87 through environmental measurements with on-board instruments or wave buoys. The measurements are covered amply by other LEWEX articles in this issue and in *Directional Ocean Wave Spectra* (Beal, R. C., ed., to be published) and will not be discussed in detail here. The *Quest*, per se, was of more direct interest to the NATO SGE(Hydro) RSG2 Group on Sea Loads, Slamming, and Green Seas Impacts, who planned to use sea loads measured on both the *Quest* and HNLMS *Tydeman* during LEWEX.

The RSG2 group is much smaller than RSG1, with participation from Canada (DREA and the Institute for Marine Dynamics, IMD), Germany (Bundesampt für Wehrtechnik und Beschaffung), The Netherlands (Royal Netherlands Navy), Norway (Marintek), Spain (Canal de Experiencias Hidrodinámicas, El Pardo), the United Kingdom (Admiralty Research Establishment, Dunfermline), and the United States (David Taylor Research Center, DTRC). In keeping with its smaller size, RSG2's work was smaller in scope than RSG1's but, as will be seen later, proved to be more difficult to complete because of the lack of extreme seas during LEWEX.

*An angular spreading that varies as cos$^2\theta$ about the dominant wave direction, that is, an effective angular spread of 90°.

RSG2 GOALS AND PLANS

The aim of RSG2 was to conduct research into slamming and green seas impact mechanisms, to improve surface ship operability in high sea states. Seakeeping trials with the *Quest* and *Tydeman* were to provide important full-scale data for RSG2, for comparison with model tests and for validation of theoretical methods. The RSG2 group also planned or identified a number of related studies. For example, Canada and the United Kingdom undertook a cooperative two-dimensional drop test program to assess scale effects on the girthwise bottom slam pressure distribution, and The Netherlands indicated that the Royal Netherlands Navy full-scale green seas loading trials might become available to the group.

The RSG2 plan for the *Quest* and *Tydeman* was straightforward:

1. Perform individual and side-by-side seakeeping trials with the *Quest* and *Tydeman* during LEWEX.
2. Conduct model tests with the *Quest*, or perhaps with both ships, in scaled LEWEX directional seas in Marintek's facilities in Trondheim, Norway. (See the article by Kjeldsen, this issue.)
3. Use the trials and model test results to validate theoretical methods used or under development by the RSG2 members.

INSTRUMENTATION

During LEWEX, the *Quest* carried or deployed the systems outlined in Table 1. The moored wavebuoys were deployed in 2700 m of water. These deep-water moorings were a high-risk element in LEWEX because they were "once-only" evolutions. The moorings had to be manufactured, before sailing, for a specified water depth, and the design had only a limited margin against failure so as to reduce the cost of the lower parts of the moorings, which would not be recovered.

The "drifting" wavebuoys typically were streamed to windward of the drifting ship in series on an approximately 1000-m polypropylene tether, which produced no apparent interference with wavebuoy motions.

The navigation radar photos experiment was an offshoot of the author's interest in deriving normalized directional wave spectra using navigational radar as a means of reducing reliance on wavebuoys during seakeeping trials. All too often, when conditions are ideal for seakeeping trials, wavebuoys cannot be deployed from the ship.

Table 1. Instrumentation carried or deployed by the *Quest* during LEWEX.

Parameter	System	Location	Sponsor
Sea state	Wavec buoy	Moored	MEDS[a]
Sea state	Endeco buoy	Moored and drifting	DREA
Sea state	Endeco buoy	Drifting	DTRC
Sea state	Delft buoy	Drifting	Delft/ DTRC
Sea state	Wavecrest buoy	Drifting	IMD
Sea state	Navigation radar photos	On board	DREA
Current	InterOcean S-4	Endeco mooring	DREA
Ship motions	"Strap-down" package	On board	DREA
Ship motions	Humphrey stable platform	On board	IMD
Sea loads	Pressure transducers	Bow flare	DREA
Sea loads	Strain gauging	Hull	DREA

[a] Marine Environmental Data Service, Department of Fisheries and Oceans, Ottawa.

Given the expected LEWEX wave spectral database for validation, it seemed appropriate to examine the navigational radar technique; Nordco Limited was contracted to develop a photographic apparatus corresponding to that used by Young et al.[1] to record radar sea-clutter information.

A number of sets of radar sea-clutter photographs were taken during LEWEX. Nordco subsequently developed analysis techniques and software[2,3] so that the radar technique could be assessed in the LEWEX comparisons.[4] In ongoing contracted research, Nordco is investigating the possibility of scaling the radar-derived spectra to allow the significant wave height to be determined.

The current meter, an InterOcean S-4 electromagnetic unit, also could measure salinity and depth. Its output, together with expendable bathythermograph records taken on station and while in transit between sites, was primarily for the benefit of LIMEX '87.

The *Quest*'s motions were measured using two ship-motion packages. The DREA's own package used strap-down pitch, roll, and yaw gyros (both angle and rate) as well as a strap-down triaxial accelerometer. Additional accelerometers were placed at other locations on the ship. The Institute for Marine Dynamics, St. John's, Newfoundland (IMD) package measured similar parameters but had a stabilized platform so that accelerations would be measured relative to Earth-fixed, rather than ship-fixed, axes.

Ten 305-mm-diameter Metrox pressure transducers, installed in the starboard bow flare (Fig. 2), were of great interest to RSG2. Large-diameter pressure transducers en-

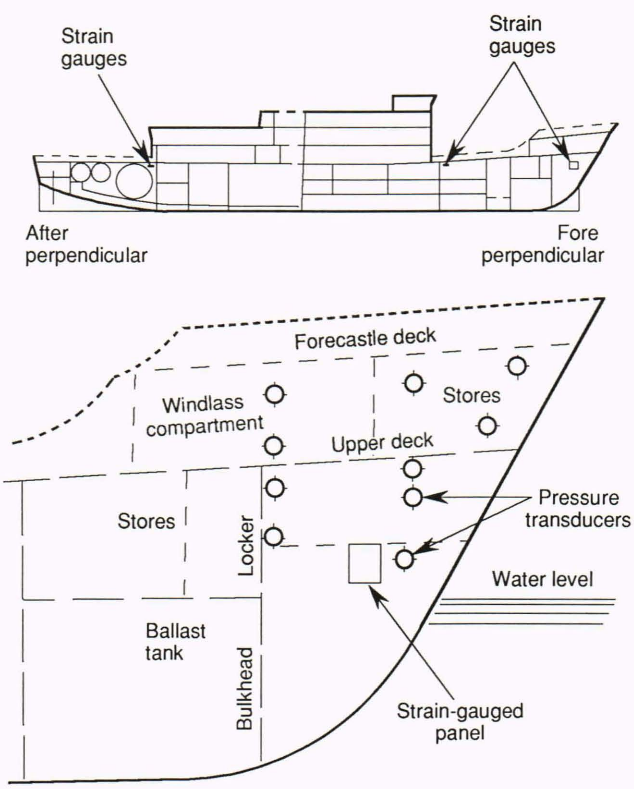

Figure 2. Starboard profile of the *Quest* and arrangement of the pressure transducers.

sured that only distributed pressures of structural significance were measured. More common small-diameter pressure transducers often detect extreme, but very localized, pressures that are of little relevance to ship structure design.

Strain gauges were also installed, both adjacent to one of the pressure transducers and on the main-deck longitudinal girders ahead of and abaft the superstructure (Fig. 2). The bow-flare gauges were arranged to complement the pressure transducers, and the deck longitudinal girder gauges assessed the bow-flare slamming-induced longitudinal bending.

SHIP PERFORMANCE AND SEA LOADS

LEWEX suffered from an excess of good weather; both the *Tydeman* and the *Quest* saw their worst weather in transit to the trials area. The *Quest* steamed from Halifax to St. John's in heavy quartering wind and sea, with freezing spray, and on the evening of 7 March 1987, while off the Laurentian Fan, an unexpectedly large wave group rolled the ship down to angles beyond the range of the bridge inclinometer (40°). Inclinometers are notably inaccurate, so it is unfortunate that neither ship-motion package was operating at the time.

The *Tydeman*'s arrival in St. John's was delayed by adverse gales and heavy pack ice, so that the *Quest* left for the LEWEX site without having made a planned pre-LEWEX rendezvous with the *Tydeman*.

On her two LEWEX sites, the *Quest* saw maximum significant wave heights, H_s, of only 4.3 m and typical significant wave heights of 2.5 to 3.5 m. Perhaps with the exception of the 4.3-m sea state of 17 March, these conditions were inadequate to provide the sea loads anticipated by RSG2 and required for full satisfaction of the RSG's goals.

The *Quest*'s seakeeping trials were planned to concentrate on the measurement of bow-flare slamming pressures, using the ten large pressure transducers described earlier. An unconventional seakeeping trial pattern was selected in recognition of that goal. Rather than measuring responses at a full range of headings to the sea, a four-heading seakeeping pattern was selected (Fig. 3). Headings ranged from head to starboard beam seas, in 30° steps (with head seas being 180°, after the standard naval architectural convention). This pattern also served to make identification of "true" head seas less critical.

Side-by-side seakeeping trials were conducted when the *Quest* and *Tydeman* were at the same site in LEWEX, with the *Tydeman* to starboard of the *Quest* so that video and cine records could be made of the relative motions at the *Quest*'s bow.

One of the most difficult on-site decisions during the LEWEX seakeeping trials was simply to determine, "In what direction are head seas?" With multimodal sea states often being the norm, leftover swell frequently was more prominent than the new wind sea; for consistency, wind direction and wind sea direction were used to select the first course to steer. On several occasions, this choice clearly proved to be wrong, as pitch angles and deck wetness were more severe on the supposed beam seas heading than the initial one in "head" seas.

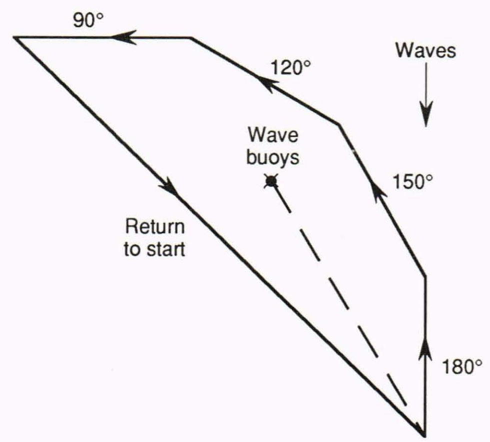

Figure 3. The *Quest*'s seakeeping pattern.

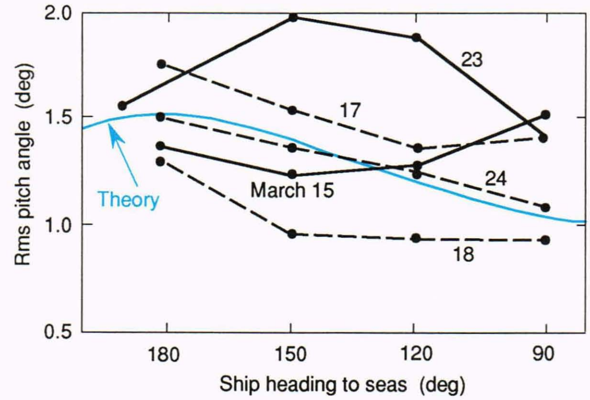

Figure 4. Variation of theoretical and trial pitch with ship heading. The theory uses a unimodal spectrum with 90° spreading.

Figure 4 illustrates this situation for the *Quest* by comparing the variation of pitch with heading with a prediction of the expected trend using SHIPMO4,[5] a typical ship theory seakeeping computer program. The SHIPMO4 prediction was performed by using a Bretschneider two-parameter spectrum with a 90° $\cos^2$ spreading function. The character of the trial results for 15 and 23 March differed markedly from the strip theory trend. A similar result might be expected for roll motions, but clear trends were obscured by the *Quest*'s roll-stabilizing tank.

Pressure data show similar divergence from heading dependencies implied by an assumption of unimodal sea states. Selected pressure transducer data are shown in Figure 5, together with SHIPMO4 predictions of trends for immersions and pressures. (The theoretical pressure trend is, in fact, the square of the relative velocity, which is proportional to pressure.) Trends for other pressure transducers also diverged from unimodal expectations, although some pressure transducer data were corrupted by amplifier overloading. A repeat bow-flare slamming trial was carried out in higher sea states in March 1989 to seek further data for RSG2.

The LEWEX sea states were so low that little useful strain data were obtained, although that could also be

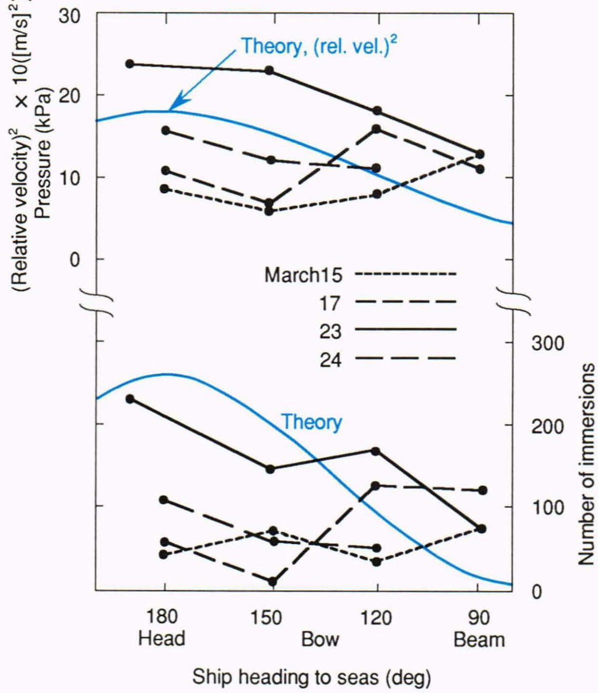

Figure 5. Immersion frequency and pressure for a selected pressure transducer, together with theoretical predictions of trends for immersion and the square of relative velocity (which is proportional to pressure) for a unimodal spectrum with 90° spreading.

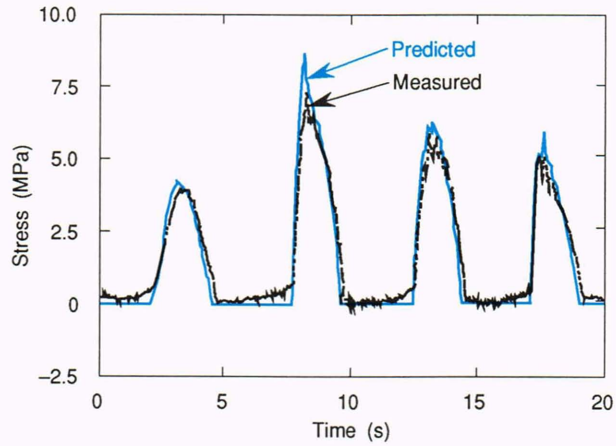

Figure 6. Experimental and finite-element-strain time series for a bow-flare plating strain gauge (see Fig. 2).

attributed to the use of the *Quest* itself. A short, deep, ice-strengthened ship cannot be expected to exhibit high main-girder strains in other than exceptional conditions.

On a positive note, the bow-flare strain gauge data were used in a finite-element validating study. Pegg et al.[6] applied measured-pressure time series to predict dynamic strains in the bow-flare region using the Vibration and Strength Analysis Program,[7] a finite-element code developed by Martec Limited under contract from DREA. The measured strains were used to validate the finite-element predictions for the same points. Figure 6 compares measured and finite-element-predicted strain-time histories.

NAVAL ARCHITECTURAL IMPLICATIONS

Before examining the naval architectural consequences of the *Quest*'s LEWEX experience in any detail, it is worth recalling the results of an earlier *Quest* ship motions trial, when the *Quest* was operating with her roll stabilizing tank empty, so that roll performance can be included in an assessment of short-crested sea effects.

During the earlier trial, a passing low-pressure system brought 20- to 40-kt winds, which veered from south-southeast through to west-southwest in 32 hours and generated 5- to 7-m sea states. The steadily veering winds ensured that there was always a very apparent short-crested character to the sea. Table 2 summarizes some sea states and ship motions during the storm. Sea state was both measured by wavebuoys and hindcast using the Ocean Data Gathering Program (ODGP) wave model.[8]

Large roll angles in nominal head seas (experiments D and E) are particularly noticeable in Table 2. If we combine this information with experiments B and C, which were consecutive beam and bow seas runs, it is again apparent that short-crested seas produce ship motions that do not vary with heading in the manner conventionally assumed. What are the consequences?

Table 2. Summary of *Quest* motions from an earlier trial.

Experiment	Speed (kt)	Heading to sea	H_s ODGP (m)	H_s Buoys (m)	Rms motions: Pitch (deg)	Rms motions: Roll (deg)	Rms motions: Center of gravity vertical acceleration (g)
A	≈0	Beam	4.9	3.5	1.93	7.94[a]	0.046
B	≈5	Beam	6.3	4.5	1.88	5.06	0.053
C	≈5	Bow	6.3	5.0	2.30	5.03	0.065
D	≈2	Head	5.5	7.0	3.06	4.80	0.066
E	≈2	Head	4.8	6.5	2.61	4.06	0.057

[a] Roll is largest in experiment A because the sea-state modal period was near roll resonance.

Many, if not most, ship seakeeping operability criteria are based on motions. For example, let us suppose that a particular shipboard operation must be curtailed when the roll angle exceeds 4° rms. Roll motions are lightly damped and thus are very sensitive to resonance. If a long-crested sea state is assumed, theory predicts that roll-curtailed operations may be restored through a simple change of heading. Even with a more realistic sea-state model using 90° $\cos^2$ spreading, a heading change can often restore operability, albeit over a smaller range of headings. If our sea-state model is extended to a typical LEWEX swell-corrupted directional spectrum, the heading sensitivity of motion response may be significantly modified. At times, operability may be curtailed at nearly all headings after only a small further increase in sea state. Figure 7 illustrates the effect of sea-state modeling on a 5200-tonne frigate steaming at 20 kt in sea state 7, with a 6-m significant wave height, and subject to a 4° rms roll angle limit on a shipboard operation.

An ad hoc group of five sea-state models was chosen for this example:

1. A Bretschneider spectrum, with a 12.4-s modal period and no spreading.
2. Same as (1), but with a 90° $\cos^2$ spreading function.
3. With (2) as the primary sea, and with (1) as the secondary, at 45° to the primary direction and with a primary-to-secondary energy ratio of 2:1, to represent conditions during the nearby passage of a low-pressure system.
4. Same as (3), but with the secondary sea 90° from the primary direction and a primary-to-secondary energy ratio of 3:1, to represent the effects of a distant weather system,
5. Same as (3), but with the secondary sea 135° from the primary direction and a primary-to-secondary energy ratio of 4:1, again to represent the effects of a distant weather system.

In reality, these models might be more representative if the total energy in models (4) and (5) were increased over that of the 6-m sea state by the amount in the secondary sea but the significant wave height were held constant to reduce the number of variables. Table 3 summarizes the results as a range of inoperable headings for both 4° and 3° roll criteria and as range of rms roll angle from best to worst heading. The 3° criterion was added because operability limits are rarely "hard" in practice. This is particularly relevant to model 4, where either a small increase in wave height or a small decrease in the acceptability criterion would significantly reduce operability. The range of roll angle between best and worst heading is so small for model 4 that degradation of operability will be very rapid with only a small sea-state increase, with little opportunity for compensatory heading change. This insensitivity of response to heading is reminiscent of much of the *Quest*'s LEWEX experience.

Similar examples could be given for other criteria, using the LEWEX experience. For example, pressure transducer immersions could be correlated with relative motion records to draw conclusions about bottom slamming or deck wetness.

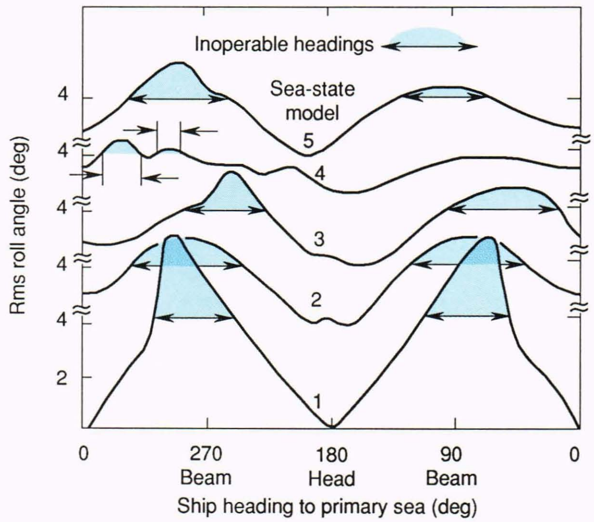

Figure 7. Operability of a 5200-tonne frigate subject to a 4° rms roll limitation on shipboard operations. See the text for the definition of a sea-state model.

Table 3. Operability of a 5200-tonne frigate in 6-m seas.

Sea-state model	Inoperable heading range (deg): 4° criterion	Inoperable heading range (deg): 3° criterion	Roll range (deg): Best – worst
1	88	168	7.0
2	164	258	3.1
3	142	231	3.5
4	43	316	2.0
5	133	254	3.4

What are the broader implications of LEWEX for naval architecture? For the most part, they are related to operability. Naval vessels are now designed with seakeeping in mind, and linear, two-dimensional theory ship-motion-prediction codes frequently are used to rank or evaluate the candidate design's lifetime or the mission's operability in locations of interest. Routinely, unimodal multidirectional seas are used, with 90° as the accepted spreading angle. The example above, together with the *Quest*'s own experience, suggests that applying spreading to unimodal spectra is not enough; the common occurrence of multimodal sea states must be recognized. This is a painful conclusion.

When Bales et al.[9] reported the results of hindcasting for NATO operational areas, they firmly established the use of short-crested sea states, in part, at least, because they reported results in a format convenient for existing frequency-domain seakeeping codes. If multimodal sea states are important to naval architecture, then the hindcasting results must be used more directly. This is considerably more onerous than simply assuming a 90° spreading angle and using a joint probability table for significant wave height and modal period.

Although feasible, simply simulating seakeeping performance and operability using an archived hindcast spectral database cannot be considered practical. To encourage the use of multimodal, multidirectional spectra, it would be better to employ a multiparameter spectrum, together with associated probability distributions for spectral parameters, to generalize an operational area hindcast for frequency-domain seakeeping calculations. Hogben and Cobb[10] have reported a parametric directional wave spectral model that, in principle, satisfies these goals. Juszko Scientific Services, under contract to DREA, is developing this model further, to address bimodal spectral modeling in Canadian operational areas.

CONCLUSION

The good weather conditions that predominated during LEWEX prevented the achievement of goals dependent on high sea states; however, the LEWEX pressure transducer and strain data were valuable for at least two reasons. First, when compared with relative motion predictions, pressure transducer data gave further evidence of the inability of a unimodal sea-state model to describe the sensitivity of ship response to heading. Second, the bow-flare pressure and strain data provided a rare opportunity to validate the ability of a finite-element code to model stresses in a complex, three-dimensional structure under dynamic loading.

The LEWEX experience confirms that multimodal spectra must be regarded as a common occurrence at sea. As a result, the relatively recent acceptance of multidirectional unimodal spectra for routine seakeeping evaluation in the design process offers insufficient improvement over the unrealistic unidirectional, unimodal sea-state model. Results of two *Quest* seakeeping trials, one in light-to-moderate seas (LEWEX) and an earlier one in heavier seas, demonstrate that unimodal sea-state models, even with spreading, fail to model properly the relationship of ship motions and heading. A simple operability example for a destroyer gives similar results.

The use of unimodal short-crested spectra, although an advance over unidirectional spectra, is insufficient to predict ship operational capability. The multimodal nature of a significant proportion of open-ocean spectra must be recognized and modeled if operational studies are to be realistic. Hindcasts offer a way to define multimodal seas, but the practical implementation of the information depends on the reformulation of hindcasts as multiparameter spectral models, with associated joint probability tables, suitable for use in frequency-domain seakeeping codes.

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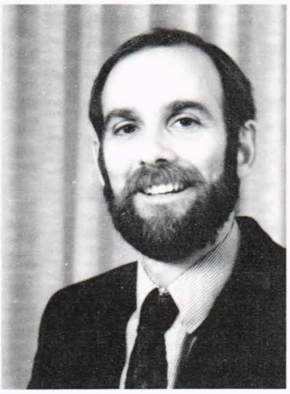
THE AUTHOR



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