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HNLMS *TYDEMAN*'S LEWEX EXPERIENCE AND MOTION SIMULATION IN MULTIMODAL SEAS

Measurements of motions of HNLMS *Tydeman* were made in a variety of multidirectional sea states during the Labrador Sea Extreme Waves Experiment. Although no extreme seas occurred, the moderate multimodal sea states illustrated that multimodality is important for time-domain predictions of ship motions and is especially useful during the design stage for assessing ultimate stability, that is, safety against capsizing.

INTRODUCTION

The Dutch vessel, Her Netherlands Majesty's Ship (HNLMS) *Tydeman* (Fig. 1), was one of two vessels participating in the Labrador Sea Extreme Waves Experiment (LEWEX). The *Tydeman* carried scientists and equipment from nine agencies within The Netherlands, United States, Federal Republic of Germany, France, United Kingdom, Norway, and Spain. The experiment was intended to support the goals of the North Atlantic Treaty Organization (NATO) Research Study Groups RSG-1 and RSG-2 of the NATO Defence Research Group, containing the Special Group of Experts on Naval Hydrodynamics and Related Problems.

HNLMS *TYDEMAN*

The *Tydeman* was the first ship in the Royal Netherlands Navy to be designed and equipped specifically for oceanographic research. The research can be for military as well as for pure scientific purposes. Civilian scientists may be assured of at least 30% of the seagoing time each year.

The *Tydeman* is well equipped for oceanographic research. Special attention was given to providing good seakeeping and maneuverability qualities, and the ability to make short, silent runs. The *Tydeman* can accommodate fifteen passengers and has ample space for laboratories, meeting areas, and various oceanographic instrumentation, including a working deck area and associated deck gear. Oceanographic and hydrographic data such as time, position, depth, temperature, salinity, wind, and pressure are all routinely and automatically collected. A summary of the *Tydeman*'s characteristics is given in Table 1.

Oceanographic research often requires overside handling of various equipment, either free-floating, towed, or anchored. The aft working deck is used mainly when traveling at normal speeds; the working deck at three-fourths of the ship's length forward is used mainly when drifting or traveling slowly. The *Tydeman* has good seakeeping properties and a passive, free surface tank to reduce roll motions to keep the working decks dry and in good operating condition up to about sea state 7.

Figure 1. The HNLMS *Tydeman*.

Table 1. The main characteristics of the *Tydeman*.

Displacement	2200 tonnes
Length	90.19 m
Molded breath	14.43 m
Draft (excluding sonar dome)	4.75 m
Draft (including sonar dome)	7.50 m
Installed power	2100 kW
Maximum speed	15 kt

To be easily maneuverable, the *Tydeman* is equipped with a bow thruster and a rudder with its own propeller, allowing rudder angles of up to 90°.

RSG-1 OBJECTIVES

The primary objectives of RSG-1 during LEWEX were to establish reliable methods to measure the directional properties of waves, and especially to improve methods for providing both measured and predicted wave conditions for full-scale sea trials and ship operations. Meeting these objectives is fundamental to validating ship-response predictions, ocean wave models and climatologies, and seakeeping surveys.

The RSG-1 plans for the *Tydeman* and the *Quest* (see the articles by Kjeldsen and Nethercote in this issue) were as follows:

1. To make simultaneous wave measurements with various *in situ* and remote instruments, some of which are still experimental.
2. To compare data from instruments and wave models for both validation and evaluation.
3. To conduct model tests with the *Quest* (and possibly the *Tydeman*) in scaled LEWEX directional seas in the Marintek facility in Trondheim.
4. To use sea trials and model simulations to evaluate the applicability and usefulness of directional wave data in ship design and operations planning.

INSTRUMENTATION

The instrumentation carried and deployed by the *Tydeman* during LEWEX is summarized in Table 2. For the first phase, the Wavescan buoy was moored in about 4000 m of water during the night of 13 March 1987, to be ready for the aircraft overflights on the following day. The mooring was performed from the aft working deck in 40-kt winds and 5-m seas by using an "anchor last" procedure. The deep-water mooring consisted of several separate sections, each wound on separate winches, so both the mooring and the recovery had to be performed in steps. In the first location (50°N, 45°W), the anchor and 300 m of line had to be abandoned.

Most of the drifting wave buoys were deployed from the forward working deck by using an A-frame or an L-frame. The Delft buoy could easily be dropped by hand, however, because of its robustness and light weight. The buoys sometimes drifted several miles or more between daily recoveries.

Table 2. Instrumentation carried and deployed by the *Tydeman* during LEWEX.

Parameter	System	Location	Country
Sea state	Wavec buoy	Drifting	The Netherlands
Sea state	Delft buoy (unidirectional)	Drifting	The Netherlands
Sea state	Endeco buoy	Drifting	United States
Sea state	Wavescan buoy	Anchored	Norway
Sea state	Infrared sensor (unidirectional)	Mounted	Federal Republic of Germany
Sea state	Navigation radar	On board	Federal Republic of Germany
Sea state	Wadirex buoy	Drifting	France
Sea state	Datawell wave-rider buoy	Drifting	France
Ship motions	Stabilized platform	On board	The Netherlands
Ship motions	Infrared sensor	Mounted	Federal Republic of Germany
Ship motions	Transducer case	On board	France
Ship motions	Comfort meter	On board	The Netherlands
Sea loads	Strain gauge	On board	United Kingdom
Oceanographic data	Oceanlog system	*Tydeman*	The Netherlands
Buoy location	Radio direction finder	On board	The Netherlands

Infrared (IR) and sonic sensors, along with navigation radar techniques,[1] are being developed to attempt to reduce the need for wave buoys during sea trials. The IR sensor was mounted on a frame (or "giraffe") far forward on deck and hung over the bow to obtain a clear vertical view of the sea surface, but it was limited by spray and large pitch and roll motions during heavy weather. The IR sensor measured only wave elevation and thus could produce only nondirectional spectra. It did have one advantage over the navigation radar, however, since its data could be processed on board. Unfortunately, structural limitations prevented the sonic sensor from being placed far enough forward on the giraffe to stay clear of the bow. The navigation radar technique required special provisions to trigger a photographic camera that recorded the plan position indicator display.

Ship motions were measured in three ways. First, the Delft hydromechanics laboratory[2] employed a platform, stabilized by a pitch, roll, and yaw gyroscope (to measure both amplitude and rate), on which three accelerometers were placed. Second, an IR sensor, stabilized by a gyroscope, measured the vertical accelerations to compute the sea state; ship motions were therefore part of its measured data. Third, a French measurement system contained three accelerometers at one location, and a transducer case contained a gyroscope, three gyrometers, and three accelerometers at a second location. In addition to these three objective measures of ship motion, a small device called a "comfort meter" was also tested. The "noncomfort index" was defined as the rate at which vertical acclerations exceeded a threshold value. Such a device could be quite useful in motion sickness research.

SHIP PERFORMANCE

Heavy seas and ice during North Atlantic transit caused a delayed arrival of the *Tydeman* in St. John's, Newfoundland, preventing a pre-LEWEX rendezvous with the *Quest*. To recover some of the lost time, the *Tydeman* moored its Wavescan buoy immediately upon arriving at the first LEWEX site (50°N, 45°W). Mooring was accomplished in the middle of the night and, ironically, in the highest seas of the experiment. During the following two days, the significant wave heights were only 3.5 to 4.5 m; the remainder of LEWEX experienced even lower seas. These seas, lower than hoped for, were insufficient to investigate the nonlinear behavior of wave buoys and ship motions. On the other hand, the sea states were more often multimodal than not, and thus served the RSG-1 goals well.

The multimodal seas (composed of both swell and wind seas) made it difficult to select a principal wave direction on which to base the seakeeping experiments. The ship runs were planned to occur in 30° increments, proceeding systematically from head seas to following seas. In preparation, the anti-roll tank was emptied to assure straightforward ship-motion predictions. Computer simulations were performed for several multimodal sea conditions experienced during LEWEX, two of which will be summarized here.

As stated earlier, a three-dimensional description of the wave field is required for operational applications such as ship routing and task optimization. The Royal Netherlands Navy considers such a description useful, even during the vessel design stage. Predicted ship motions in multimodal seas can strongly influence the choice of ship design criteria. Extreme roll motion, including capsizing, is an important operational consideration.

Our plans for the future therefore include the following: (1) establishing a standard procedure to treat ship motions, including the nonlinear effects induced by multimodal high seas; (2) checking the reliability of the computed motions by comparing simulated motions with full-scale motions in multimodal high seas; (3) comparing full-scale results for unimodal and multimodal spectral representations, both having identical total energy; and (4) comparing calculated motion results for various ship designs and ship operations over a variety of sea states. These efforts will result in better ship design criteria to improve safety in high seas, and the design criteria will be extended to a set of operational rules for ships operating in extreme sea states.

Some results of a time-domain calculation are presented in the next section and are compared with the full-scale data measured during LEWEX. Ship motions, calculated with and without accounting for multimodality, are also presented.

MOTION SIMULATION

Motions of the *Tydeman* have been simulated by using computer programs developed for the Royal Netherlands Navy by the Marine Research Institute of The Netherlands.[3] The time-domain simulation sums all the relevant forces at each time step to solve the six equations of motion. The relevant forces include inertial effects, hull damping forces, weight and buoyancy forces, propeller and rudder forces, and wind and wave forces. In the LEWEX runs, however, only the roll, pitch, and heave motions were calculated; the wind forces were neglected, and the rudder was fixed in the zero-angle position. Pierson–Moskowitz[4] spectral forms were used to model both unimodal and bimodal representations of the LEWEX wave conditions. Multimodal seas were modeled by a unimodal representation by integrating the spectral density over all wave directions and fitting the data to a Pierson–Moskowitz spectrum. A bimodal wave spectrum was modeled by identifying the two principal wave directions and by assuming that the sum of the energy from each system was equal to the total measured energy. The same assumption was also made for the energy moment, that is, the product of energy and wave direction.

RESULTS

Table 3. Summary of wave specifications at the *Tydeman* for two separate runs.

	14 March Run No. 8		23 March Run No. 102	
Parameter	Unimodal model	Bimodal model	Unimodal model	Bimodal model
Significant wave height (m)	3.70	2.47 1.28	3.33	2.25 1.10
Average period (s)	9.2	9.4 8.9	7.6	8.1 6.6
Peak period (s)	11.4	11.6 11.0	9.4	10.0 8.2
Relative wave direction (deg)	0	30 −80	0	34 −41

Table 3 shows principal wave characteristics for both 14 March and 23 March; calculated bimodal values are given for significant wave height, average period, and peak period, with relative wave directions of each of the modes.[5] Figure 2 compares both the unimodal and bimodal predictions for the same days with actual roll, pitch, and heave measurements at various ship headings.

On 14 March (solid curves in Fig. 2), measured roll amplitudes, most important when considering capsizing, show good agreement with the bimodal simulation, although simulated roll motions for the mean (unimodal) wave approximation are too low in head seas and too high in beam seas. Simulated pitch motions are, for some unknown reason, substantially underestimated. The simulated roll motions using a bimodal sea are more realistic than those using a unimodal, long-crested, irregular sea. The unimodal wave results are reasonably good, however, and for some types of motion are even better than the bimodal results, because those types of motion are less sensitive to changes of heading and modal characteristics.

The results of 23 March (dashed curves in Fig. 2) were collected during higher-speed runs between 11.3 and 12.6 kt in seas having a 3.3-m significant wave height. Contrary to the bimodal roll-motion simulations of 14 March, which compare rather well with the measured results, the roll comparisons of 23 March are not as favorable in either absolute values or trends. Pitch simulations again compare poorly with measurements, but bimodal heave simulations compare well at all headings. This apparent lack of success in the model simulations has several possible explanations:

1. Oversimplified multidirectional modeling: Roll is particularly sensitive to the frequency of encounter of the forcing sea state, and apparently minor changes in a simplified spectral model may have a significant effect on roll predictions. Figure 2 shows that spectral variations at nominally the same significant wave height may lead to order-of-magnitude changes in roll, whereas heave changes by 40% at most.

2. Irregularity of the seaway: Directional spectra give substantial information about a seaway. Nevertheless, although the spectra may be identical, the actual 30-min wave train experienced by a ship is not the same as that used in the motion simulation. Several simulations are required to reach a statistically significant result. Table

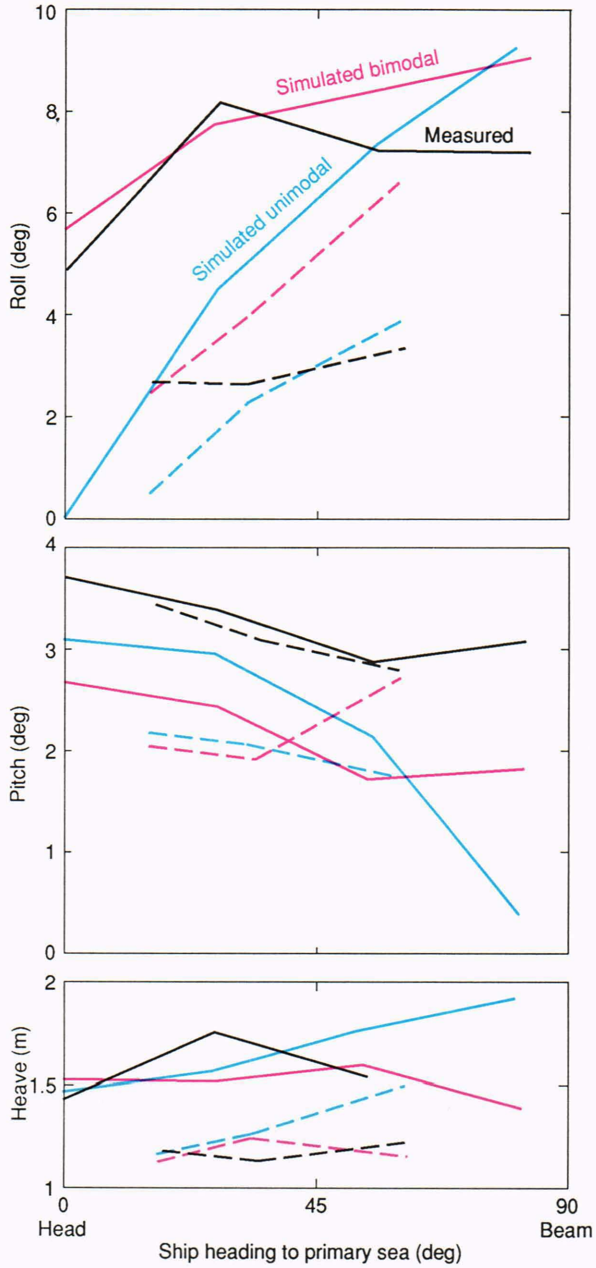

Figure 2. Comparisons of measured (black curves) and simulated significant ship motions. The red curves are the bimodal simulations, and the blue curves are the unimodal simulations. The solid curves are for 14 March, significant wave height = 3.7 m, and the dashed curves are for 23 March, significant wave height = 3.3 m.

Table 4. Variability in modeled ship motions resulting from five 30-min simulation runs.

	Run number				
	1	2	3	4	5
Wave height (m)					
Maximum	−2.94	3.05	3.00	3.20	−3.18
Heave (m)					
Maximum	−2.58	−2.45	−2.49	−2.57	−2.63
σ_H	0.76	0.76	0.75	0.75	0.76
Roll (deg)					
Maximum	12.7	13.3	13.0	12.4	13.3
σ_R	3.89	3.84	3.92	3.94	3.89
Pitch (deg)					
Maximum	−3.81	3.47	3.79	−4.02	−3.93
σ_P	1.24	1.23	1.24	1.24	1.25

Note: The ship speed was 2 kt, and the heading was 30° off the "head seas" for the LEWEX wave system of 14 March, Run No. 8, as defined in Table 3. All runs are for a significant wave height of 3.7 m; σ is the standard deviation in heave, roll, or pitch.

4 shows the variation obtained from a sequence of five 30-min simulations, each driven with an identical spectrum. The results indicate the ranges of ship-motion uncertainty expected for a single simulation run.

3. Accuracy of full-scale measurements: The results of the full-scale observations are determined by the accuracy of the measuring devices and the errors in the analytical techniques. Comparisons of simultaneous measurements made with different sensors illustrate the problem. For example, simultaneous measurements of significant roll from two separate measurement systems sometimes disagreed by nearly a factor of 2.[2,6]

4. Ship loading and control: Ship load condition, as well as its control, could have varied during the trial, although neither was found to influence the results when load condition and autopilot settings were varied during the simulations.

ULTIMATE STABILITY

The extreme roll behavior of a ship in complex seas is of great interest to both ship designers and operators. Methods now used to evaluate a ship's margin of safety against capsizing are based mainly on experience and do not give much physical insight into the relation between ultimate stability and ship design or operational performance. The time-domain simulation program, using multimodal sea states, revealed several concerns that involve ultimate ship stability. The differences between the bidirectional and the unidirectional simulations are too great to be neglected. Knowledge of the multimodal behavior of the sea is necessary to evaluate accurately the ultimate stability of a ship.

Additionally, to account for wave groups, freak waves, and similar inhomogeneous wave phenomena, the ship-motion simulation can and should deal with the real three-dimensional sea surface description, not simply the spectrum. The actual time history of the waves should be used as an input for motion-simulation programs and for defining the relevant parameters in ship design and operation.

In a multimodal sea, a straightforward simulation shows that a safe ship heading to prevent capsizing is not easy to find. Given the existence of extreme waves and the presence of multimodal seas, more detailed knowledge is required as to where and when these waves and seas occur so that they can be avoided. Multimodal spectra can then be used as an indication of ship safety.

CONCLUSION

The LEWEX seakeeping trials with the *Tydeman* indicate that a unimodal model of the seaway is inadequate for ship design and evaluation, whereas a multimodal description is both feasible and necessary. For ultimate stability assessment, it may even be necessary to specify wave-elevation time series.

With better sea-state models, numerical ship-motion programs offer the promise of realistic ship-performance predictions, but the predictions will need to be validated in higher sea states than those obtained in LEWEX. The simulation code used herein requires further development to reconcile pitch-prediction anomalies.

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