SEAKEEPING CORRELATION STUDIES

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Abstract.

At the heart of any model or numerical study of the dynamics of a ship in a seaway is the tacit assumption of a good correlation between the motions observed in the model study or the predictions in a numerical study with the motions that would be obtained for the full scale vessel. The following paper describes the results of a study investigating these correlations. One of the more noteworthy conclusions of the study is the clear need for an adequate description of the seaway in which the sea trials were performed. In particular, sea trials are generally performed not too far from land where sea spectra are quite likely to be directional. Unless the directional spectrum is properly resolved, predictions from model or numerical studies are likely to differ from the observed full scale data.

1. INTRODUCTION

Over the past number of years there have been some significant advances in the area of Ship Performance Evaluation. The three main headings that characterize Ship Performance are (i) Resistance and Propulsion, (ii) Seakeeping, (iii) and Manoeuvring. Their evaluation is based on numerical and experimental analyses, and full scale trials. The last named method is generally the most expensive and in some ways the most difficult to carry out. The expense is related to the cost of chartering a vessel and instrumenting it. The charter costs are considerably amplified by the need to have the vessel on standby for a number of days awaiting manoeuvring, or seakeeping tests. It is surprising how many consecutive days of flat calm there are when awaiting seakeeping trials and how few when 'calm' is the required condition! In short, the lack of control of environmental conditions is what makes sea trials both expensive and not always reliable. The results from a seakeeping trial are useful only if environmental conditions (wind, waves and current), and ship conditions (GM, displacement, draft etc.) are sufficiently well determined to allow for extrapolation to sea states and other ship conditions that might be of more interest than those for which the sea trials were conducted.

A collaborative project (the 'Ship-Model Correlation Study ') was set up between Memorial University of Newfoundland (MUN), the Institute for Marine Dynamics (IMD) and Oceanic Consulting Corporation to evaluate the correlations between Model experimental data, Numerical model data and full scale sea trial data in the three areas already alluded to above. The study was funded by a grant from NSERC, NRC and Oceanic together with in kind contributions from all three participants. The vessel used for the study was a research/training vessel (*M/V Louis M. Lauzier*) leased by Memorial University from the Canadian Coast Guard and is described below. This paper describes the seakeeping portion of the Ship-Model Correlation study.

2. DESCRIPTION OF THE *M/V LOUIS M. LAUZIER*

The 'Lauzier' is a 40 m long coastal research and survey vessel on long term lease by the Marine Institute of Memorial University from the Canadian Coast Guard (CCG), Central & Arctic Region. The vessel is currently based in St. John's, Newfoundland and is primarily used by the Marine Institute as a training platform for mariners as well as a research platform by the MUN Oceanography Dept. The 'Lauzier' is a hard chine aluminum hulled, twin screw fitted with four bladed fixed pitch propellers, twin rudders, bow thruster, centerline skeg and cylindrical shaped bulbous bow. Each propeller is supported on a long length of external exposed shafting by one set of 'A' brackets. The rudders are of simple balanced under-hung flat plate design controlled in tandem using a single control signal. Other appendages include a set of flat plate bilge keels fitted inboard of the chine and a large bottom mounted sounder caisson off the longitudinal centerline just forward of midships on the starboard side. The vessel is endowed with a modern navigation suite and can be steered using autopilot or manual control. Originally the 'Lauzier' was designed as a fisheries patrol vessel capable of speeds of well over 20 knots. The role of the vessel has been changed several times since it was built by Breton Industries Ltd. of Port Hawkesbury, NS in 1976. The stern was extended, the vessel has been re-engined, new propellers designed and fitted, and a bow thruster and bulbous bow added. The maximum speed of the 'Lauzier' has been reduced to 11.5 knots. The principal dimensions are provided below.

Principal Particulars:

Length Overall	40 m
Length Between Perpendiculars	37.1 m
Breadth	8.2 m
Draft	2.44 m

Gross Displacement	332 t
Maximum Speed	11.5 kt

3. INSTRUMENTATION FOR SEA TRIALS

A number of ship motion sensors were fitted to the 'Lauzier' to measure:

- Orthogonal angular (roll/pitch/yaw) rates (deg./s);
- Orthogonal linear (surge/sway/heave) accelerations (m/s^2); and
- Roll and pitch angle (deg.).

Angular motions can be measured anywhere on the ship and so it is generally convenient to measure these motions close to the location of the data acquisition package to reduce signal cable runs. It is desirable to measure accelerations as close to the ship's center of gravity however and this meant mounting a tri-axial accelerometer package in the engine room on the 'Lauzier'. The accelerometers and angle measurement instrumentation can be physically calibrated by orienting the devices through a series of known angles. The rate gyros could only be calibrated by using information from the manufacturer's specifications.

3.1 Ship's Heading Gyro.

Ship's heading angle was measured by tapping the signal off a repeater for the ship's Sperry Mark 37 Mod. 1 gyrocompass fitted in the compartment aft of the data acquisition computer location on the Wheelhouse Deck. The stepping motor signal was interfaced with the data acquisition computer through a NAVGYRO – Mark II microprocessor based marine gyrocompass interface to convert the signal to a standard compatible digital format prior to acquiring the data. It was convenient to acquire the signal from a repeater source since the repeater could be isolated and shut down when the connection to the data acquisition computer was being installed without having to spin down the ship's gyro.

3.2 Position, Forward Speed Information.

A Differential Global Positioning System (DGPS) signal was acquired as a convenient method of recording planar (Latitude and Longitude) position, forward speed over the ground, as well as a second heading angle. DGPS provides greater positioning accuracy than standard GPS since error corrections can be incorporated using a second GPS signal transmitted via HF from a receiver located at a known location on land. For the 'Lauzier' trial, a Coast Guard correction signal transmitted from Cape Race, Newfoundland was acquired. To acquire DGPS data, IMD installed a Trimble model NT200D DGPS receiver adjacent to the data acquisition system with the antenna fitted on a temporary mast fixed to a stanchion on the top of the superstructure. Care was taken to fit the antenna as far from obstructions as possible to minimize the risk of signal interference. Although the 'Lauzier' is fitted with two DGPS systems for navigation, it is standard practice at IMD to fit a dedicated GPS system so that data acquisition software can be verified in the lab prior to the trial and also the possibility of any interference with a ship's integrated navigation system is eliminated.

3.3 Data Acquisition System.

A PC based data acquisition system was installed in the Biology Wet Lab on the wheelhouse deck to provide a quiet space with abundant countertop area available for mounting equipment in a compartment that was not generally used by the crew. The lab was located just aft of the Bridge so communication between the trials staff and Bridge crew was not a problem. The computer included the following attributes:

- windows based operating system;
- data compression software to conveniently store the data on 250 MB ZIP disks;
- spreadsheet software for convenient data analysis during the trial to monitor the integrity of the acquired data; and
- acquisition software as well as software for viewing the time series data graphically.

A dedicated data analysis software package was developed to acquire data from both analog and digital sources in parallel, monitor the relevant ship control parameters real time and store the data in a convenient compressed data format to reduce required memory. Additional hardware included:

- NavGyro Interface – used to interface with ship's heading gyro
- NavMux – used to multiplex digital signals from navigation sensors
- Signal Conditioning hardware for filtering, digitizing and interfacing analog channels.
- Uninterrupted Power Supply (UPS) to sanitize ship's AC power supply and provide power to the data acquisition system in the event of a short power outage.

3.4 Wave Buoy.

A small discus shaped directional wave buoy procured by MUN for these sea trials using NSERC funding was deployed to acquire information on the wave conditions during the seakeeping trials. The buoy was configured to acquire data to compute wave height, period and wave direction for 17 minutes every half hour - processing and storing the data in an ASCII format file on an internal non-volatile flash disk. A radio modem was used to communicate between a base station on the 'Lauzier' and the buoy over line of sight range using a spread spectrum device operating in the UHF 902-928 MHz frequency band. Personnel from the MUN Oceanography Dept. designed a buoy mooring system suitable for 165 m depth of water after discussions with the buoy manufacturer. An adjacent float fitted with radar reflector and strobe light designed to facilitate locating the buoy at night and in poor visibility conditions was included in the deployment. The buoy was launched/recovered by hand over the side of the vessel each day of the seakeeping trials.

4. SEAKEEPING TRIALS

Plans were made to acquire seakeeping data on the 'Lauzier' outside the St. John's traffic zone about 17 nautical miles east of St. John's. The location was selected to provide exposure to incident waves relatively free from the influence of land in an area where little traffic was expected. Successfully launching or recovering an expensive wave buoy in heavy seas without damaging this sensitive instrumentation is the most challenging facet of a seakeeping trial. MUN Oceanography staff provided assistance by designing a suitable mooring arrangement for the buoy to be anchored in 90 fathoms of water. Once the buoy was deployed, a series of five 20 minute runs for two forward speeds (6 and 10 kt nominally) were carried out around the buoy in a pentagon pattern and ship motions measured in head, bow, beam, quartering and following seas. Two tests at zero speed in beam seas were also conducted, one at the start and one at the end of the trials.

A seakeeping trial is scheduled when statistically there is a high probability of getting the desired environmental conditions. In the case of the 'Lauzier' trial, waves generated in sea state 3 to 5 were targeted. Four attempts were made to acquire seakeeping data on the 'Lauzier' in the fall of 2001. The first attempt on September 10th failed due to flat calm weather. The second trial on September 28th was also unsuccessful due to a failure of the wave buoy communications hardware. An attempt on October 24th also failed due to a lack of suitable weather conditions. Finally on November 6th, data was acquired in sea state 3 waves propelled ahead of a storm front. The measured motions were not as high as the trials team would have liked but time and resources were running out.

Draft readings were taken at dockside at the beginning and at the end of the trials together with water temperature and density. The hydrostatic conditions of the vessel at the time of the trials were then determined from the ship's stability booklet.

5. NUMERICAL CORRELATION STUDY

Numerical predictions of the motions of the Lauzier for the conditions of the sea trials were carried out using a time domain motion prediction code MOTSIM developed by IMD in conjunction with MUN [1]

MOTSIM is a non-linear time domain Seakeeping code that simulates six degrees of freedom motion, with forward speed in arbitrary wave conditions. The ship's geometry is defined in terms of a sequence of sections, each of which is described by a set of panels. At each time step, the code determines the intersection of these panels with the waterline and redefines the paneling describing the ship's wetted surface. The pressure forces associated with the incident waves are then numerically integrated over this surface, using second order Gaussian Quadrature. The waves are taken as second order Stokes waves. The normal velocity distribution associated with the velocity of the vessel and the incident wave particle velocities is averaged over each panel and then a least squares fitting of this distribution based on the wetted panels belonging to a particular section is made such that a unique decomposition of the modal velocities (surge, sway, heave and roll) is obtained that most closely satisfies the body boundary condition on the section. The use of the wetted surface to determine modal velocities serves as an approximation to a non-linear body boundary condition. The code allows for more general decompositions of the velocity distribution to be made using a higher number of standard or non-standard modes. From this decomposition, the scattering forces and moments are determined for each section based on pre-calculated >memory= functions. The memory functions for each section are derived from added mass and damping coefficients from zero speed linear theory over a truncated semi-infinite frequency range. Their use allows for arbitrary frequency content in the scattering forces and moments. The added mass and damping coefficients can be either 2 or 3 dimensional. Corrections are made for forward speed. Viscous effects associated with roll damping and manoeuvring are determined using semi-empirical formulae or experimentally determined coefficients. The total forces are then used in the non-linear equations of motion to determine the motions of the vessel.

One of the requirements to simulate the motions of the Lauzier (or any vessel) obtained in sea trials is to determine the wave conditions and the heading of the vessel relative to those waves. The wave buoy as described above determines a directional spectrum for the wave field at the deployment location. The output from the software that comes with the wave buoy is presented in terms of a non-directional spectrum S (ω) together with a spreading function D(ω,α). The spreading function is calculated by the wave buoy software based on fitting the data derived from the pitch and roll of the buoy. A typical example of a non-directional spectrum based on one of the sea trials is shown in figure 1. The form of the spreading function is given by;

$$D(\omega,\alpha) = {}^{1}\!/_{\pi}\,(0.5 + r_1 \cos(\alpha - \alpha_1) + r_2 \cos 2(\alpha - \alpha_2))$$

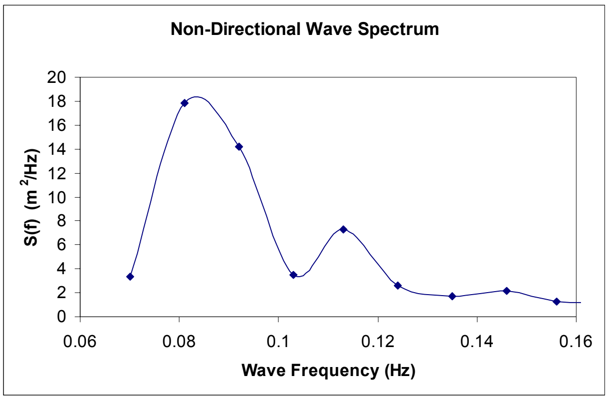

Figure 1. Non-dimensional Spectrum from Sea Trials

The coefficients r_1 and r_2 are given in tabular form for each frequency ω in the derived non-directional spectrum. α_1 and α_2 are the average and dominant wave directions. There were some discrepancies in the sea trials between what was perceived as a beam sea by observers on board the vessel and the direction of the vessel relative to the dominant or average wave direction as determined by the wave buoy software. The headings at which the trials took place were therefore not the expected 90 degrees for beam seas and 180 for head seas etc. but rather for example, 75 degrees and 165 degrees. There were also likely differences in the wave field as the vessel steamed away from the wave buoy. After each trial the vessel heading was changed by 45 degrees. Because of the initial error in the perceived wave direction (it is difficult to determine in a short crested sea), the 'error' was propagated and possibly increased in subsequent trials.

Results of the simulations compared to the trial data for significant amplitudes of roll, heave, pitch and yaw are shown in figures 2 to 9 below. Also shown in these figures are results from simulations using different spectral representations of the sea state. One is for a uni-directional wave system, another for a standard JONSWAP spectrum using a standard cosine squared spreading function, and a similar one that uses the broader Bretschneider spectrum (both of these use significant wave height and mean wave period as input parameters, and the gamma factor in the JONSWAP is 3.3) and finally the wave spectrum as derived from the wave buoy software (indicated as the 'measured directional' wave system in the legend). It is clear that there are significant differences between the predictions for the different representations and that derived from the wave buoy data clearly gives overall the best predictions. There is of course a level of uncertainty in the spectrum derived from the wave buoy data, uncertainty due to distance from the buoy, and uncertainty about the precise heading of the 'Lauzier' relative to the waves. The motions of the vessel can at least be expected to lie in the range indicated by the differing spectra, which they do.

6. EXPERIMENTAL CORRELATION

6.1 Description of the Lauzier Model

Two model scale replicas were constructed of the 'Lauzier'. These models were used to carry out tests characterizing different components of the ship's performance. A 1:6 scale model was used to generate results for calm water Resistance and Propulsion, while a 1:12 scale model was used for Seakeeping and Manoeuvring experiments. The model hulls were constructed using a foam mold with a fiberglass shell.

Like the hull, the appendages are scaled versions of those on the 'Lauzier': 4 bladed fixed pitch propellers, twin rudders operated by a single rudder servo, centerline skeg, bilge keels, sonar caisson, and a cylindrical shaped bulbous bow.

For the seakeeping experiments, it was not necessary to model the superstructure of the 'Lauzier'. Instead a 15 cm high plexiglass coaming was fitted around the perimeter of the entire main deck. On the stern, the coaming was raised another 15 cm. This was deemed a reasonable height since the sea state that the model will experience will only produce limited amounts of spraying and/or green water. The coaming was also modified in the bow in order to accommodate two large 24 V batteries. The batteries were placed in this location in order to achieve the target GM of 0.18 m and radius of gyration for roll of 0.315 m. These batteries are primarily used to activate the electric propulsion motors - consisting of two small Faulhaber motors with an integral 3.75:1 gearbox. This gave a recommended maximum continuous rating of 18 rps. However, the motors can achieve values as high as 22 rps for short periods of time.

6.2 Instrumentation

This section describes the instrumentation onboard the 'Lauzier'.

Model Motions

Model motions were measured using the following independent systems:

1) Systron Donner MotionPak II: Model motions with six degrees of freedom were measured using this unit located at the CG of the model. The sensor unit consists of three orthogonal linear accelerometers measuring heave, sway and surge accelerations and three orthogonal angular rate sensors measuring roll, pitch and yaw rates (deg./s).

QUALYSIS System: Six infrared emitters were fitted on lightweight Plexiglass masts to the model permitting the model to be tracked using an array of ten cameras located at the east end of the Offshore Engineering Basin (OEB). The system was used to measure the following six motions: orthogonal linear displacement (X, Y, Z) of the model CG in a tank co-ordinate system; heading angle relative to a tank co-ordinate system; pitch and roll angle in a body co-ordinate system. Planar (X, Y) position from the QUALYSIS system was used to determine model speed over ground.

Rudder Angle

This was measured using a rotational potentiometer at the pivot point of one of the rudders. The rudders were connected together by a single rod and controlled by a single rudder servo.

Shaft Rotation

The shaft rotation was measured by attaching a tachometer driven by individual belt drives to each shaft, just aft of the motors. The tachometers provide an analogue signal linearly proportional to shaft speed, which was calibrated using a laser tachometer aimed at a piece of reflective tape located on the shaft.

Wave Elevation

Wave Elevations were measured using four freestanding capacitance wave probes. The waves were matched using a separate wave probe fitted during the wave matching process at a position defined as test center - a central point in the OEB.

Due to time constraints associated with wave matching, of the ten different spectra collected during the sea trials, only one was chosen to be used for the model tests, even though there were some variations in the spectra derived from the wave buoy over the course of the trials. The non-dimensional spectrum shown in figure 1 was chosen as the representative spectrum with spreading function determined for that particular trial. The double peak shown in figure 1 was thought to represent well the general nature of the seas during the period of the sea trials.

However it should be noted that relatively few points were used to represent this non-dimensional spectrum (see figure 1) over the frequencies where there is most energy leaving some doubt as to how well the spectrum represents the true sea state.

The wave matching process carried out in the OEB matched the non-dimensional spectrum. The spreading function was simulated using software developed at IMD for generating multidirectional seas. Just how well the final short crested seas in the OEB matched those of the sea trials was not entirely clear.

Data Acquisition System

All analogue data was low pass filtered at 10 Hz, amplified as required and digitized at 50 Hz. All data acquired on the model was conditioned on the model prior to transfer to the shore based data acquisition computer via radio telemetry. The wave elevation and QUALYSIS data was transferred to the data acquisition system via cable, conditioned and digitized using a NEFF signal conditioner and stored in parallel with the telemetry data. Synchronization between the NEFF data and telemetry data is nominally within 0.2 s.

Model Control System

The shaft speed and rudder angle are controlled and manipulated by software installed on an on-shore computer that communicates with the model via a wireless modem. The computer operator can control the model using either the levers on the software control panel or a steering wheel and pedals set.

During seakeeping testing, the software is set to autopilot mode. This mode keeps the model on a set course during the test run by monitoring the heading angle supplied to the computer by the Qualysis system and independently controlling the rudder angle. All the operator needs to do is to set the shaft speed and required direction before the run and take control of model at the end of the run.

6.3 Description of Experimental Set-Up

The IMD Offshore Engineering Basin (OEB) has a working area of 26 m by 65.8 m with a depth that can be varied from 0.1 m to 3.2 m. The depth used for these tests was 2.5 m. Waves are generated using 168 individual, computer controlled wet back wavemaker segments, hydraulically activated, fitted around the perimeter of the tank in an "L" configuration. Each segment can be operated in one of three modes of articulation: flapper mode (± 15º), piston mode (± 400 mm) or a combination of both modes. The wavemakers are capable of generating both regular and irregular waves up to 0.5 m significant wave height. Passive wave absorbers are fitted around the other two sides of the tank.

Wave Generation: An irregular short crested wave field was generated at two different wave directions (25° and 65° relative to the west wall of the OEB), depending on the relative heading angle of the model. The length of the irregular wave record is 347 seconds (20 minutes full-scale).

Test Program

The test program consists of two forward speeds with five headings per speed. The two speeds were nominally 6 kt and 10 kt. The heading angle is based on the heading experienced by the 'Lauzier' during its seakeeping trials (as noted above). 180° is defined as head seas. In addition, a zero forward speed drift run was carried out in nominally beam seas.

To achieve these headings while obtaining maximum test run length at the required speed, a moveable static-weight-based model acceleration system was used. The launching system allows the model to accelerate more quickly to the desired model speed by thrusting the model forward at the beginning of the run. To achieve the longest testable distance, the model acceleration system is moved to various locations around the tank. Even with this improvement it was still necessary to run the model down the tank for the same heading for as many as twenty times to obtain a full twenty minutes (full scale) of data. The time history of the wave spectrum to be generated was segmented with overlaps, and the appropriate segment used for each of the repeated runs.

Results.

Unfortunately only some of the results from the experimental program were available at the time of writing of this paper. Results for the 6 kt tests are shown in figures 10 to 12. Results from the full scale trials and the numerical predictions from Motsim are shown in the same figures. Also at the time of writing it has become evident that there were transients in the autopilot operation at the beginning of the runs that will need to be filtered out in order for yaw amplitudes to be correctly identified. The results in figures 10, 11,and 12 are only for heave, roll and pitch. The agreement (ie the correlation) between the three sets of results seems reasonable given the uncertainties associated with the precise heading relative to the waves and the description and representation of the spectra derived at the time of the sea trials. The results for the zero speed beam seas are shown in table 1 below. The model drifted down the tank in the experiments and ended by being about 30 degrees off its original heading (with the bow pointing more into the incoming waves). Similar observations were made during the sea trial although the heading change was not as great (possibly due to wind and current effects). That would probably account for the pitch being greater in the experiment and simulation.

Table 1. Zero Speed Beam Sea Results

	Motsim	Sea Trial	Expt
Heave(m)	1.54	1.58	1.62
Roll (dg)	10.3	10.5	9.9
Pitch (dg)	3.1	2.5	3.4

7. CONCLUSION.

The motions derived from the numerical code, and full scale observations are in reasonable agreement. The limited results from the experimental program show similar agreement. The difficulty of representing the sea state at the time of the trials both numerically and in a model basin are thought to be the chief cause of discrepancies rather than scale effects, although it is possible that differences in roll motion were associated with scaling. A more thorough analysis of the differences between the three modes of evaluation will need to be made. A likely approach would be by simulation. In fact some preliminary work along these lines has already been carried out.

8. REFERENCES

[1] Pawlowski, J.S., Bass, D.W., >Theoretical and Numerical Study of Ship Motions in Heavy Seas=, Trans. SNAME, New York, October 1991.

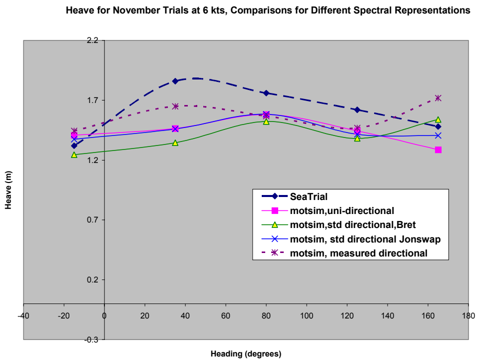

Figure 2. Heave at 6 kt

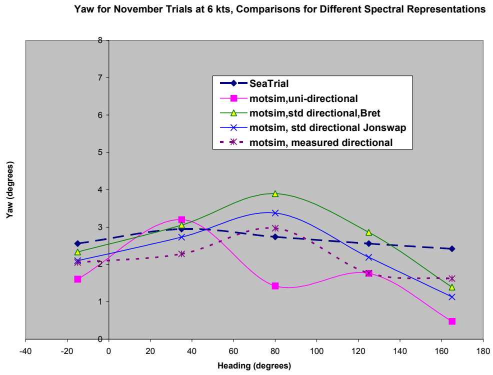

Figure 5 Yaw at 6 kt

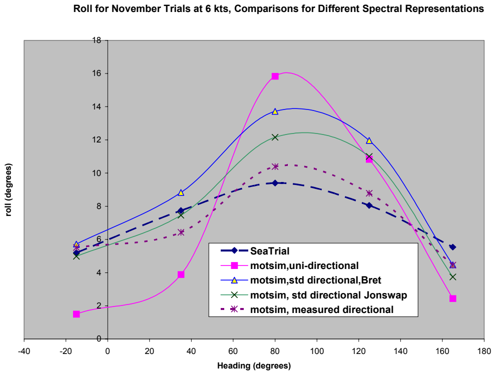

Figure 3. Roll at 6 kt

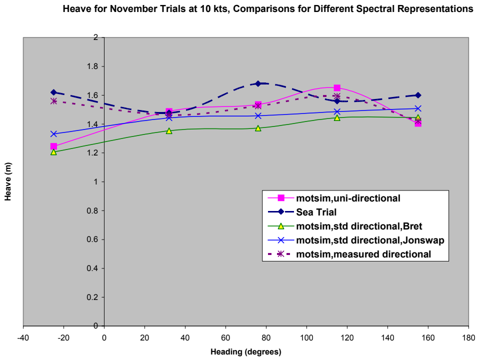

Figure 6. Heave at 10 kt

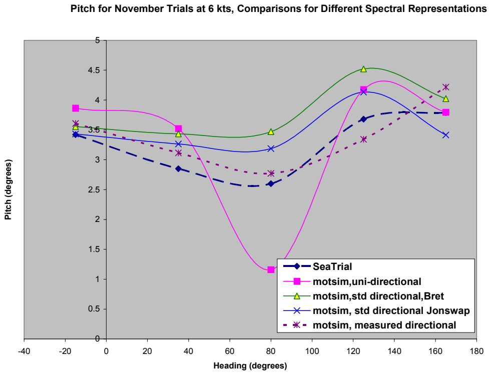

Figure 4. Pitch at 6 kt

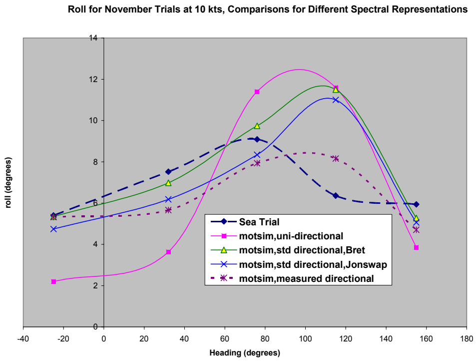

Figure 7. Roll at 10 kt

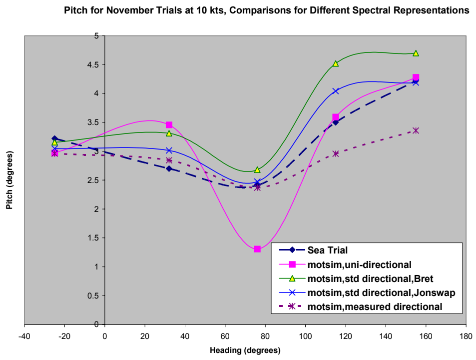

Figure 8. Pitch at 10 kt

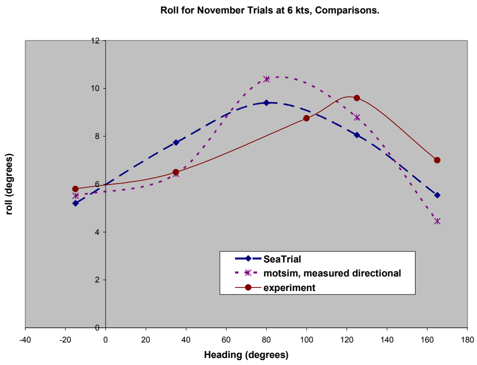

Figure 11. Roll at 6 kt

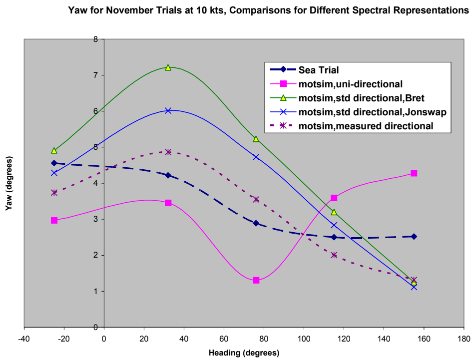

Figure 9. Yaw at 10 kt

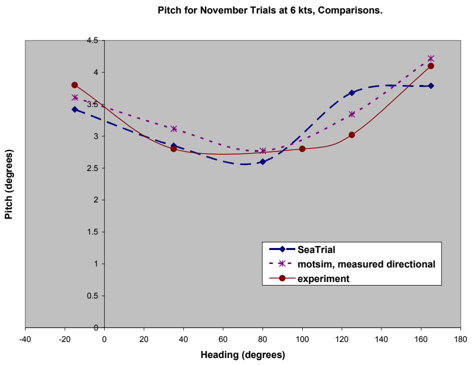

Figure 12. Pitch at 6 kt

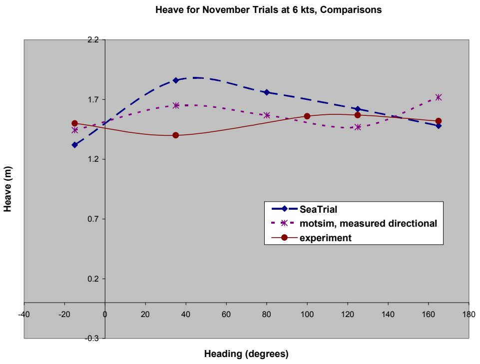

Figure 10. Heave at 6 kt