Measurement and linear prediction of motion and wave load spectra on HMCS NIPIGON

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ABSTRACT

During early December 1997 a sea trial was conducted on HMCS NIPIGON to measure structural loads in moderate seas. During the trial seventy-one dedicated runs of 20 minute duration were conducted at constant speed and heading. The runs were conducted at two speeds in head, bow, beam, quartering and following seas, with significant wave heights ranging from 1.4 m to 5.5 m. During each run, ship motions, hull pressures, hull girder strains, and local strains in the vicinity of a hatch were recorded as digitized time series and analogue tape recordings. A wave buoy was used to measure directional sea spectra during the runs. This paper presents a comparison of measured ship motions and bending moment loads with predictions obtained by combining motions and bending moment transfer functions with the directional wave spectra. The motion and load transfer functions were obtained with the DREA code SHIPMO7 (based on linear strip theory) and a proprietary 3D linear hydrodynamic code PRECAL 2.0. PRECAL was also used to predict hull pressure transfer functions which were combined with the measured wave spectra to predict hull pressure spectra. The sea trial has provided a large data base of wave spectra and ship motion, hull pressure and strain time series during dedicated runs under a variety of sea states and ship operational conditions. The sea trial data has been used to provide full scale validation of linear codes for predictions of ship motions and hull girder bending loads. In the near future these data will be used to validate a spectral method for prediction of local strain based on direct application of hull pressures and inertia loads to a full ship structural finite element model.

INTRODUCTION

Recent advances in computing technology have resulted in improved methods for modeling the loads acting on a ship operating in a defined seaway and the corresponding response of the complex ship structure. The Warship Signatures and Safety (WSS) Section at DREA has been developing methods for prediction of realistic sea loads and their application to finite element models of the hull structure to predict fatigue and ultimate strength performance. This has mainly been done to address in-service assessment and improve life-cycle management. Much of this work has been incorporated into a Defence Research and Development Board major project entitled Improved Ship Structural Maintenance Management [1, 2, 3] (ISSMM). The WSS Section has also been involved in NSMB (Netherlands Ship Model Basin, now known as MARIN - MARitime Institute of the Netherlands) Cooperative Research Ships (CRS) projects related to prediction and validation of structural loads on ships. The CRS research cooperative has a membership consisting of other navies, ship classification societies, industrial research agencies, and shipyards.

A variety of sea load prediction tools are being developed by CRS members for their own, or the ship design community use. Validation of the various sea load and structural response prediction methods is a key step in having these tools accepted for ship design and analysis. While there are some model scale data available, there are few full scale data sets of sea load and structural response measurements. As part of the validation component of the ISSMM project, DREA planned and undertook a dedicated structural loads trial on HMCS NIPIGON, the last steam-driven destroyer in the Canadian Fleet. The ship was extensively instrumented and data were recorded in a variety of operating conditions and sea states over a two week period in December, 1997. Data were gathered from an array of 24 pressure transducers outfitted below the waterline, 15 single strain gauges and 4 rosette strain gauges, a wave buoy, and an over-the-bow wave height meter.

This paper gives an overview of the NIPIGON sea trial and presents some of the comparisons of measured RMS and frequency domain data with ship motion, hull pressure, and hull girder bending load predictions with 2D and 3D linear hydrodynamic codes and a structural finite element code.

DESCRIPTION OF THE SEA TRIAL

The sea trial was carried out on HMCS NIPIGON (3030 tonne displacement, 112 m length, 12.8 m beam and 4.3 m draft) by the DREA Structural Acoustics and Strength Group. The trial began by departing Halifax, Nova Scotia on December 1, 1997. It was intended to transit to the Hibernia oil platform site some 400 miles southeast of Newfoundland. Problems with one of the ships boilers and heavy sea states prevented the vessel from reaching this location and trials were done approximately 100 miles south of Newfoundland. The ship spent December 6th and 7th in port in St Johns, Newfoundland and returned to sea on December 8th. The trial ended on December 12th upon return to Halifax.

A series of trial runs of 20 minute duration were undertaken at two ship speeds in head, bow, beam, quartering and following seas. Data were collected in higher sea states (4,5 and 6) for three days over December 2, 3 and 4th and for four days at lower sea states (2 and 3) over December 8 to 11th. The 'low' ship speed was about 8 knots and 'high' ship speed was between 14 and 18 knots depending on what speed the ship could maintain in the given sea state. Speed was limited due to the loss of one of the two ship's boilers on the first day of the trial.

Wave buoy data was collected for 20 minutes of every hour from the wave buoy. Both the wave data closest to the run time and the wave data next closest to the run time were used in the predictions of response for comparison to the experimental data.

Instrumentation

Four types of data were measured during the trials; the sea state, ship motions, hull pressures and hull strains. Wave height, period and direction were measured by deploying two types of directional Endeco wave buoys in the trials area. An Endeco type 1156 buoy was used for the first 3 days of the trial, and a type 956 buoy was used for the last 4 days. An over-the-bow downward looking TSK Doppler radar unit was also employed to measure wave height and encounter period. It was intended that sea spectra also be measured using a ship mounted Furuno radar unit, however a suitable working unit could not be supplied in time for the trial. Data from permanently moored Wavec buoys were also investigated for additional confidence in sea state measurements, but the only ones in the vicinity were not recording at the time of the trials.

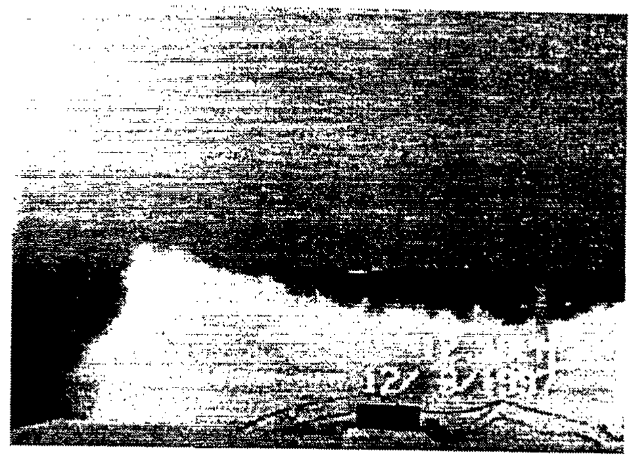

Figure 2: Freeze-frame of recording from video camera from bridge

Ship operations were logged manually for each of the 20 minute data collection periods. DREA's ship motions package was installed near the ship center of gravity (CG) as shown in Figure 1 along with locations of pressure transducers and strain gauges. Twenty-four pressure transducers were outfitted below the waterline to measure hull pressures. Fifteen strain gauges (5 gauges at each of 3 longitudinal stations) were used to measure the hull girder strain. Four rosette strain gauges were located in the vicinity of a hatch opening to measure local strain response.

Data acquisition

Two data acquisition systems were used for the trial. The main system was a PC-based Labview system. All sixty instrumentation channels were recorded at 20 Hz. Time histories, statistical distributions and minimum and maximum values were determined and recorded. The second acquisition system consisted of two TEAC XR9000 28-channel VHS recorders. Signal conditioner amplifiers and filters were used for all channels. All channels were calibrated to zero at dockside. The system was started at the beginning of each 20-minute data set. A few minutes of video recording from the ships bridge of the sea over the bow for each 20-minute data set was also made for future reference of sea conditions. Figure 2 shows a freeze-frame of the video recording. The bow of the vessel with the safety line can be seen in the lower right corner of the photo.

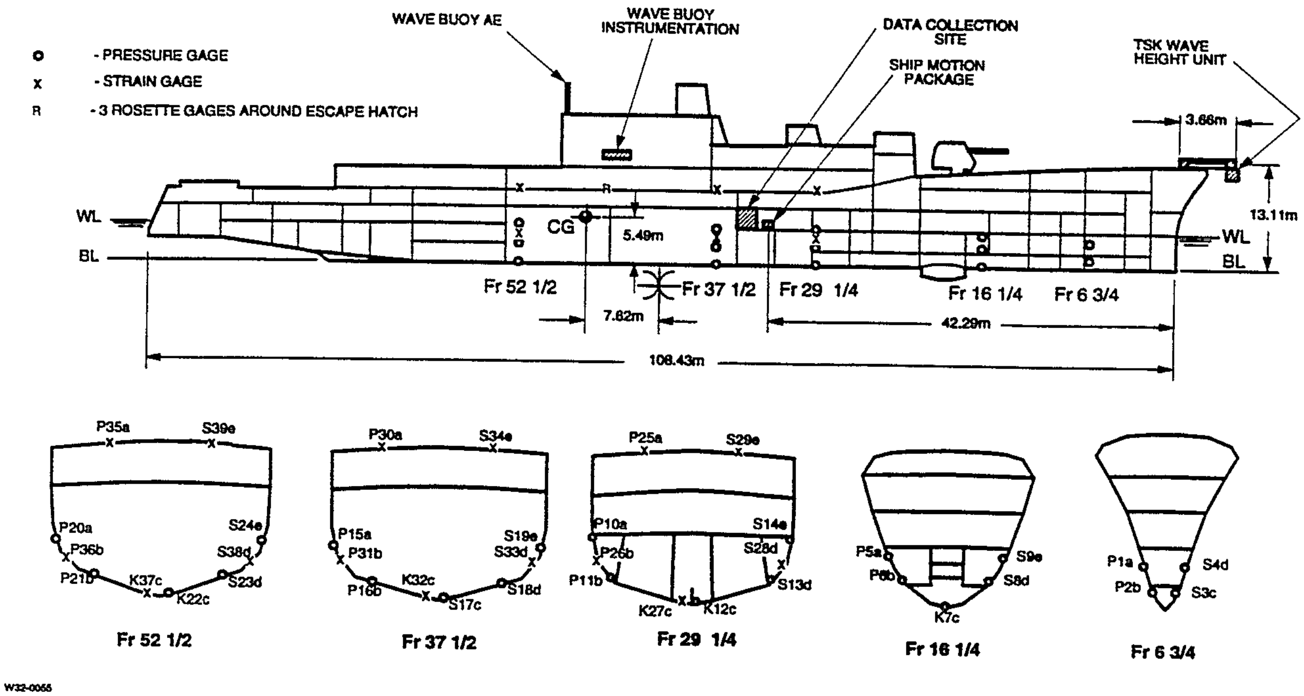

Figure 1: Location of instrumentation

Table 1: Typical Daily Operation

08:00	Check and balance instrumentation
08:30	Deploy wave buoy in a free float operation
09:00	Begin 14 leg trial pattern as indicated in Figure 3. Each leg lasted 20 minutes. Each of the seven directions was run at two speeds, a low speed run of approximately 8-10 knots and a high speed run depending on the vessels capability under the given conditions (usually 16-18 knots).
15:00	Recover the wave buoy before dark.

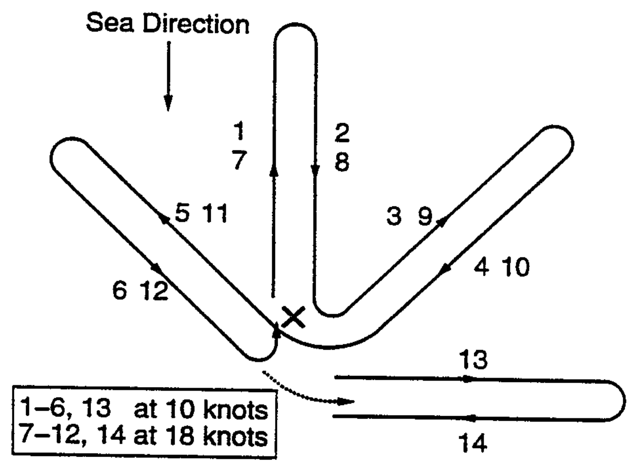

Figure 3: Sea keeping pattern used for the trial (X marks buoy)

Trials Operation

The trial required daily launching and recovery of the Endeco wave buoy. A series of fourteen 20-minute data collection runs at different speeds and headings was planned for each day. A typical daily operational plan is shown in Table 1.

This pattern varied somewhat from day to day due to daylight or sea conditions. On some of the earlier days of the trial during high sea states, the beam sea runs were omitted, and in the latter days of the trial where low sea states were encountered, only the high

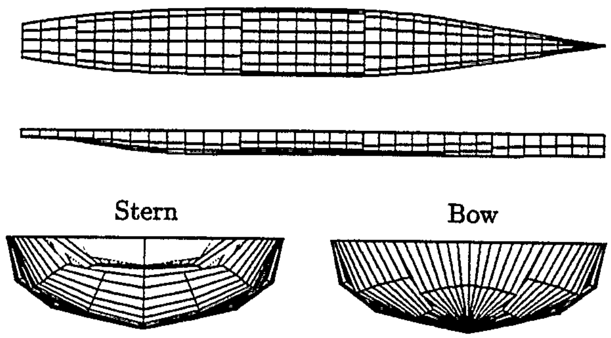

Figure 4: Example PRECAL hydrodynamic mesh

speed runs were undertaken. During the initial part of the trial when high sea states were encountered, it was not possible to recover the wave buoy at the end of the day and it was left in the water with the ship maintaining station nearby. The wave buoy was damaged on recovery during the third day. A replacement wave buoy was deployed for the remainder of the trial.

HYDRODYNAMIC PREDICTION CODES

The predictions of linear hydrodynamic codes, PRECAL 2.0 and SHIPMO7 [4] have been compared with the sea trial measurements. PRECAL is a proprietary suite of programs which was developed by the CRS organization and used in this study to predict ship motions, sectional loads and hull pressures in regular waves using three dimensional linear potential flow theory. SHIPMO is a strip theory code developed at DREA which was used to predict ship motions and sectional loads.

For a given ship speed and specified regular wave, PRECAL calculates the pressure response (amplitude and phase) for each of the elements (facets) into which the wetted surface of the hull has been discretized. Figure 4 shows the element discretization used for the PRECAL analysis of NIPIGON which was automatically generated by PRECAL based on the ship lines of form. Facet pressures were interpolated to provide responses for each pressure transducer location.

RESPONSE SPECTRA PREDICTION

Selection of wave spectra for analysis

The wave buoy sampled for a period of twenty minutes in each hour and provided a directional wave spectrum with 10 degree heading angle resolution and 0.01 Hz wave frequency resolution between 0.03 Hz and 0.50 Hz. The analysis for each run was conducted based on the two wave spectra closest to the run time period.

Prediction of encounter frequency spectra

The digitized time series from motions, hull pressure, and strain measurements for each run were used to derive the power spectra through Fast Fourier Transform (FFT) processing. Since the measurements were conducted on a moving ship, the resulting frequency spectra are a function of encounter frequency. The prediction codes were run for regular wave conditions at 10 degree increments in heading angle combined with wave frequencies of 0.03 Hz to 0.50 Hz inclusive at 0.01 Hz intervals (to match the measured wave spectra angular and frequency resolution). The encounter frequency spectra (motion, pressure or sectional loads) were predicted by combining the measured directional wave spectra and the predicted transfer functions from the PRECAL or SHIPMO output files and integrating over 0.01 Hz wide bands of encounter frequency. The details of the procedure are given in Reference [5].

MEASUREMENT OF BM LOADS

Hull girder bending moments and shears are the primary loads used in the design and analysis of vessels. Most sea-keeping codes give predictions of hull girder sectional loads which can be used for structural analysis; either as load histories for fatigue calculations or as extreme values for ultimate strength calculations. Bending moments and shears are load summation quantities which are derived from the local imbalance between hull pressures and inertia forces and as such cannot be directly measured. Assuming that longitudinal strains at a ship cross section are linearly proportional to the sectional bending moment, the bending moments can be indirectly measured by using an array of strain gauges at the section and a transfer function between the strain values and the bending moment. The transfer function can be calculated using linear beam theory and the sectional modulus of the cross section, but a more accurate method is to use a three-dimensional finite element (FE) model of the ship to develop transfer functions between the gauge locations and sectional bending moments.

The hull girder strains collected at three longitudinal sections (5 gauges at each section) were used to measure the sectional vertical bending moment (VBM) and lateral bending moment (LBM) with BM-to-strain transfer functions obtained from a global full ship Maestro [6] model (see Figure 5) and top-down global to local VAST [7] finite element analyses using Maestro

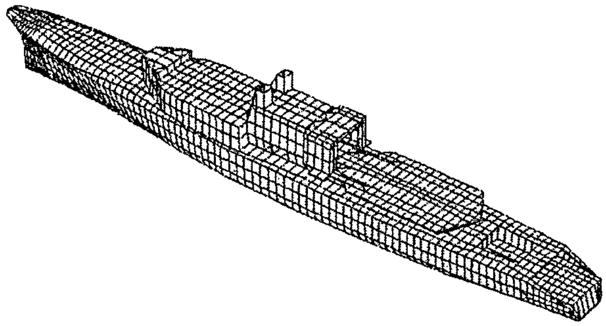

Figure 5: Maestro model of HMCS NIPIGON

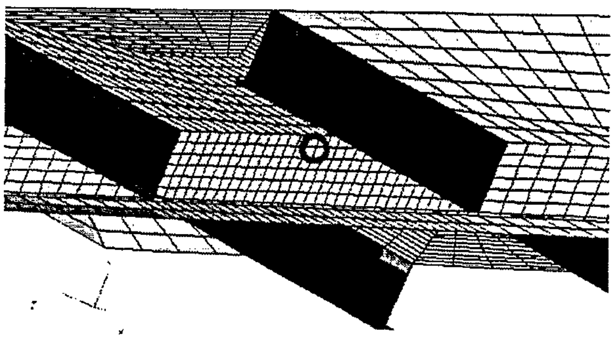

Figure 6: Local finite element model of deck detail (○ strain gauge on longitudinal girder)

Version 7.2.1. and MGDSA [8]. Examples of local finite element models are shown in Figures 6 and 7. The strains were predicted at the gauge locations with application of a static uniform VBM (application of a VBM near the bow and stern of the Maestro model) and also with application of a uniform LBM to the model. At a given longitudinal station the complex FFTs from the strain time series for the five gauges at the station were used in conjunction with the BM-to-strain transfer functions to determine the LBM and VBM FFTs which provided the best fit to the measured strain data. These 'measured' BM FFTs were then used to calculate spectral density for the LBM and VBM components, and cross spectral density, correlation coefficients, and ratios of amplitudes and phase angles between the components. Note that errors in the 'measured' BMs included errors in the measured strains and errors in the finite element prediction of BM-to-strain transfer functions.

RESULTS

Results are presented here for ship motion, hull pressure, VBMs, and LBMs. The RMS values are presented in graphs comparing measurements and prediction for 69 usable runs. Predicted values, for the closest wave spectrum to the run time period, are plotted with a symbol defining the dominant wave heading for the run. A vertical line is drawn from this point to the prediction for the next closest wave spectrum. Response frequency spectra are also given for one of the runs at 8 knots in a port bow sea (significant wave height $H_s = 4.7m$). The plots are shown with the measurement as a solid line, the prediction for the closest wave spectrum by a dashed line and the prediction for the next closest spectrum as a dotted line.

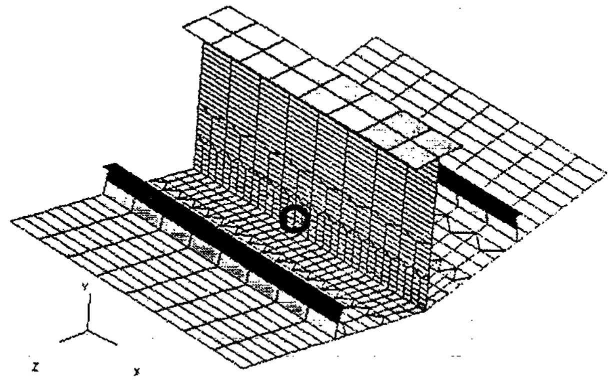

Figure 7: Local finite element model of keel detail (○ strain gauge on vertical keel structure)

Ship Motion

Roll, heave, and pitch ship motions were measured and recorded throughout the trial period with a standard gyro-based package located close to the ship CG as indicated in Figure 1. The measured motions data are compared to predictions obtained by combining motion response amplitude operators (RAOs) calculated by PRECAL and SHIPMO (calculated with the same angular resolution as the directional wave spectra) with measured directional wave spectra. Figure 8 shows a comparison of predicted (SHIPMO) and measured RMS values for all runs. Comparison of measured and predicted motions by both PRECAL and SHIPMO7 were very good for all runs. Comparisons of ship motions is a key part of validating sea keeping codes as motions are usually predicted better than the ship loads. Figure 9 shows a comparison of predicted and measured motion spectra using the closest and next closest wave spectra measurements for the PRECAL predictions.

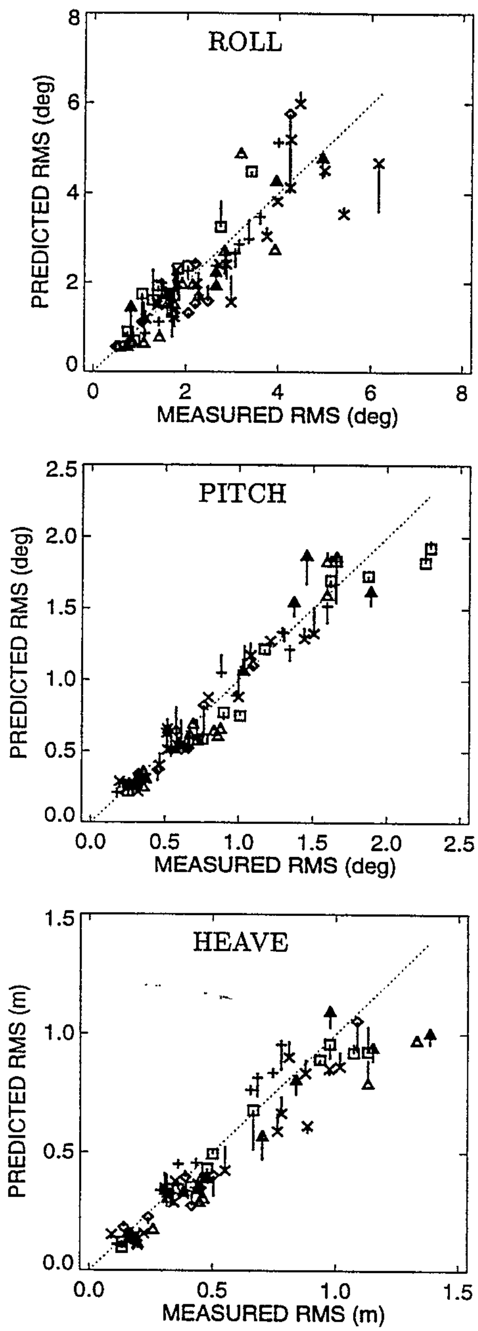

Figure 8: Comparison of predicted (SHIPMO) and measured RMS Motions (□ Head, △ Bow, ◇ Beam, × Quartering, + Following)

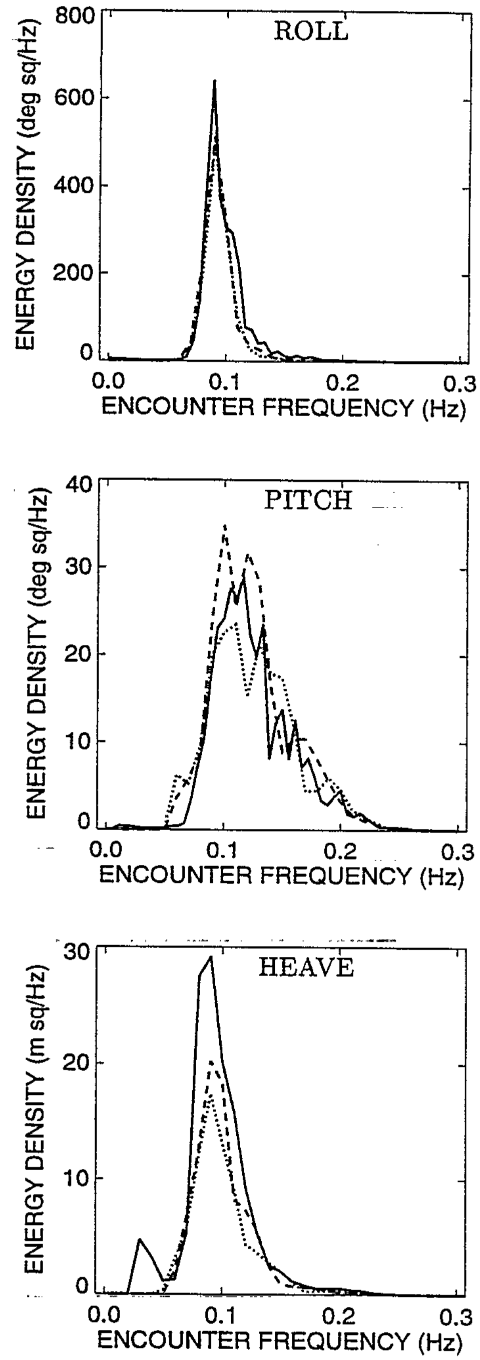

Figure 9: Comparison of measured (—) and predicted (PRECAL) motion spectra as a function of encounter frequency for closest (- - -) and next closest (. . .) wave spectra

Hull Pressure

Hull pressure predictions are the next phase of verifying the sea load prediction codes. Only the PRECAL code was capable of calculating hull pressures. Hull pressures were measured at five frame stations along the hull as indicated in Figure 1. Four pressure transducers were used at the forward most frame station (Frame 6.5), at mirrored locations port and starboard, two nearer the surface and two deeper. At the four other stations a fifth pressure transducer was located near the keel. PRECAL pressure RAOs were calculated for each gauge location by interpolation of predicted pressures at centroids of surrounding hydrodynamic mesh panels and used in conjunction with the closest and next closest wave spectra to calculate RMS pressures and pressure spectra at each pressure transducer location.

Figure 10 shows a comparison of PRECAL predictions with RMS pressure measurements for all runs at three pressure transducers, one at the forward station, Frame 6.5 and two at Frame 37.5. Figure 11 shows an example comparison of pressure spectra for these locations for a port bow run. In general, pressure predictions compared well with measurements and were consistent along the length of the vessel.

Sectional Bending Moment Loads

Figure 12 shows a plot of RMS VBM at the middle of the three instrumented sections (Frame 37.5) for all 69 usable data runs. Comparisons of both PRECAL and SHIPMO predictions to the measured values are shown. SHIPMO predictions of VBM were on average 18% higher than PRECAL predictions. Figure 13 shows a plot of RMS LBM at Frame 37.5 comparing measurements to PRECAL and SHIPMO predictions. Figure 14 shows a comparison of measured and predicted vertical and lateral bending moment spectra at frame 37.5 for a port bow sea run. The comparison of measured and predicted LBM (RMS and spectra) was poorer than found for the VBM. This may be partly due to errors in measurement due to difficulties of extraction of relatively small lateral bending strains from noisy signals dominated by the vertical bending component.

Prediction of the structural response to combined vertical and lateral bending loads in regular wave conditions requires knowledge of the phase relationship between BM components. The VBM and LBM FFTs derived from the strain measurements at the instrumented sections were used to derive the ratio of LBM to VBM for selected runs. Figure 15 compares the amplitude ratio and phase angle between the LBM and VBM at Frame 37.5 for the same port bow run for which motion, pressure, and BM spectra have been present. The measured ratio is compared to the PRECAL prediction with the closest and next closest wave spectra. Both the amplitude ratios and the phase angles changed significantly for runs in different wave headings. Typically the amplitude ratios increased with higher encounter frequency.

In irregular wave conditions correlation coefficients can be used to predict the structural response to combined vertical and lateral bending loads. The measured and predicted VBMs and LBMs were used to calculate the correlation coefficient between these components. The measured correlation coefficients ranged from -0.8 to +.8 for individual runs. A coefficient of zero means that the combined RMS response is the square root of the sum of the squares of component RMS responses. A coefficient of +1 means that the components are summed arithmetically and a value of -1 means they are subtracted to obtain the combined response.

As shown in Figure 16 there was poor agreement between measured and predicted correlation coefficients. There is likely considerable uncertainty in both the measured and predicted coefficients. The measured coefficients could be in error because of inaccurate measurement of the LBMs. The predicted coefficients were very sensitive to the choice of measured wave spectra for many runs. It was found that there was a well defined relationship between the correlation coefficients predicted with PRECAL and those predicted with SHIPMO as shown in Figure 17.

In addition to being able to predict sectional loads, it is useful to validate the ability of the combined sea loads and structural analysis programs to predict stress at a structural detail. Successful validation means that stress histories could be derived for representative ship operational profiles to use for fatigue assessments. To undertake this validation, strains were measured at one corner of a main strength deck opening. Fine mesh finite element models of this region were produced to be used in the top-down finite element analysis which will be used to predict the strains for direct comparison to the measured strain values for each of the individual data runs. To date, there has not been any comparison done of this data.

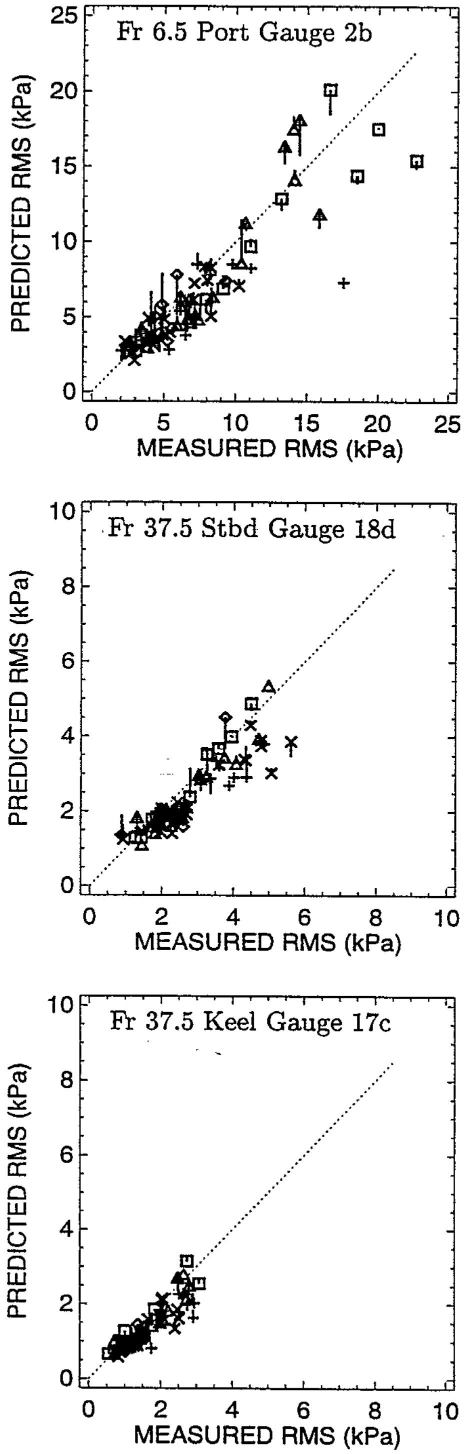

Figure 10: Comparison of measured and predicted RMS pressures for all runs (□ Head, △ Bow, ◇ Beam, × Quartering, + Following)

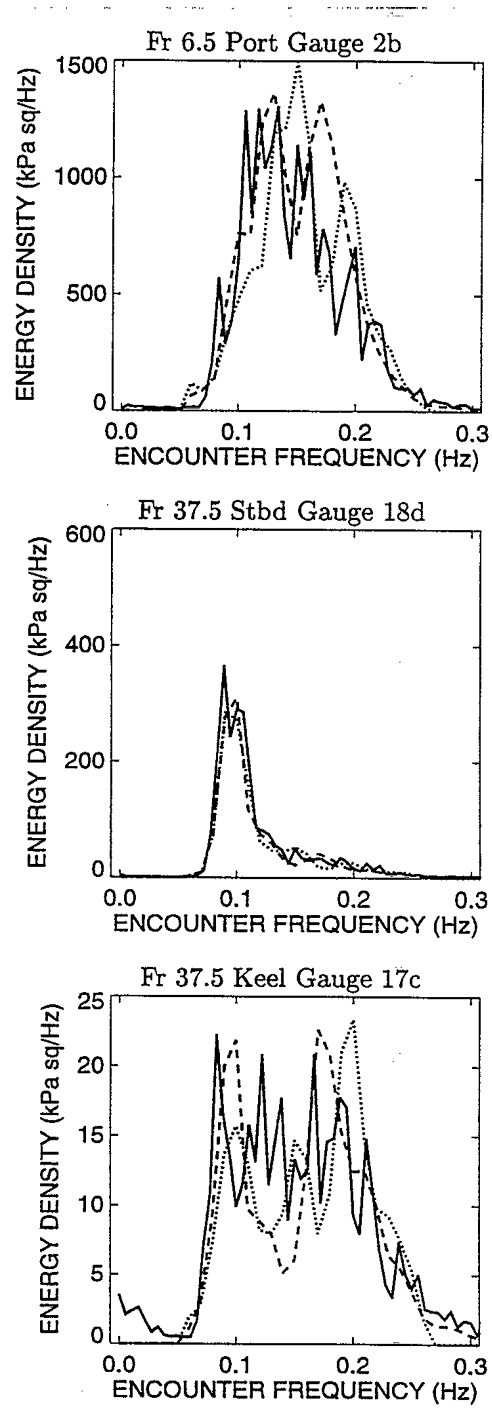

Figure 11: Comparison of measured (—) and predicted (PRECAL) hull pressure spectra as a function of encounter frequency for closest (- - -) and next closest (. . .) wave spectra

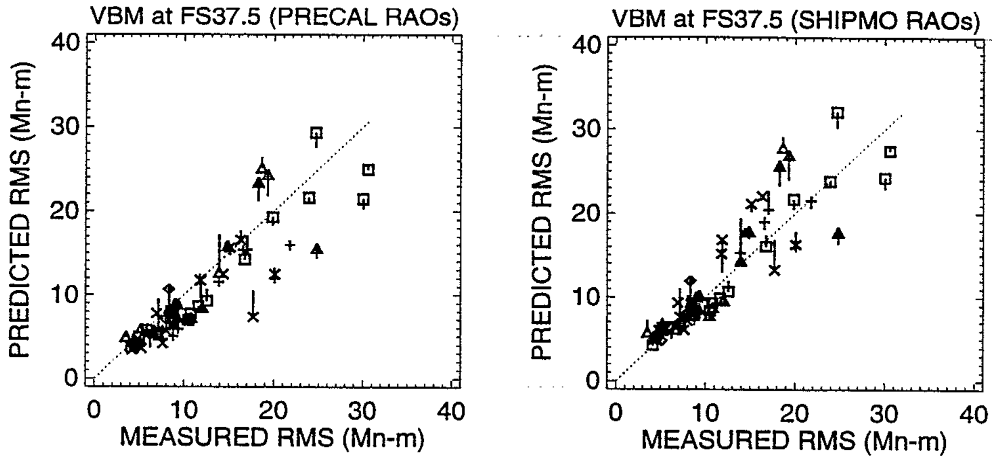

Figure 12: Comparison of predicted (PRECAL and SHIPMO) and measured vertical bending moment loads at Frame 37.5 (□ Head, △ Bow, ◇ Beam, × Quartering, + Following)

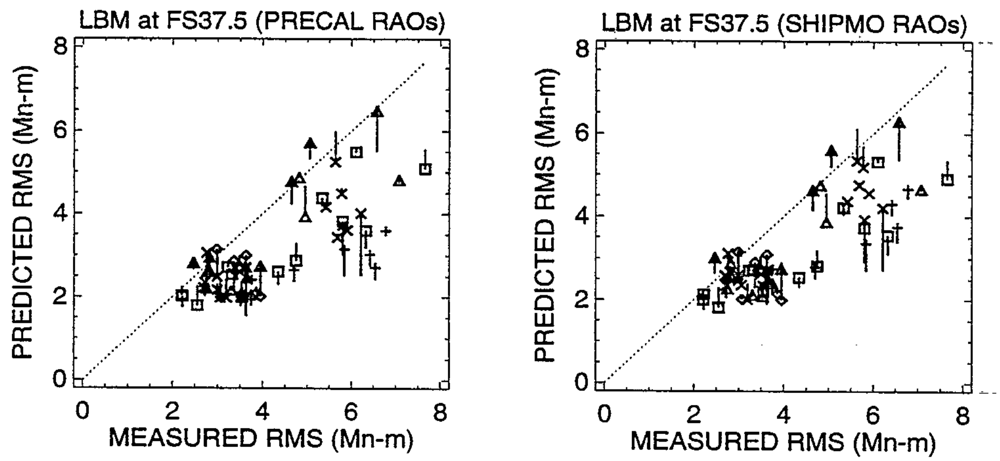

Figure 13: Comparison of predicted (PRECAL and SHIPMO) and measured lateral bending moment loads at Frame 37.5 (□ Head, △ Bow, ◇ Beam, × Quartering, + Following)

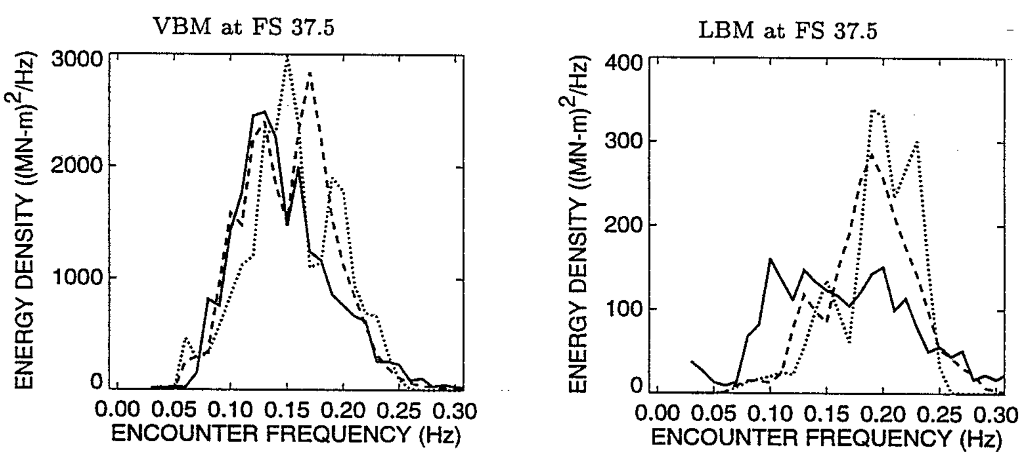

Figure 14: Comparison of measured (—) and predicted (PRECAL) vertical and lateral bending moment spectra as a function of encounter frequency for closest (- - -) and next closest (. . .) wave spectra

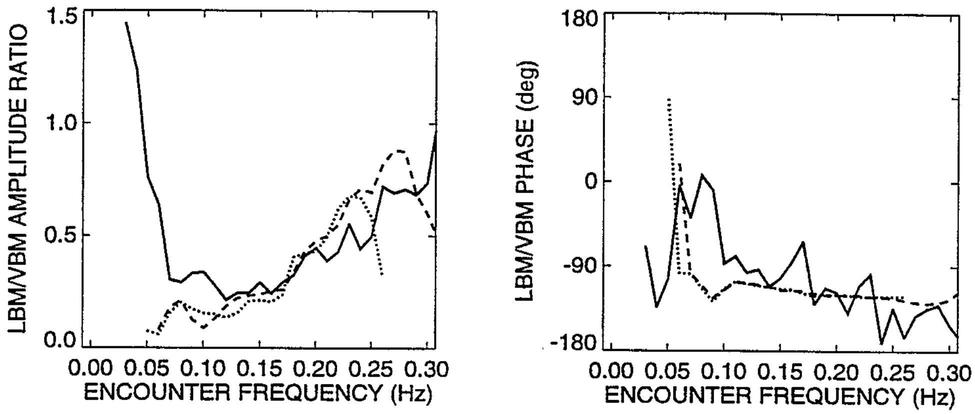

Figure 15: Comparison of measured (—) and predicted (PRECAL) ratio of lateral to vertical bending moment as a function of encounter frequency for closest (- - -) and next closest (...) wave spectra

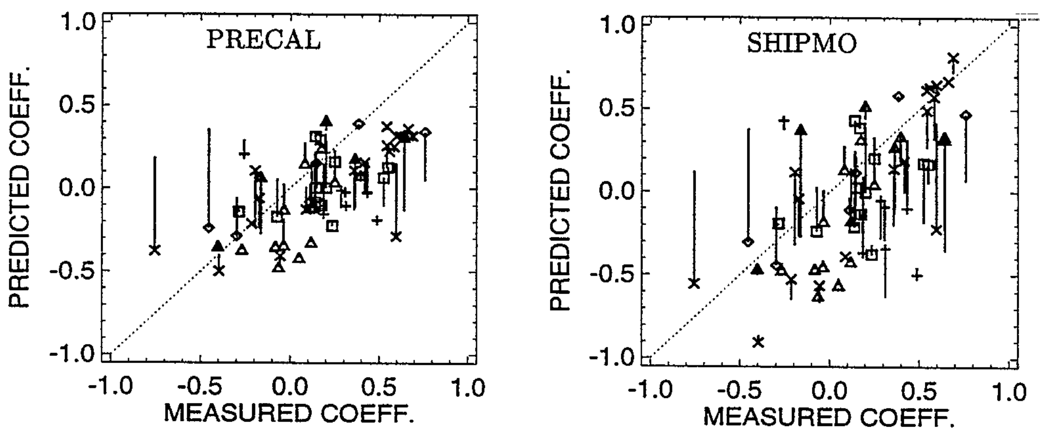

Figure 16: Comparison of predicted (PRECAL and SHIPMO) and measured correlation coefficients between LBM and VBM loads at Frame 37.5 (□ Head, △ Bow, ◇ Beam, × Quartering, + Following)

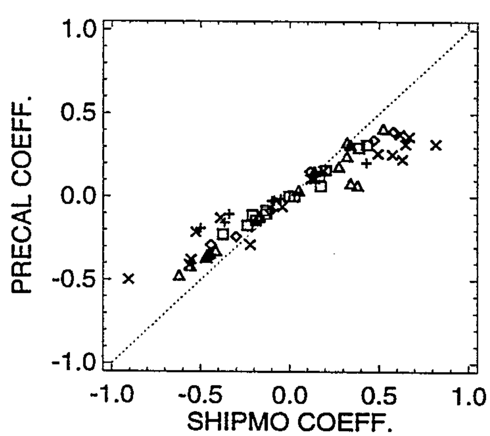

Figure 17: Comparison of predictions of correlation coefficients between LBM and VBM loads at Frame 37.5

CONCLUDING REMARKS

This paper has given an overview of the HMCS NIPIGON structural loads trial and a brief review of the results that have been determined so far. The trial was a comprehensive dedicated trial that allowed measurement of the sea state, the ship operation and the resulting motions, pressures and structural loads. A very good range of operating conditions occurred during the trial and all data acquisition equipment and measurement transducers functioned throughout the trial without failure. This in itself is a rare occurrence in sea trials. Data were recorded for a full range of ship headings, at high and low speed in sea states ranging from 2 to 6 with maximum wave height values reaching 10 meters.

Comparisons of measurement data to predictions from linear sea load codes indicates agreement comparable to model tests for motions, pressures and sectional forces. In the near future these data will be used to validate a spectral method [9, 10] for prediction of local strain based on direct application of hull pressures and inertia loads to a full ship structural finite element models.

ACKNOWLEDGEMENTS

Sea trials such as this require the efforts of many people. The authors thank the Commander and Crew of HMCS NIPIGON for dedicating their ship to this trial and giving us full support in difficult sea conditions; the WSS technical staff; Alex Ritchie, Ed Brunt, Terry MacFarlane and David Heath; the ship liason and trial support provided by Lt.(N) Heather Skaarup; and the contribution of the CRS organization and the SMACS working group.

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