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TITLE

COMPARISON OF MOTION AND LOAD PREDICTIONS WITH FULL SCALE TRIAL MEASUREMENTS ON CFAV QUEST

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Comparison of Motion and Load Predictions with Full Scale Trial Measurements on CFAV QUEST

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ABSTRACT

This paper describes results of measurements and predictions of ship motions, hull pressure loads and vertical bending moment loads from sea trials undertaken in November 1993 on CFAV QUEST during various operational conditions in moderate seas. Motion and hull pressure spectra derived from the measurements are compared to predictions computed by combining regular wave transfer functions computed with PRECAL, a three-dimensional linear ship motion and load prediction code, with directional wave spectra collected with a directional wave buoy during the trial. Vertical bending moment spectra calculated in a similar manner are compared to bending moment spectra derived from measured strain spectra and full ship finite element analysis. Measured and predicted pressure and bending moment spectra show reasonable agreement, indicating the strong potential of using PRECAL in combination with structural finite element methods to predict structural response spectra for use in spectral fatigue analysis of ship hull structures.

INTRODUCTION

Traditional ship structural analysis is based on a static equivalent beam analysis of the ship hull girder balanced on a design wave. Recent advances in computing technology have resulted in improved methods for modelling the loads acting on a ship operating in a defined seaway and the corresponding response of the complex ship structure. Both naval and commercial sectors are developing analysis tools based on these physical modelling approaches. The Hydronautics 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. Through cooperative research with the NSMB (Netherlands Ship Model Basin) Cooperative Research Ships organization, a linear three-dimensional seakeeping code, PRECAL, was developed to predict pressures for the ship hull operating in a seaway [1]. The PRECAL code has been used in conjunction with the Canadian Department of National Defence (DND) finite element code VAST [2] to predict stress spectra at critical details in the ship hull. These stress spectra can be used to predict fatigue crack initiation and crack growth behaviour for a given operating profile of a vessel. The PRECAL results can also be used with extremal theory to establish the most likely maximum loads on the hull structure to determine safety levels against ultimate strength, subject to the assumption of linearity and neglecting effects of transients such as slamming and green sea loads.

While there is a small amount of model scale data available, there are few, if any, full scale data available for verification of the pressure load and structural response predictions from PRECAL and VAST. CFAV QUEST Trial Q210 was designed to measure the hull pressure fields, the hull girder strains and the conditions in which they occurred, to determine if the computer code predictions were giving reasonable results.

This paper presents comparisons of ship motions data and pressure spectra measured during the trials and those predicted by combining PRECAL motion and pressure transfer functions with measured directional wave spectra. The measured strain data were used in conjunction with full ship finite element analyses to obtain vertical bending moment spectra which are also compared to PRECAL predictions.

DESCRIPTION OF THE TRIAL

The trial was carried out on CFAV QUEST (2400 tonne displacement, 71.6 m length, 12.8 m beam and 4.9 m draft) by the Structural Mechanics Group of DREA during the period of November 4 to 18th, 1993 in the Atlantic Canada Maritime region. QUEST was instrumented to determine pressure distributions over the hull and corresponding strains in a variety of operating conditions. Data was gathered from an array of 38 pressure transducers outfitted below the waterline, 18 strain gauges, a wave buoy, a microwave over-the-bow wave height meter, a radar wave imaging system and a ship motions measurement package. A series of both high (11 knots) and low (5 knots) speed trial runs of 30 minute duration were undertaken in dominantly head, bow, beam, quartering and following seas with significant wave heights ranging from 0.9 to 4.2 m.

Instrumentation

The pressure transducers (4.75 mm diameter) were installed through drilled and tapped holes in the hull plating below the waterline with the ship in drydock. Locations are shown in Fig. 1 at frame stations 5.25, 15.25, 30.75, 50.75, 69.5 and 91.75. The zero Z-coordinate is at the waterline. Some pressure transducers failed either before or during the trial which commenced with only 32 working transducers. Only 18 transducers worked for the entire trial period. Four strain gauges were placed in pairs on the two main

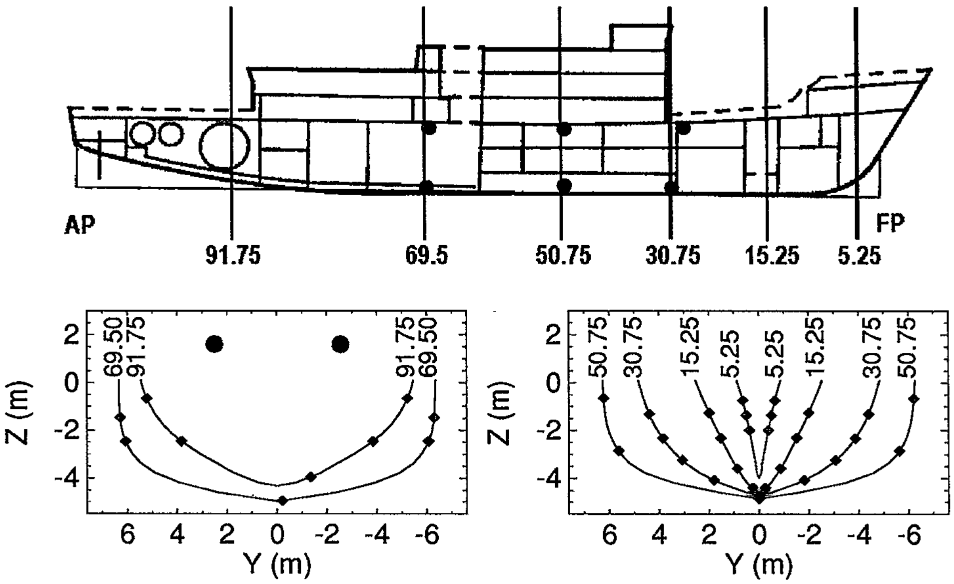


Figure 1: Locations of the pressure transducers ◇ and strain gauges •

deck girders and two on the keel in each of three locations along the ship for measuring hull girder response as shown in Fig. 1. The locations of instrumentation for motions and seastate measurements are shown in Fig. 2. The DREA ship motions measurement package was installed close to the ship CG, and the ship's Non-Acoustic Data Acquisition System (NADAS) was used to give information on ship heading, position, and speed. Wave height and direction measurements were done with the DREA Endeco Wavetrack directional wave buoy in a free float deployment each day. A TSK over-the-bow microwave wave height meter was also used to measure significant wave height and encounter period. A special boom had to be constructed to hold the unit over the bow. A MacLaren Plansearch 'MacRadar' system [3] was employed to determine wave direction using the ship's radar. The MacRadar unit proved useful in determining predominant wave direction during confused seas. The MacRadar system used the NADAS ship ground speed and direction data to correct for ship velocity.

Data acquisition

The primary data acquisition system consisted of three XR9000 TEAC 28 Channel VHS recorders. PC Labview software was used to monitor the data as it was being collected and to analyze the data after collection.

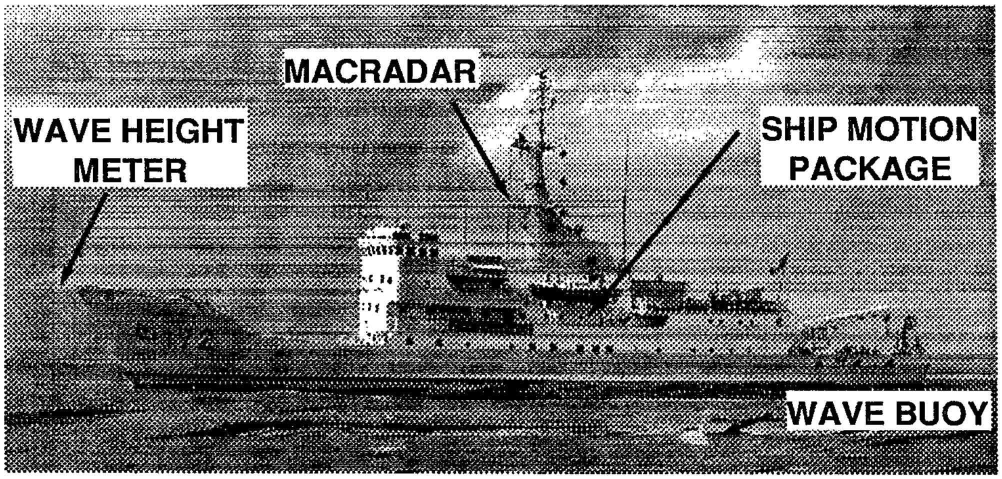


Figure 2: Location of instrumentation on CFAV Quest

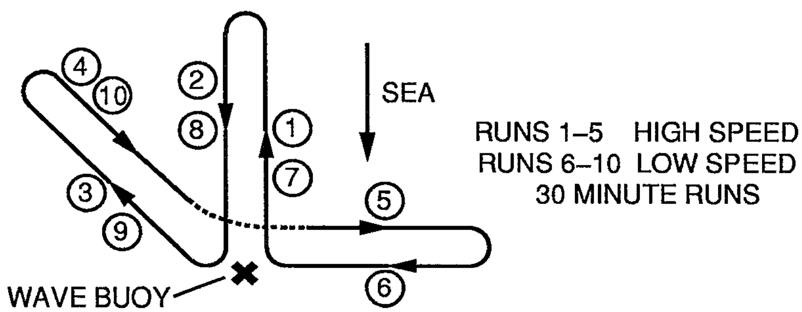


Figure 3: Operating pattern for Q210 trials

Trials plan

A daily operating pattern as shown in Fig. 3 was used to provide the required speed and heading matrix for each sea state. The wave buoy was deployed in a free-float format at the beginning of each day and recovered at the end of the day. The operating pattern was undertaken in the vicinity of the buoy.

MOTION AND PRESSURE SPECTRA PREDICTION

The 3D linear seakeeping program - PRECAL

PRECAL Version 1.0 is a proprietary suite of programs [1] which was developed by the NSMB Cooperative Research Ships organization to predict vessel motions, sectional loads and hull pressures in regular and random waves using three dimensional linear potential flow theory.

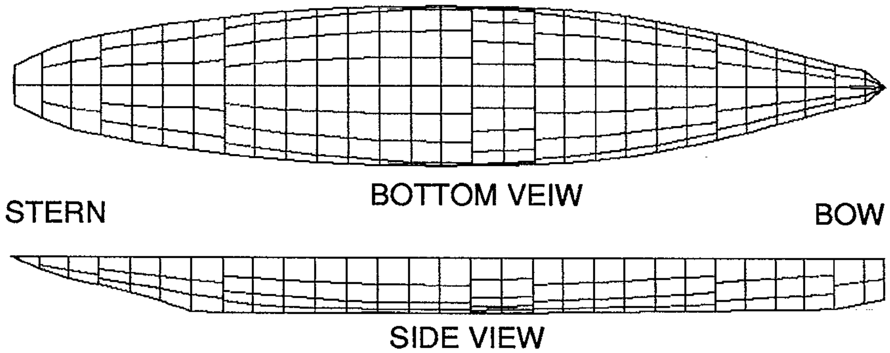


Figure 4: PRECAL hydrodynamic facet geometry (automatic generation)

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. Fig. 4 shows the element discretization used for the PRECAL analysis of QUEST which was automatically generated by PRECAL based on the ship lines of form. The code also allowed interpolation of facet pressures to provide predictions for each pressure transducer location.

Selection of spectra and trial runs for analysis

The wave buoy sampled for a period of seventeen 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 0.40 Hz. The wave spectrum closest to the time period of a trial was selected for analysis of the run. Only trial runs having wave spectrum samples within half an hour of the run periods were selected for the analysis.

Method for prediction of encounter frequency spectra

Since the motion, hull pressure, and strain spectra were measured on a moving ship, the spectra, as measured, are a function of encounter frequency. PRECAL was run for wave headings of 0 degrees to 350 degrees at 10 degree increments combined with wave frequencies of 0.03 Hz to 0.40 Hz inclusive at 0.01 Hz intervals (to match the measured wave spectra angular and frequency discretization) for ship speeds of 5 knots and 11 knots. The encounter frequency spectra (motion, pressure or bending moment) were predicted by combining the wave buoy directional spectra and the amplitudes of the regular wave transfer functions from the PRECAL output files and integrating over 0.01 Hz wide bands of encounter frequency. The details of the procedure are given in Reference [4].

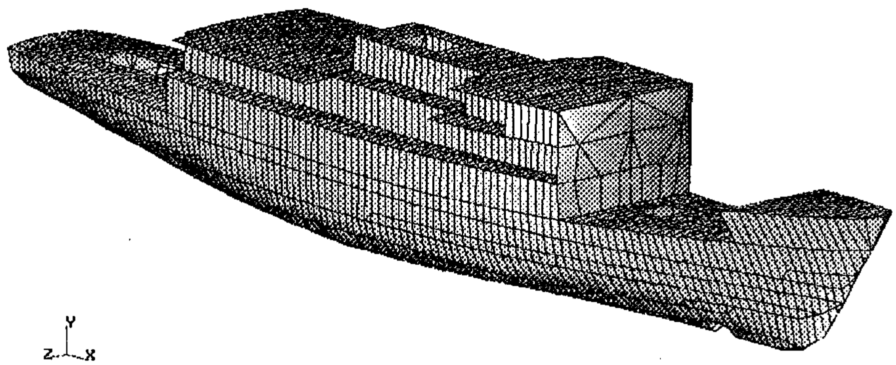


Figure 5: Quest finite element model

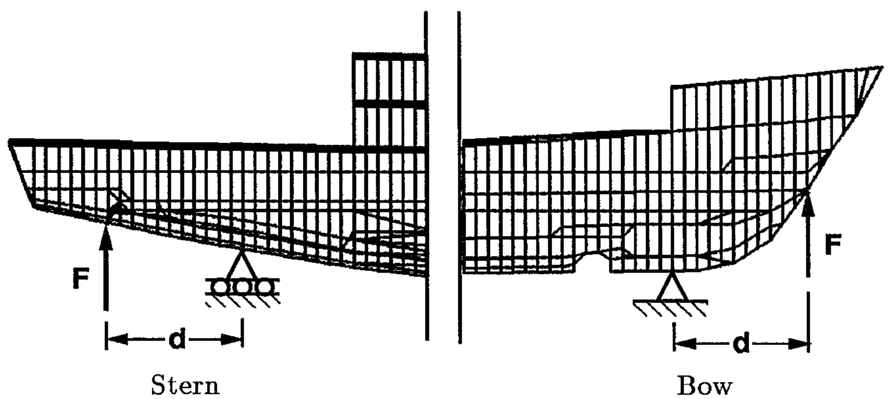


Figure 6: Four-point-bending loads applied to the Quest FE model

'Measured' vertical bending moment spectra determination

The measured strain spectra were multiplied by strain to bending moment scaling factors derived from a full ship finite element model to obtain vertical bending moment (VBM) spectra at frame stations where strain gauges were installed. The VAST structural finite element model used to determine scaling factors is shown in Fig. 5. The application of four-point-bending loads to the FE model is shown in Fig. 6.

The predicted strains, in the vicinity of Frame Station 50.5 due to the applied VBM, are shown in Fig. 7. A section of the hull has been removed to show the keel strains. The resulting strain-to-bending-moment scaling factors at this frame station were 0.90 MN-m/$\mu\epsilon$, 0.81 MN-m/$\mu\epsilon$, and 0.51 MN-m/$\mu\epsilon$ at the port deck girder, starboard deck girder and keel gauge locations, respectively.

RESULTS

Ship Motion

Measurement and prediction of pitch motion for runs in head seas and roll motion in beam seas were compared to establish that the PRECAL model was giving realistic predictions of motions prior to consideration of hull pressures and bending moments. The predicted RMS pitch values for several head sea runs are compared to the measured RMS values in Fig. 8. Also shown are values predicted using the directional wave spectra in conjunction with the DND two dimensional linear strip theory code SHIPMO6 [5]. The SHIPMO6 and PRECAL predictions are in very good agreement. Example predicted and measured pitch spectra are also shown in Fig. 8. The spectra are shown in terms of the square root of power spectral density with units of rad/$\sqrt{\text{Hz}}$.

The roll damping prediction in PRECAL Version 1.0 is not considered to be very accurate (improvements are being being made for the next release of the code). This was checked with the intention of modifying the roll damping as necessary to obtain correct roll motion before continuing on to the next stage; the prediction of hull pressures. A plot of the predicted versus measured RMS roll for a number of beam sea runs is shown in Fig. 9 with the default PRECAL roll damping and for one fifth of the default values. Least square fitted lines are also shown. The graph shows that the initially predicted roll angles were 29% of the measured values. Decreasing the damping by a factor of five gave much better agreement with measured roll and is in agreement with damping predictions of SHIPMO6. Fig. 9 also shows an example of predicted and measured roll spectra. The measured roll spectra typically had two peaks compared to only one peak in the predicted roll spectra. The differences are attributed to the effect of anti-roll tanks operating during the trial which could not be modeled with the PRECAL code.

A report on the tuning of the QUEST anti-roll tanks [6] provided wave and roll spectra measured with the ship operating in beam seas (3.3m significant wave height). Roll responses estimated from this data with the ship stopped, moving at 5 knots and moving at 11 knots are compared to the PRECAL prediction in Fig. 10. The comparison is consistent with the differences between PRECAL predictions of roll and the measured roll spectra for the beam sea runs given in Fig. 9, with the measured spectra again showing a two-peaked character.

Hull Pressure

The hull pressures were predicted at 18 of the pressure transducer locations for 39 of the trial runs. Pressure spectra were predicted at a given location for a given run by combining the wave buoy directional wave spectrum and the PRECAL hull pressure transfer functions for the location. PRE-

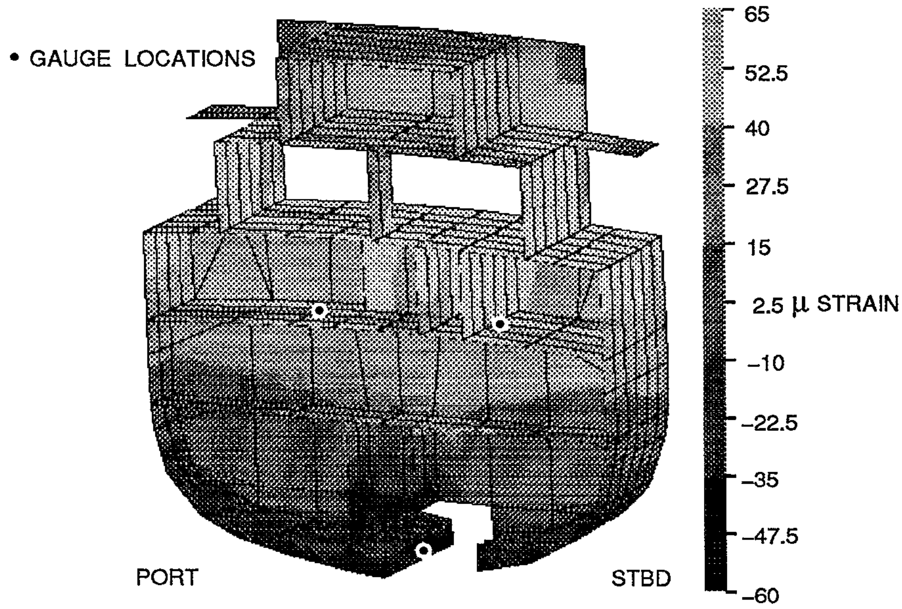


Figure 7: Longitudinal strain in the vicinity of the Frame 50.5 gauge locations

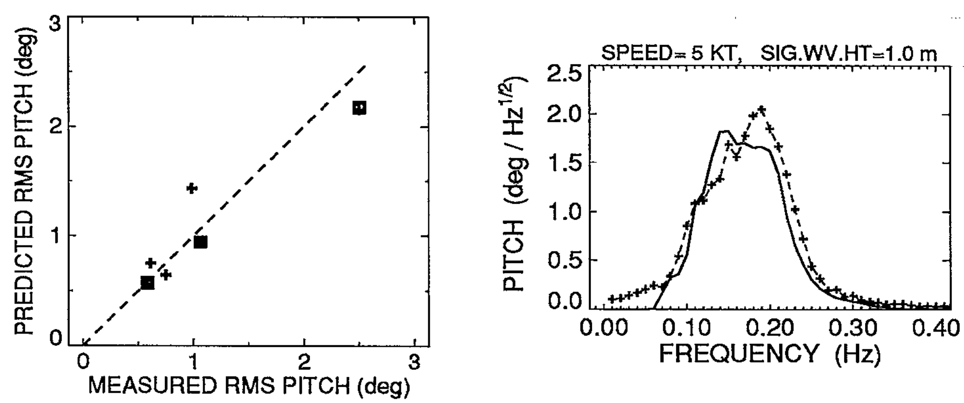


Figure 8: Comparison of predicted and measured pitch (RMS and spectra) during head sea runs; RMS: + PRECAL, □ SHIPMO6; SPECTRA: — Wave buoy/PRECAL prediction, + Measured

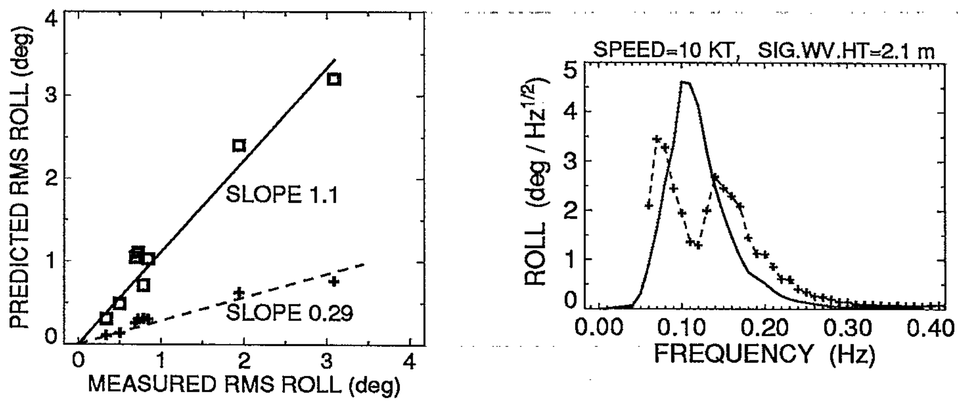


Figure 9: Comparison of predicted and measured roll (RMS and spectra) during beam sea runs; PRECAL RMS: + default roll damping , □ 1/5 default damping; SPECTRA: — Wave buoy/PRECAL prediction, + Measured

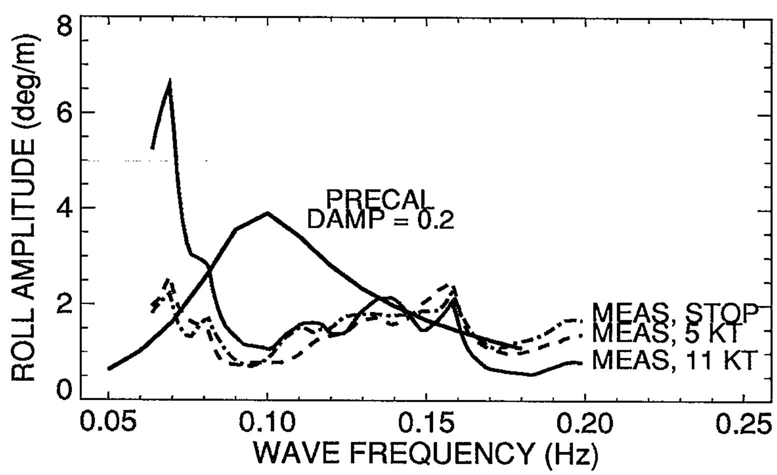


Figure 10: Comparison of the beam sea roll response predicted by PRECAL to measurements with anti-roll tanks in operation

CAL contains an option to alleviate problems due to irregular frequencies by adding a free-surface panel distribution to the hydrodynamic hull mesh. The suppression worked well at a speed of 5 knots but at a ship speed of 11 knots some spurious peaks still occurred and were graphically edited out of the pressure transfer functions before calculating pressure spectra.

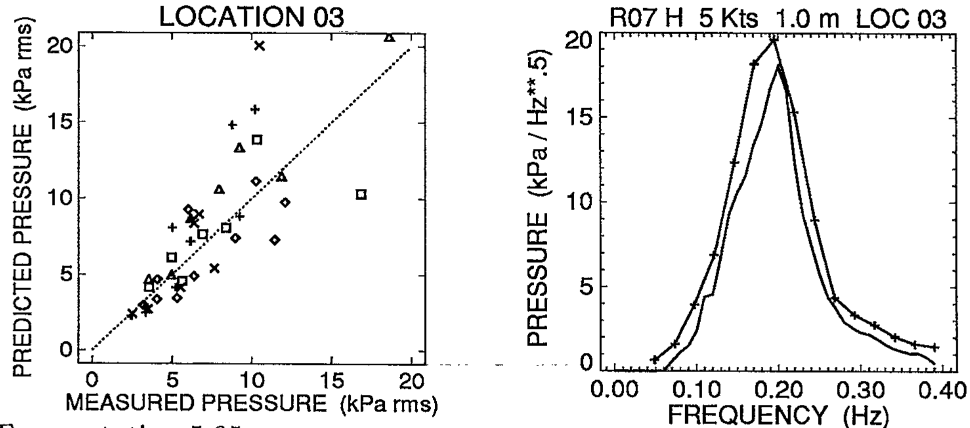
Since the PRECAL model could not correctly predict the effect of anti-roll tanks on the roll motion, the sensitivity of the pressure transfer functions to roll was checked. Doubling of roll amplitudes changed pressure amplitudes by less than 5 % suggesting that the effect of anti-roll tanks would not significantly influence the pressure analysis.

Plots of RMS hull pressures, calculated from the predicted pressure spectra, versus the measured RMS pressures are shown in Figure 11 for three pressure transducer locations, one near the bow (Frame station 5.25), one near midships (Frame station 50.75) and one furthest aft (Frame station 91.75). A dotted line indicating perfect correlation between measured and predicted pressure is also shown for reference on each plot. The points are plotted with different symbols to distinguish between nominal head, bow, beam, quartering or following irregular sea runs.

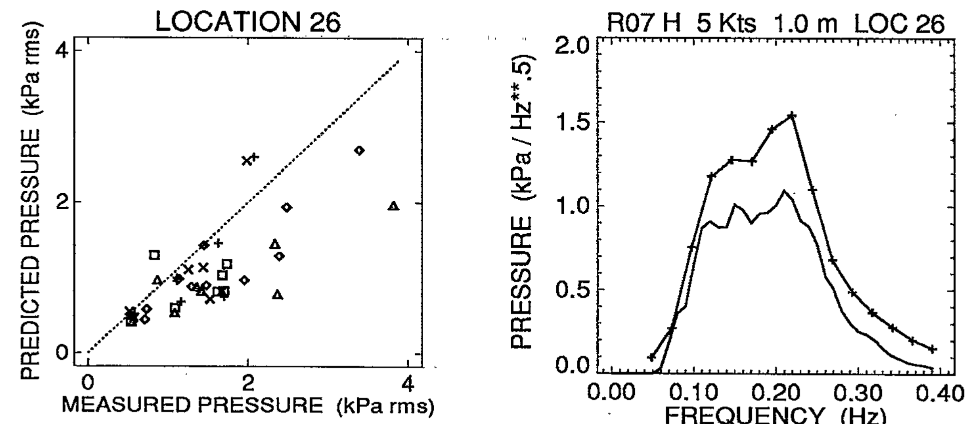
Examination of the RMS pressure graphs shows that there is better agreement between predictions and measurements for locations near the bow than for those further aft where the predicted pressures tend to be lower than the measured values. The average slopes of least square fitted curves through the data of Figure 11 decreased from a value 1.1 at the bow to about 0.7 near midships and remained in the range of 0.75 to 0.90 further aft. The graphs of RMS pressure show significant scatter which increases at higher pressure values. The bounds of the scatter roughly form a wedge with an apex at the origin, suggesting that the error band is a constant fraction of the pressure value.

Fig. 11 also shows comparisons of measured and predicted hull pressure spectra at three locations along the length of the ship for the same head sea run at 5 knots in 1.0 m significant wave heights. Note that the spectrum shape changes significantly along the length of the ship. In general there was best agreement between measured and predicted spectra near the bow.

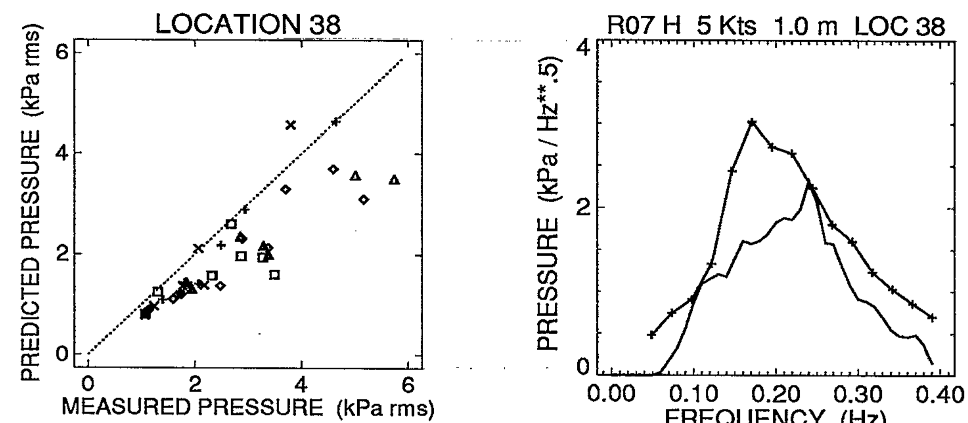
Example comparisons of measured and predicted hull pressures (RMS and spectra) are plotted based on the dominant wave heading in Fig. 12. The best fit of RMS data was obtained for bow seas where the predicted RMS pressures averaged four percent higher than measured. The head and beam sea predictions averaged 13 and 15 percent lower than measured, respectively. For following and quartering seas the predicted RMS pressures averaged 34 percent higher than measured. The points on the plots have been identified based on the pressure transducer frame station and show that highest pressures occurred at the forward locations and lowest pressures at the aft locations for all headings. The high slopes of the fitted curves for following and quartering seas are controlled by the over prediction of pressures at forward locations. The points at aft locations are grouped close to



a) Frame station 5.25



b) Frame station 50.75



c) Frame station 91.75

Figure 11: Comparison of the hull pressures (RMS and spectra) sorted by location; Dominant Sea: □ Head , △ Bow, ◇ Beam, × Quartering, + Following; SPECTRA: — Wave buoy/PRECAL prediction, + Measured

the origin for all headings, and for following and quartering seas generally show predicted pressures slightly lower than measured. Fig. 12 also shows example hull pressure spectra for locations near the bow under the different dominate wave headings and illustrates the effect of encounter frequency, giving a large change in spectral shape between head and following seas.

Fig. 13 shows example plots of predicted versus measured RMS pressure for all operating pressure transducers for individual runs. The graphs show a strong linear correlation indicating that for a given run there were similar errors at all transducer locations. Similar graphs were obtained for all runs. The average prediction error for each run did not appear to be related to any combination of ship speed, heading or wave height but seemed to vary almost randomly from run to run. The scatter in the combined plots for all runs is thought to be due mainly to uncertainty in the measurement of directional information in the wave spectra.

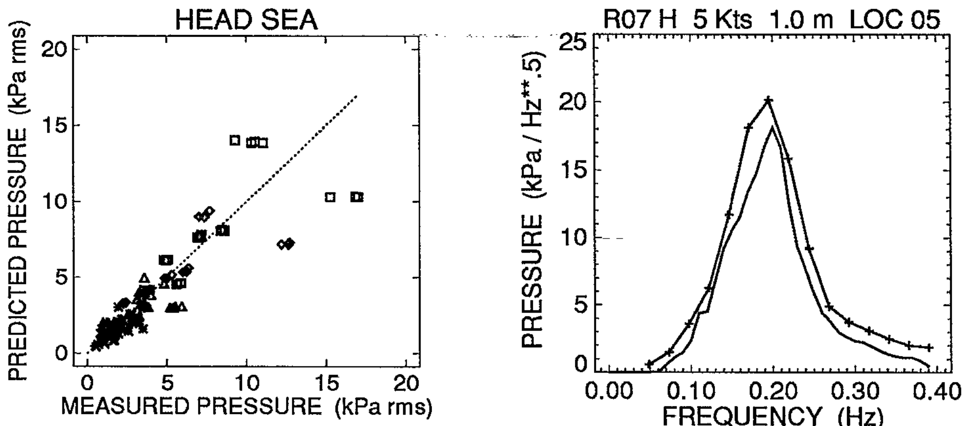
Vertical bending moment near midship

The analysis of strain data is still underway and only preliminary results of some of the runs are reported here. Fig. 14 compares predicted RMS VBMs (PRECAL & wave buoy spectra) with measured bending moments (measured strain spectra & VAST FE strain-to-VBM factor) for a number of head sea runs. The graph shows a linear trend with predictions averaging approximately 20% lower than measured. Points plotted for individual strain gauges for each run (plotted at the same predicted VBM) show reasonable agreement with maximum differences of 20% between deck and keel gauge prediction of RMS VBM. Fig. 15 shows example comparisons of measured and predicted VBM spectra for different dominant sea headings. The graphs show good agreement between measured spectra based on different gauges and the predicted spectral shapes based on PRECAL. Why the predicted bending moments averaged 20% lower than measured has not been determined. The finite element discretization produces a model which is stiffer than the real ship, leading to higher 'measured' VBMs. The finite element mesh discretization employed is expected to produce less than 5% error. A further refinement of the finite element mesh would be required to confirm this.

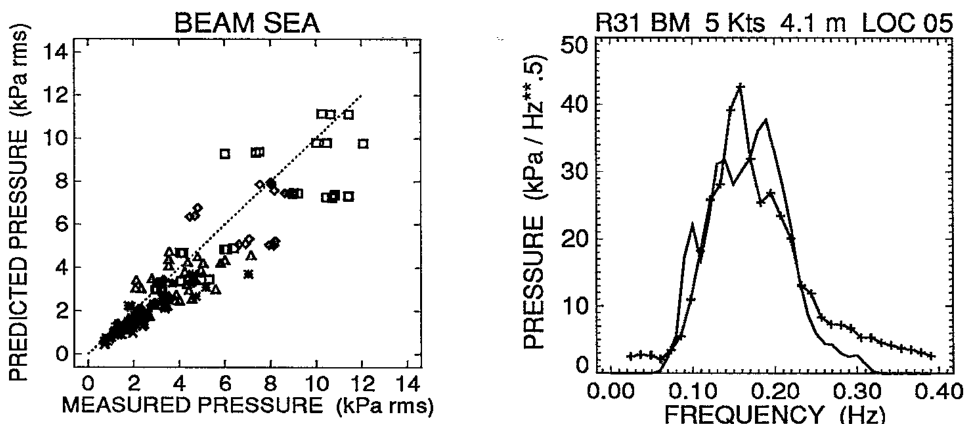
SUMMARY AND CONCLUSIONS

Overall, the trial was successful. A fairly good variety of sea states was encountered and data recording equipment functioned well. The pressure transducers were a disappointment as a significant portion of them failed during the trial or pre-trial testing. The Labview data acquisition system was programmed to provide a real time data monitoring and analysis capability which was a significant improvement over capabilities in past trials.

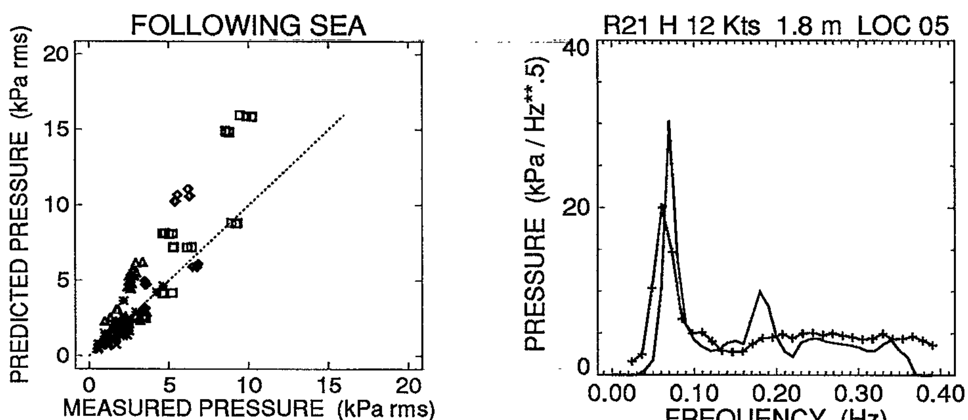
In the measurements of the sea state, the directional Endeco Wavetrack



a) Head sea



b) Beam sea



c) Following sea

Figure 12: Comparison of the hull pressures (RMS and spectra) sorted by dominant sea direction; Frame Station: □ 5.25, ◇ 15.25, △ 30.75, × 50.75, + 69.5, ∗ 92.75; SPECTRA: — Wave buoy/PRECAL prediction, + Measured

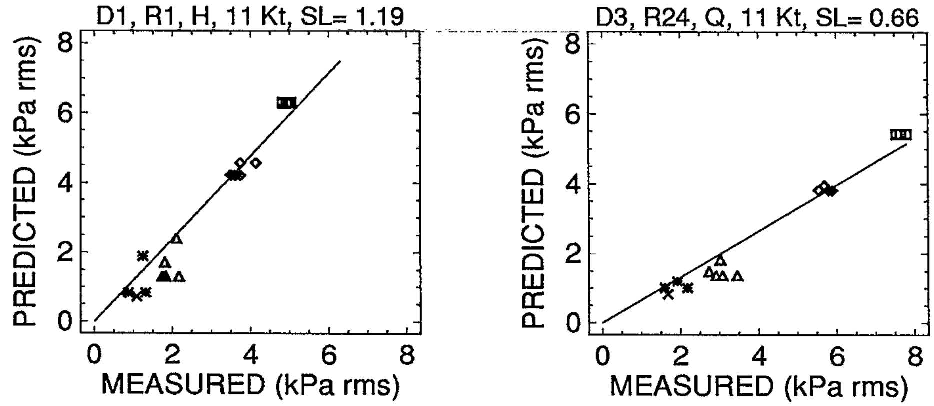


Figure 13: Plots of RMS pressures for individual runs; Frame Station: □ 5.25, ◇ 15.25, △ 30.75, × 50.75, + 69.5, ∗ 92.75

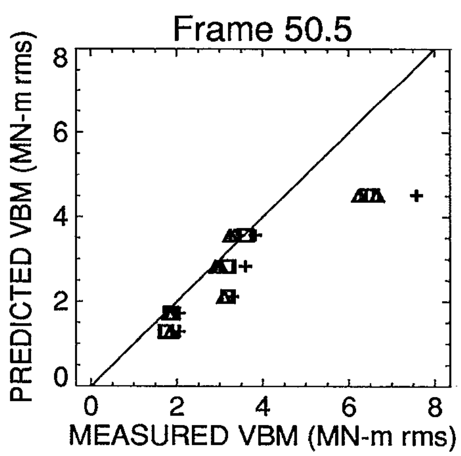


Figure 14: Comparison of 'Predicted' RMS Vertical Bending Moment at Frame Station 50.5 (derived from PRECAL and measured wave buoy directional spectra) with 'Measured' RMS VBMs (derived from measured strain spectra and FE bending-moment-to-strain factors);+ Keel Ga., Main Deck: □ Port Ga., △ Stbd. Ga.

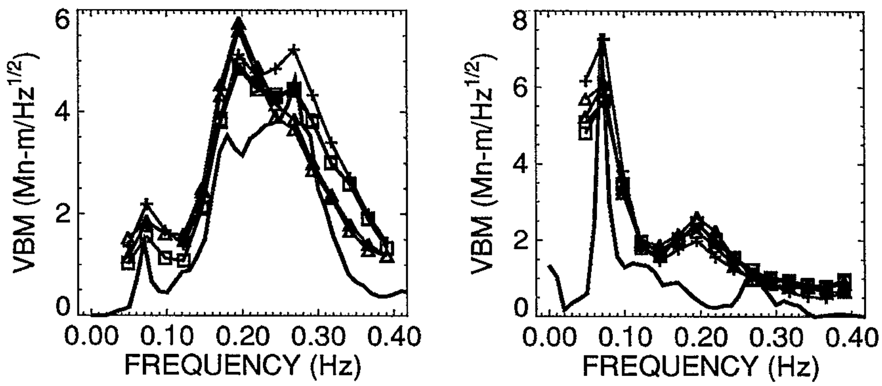


Figure 15: Comparison of 'Predicted' Vertical Bending Moment Spectra (derived from PRECAL and measured wave buoy directional spectra) with 'Measured' VBM Spectra (derived from measured strain spectra and FE bending-moment-to-strain factors);— PRECAL,+ Keel Ga., Main Deck: □ Port Ga., △ Stbd. Ga.

wave buoy proved to be acceptable, although scatter in the results suggests significant uncertainty in the directional measurements. Deployment and recovery of the buoy in heavy seas caused some difficulty and resulted in less than ideal sea state measurements on some days. The over-the-bow microwave wave height meter worked well and proved to be very useful for obtaining instantaneous sea state estimates. The 'MacRadar' system proved useful in ascertaining predominant sea direction in confused seas.

There was good agreement between PRECAL, SHIPMO and trial results for RMS pitch motion in head seas. Pitch spectra were in agreement between PRECAL and trial results. There were significant differences in regular wave roll response between PRECAL and measured data in beam seas. There were also significant differences between predicted and measured roll spectra, most noticeable at the higher speeds (11 knots) likely due to the effect of the anti-roll tanks.

The PRECAL predictions of RMS hull pressures showed good agreement with measurements at the bow, averaged 30 percent low at midships (based on only one operational transducer near midships) and averaged 10 to 25 percent low at stations further aft. PRECAL predictions of pressure spectra gave good agreement with measured results at the bow for many of the runs, but poorer agreement in spectral shape at midships and further aft. A few runs showed poorer agreement in spectral shape at all locations, suggesting differences between the wave spectra seen by the ship during the run and the directional wave spectra measured by the wave buoy.

The preliminary vertical bending moment predictions in head seas averaged 20 percent below measured bending moments. There was reasonable agreement between measured and vertical bending moment spectrum shapes for different dominant sea headings.

Considering the number of uncertainties and sources of error in full scale trials, the comparison of predicted and measured ship motions and hull pressures and bending moments was satisfactory. The most significant result in considering structural performance is the ability to predict strains in the hull structure resulting from the sea state. This part of the problem will be addressed in more detail in subsequent work. It is planned that strain spectral predictions will be made based on finite element methods and the use of combined vertical and lateral bending moments. Work is also underway on a spectral response method which will allow prediction of structural response spectra based on PRECAL hull pressure predictions and a top-down finite element analysis procedure to model combined hull girder loads and local pressure loads.

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