Puerto de la Coruna

PART VI

SHIP MOTIONS

"Camino II," —puerto de Cadiz

CHAPTER 216

WAVE-INDUCED SHIP MOTIONS IN HARBOUR APPROACH CHANNELS

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ABSTRACT

The results of scale-model simulation of wave-induced hull motions of large bulk carriers under conditions representative of those for coastal ports are presented and discussed to illustrate their usefulness in studies aimed at evaluating the optimum depth requirements for port approach channels.

1. INTRODUCTION

Port accessibility, particularly with regard to safe underkeel clearance for deep-draught vessels, is receiving close attention at South Africa's major export harbours. Saldanha Bay harbour on the west coast provides for ships up to about 270 kt deadweight and Richards Bay harbour, on the east coast, for ships up to 180 kt deadweight. Model studies are at present being carried out to determine the conditions under which ships of 270 kt deadweight could be considered in the future.

The CSIR has been engaged in an extensive programme of research including field measurements and physical and mathematical model simulations to study the behaviour of these deep-draught ships in port approaches of limited depth and exposed to waves, particularly long-period swell.

This paper deals mainly with the ship responses as function of the wave direction and water depth.

2. APPROACH

Fundamental model simulation studies were conducted to determine the responses of two models, the M150 (draught = 17 m) and the M270 (draught = 21 m), representing typical 150 and 270 kt deadweight bulk carriers in terms of their

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vertical hull motions resulting from heaving, pitching and rolling in waves from various directions and in different depths of water. The primary test conditions were selected to represent, in broad outline, the range of conditions most likely to influence ship behaviour at the major South African ports.

The ship model responses to these conditions were determined by physical modelling to a 1:100 scale as well as by mathematical simulation using a 3-D source method.

Subsequent to these fundamental studies the physical model tests were extended to cover the operational conditions characteristic of the approach channel to Richards Bay harbour. During these tests due account was taken of the spatial variations in the wave conditions due to the local wave refraction for different deep-sea swell directions. Prior to and also during the course of these model studies, a comprehensive field monitoring study was conducted at Richards Bay harbour to record the behaviour of prototype vessels presently using the entrance channel to this port. The results of these field measurements primarily served to validate the results obtained with the model studies for the 150 kt deadweight class ship.

3. TECHNIQUES AND FACILITIES

The techniques and facilities used for both the field monitoring and scale-model studies were described in detail by Van Wyk (1982) and Van Wyk and Zwamborn (1984).

The field monitoring basically comprised the photographic recording of the behaviour of ships while transiting the approach channel to Richards Bay harbour during both entry and departure. The photographic records were processed to derive the time series of the wave-induced hull motions of the ships during the selected channel transits and wave conditions.

The scale model tests were conducted in a 23 x 28 m flat-bottomed basin with variable water-depth and in a scaled model of the Richards Bay harbour entrance channel. A bank of programmable wave generators, of the modular paddle type, was used for simulating typical swell conditions.

The hull geometries for the two 1-in-100 scale model ships were determined from line drawings of existing prototype vessels. The propulsion and steering systems were designed in accordance with the scale model laws to ensure realistic steerability. The required loading conditions were obtained by the proper distribution of lead weights, both horizontally and vertically, to ensure correct metacentric heights and radii of gyration for both rolling and pitching. These determine the natural periods for the two rotational modes of movement.

Four ultrasonic sensors fitted at relevant positions on the hulls of these models served to measure the instantaneous distances between these hull points and the basin floor (underkeel clearances). These sensors had a measuring resolution of about 2 mm and could sample at 0,2 s intervals. The models' horizontal excursions were monitored by two remote-controlled overhead cameras. Three flashing lights on the decks, triggered at 3 s intervals, were time-exposed on film and served to position the models relative to their intended course.

Both the propeller revolutions and rudder movement were remote radio-controlled. The propeller speed, rudder angle and underkeel clearances were sampled at 0,2 s intervals and were transmitted by six-channel telemetry equipment to a data acquisition system linked to an in-house mini computer. Three additional channels were used for recording wave conditions in the test basin.

During testing each model was run along a straight course at the appropriate angle to the waves, covering a distance of about 20 m (2 km prototype). Each test condition was repeated between 20 and 30 times to obtain sufficient data for reliable statistical analysis.

During a time-domain analysis the recorded motion time series were used to derive time series of roll, pitch and heave and these principal motions were then used to calculate the vertical motion time series at the perpendiculars, shoulders and quarters of the models for each individual run.

These time series together with the recorded waves were spectrally analyzed individually and averaged over the number of runs during the test. The averaged spectra were then used to calculate the significant wave height and significant motion amplitudes (defined as twice the standard deviation of the motion time series) for roll, pitch and heave and for the vertical motions at the six hull points (i.e. the perpendiculars, shoulders and quarters). The data were also reduced to amplitude response functions for the said principal and hull motions using the encountered wave spectra derived from the incident wave spectra, average angle of wave incidence and average ship speed during the test.

4. SCALE-MODEL TEST PROGRAMME

A test programme was devised to enable coverage of as wide a range of test variables as possible in the available time. The test conditions were selected to represent, in broad outline, the range of conditions most likely to influence ship behaviour at the major South African ports.

In this respect only swells ranging from 1 to 4 m in height and with spectral periods of 12 to 16 s and longer would have to be considered. The angles of wave incidence relative to the models could, depending on their sailing directions, vary from following waves, through beam waves, to heading waves.

Overdepths could range from as little as 10 per cent to as much as 50 (to 75) per cent of the draughts of the model ships.

Ship speeds in and around ports would probably not exceed about 6 m/s (12 kn).

In planning a justifiable test programme, the following assumptions, based on earlier literature surveys, were first made:

(i) The irregular nature of both waves and wave-induced ship motions could be described by a linear superpositioning of sinusoidal components of different frequencies, these frequency compositions being fully described by one-dimensional energy density spectra.

(ii) In a given water-depth and for a given ship speed, the wave-induced ship motion amplitudes were assumed to be linearly related to wave amplitudes for each frequency of wave encounter with the result that the model's motion responses could be expressed in terms of frequency response functions for each angle of wave incidence.

Based on the above assumptions, the initial tests were done with one spectral shape (fixed wave height and spectral peak period) and one ship speed. Thus, only the angle of wave incidence and the relative water-depth were varied which were expected to be the most important variables.

A typical swell spectral shape, based on field measurements, was used to reconstruct a swell spectrum with a significant wave height of 3 m and a spectral peak period of 14 s. An appropriate ship speed of advance of 4 m/s (8 kn) was chosen to run the models in the specified swell conditions with the angles of wave incidence relative to the models to be incremented in steps of 15°. These tests were all done in a relative water-depth (depth-to-draught ratio) of 1,3.

The influence of different relative water depths, ranging from 1,1 to 1,5 in steps of 0,1 was studied for the primary angles of wave incidence, that is, following (α = 0°), heading (α = 180°), beam (α = 270°) and stern- and bow quartering waves (α = 315° and 135°).

In addition to the primary tests, secondary test programmes were devised to serve both for checking the validity of the above assumptions and for studying the influence of additional factors such as the absence/presence of bilge keels on the models, different loading conditions and different spectral shapes.

On completion of the fundamental model tests, a series of tests were planned to simulate typical port entries and departures with both models in a scale model of the Richards Bay harbour approach channel for comparison with data collected during the field monitoring study as well as for determining port accessibility for the deeper draught (21 m draught) model ship.

5. TEST RESULTS

5.1 Wave-induced Hull Motions Versus Angle Of Wave Incidence And Depth Of Water

The significant motion responses, A_{moz}/H_{mo}, versus angle of wave incidence, α, are shown for the perpendiculars, shoulders and quarters of the two models for the case with a relative water-depth, $d/_D$, of 1,3 in Figures 1a and b.

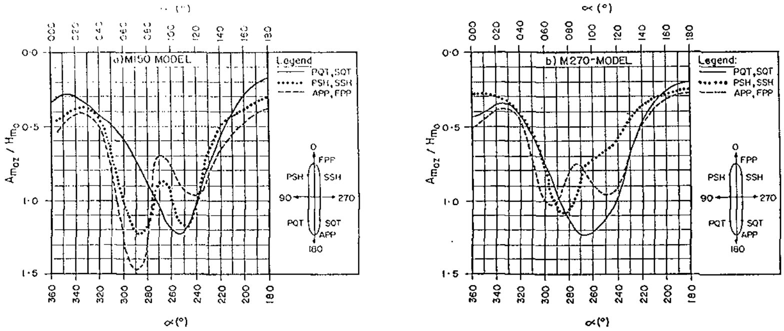

Figure 1a & b. Significant motion response at critical hull points versus angle of wave incidence for $d/_D$ = 1,3 and H_{mo} = 3m, T_p = 14s

The **maximum** significant motion responses are given by the lower limits of the envelopes described by these trend curves.

The effect of the relative water-depth (depth-to-draught ratio, $d/_D$) on these maximum significant hull motions was studied for following (α = 0°), heading (α =180°), beam (α = 270°) and bow and stern quartering (α = 135° and 315°) waves. The results for the M270 model are shown in Figure 2.

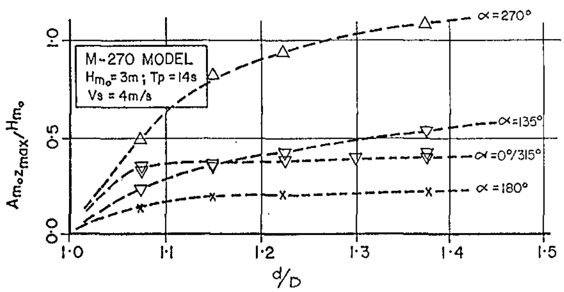

Figure 2. Maximum significant motion amplitude versus water depth

The dependence on water-depth is most noticeable (for both models) in beam and quartering waves indicating a gradual reduction in motion with decrease in underkeel clearance.

The maximum significant motion responses versus angle of wave incidence and relative water-depth, based on the above data, are shown for the two models in Figures 3a and b.

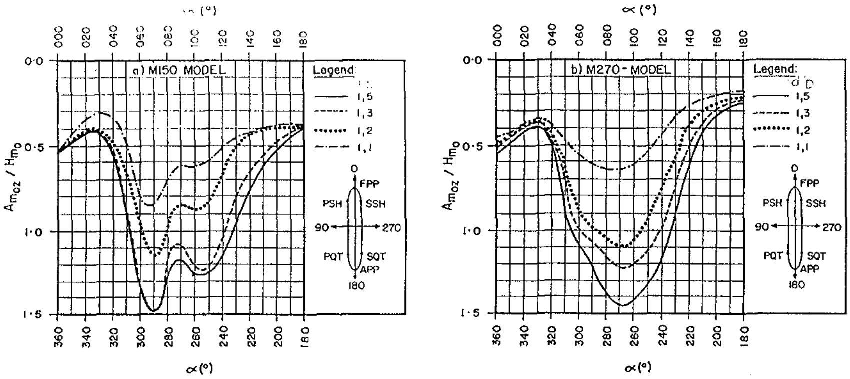

Figure 3a & b. Maximum significant motion response versus angle of wave incidence and relative water depth for H_{mo} = 3m, T_p = 14 s

Figures 1 and 3a and b show significantly different responses for the two models in equal wave conditions and relative water-depths. The most severe motions, for the M150 model, occurred at the perpendiculars for values of α around 70° (or 290°) and were caused mainly by pitching. Fairly severe motions were, however, also recorded at the quarters and shoulders for values of α between 90° and 120° (or 270° and 240°).

In the case of the M270 model the motions were largest at the quarters during rolling in beam waves (α = 90° or 270°). Motions were also quite severe at the shoulders for values of α around 75° (or 285°) and at the perpendiculars around 65° and 110° (or 295° and 250°).

The least vertical motions, for both models, occurred during heading waves (α = 180°) and were usually largest at the perpendiculars.

Motions in following waves (α = 0°) were generally larger than those in heading waves particularly for the M270 model where these were almost twice the magnitude of those in heading waves.

The differences in the motion responses for the two models can be ascribed to the differences in their principal dimensions and loading conditions as well as to the differences in absolute underkeel clearances for equal relative water-depths (e.g. with $d/_D$ = 1,3 the underkeel clearance for the M150 model (D = 17 m) was 5,1 m while that for the M270 model (D = 21 m) was 6,3 m).

Recorded maximum significant motion responses for both models are compared with mathematically predicted responses (using the VESDYN model) in Figures 4a and b.

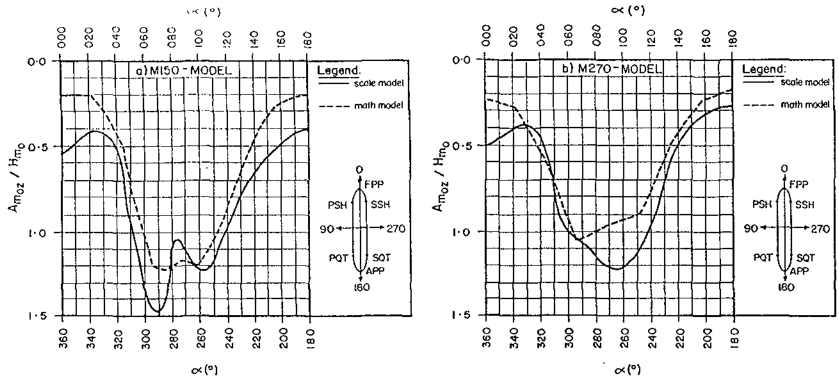

Figure 4a & b. Measured versus predicted significant motion response for $d/_D$ = 1,3 and H_{mo} = 3 m, T_p = 14 s

Measured motions were generally larger than those predicted particularly in following and heading waves and for angles of wave incidence where extreme motions were recorded.

5.2 The Effect Of Wave Height

The effect of wave height on the vertical motion response of the model ships was studied for the primary angles of wave incidence, namely heading (α = 180°), following (α = 0°), beam (α = 270°), bow quartering (α = 135°) and stern quartering (α = 315°) waves. These tests were all done in a relative water-depth of 1,3 and in a 14 s peak period swell with the models advancing at 4 m/s. Wave heights were varied between about 1 m and 5 m.

Figure 5 illustrates the effect of wave height on the maximum significant motion amplitudes for the M270 model for the different angles of wave incidence. Similar trends were also obtained for the M150 model.

The significant motion amplitudes showed an almost linear increase with increase in wave height for all test conditions except those in following waves (α = 0°). During this latter conditions the maximum motions were recorded at the aft perpendiculars of the models and would therefore have resulted from a combination of heaving and pitching.

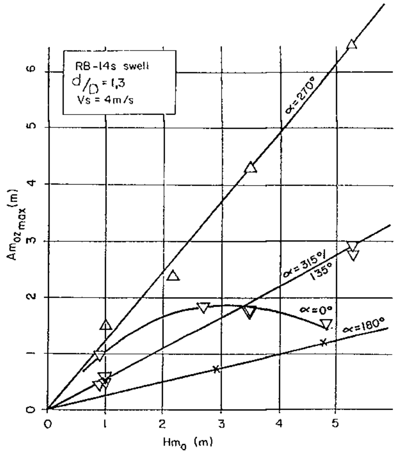

Figure 5. Maximum significant motion amplitude versus wave height for M270 Model

5.3 Sensitivity To Wave Spectral Shape, Peak Period And Ship Speed

Sensitivity tests were conducted to study the influence on wave-induced motion response for different wave spectral shapes, spectral peak wave periods and ship speeds.

The tests confirmed the assumption of linearity in response with respect to the above variables in the sense that hull motion **response amplitude operators** (RAOs) show only insignificantly small changes for the range of conditions tested.

As would be expected significantly large differences were, however, recorded in the resulting significant hull motions for different spectral shapes, peak periods and ship speeds for different angles of wave incidence. The differences primarily result from the differences in the distribution of wave energy with frequency of wave encounter and emphasize the need for using measured (or calculated) RAOs (response amplitude operators) as functions of angle of wave incidence and relative water-depth together with the operating condition, determined by the ship speed, angle of wave incidence and wave spectrum, to determine the resulting hull motion response. Sample ROAs as function of angle of wave incidence for the M270 model in a relative water-depth of 1,3 are shown in Figure 6.

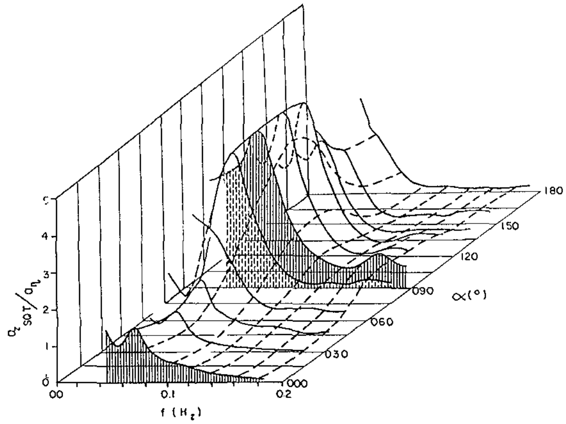

Figure 6. Motion amplitude response function for M270 Model

5.4 Maximum Versus Significant Vertical Hull Motions

The most probable maximum motion amplitude can be approximated by the mean of maxima obtained for the number of repeat runs for each test condition. This mean value, A_{max}, is shown versus A_{moz} for a representative number of tests with the M150 model in different relative water-depths and with different significant wave heights and angles of wave incidence in Figure 7.

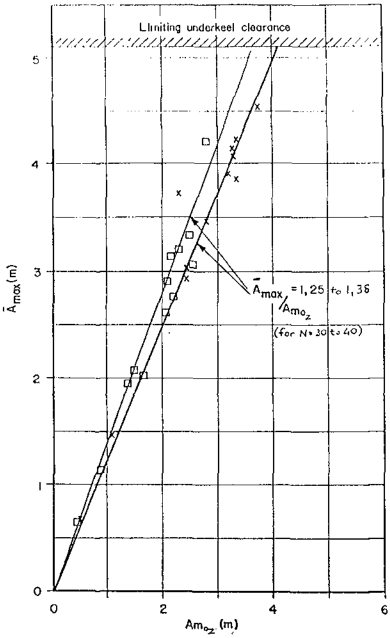

Figure 7. Maximum motion aplitude versus significant motion amplitude

The data indicate ratios of A_{max}/A_{moz} of between 1,25 and 1,38 for motion time series resulting in, on average, 30 to 40 motion oscillations. The apparent linearity of this relationship implies that extreme hull motions are also not affected by the limited underkeel clearances. The data of Figure 7 also appear to confirm the assumption that ship motions are approximately Rayleigh distributed.

The data of Figure 7 also appear to confirm the assumption that ship motions are approximately Rayleigh distributed. This assumption implies that the most probable maximum motion amplitude, μ (A_{max}) can be found from the relationship

$$\mu\ (A_{max}) = \frac{1}{\sqrt{2}}\ (\ln N)^{0,5}\ .\ A_{moz}$$

where N is the average number of oscillations of the ship for the duration of the tests. For values of N of 30 to 40 the theoretical most probable maxima show good agreement with the means of maxima obtained from the model data (Figure 7).

5.5 Ship Motions in the Richards Bay Harbour Entrance Channel

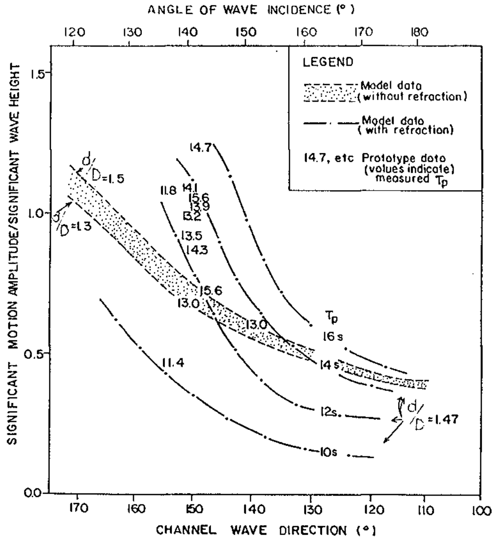

Figure 8. 150kt deadweight (17 m draught) ship: model and prototype response in Richards Bay harbour entrance channel and comparison with model response in undirectional waves

Figure 8 presents the results of the model tests with the M150 model during departure in the Richards Bay harbour approach channel together with those obtained from the field measurements and the model tests in the flat-bottomed basin.

The significant hull motions of the model in the channel were significantly larger than those obtained from the tests in the flat-bottomed basin. This phenomenon is explained by the fact that the wave energy, having accounted for wave directionality due to refraction for any given incident wave spectrum, was much more concentrated at frequencies of wave encounter close to the natural frequencies of motion of the model.

Good agreement was also found between the M150 model results and the prototype data and thus gave confidence in the model study approach and results also for the larger ship model.

CONCLUSIONS

The tests with the two model ships showed that there are significant differences in their vertical motion responses even with identical wave conditions and identical relative water-depths.

For both models the water-depth appeared to have effected the vertical motions for relative depths less than about 20 to 30 per cent of their draughts. This resulted in a non-linear reduction in motion with decrease in water-depth.

Vertical motions at any given depth of water appeared to have increased almost linearly with wave height except during following waves in which case the hull motions appeared to be relatively insensitive to wave height.

The amplitude response functions were found to be insensitive to ship speeds ranging from 0 to about 5 m/s. The amplitude response functions also were not affected by the spectral shape (peak period) although the significant motion amplitudes as such could differ appreciably.

In this respect use should rather be made of the actual amplitude response functions versus angle of wave incidence for given ships and of the wave spectra (accounting for directional spreading and refraction) to be encountered by these ships to determine their significant motion response for operating conditions other than those used during the tests.

The study further showed that local wave conditions in a harbour entrance can cause large differences in ship behavior. In the case of Richards Bay, vertical motion predictions based on the fundamental study results (flat-bottomed basin tests) were considerably less than those recorded by prototype ship monitoring at Richards Bay. Only after carrying out detailed tests in an accurately scaled model of the entrance area of Richards Bay and by reproducing correctly refracted directional swells could the recorded prototype motions be adequately reproduced.

The results of these studies, in general, are believed to offer a significant contribution to the state-of-the-art knowledge of wave-induced ship behaviour in limited depths of water. Since the model results could be verified by prototype measurements, these can be applied with more confidence in the determination of optimum depths for safe harbour approaches.

ACKNOWLEDGEMENT

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