Broaching and capsize model tests for validation of numerical ship motion predictions

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ABSTRACT

Model tests have been carried out with a frigate-type hull in waves leading to a variety of extreme motion events including capsizing. A specific requirement was the ability to perform tests in critical, stern quartering wave conditions at high speed and measure relevant parameters for validation of a large amplitude ship motion simulation program.

The paper describes model testing techniques, test data and some comparisons with numerical simulations related to large amplitude rolling, surfriding, broaching and capsizing in following to beam waves. Tests comprised maneuvering (zigzag) tests, roll decay in calm water, and regular waves of moderate to extreme steepness for a range of GM values.

INTRODUCTION

Since the cooperative research work presented by De Kat et al (1994), a second 4-year joint research effort on ship stability started in 1995 under sponsorship from the Cooperative Research Navies group. This CRNAV group, which comprises five navies (from Australia, Canada, Netherlands, United Kingdom and United States), U.S. Coast Guard and MARIN, focuses its current activities on the dynamic stability assessment of intact and damaged ships using numerical simulations.

The applied numerical tools should be subjected to proper verification and validation. An extensive database is available with seakeeping and manoeuvering data for intact ships. Suitable validation data concerning large amplitude ship motions of intact ships (including broaching and capsizing) are available to a very limited extent. To make the validation database more complete in terms of extreme conditions, tests were carried out in 1997 with a free-running frigate model.

This paper describes these model tests in detail, with the objective to provide insights into the physics of extreme motion events observed in the tests and discuss validation issues from a model testing perspective. The tests cover the most critical wave directions concerning dynamic stability during ship operations: following, stern quartering and beam seas were tested at different ship speeds with Froude number ranging from Fn = 0.1 to 0.4. Observed events include surfriding, broaching associated with surfriding, extreme rolling, and capsizing in a variety of modes.

EXPERIMENTAL SETUP

Fulfilment of the extreme motion objectives required a large basin capable of generating moderate and steep waves under arbitrary heading angles. A large test basin was required to maximize run length. The capability to generate steep waves allowed a test matrix to be developed, which would ensure the occurrence of extreme events. In addition to the tests in waves, the requirements included zigzag tests and roll decay tests at different speeds in calm water.

The test matrix for runs in waves required:

1. High speed runs in beam seas through following seas of suitable run lengths to allow capsizing, broaching, and surfriding.
2. Large amplitude regular waves having typical steepnesses (H/λ) of 1/20, 1/15, 1/10.

3. wave length to ship length ratios (λ /l) between .75 and 2.5

Basin

The capsize model tests and the calm water experiments were carried out in the Maneuvering and Seakeeping (MASK) Basin of the Carderock Division, Naval Surface Warfare Center.

The MASK is an indoor basin having an overall length of 110 m, a width of 73 m and a depth of 6.1 m, except for a 10.7 m wide trench parallel to the long side of the basin. The Basin is spanned by a 115 m long bridge supported on a rail system that permits the bridge to transverse half the width of the basin and to rotate up to 45 degrees from the longitudinal centerline. Models can be tested at all headings relative to the waves, with the wave makers located along two adjacent sides of the basin. A towing carriage is hung from the bridge. The carriage has a maximum speed of 7.7 m/s.

MODEL DESCRIPTION

The model chosen for this study has a conventional frigate hull form; a 1/36th scale was chosen for the fiberglass model. See Figure 1. The 3 meter model was large enough for accurate seakeeping measurements, yet was small enough to take advantage of the steeper waves produced in the MASK. The model was assigned the number 9096 by the Carderock Division, Naval Surface Warfare Center (CDNSWC).

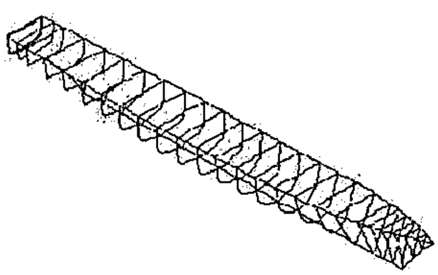

Figure 1. *Isometric sketch of frigate (Model 9096)*

The model was outfitted to be self-propelled using an autopilot for heading control. This autopilot uses a simple PID controller algorithm such that the desired rudder angle is:

$$\delta_{d\psi} = C_{1D}(\psi - \psi_d) + C_{2D}\dot{\psi}$$

where C_{1D} is the yaw gain and C_{2D} is the yaw rate gain.

The model was outfitted with bilge keels and twin rudders. Two four-bladed fixed pitch propellers (CDNSWC numbers 1991 and 1992) were installed on the model for inboard rotation.

A Plexiglas deck was installed to protect the instrumentation and machinery systems inside the hull from water damage during capsize events. The model was painted to enhance the display of the model during video recordings.

The outfitted model was tethered to the carriage by a cable bundle that contained control, power, and data signals. The cable was looped to minimize the effect of the cable tension on the model. The cable was connected to an overhead boom via a pulley that could be reeled in and out by a boom operator who stood on a platform mounted on the carriage. The boom could be yawed as desired by the boom operator. During the calm water and regular wave experiments, the carriage followed the model and the boom operator ensured that cable tension did not affect the model. The boom operator did this by pointing the boom so that it stayed above the model while reeling in or out the overhead pulley so that the cable remained slack. See Figure 2.

Before the start of a test in waves, the wave maker was turned on and the model held in position until a sufficient number of waves had passed. Subsequently the model would start slowly under its own power (at low RPM) and once it was on course properly, the propeller RPM was set to the required level associated with a calibrated speed in calm water. The boom and trolley system followed the model during the test.

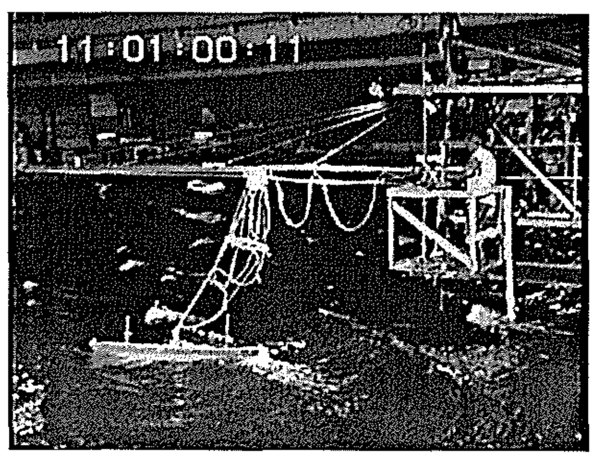

Figure 2. *Model tether arrangement*

Instrumentation

The carriage was equipped with a Ship Motion Recording (SMR) system developed by the CDNSWC Seakeeping Department. This system was connected to the sensors used in the model test as listed in Table 1 and described below.

Table 1. *Capsize model test data channels*

Measurement	Source
Basin Wave Height From Carriage (cm)	Sonic Transducer
Basin Wave Height on shore (cm)	Sonic Transducer
Carriage Speed (m/s)	Tachometer
Propeller RPM (rev/minute)	Tachometer
INS Hull Speed (m/s)	MILNAV™
INS Azimuth (°T)	MILNAV™
Pitch (deg)	MILNAV™
Pitch rate (deg/s)	MILNAV™
Roll (deg)	MILNAV™
Roll Rate (deg/s)	MILNAV™
Yaw Rate (deg/s)	MILNAV™
Rudder Angle (deg)	Autopilot
Rudder force, X direction (Newtons)	Block Gauge
Rudder Side force (Newton)	Block Gauge
Vertical Acceleration Forward (g)	Accelerometer
Longitudinal Acceleration Forward (g)	Accelerometer
Transverse Acceleration Forward (g)	Accelerometer
Vertical Acceleration Starboard (g)	Accelerometer
Longitudinal Acceleration Starboard (g)	Accelerometer
Transverse Acceleration Starboard (g)	Accelerometer
Relative Bow Motion, Port and Starboard (cm	Capacitance Probe
Relative Stern Motion, Port and Starboard (cm	Capacitance Probe

The primary sensor used in the model test was a KEARFOTT T16 *Miniature Integrated Land Navigation System* (MILNAV™). This inertial navigation system (INS) included a monolithic 3-axis Ring Laser Gyroscope and three, single axis linear accelerometers. The MILNAV had the capability to measure extreme pitch, roll, and yaw angles, rates and accelerations. It was also used to determine surge, sway, and heave displacements, velocities, and accelerations near the center of gravity of the model. These motions were translated to the ship's center of gravity reference for each load condition.

More details have been described by De Kat and Thomas (1998). Model speed was measured in three orthogonal directions using the MILNAV™ inertial navigation system. Propeller speed was measured using a tachometer which was mounted to the propeller shafting. Rudder angle was measured using the rudder feedback unit which as mechanically linked to the rudder tiller arm. Longitudinal and transverse rudder forces were measured using block gauges mounted on a free-floating plate that was attached to the rudder posts.

Model hydrostatics

The model was tested in three load configurations. These configurations comprised:

1. Full Load condition
2. Marginal GM condition
3. Failed GM condition

The load conditions were chosen with first priority given to the validation of the time domain simulation program FREDYN developed by the CRNAV group. Since the capsizing characteristics of this frigate were previously unknown, it was deemed necessary to choose a load condition to ensure that capsizing would occur. As an additional consideration, it was desired that one load condition resemble a realistic operating condition of the ship. Thus, the first and most conservative condition tested closely resembled the typical frigate Full Load operating condition. The two remaining load conditions were achieved by the raising of weights above the deck of the model to reduce transverse GM. This procedure ensured that displacement and freeboard remained constant for the three load conditions. Thus, the second load condition called "Marginal GM" represented a decrease in GM such that the model is in marginal compliance with the U. S. Navy Criteria (NAVSEA, 1976), which include a weather criterion. The third load condition called "Failed GM" represented a load configuration that is in violation of the U. S. Navy Stability Criteria; as such this is not a realistic operating condition.

A summary of the full scale load configurations tested is presented in Table 2. The GZ curve was measured for the full range from 0 to 180 degrees heel angle for the three loading conditions to provide comparison data as regards the computed hydrostatics.

Table 2. *Full Scale Load Conditions corresponding to model test*

Parameter	Load condition		
	Full load	Marginal GM	Failed GM
L_{PP} (m)	106.68	106.68	106.68
B (m)	12.78	12.78	12.78
T (m)	4.73	4.73	4.73
GM_T (m)	0.78	0.68	0.43
T_ϕ (sec)	12.3	13.3	17.1

The transverse metacentric height (GM_T) was checked prior to each run series in waves by conducting an inclining experiment. The roll, pitch and yaw gyradii (k_{44}, k_{55} and k_{66}) were determined using the pendulum method by swinging the model in the air. For each load condition, the model was suspended by a pivot located above the COG of the model and allowed to oscillate in e.g. pitch or roll. The gyradii were calculated from the respective oscillation periods.

Test conditions

The model test matrix was designed for runs in regular waves for the three load (GM) conditions for the purpose of identifying critical, extreme motion situations, including capsizing, broaching, harmonic resonance and surfriding. Regular waves were chosen instead of irregular waves to allow a better understanding of observed extreme events in terms of known wave length, steepness, and phase relation with respect to the model; an important factor was the ability to use the data for validating a time domain simulation model.

The critical wave length range involved waves with λ/L between 0.75 and 2.50 with associated wave steepness in the range of 1/20 and 1/10. Model speeds were chosen between Fn_0 = 0.1 and 0.35 in combination with the selected wave and heading conditions. The critical wave headings chosen included following seas and stern quartering seas predominantly. Some runs were performed in beam seas.

Runs were performed at selected critical headings and speeds, which were based on time domain simulations carried out *a priori*. In case of the "Failed GM" loading condition, the occurrence of a capsize event invoked procedures that isolated the capsize region at the particular wave length λ/L. In general this meant that follow-up runs were made in higher and lower wave steepnesses and at lower (or higher) speeds until no capsizes were found. Adjacent headings were also tested at the capsize steepness to identify the effects of heading variations.

Table 3 provides an overview of the test runs for the ship with the Failed GM condition; χ represents the nominal heading angle. Test conditions for the other two loading conditions were in principle similar.

λ/L	H/λ	Fn	χ (deg)						
			0	15	30	45	60	75	90
0.75	1/15	0.1							
		0.2			X				
		0.3							
		0.35		X	X				
	1/10	0.1		X					
		0.2			X				
		0.3		X					
		0.35		X	X	X			

λ/L	H/λ	Fn	χ (deg)						
			0	15	30	45	60	75	90
1.00	1/20	0.1							
		0.2			X				
		0.3			X				
		0.35		X	X				
	1/15	0.1			X				
		0.2				X			
		0.3		X	X	X			
		0.35	X	X	X	X			
	1/10	0.1							
		0.2							
		0.3		X	X				
		0.35		X	X	X			

λ/L	H/λ	Fn	χ (deg) 0	15	30	45	60	75	90
1.25	1/20	0.1							
		0.2			X				
		0.3			X				
		0.35	?	X	X				
	1/15	0.1				X			
		0.2				X	X		
		0.3			X	X			
		0.35	X	X	X	X	X		
	1/10	0.2							
		0.2		X	X				
		0.3		X	X				
		0.35			X				

λ/L	H/λ	Fn	χ (deg) 0	15	30	45	60	75	90
1.50	1/20	0.1							
		0.2							
		0.3							
		0.35			X				
	1/15	0.1				X			
		0.2				X			
		0.3		X	X		X		
		0.35		X	X	X	X		
	1/10	0.1							
		0.2							
		0.3		X	X				
		0.35		X	X	X	X		

λ/L	H/λ	Fn	χ (deg) 0	15	30	45	60	75	90
2.00	1/20	0.1							
		0.2							
		0.3		X					
		0.35		X					
	1/15	0.1							X
		0.2							
		0.3							
		0.35		X	X				

λ/L	H/λ	Fn	χ (deg) 0	15	30	45	60	75	90
2.50	1/20	0.1							
		0.2							
		0.3							
		0.35			X				
	1/15	0.1			X				X
		0.2							
		0.3			X				
		0.35		X	X				

Table 3. *Test matrix for Model 9096 in Failed GM condition (0 degrees is following seas)*

EXTREME MOTION EVENTS

The following provides a description of some extreme motion events, including:

- Surfriding (and periodic surging)
- Broaching
- Extreme rolling
- Capsizing

Surfriding

A ship in following seas can experience large speed fluctuations (at low encounter frequencies) about its mean forward speed. If the ship speed is sufficiently high, i.e. the speed that would be attained in calm water at a given propeller RPM and thrust, a wave may capture the ship and propel it at wave phase speed. The resulting speed can be significantly higher than the calm water speed.

The typical conjecture in surfriding research is that once captured by a wave, the ship attains a steady speed. An interesting result of the model tests presented here is that the ship can reach speeds well beyond the (steady) wave phase speed for an extended period before reaching a steady-state condition. To illustrate this, we consider the frigate running in following seas (zero degrees heading angle) of different periods and heights. The loading condition corresponds to the Full Load case discussed above. At a propeller RPM setting for calm water Froude number of Fn_0 = 0.3, the ship experiences periodic oscillations in forward speed of significant amplitude, which increases with increasing wave amplitude (De Kat and Thomas, 1998).

The model tests show that for the speed range Fn_0 ≤ 0.3 wave capture (and hence surfriding) does not occur in the wave conditions tested. For Fn_0 = 0.35 a drastic change in surge character occurs, for at this speed setting the frigate model does experience wave capture and surfriding events. In a number of tests where wave capture takes place in following waves, the ship is accelerated to a speed that lies well beyond the phase speed of the wave. Figure 3 provides an overview of measured maximum speeds for Fn_0 = 0.35. The maximum ship speed increases with increasing wave steepness; for the conditions with $\lambda/L = 1$ the steepness tested is $H/\lambda = 0.077$ and 0.097, while for $\lambda/L = 1.25$ the steepness is $H/\lambda = 0.051$ and 0.092.

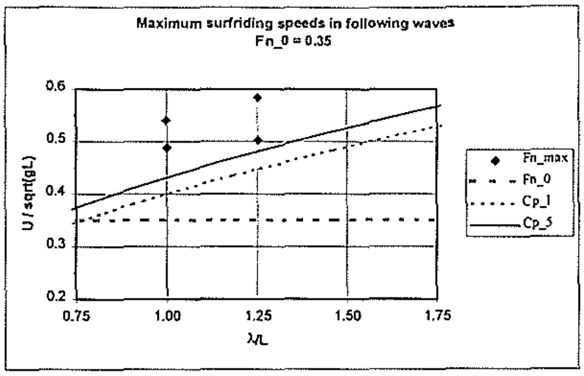

Figure 3. *Maximum attained ship speed (Fn_max) following wave capture in experiments. Cp_1 is the phase velocity based on linear wave theory; Cp_5 is the phase velocity for H/λ = 0.1*

For reference purposes in the figures presented in this paper, we use a definition for wavelength based on linear wave theory in deep water, i.e. $\lambda = gT^2/2\pi$, where T is the period. Cp_1 represents the phase speed according to linear wave theory, while Cp_5 is the phase speed determined according to Stokes 5th order theory (Fenton [5]); the phase speeds have been normalized by the square root of gL.

Figure 3 shows that especially for the steepest waves, the maximum ship speed reaches very high values. The time series describe the character of this behavior, as shown for run 231 in Figure 4, where λ/L = 1.0 and H/λ = 0.1.

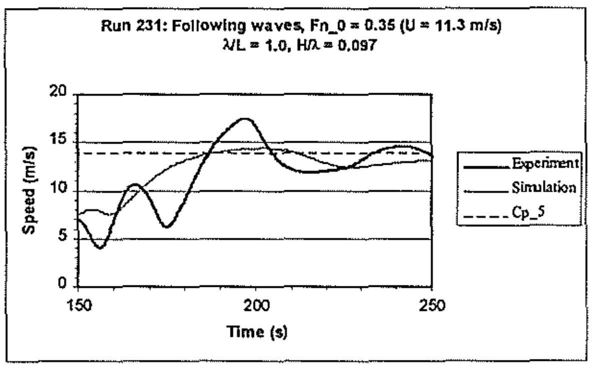

Figure 4. *Measured and predicted ship speed during surfriding events for run 231*

This figure shows that as the ship reaches a critical speed level in the model test, wave capture occurs and the ship accelerates to a speed well beyond its calm water speed. The observed mechanism is as follows: at approximately t = 180 s a wave crest reaches the stern of the ship and causes the ship to surge forward. At around t = 185 s the crest has reached the aft quarter (i.e. it has overtaken the ship slowly until the ship speed equals the celerity), at which stage the ship is subjected to a large surge force. This causes the ship to accelerate and overtake the wave crest, which by t = 200 s is situated at the stern again; the maximum speed is 17.5 m/s. While the ship accelerates and overtakes the wave crest, it buries the bow in the back slope of the preceding wave.

The (complete) submergence of the bow increases the resistance and eventually causes the ship to decelerate; between t = 205 s and 235 s the speed decreases to below the wave celerity. As the crest overtakes the ship, the ship speed increases again to the wave celerity level. As a consequence, the speed drops to 11.9 m/s before accelerating again to wave celerity level.

Numerical simulations (De Kat and Thomas, 1998) predict similar trends in forward speed fluctuations, but the maximum simulated speed of 14.4 m/s lies well below the measured maximum speed. As a consequence of the linear wave model in the simulation, the surfriding speed is equal to the linear wave celerity (Cp_1), which lies below the actual wave speed, Cp_5, by about 10%.

So far, the issue of transient forward speed above the wave phase speed has not been addressed in detail. The issue is of relevance especially for irregular following seas, where steep waves will be able to push the ship speed to high values for some time and cause bow submergence, with broaching as a possible consequence.

Broaching

The model tests show that the frigate investigated can experience broaching under certain conditions at high Froude number only (Fn_0 = 0.35). In general the ship proved to have good course keeping qualities in following and stern quartering waves, i.e. broaching did not occur frequently in the conditions tested at high Froude number. Two modes of broaching were observed:

1. High speed broach preceded by surfriding, with rapidly and monotonically increasing heading deviation in following and stern quartering waves
2. Large amplitude, low-frequency yaw (heading) oscillations in stern quartering waves

Figures 5a and 5b depict the occurrence of the first broaching mode for the ship in the Marginal GM Condition. The nominal (desired) heading is 15 degrees. Figure 5a shows both the longitudinal and transverse ship speeds, where Us is defined in the horizontal plane along the x-axis of the yawed ship, and Vs is perpendicular to Us in the horizontal plane. Figure 8 shows the steadily increasing heading angle once the ship has been captured by the wave afterv t = 70 s; the ship experiences moderately large heeling angles during the event. As a consequence of the test set-up, the broach ended when a tight tether line limited the motions.

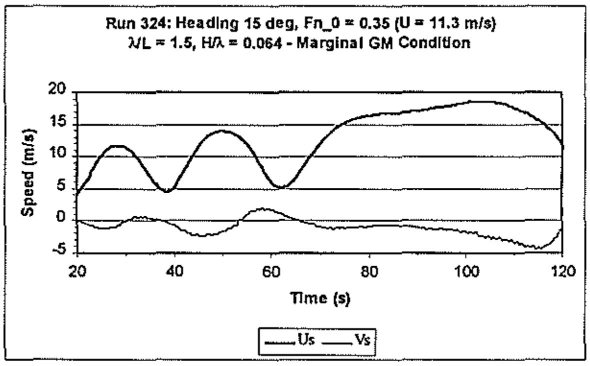

Figure 5a. *Mode 1 broach: Measured longitudinal and transverse ship speeds for run 324*

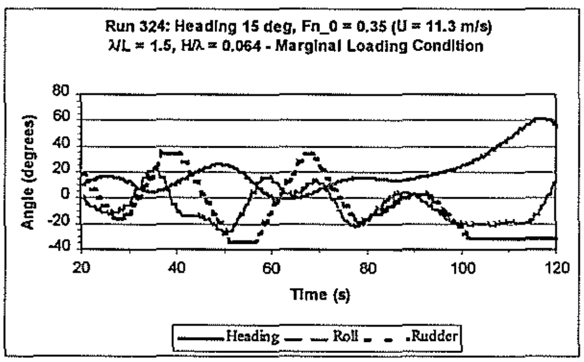

Figure 5b. *Mode 1 broach: Measured heading, roll and rudder angles for run 324*

Figures 6a and 6b depict the occurrence of the second broaching mode for the ship in the Full Load Condition, illustrating that the ship can experience large roll angles in this condition. Figure 8a shows that the ship has a significant mean negative drift velocity, i.e. it experiences a rather large drift speed to leeward while yawing. The highest transverse drift velocity occurs when the yaw angle (toward the wave) and forward speed increase while a wave crest is overtaking the ship (from aft to amidships). When the crest is in the midship area and the ship has reached its largest yaw deviation into the wave, the roll angle to leeward (negative sign) is largest; the reduction of the righting arm in the wave crest leads to asymmetric roll motions. In this case the ship experiences large roll angles, but it does not capsize.

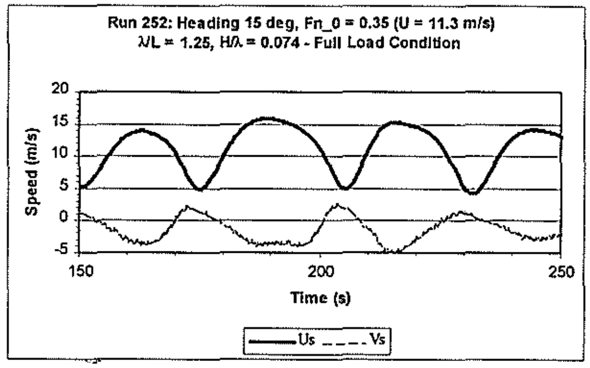

Figure 6a. *Mode 2 broach: Measured longitudinal and transverse ship speeds for run 252*

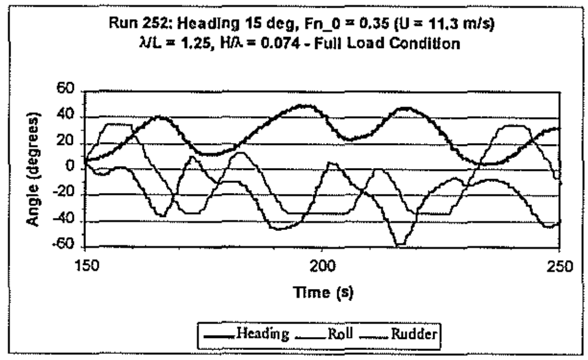

Figure 6b. *Mode 2 broach: Measured heading, roll and rudder angles for run 252*

The stable course keeping properties of the frigate in waves may be linked to its degree of directional stability in calm water. According to the simulations the ship is directionally very stable. The large skeg and twin rudders contribute to the frigate's directional stability.

Capsizing

The frigate did not capsize under any of the speed, heading and wave combinations tested in either the Full Load or Marginal Loading Condition. In the Failed Loading Condition, however, capsizes did occur frequently at the highest ship speeds (Fn_0 $\geq$ 0.3) in following and stern quartering waves; no capsizes occurred at Fn_0 < 0.3, even though conditions included harmonic resonance in steep stern quartering and beam seas.

The following main modes of capsize could be distinguished from the experiments:

1. Loss of transverse stability in wave crest associated with surfriding or periodic surging
2. Dynamic loss of stability due to surge-sway-roll-yaw coupling
3. Broaching (mode 1 and 2)
4. Combinations of modes

The majority of observed capsizes were of mode 1 and 2. A mode 1 capsize is one where the ship capsizes while being overtaken slowly by a wave crest. For this capsize mode, typically the ship does not experience extreme roll motions before the final "half roll."

A mode 2 capsize involves significant rolling, and often the roll motion tends to build up in severity before capsizing occurs. We illustrate this mode for three experimental cases: run 414 with a short wavelength ratio ($\lambda/L = 0.8$), run 427 with $\lambda/L = 1.25$, and run 448 with a relatively long wave ($\lambda/L = 2.5$), as shown in Figures 7, 8 and 9, respectively.

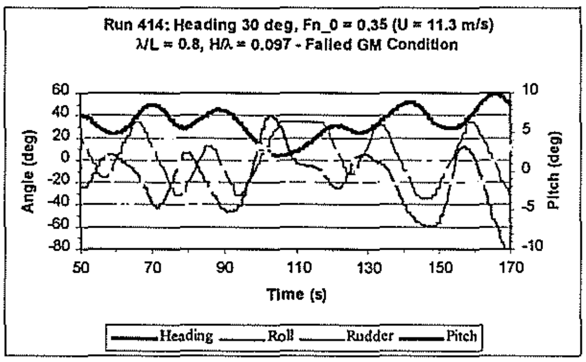

Figure 7a. *Mode 2 capsize: dynamic loss of stability (run 414) with measured heading, roll, pitch and rudder angles*

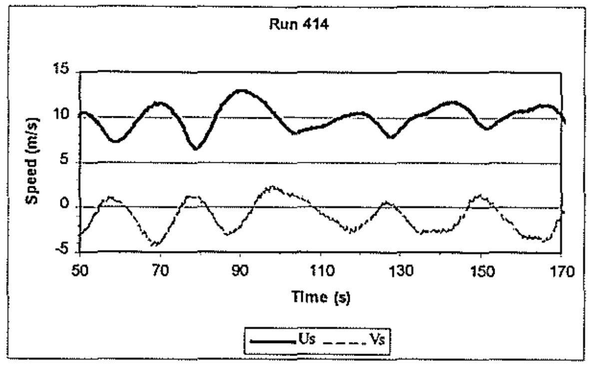

Figure 7b. *Measured ship velocities associated with mode 2 capsize (run 414)*

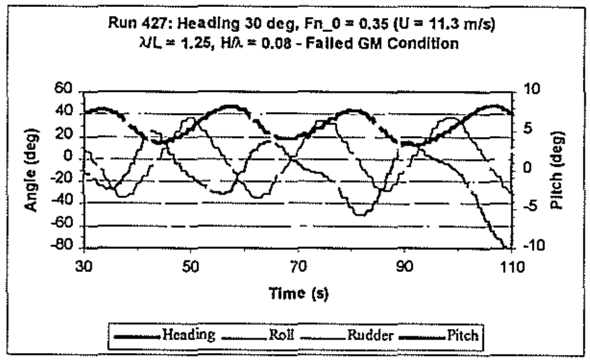

Figure 8. *Mode 2 capsize: dynamic loss of stability (run 427) with measured heading, roll, pitch and rudder angles*

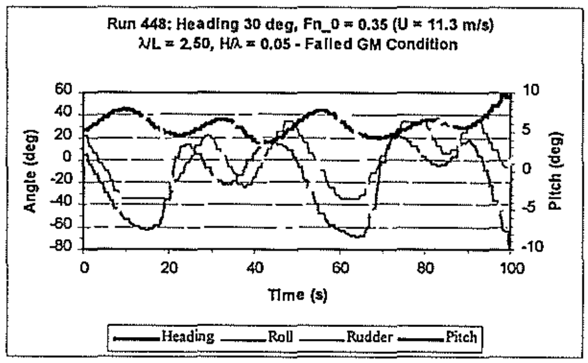

Figure 9a. *Mode 2 capsize: dynamic loss of stability (run 448)*

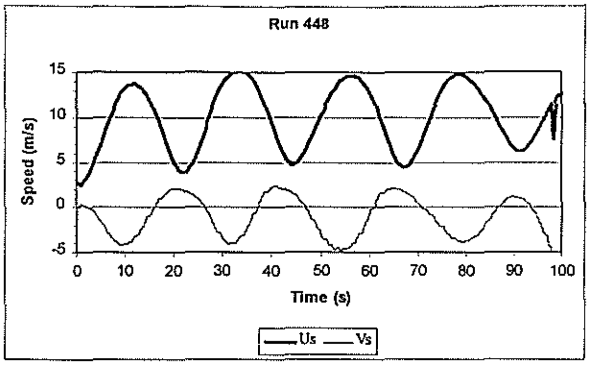

Figure 9b. *Ship velocities associated with mode 2 capsize (run 448)*

Although all three cases involve dynamically coupled rolling, the motion behavior differs significantly: for instance, the speed variations in run 414 are limited to relatively small fluctuations about the mean forward speed, the roll motion in run 427 shows increasing extreme roll angles to port (negative sign, to leeward), and the roll motion in run 448 has a double period. Concerning the latter, double period rolling ("period bifurcation") has been observed in some model tests with containerships in regular waves (Kan et al, 1994). In these dynamic (mode 2) capsize events the ship capsizes typically in the wave crest.

VALIDATION ASPECTS

This section discusses some model testing issues that bear relevance on validation of numerical simulations. In conjunction with the tests described above we will cover the following:

- Roll decay and influence of autopilot
- Measurement of ship velocities
- Measurement of ship position
- Wave height at ship-fixed reference point

Roll decay and inluence of autopilot

Roll decay tests in calm water provide information on roll period and damping as a funciton of ship speed. This type of testing is useful for validation against numerical predictions in the time domain.

Figure 10 provides an example of measured and predicted roll motion response in calm water at a Froude number Fn = 0.3 with an initial roll angle of 40 degrees. The two curves compare quite well for the frigate hull, but there is an offset in the model test data. The cause of the offset was found to be the autoilot: as the model heeled, a yaw moment was induced and the model started to veer off course. The ensuing rudder action demanded by the autopilot resulted in a (quasi-steady) heeling moment.

The recommendation for performing roll decay tests with large initial heel angles at forward speed is to switch off the autopilot.

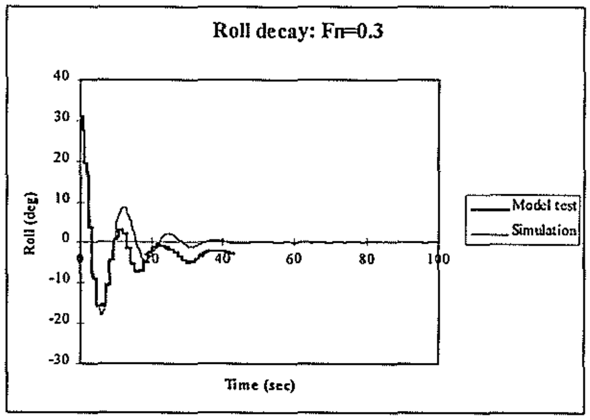

Figure 10. *Roll decay test at Fn = 0.3*

Measurement of ship velocities

It is not standard practice in seakeeping or capsize model tests to measure ship speed in longitudinal and transverse directions; even the direct measurement of instantaneous forward speed is not common. Typically one knows the calm water speed associated with the propeller RPM, which is assumed to be the mean speed.

As some of the tests discussed above show, a ship can experience significant velocity fluctuations periodically in both forward and transverse directions. Quantitative knowledge of these speed variations will contribute to a better understanding of the physics in the validation process.

Let us consider a typical stern quartering condition case: Figure 11a represents motion measurements for run 337. Waves overtake the ship (with Marginal GM) slowly from the starboard quarter. Each passing wave captures the ship briefly while the crest passes the amidships area. The stability reduction experienced by the ship induces the ship to heel to port at a large angle of roll. As the ship is released by the wave, the ship rolls back to starboard and uprights itself in the wave trough, resulting in asymmetrical roll behavior. This cycle repeats with the next overtaking wave.

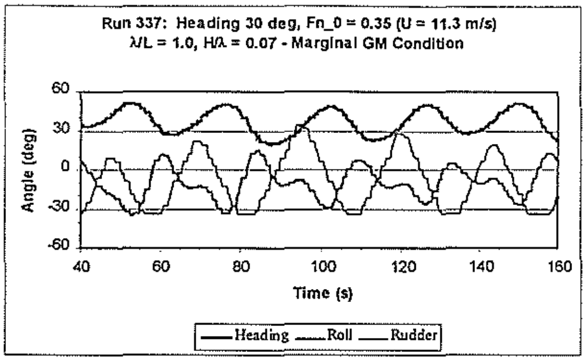

Figure 11a. *Run 337: motions in stern quartering waves (Marginal GM condition, Fn_0 = 0.35)*

As a consequence of the speed changes, the instantaneous drift angles can be substantial. To illustrate this aspect, we consider the velocity components Us and Vs associated with run 337 in Figure 13b. The instantaneous drift angle is given by

$$\beta(t) = \arctan\frac{Vs}{Us}$$

i.e., this is the drift angle with respect to the yawed x-axis of the ship in the horizontal plane.

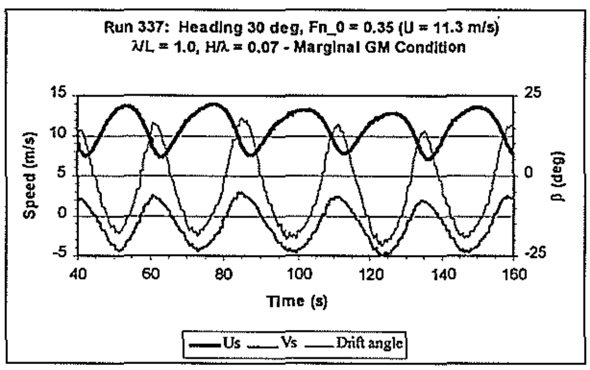

Figure 11b. *Ship velocities and drift angle associated with run 337*

Figure 11b shows the following:

- The transverse velocity can reach high values (up to -5 m/s to port) and it has a negative mean.
- The frigate undergoes large variations in instantaneous drift angle, with maxima of around 20 degrees to either side with respect to its longitudinal axis.
- The drift angle variations suggest a mean negative drift angle.

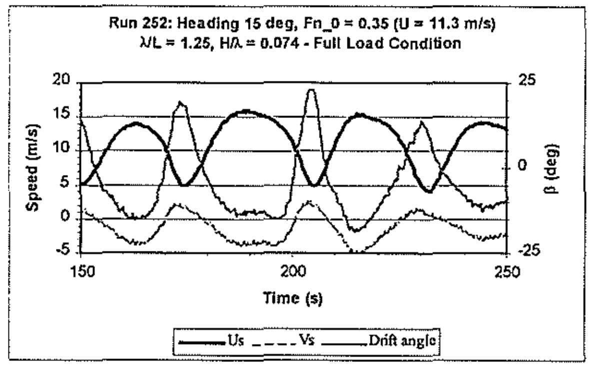

Figure 12. *Ship velocities and drift angle associated with run 252 (Broach shown in Fig. 6)*

Figure 12 shows the drift angle for run 252 (Mode 2 broach, see Fig. 6). It is noted for run 252 and 337 that while the ship is undergoing these velocity and drift angle variations, it is at the same time undergoing large yaw (heading) changes. The large drift angles and drift velocities will influence the ship motions and course keeping behavior, noting that seakeeping and maneuvering are intricately intertwined and should not be modeled independently to predict motions in these conditions.

Measurement of ship position

As is the case for ship velocities, ship position is typically not measured in seakeeping and capsize tests. Yet knowing the earth-fixed position of the ship's CoG at each time instant, allows the comparison between measured and simulated ship track in space for validation purposes.

The ship track provides an indication of the amount of drift a ship may experience in stern quartering waves, for example. Figure 13 shows the measured track for run 252, referenced against the "no drift" track, which is the track the ship would have followed along its average heading (around 30 degrees) in the absence of mean drift effects as of the point in time at t = 150 s. Also shown is the actual heading angle, which corresponds to the one shown in Figure 8b for the time period between t = 150 and 250 s.

Figure 14 shows similar information for run 337 between t = 50 and 150 s. Here the "No drift" track is based on a mean heading of 35 degrees. Figures 15 and 16 illustrate the amount of drift a ship can experience in steep stern quartering waves, noting that the autopilot algorithm employed in the tests did not account for deviation from the desired path.

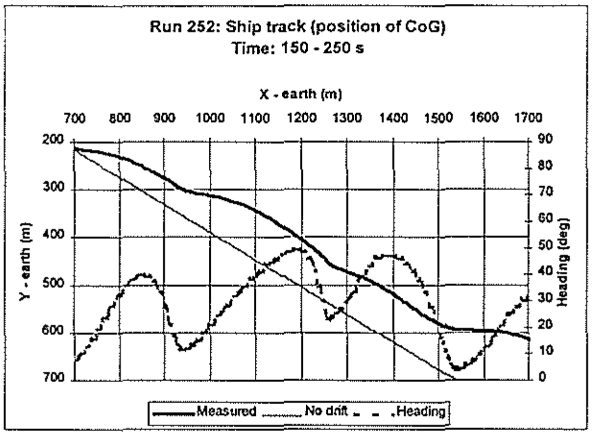

Figure 13. *Ship track and heading between associated with run 252 in stern quartering waves (waves travel along X-earth axis)*

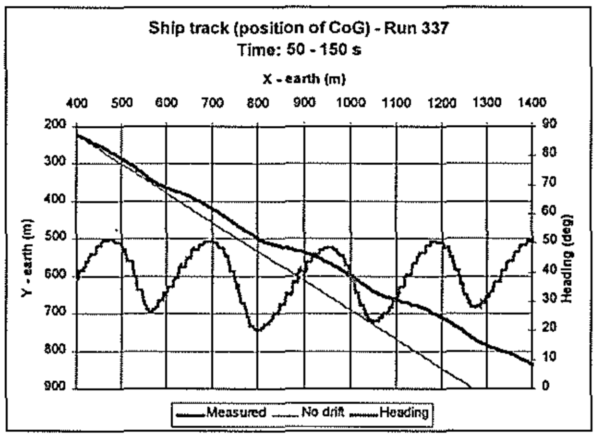

Figure 14. *Ship track and heading between associated with run 337 in stern quartering waves (waves travel along X-earth axis))*

In addition to defining the ship track, earth-fixed measurements will allow the determination of the ship with respect to the (presumably known) wave system.

Wave height at ship-fixed reference point

To achieve simulation conditions that are similar to the model test, it is necessary to know the position of the ship in the wave at any time instant. This allows e.g. to start the simulation with the correct initial conditions and phasing with respect to the wave crest.

In the tests discussed here the wave elevation was measured at a basin-fixed location and at two locations on the towing carriage. Using the latter data and the measured ship motions (including positions), the time series of the wave height at the center of gravity could be generated. Figure 15 provides an illustration of the estimated wave elevation for run 252.

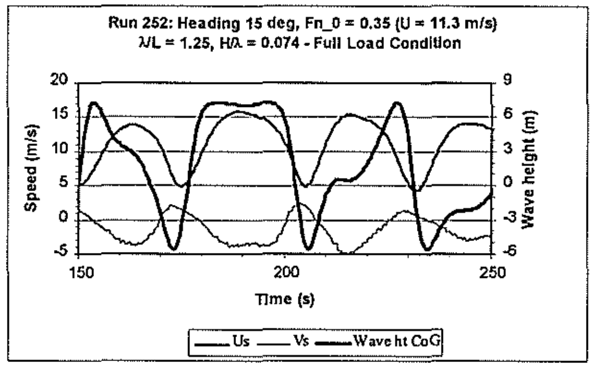

Figure 15. *Ship velocities and wave height at CoG for run 252 (Broach shown in Fig. 6)*

Figure 15 shows that while the ship experiences a significant transverse velocity to port (negative sign), it has a high forward speed and runs with the wave crest at the CoG (i.e., amidships) for an extended period of time between t = 175 and 200 s. Comparison with Figure 8b shows that the roll motions to port are in phase with the wave crest coinciding approximately with the CoG position, leading to reduced stability and hence large roll angles to the leeside during the passage of the wave.

CONCLUSIONS

Model tests with an intact frigate-type hull form were carried out to obtain data on extreme motions and capsizing in critical wave conditions. To control the conditions leading to these events, all tests comprised regular waves of moderate to extreme steepness. A primary objective of these tests was to generate data that would be suitable for the vallidation of a time domain, large amplitude ship motion simulation program.

The paper discusses details of the experimental setup and test procedures, as well as physics associated with some observed extreme motion events in astern wave conditions:

- Periodic surging and surfriding
- Broaching
- Extreme rolling
- Capsizing

Test conditions leading to surfriding show that a ship could attain transient speeds that exceed not only its calm water speed, but also the wave phase speed; bow submergence causes a significant increase in resistance and subsequent deceleration. A numerical model, which makes use of linear wave theory, underpredicts wave celerity and hence surfriding speeds for steep wave conditions.

KG was varied to simulate three load conditions in the model tests: (1) typical Full Load condition, (2) Marginal GM condition that just meets the navy stability criteria, and (3) a Failed GM condition. No capsizes occurred for the first two load conditions. Tthe most extreme rolling and capsizing occurred at high speed ($Fn \geq 0.3$) in stern quartering waves.

An important observation is that a ship in steep stern quartering waves can experience large amplitude fluctuations in speed, both in longitudinal and transverse directions, and mean drift to leeward can be significant. Large variations in speed contribute to asymmetric rolling, as the ship spends more time (at higher speed and with reduced transverse stability) in a wave crest than in the wave trough.

From a validation perspective of a numerical simulation model, some of the conclusions for large amplitude motion tests in following and stern quartering waves are as follows.

- The autopilot should be switched off during roll decay tests at forward speed to avoid roll-yaw coupling.
- The measurement of ship velocity in longitudinal and transverse directions provides useful information on speed behavior and instantaneous drift angles.
- The measurement of earth-fixed ship position provides useful data on ship track and mean drift.
- Knowing the characteristics of the incoming wave system and earth-fixed ship position, enables one to determine the wave with respect to the ship model at any time instant.

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